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NUMERICAL SIMULATION OF THE "KULLUK" IN PACK ICE CONDITIONS

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ABSTRACT
Vessel stationkeeping in moving pack ice is an important issue for floating production systems that are being considered for use in ice-covered waters. In order to be effective, it is important that the loads generated by moving pack ice are within the range of the capabilities of their mooring systems. To better understand loads on moored vessels in ice, the full-scale data from the Kulluk, which was a floating drilling unit used in the Beaufort Sea, were analyzed and summarized for different conditions. A new two-dimensional model of ice-structure interaction was applied and compared to the full-scale Kulluk data. One base case was selected and a good correlation was obtained by adjusting the mechanical properties of the pack ice in the numerical model. The analysis shows that this model, with suitable calibration, can be used to predict loads on a moored vessel over a wide range of pack ice conditions, such as those found in the Grand Banks of Canada, the Pechora Sea or offshore Sakhalin in Russia.

INTRODUCTION
The "Kulluk" was a conical drilling unit that was used for exploratory drilling in the intermediate to deeper waters (20m - 50m) of the Beaufort Sea during the 1980's and early 1990's. It was designed as a "second generation" drilling system to significantly extend the open water season, by beginning drilling operations in the spring break-up period and continuing until early winter. It drilled twelve wells at a variety of locations.

During its deployment in the Beaufort Sea, it was exposed to a wide range of moving pack ice conditions. This is the only moored vessel, on a worldwide basis, that has stationkept in a "near full spectrum" of pack ice, from low concentrations of thin ice to high concentrations of rough first-year and multi-year ice. The loads on the mooring lines were monitored and this information provides a unique data set of the forces of a moored vessel in pack ice conditions (Wright 1999).

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Stationkeeping in moving pack ice is an important area of ice engineering in many different applications. For example, on the East Coast of Canada, the Terra Nova development will soon begin using a Floating Production Storage and Offloading (FPSO) system that will have to stationkeep, on occasion, in moving pack ice conditions. In other ice-covered regions such as the Beaufort Sea, the Pechora Sea and offshore Sakhalin, proposals have been considered to load tankers in moving pack ice conditions from offshore terminals. Thus, this topic has important implications in ice engineering for many ice-infested offshore regions.

The data from the Kulluk in the Beaufort Sea are extremely valuable and cover a wide range of ice conditions. However, the results are vessel specific and they do not cover the full range of situations that could be encountered in a moving pack ice scenario. A two-dimensional numerical model, which is based on a "Particle in Cell" approach, has been developed that can extend the range for predicting loads to other vessel shapes. In this paper, the loads on the Kulluk are briefly described. Then, the numerical model is briefly presented, and the results of different full-scale situations are presented.

FULL-SCALE KULLUK DATA

The Kulluk had deck and waterline diameters of 100 m and 70 m respectively, an operating draft of 11.5 m, and a displacement of 28,000 tonnes. It had a unique downward sloping circular hull which failed the oncoming ice in flexure at relatively low force levels, and an outward flare near its bottom, to ensure that broken ice pieces cleared around it and did not enter the moonpool or become entangled in the mooring lines (see Figure 1). The vessel had a strong radially symmetric mooring that, in combination with its circular shape, provided an omni-directional capability to resist ice and storm wave forces. The mooring system was comprised of twelve 0.09 m wire lines and was capable of resisting relatively high ice forces. Ice management was a very important factor in enhancing the Kulluk's stationkeeping performance in ice. Typically, the Kulluk was supported by several CAC 2 icebreakers during its Beaufort Sea operations in heavy pack ice conditions. These icebreaking vessels broke the ice updrift of the Kulluk into small fragments, which were typically 10 to 30 m in diameter.

The loads on the mooring lines were measured during the Kulluk's deployment. Wright (1999) has summarized the loads and categorized them according to the ice conditions. Figure 2 shows a plot of the measured full-scale loads as a function of the ice thickness, for ice concentrations of 0.9 (i.e. $9/10^s$ coverage) and higher. For this sub-set of the data, there was good ice management but relatively poor clearance around the Kulluk. In these situations, there was a "tightness" in the pack ice, which resulted in the formation of an updrift rubble wedge at the structure (see Figure 3). Note that, although there is scatter, there is a definite trend of increasing load with increasing thickness. Wright has characterized the upper bound load (L_p) as a linear relationship with thickness (h) as (see Figure 2):

$$Lp\ [MN] = 0.86h\ [m] + 0.91 \qquad (1)$$

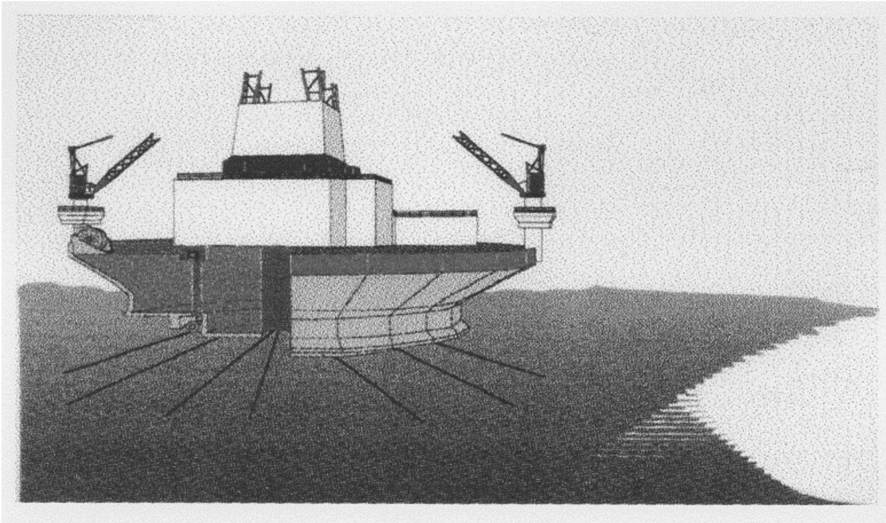

Figure 1 Illustration of the Kulluk showing its key design features.

NUMERICAL MODEL

The two-dimensional numerical model used in the present study was developed by Sayed et al. (2000). The model captures the salient features of several scenarios of ice-structure interaction. For example, ice thickness build-up and moving ice edges as well as the formation and evolution of leads can be simulated. The model also has the flexibility to include appropriate formulations of ice rheology such as the Mohr-Coulomb yield criterion. An overview of the main approach is given here. Details of the formulation of the model, however, cannot be adequately covered because of space limitations. For those details, see Sayed et al. (2000) and Barker et al. (2000).

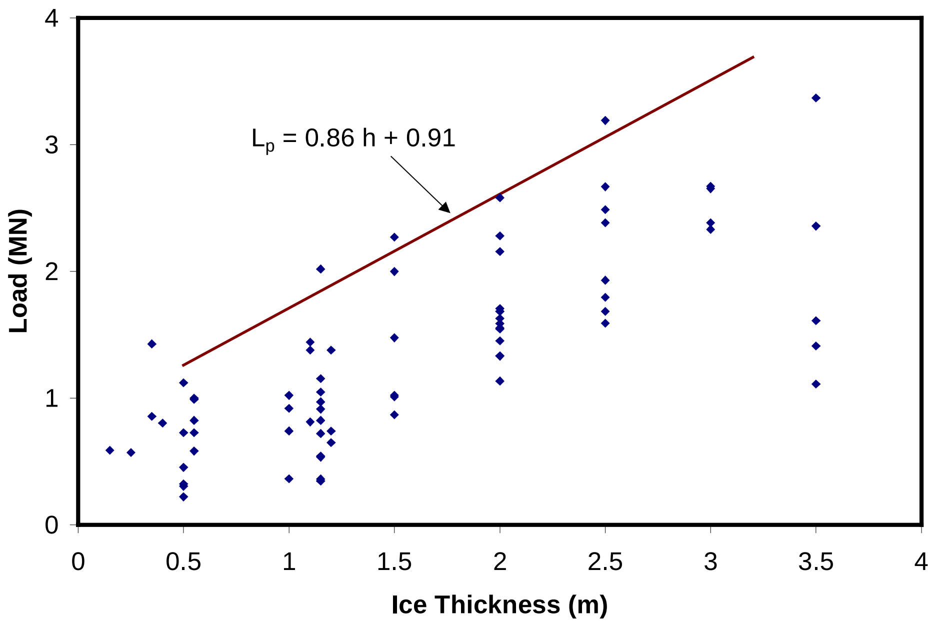

Figure 2 Measured loads on the Kulluk in tight managed ice with poor clearance and updrift rubble wedge (after Wright 1999).

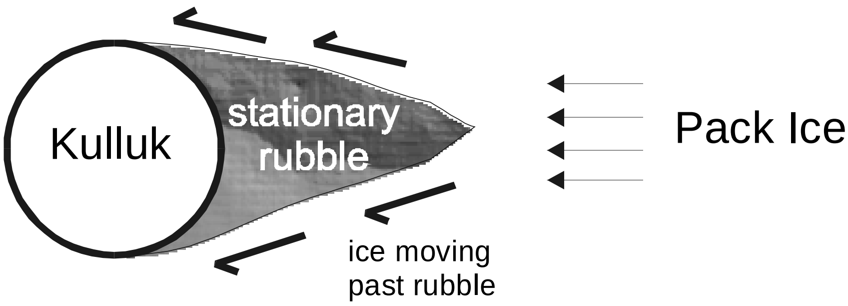

Figure 3 Schematic of updrift rubble wedge at Kulluk in tight pack ice (after Wright, 1999)

The main features of the model include a plastic yield rheology, a Particle-In-Cell (PIC) approach for ice advection, and an implicit solution of the governing equations. The behaviour of broken ice covers has always been considered to follow a cohesionless Mohr-Coulomb yield criterion. This intuitive assumption is based on the discrete nature of the ice cover and observations of deformation modes that resemble those of coarse granular materials. The idealized rigid-plastic rheology is implemented in the numerical model using a viscous plastic formulation (Hibler, 1979). For the cohesionless Mohr-Coulomb yield condition, material properties are expressed in terms of an angle of internal friction, ϕ, which accounts for the frictional *strength* of the material. The numerical implementation of the viscous plastic model also includes a compressibility formula. That formula relates the mean normal stress (or pressure) to ice concentration (or aerial coverage). A parameter, P*, is used to express the compressibility of the ice cover (see Sayed et al., 2000).

In the present model, according to the PIC approach, an ensemble of discrete particles represents the ice cover. Each particle has a volume, which remains constant. The area of each particle may be reduced, and the thickness accordingly increases, as pressure increases. This situation would correspond to increasing ice thickness. Thus, ice pile-up and ridging can be accounted for. Note that ice growth and decay are not a concern for the present problem.

The linear momentum and rheology equations govern the movement and deformation of the ice cover. Particles are individually advected in a Lagrangian manner. Therefore, a continuity equation is not needed. The linear momentum equations include the inertial terms, water drag, and gradient of the internal ice stress. The momentum and rheology equations are solved using an Eulerian (fixed) grid. The semi-implicit finite difference method of Zhang and Hibler (1997) is used.

TEST CASE

For the test case, records in tight, managed ice were extracted from the original Kulluk database into an Excel spreadsheet. For these cases, there was good ice management but poor clearance around the structure with the formation of a rubble wedge upstream of the structure (see Figure 3). A base case was selected that had the following properties: mean ice thickness (h) of 1.5m, ambient ice drift speed (v) of 0.2m/s and local ice concentration (c) of 0.95.

Although several laboratory studies examined the properties of ice rubble, the results cannot be extrapolated to the larger scale of the present ice cover. Therefore, the values of material properties had to be determined by matching the numerical predictions and field observations of a well-documented case. Model performance is subsequently tested by comparing predicted peak loads, using those material properties under a range of conditions, to observations. Preliminary runs examined a range of values of the two parameters that determine material properties. From those runs, and previous results (Sayed et al. 2000), a value of 25 kPa for the compressibility parameter, P*, was found to produce the appropriate behaviour. The runs also examined the influence of the angle of internal friction, ϕ, on the predicted load. The resulting load on the vessel is plotted versus time for different values of ϕ in Figure 4. The runs show that a ϕ of 27° results in a good agreement between the predicted and measured peak loads (predicted peak load = 2.27 MN, and measured peak load = 2.20 MN).

Four other representative runs were performed, varying the velocity and thickness parameters, creating a small parametric study. The ϕ, P* and concentration values remained the same throughout these runs. These test runs and their resulting peak loads may be found in Table 1.

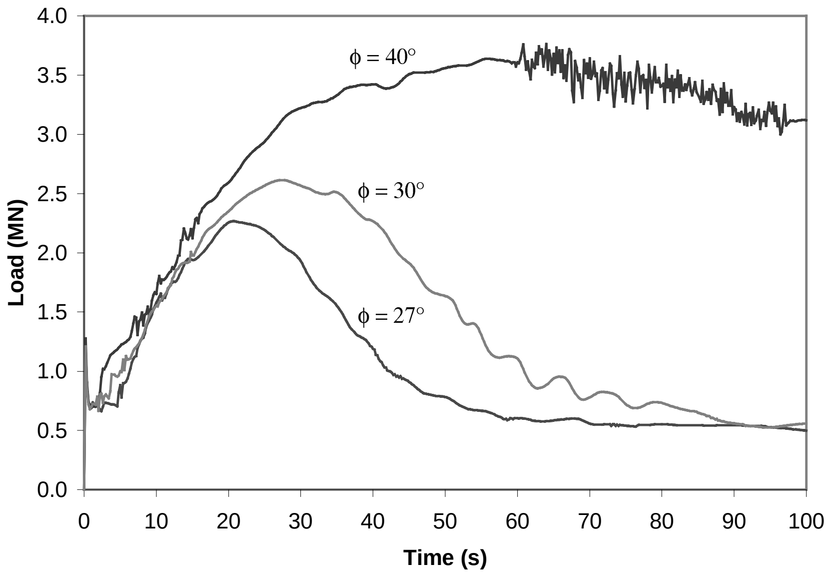

Figure 4 The effect of ϕ on numerical peak load

Figure 5 shows the effects of ice thickness and velocity on the peak numerical load. Also plotted in Figure 5 are the full-scale peak loads for various ice thickness. There is a linear dependency of load upon thickness, similar to Figure 2. Also, the three data points at h=1.5m represent three different velocities. In this case, the model shows a linear dependency upon velocity. This dependency is not observed in the full-scale data over the range of full-scale velocities and due to the scatter in the full-scale data. The model dependency occurs as a result of the momentum of the pack ice and produces a relationship where load increases with increasing velocity, as one would expect.

Table 1 Numerical program input data and peak loads

	Velocity (m/s)	Thickness (m)	ϕ (°)	Concentration	Full-Scale Peak Load (MN)	Numerical Peak Load (MN)
Base case	0.2	1.5	27	0.95	2.20	2.27
Run1	0.2	1.0	27	0.95	1.77	1.52
Run2	0.2	2.0	27	0.95	2.63	3.10
Run3	0.1	1.5	27	0.95	2.20	1.71
Run4	0.3	1.5	27	0.95	2.20	2.58

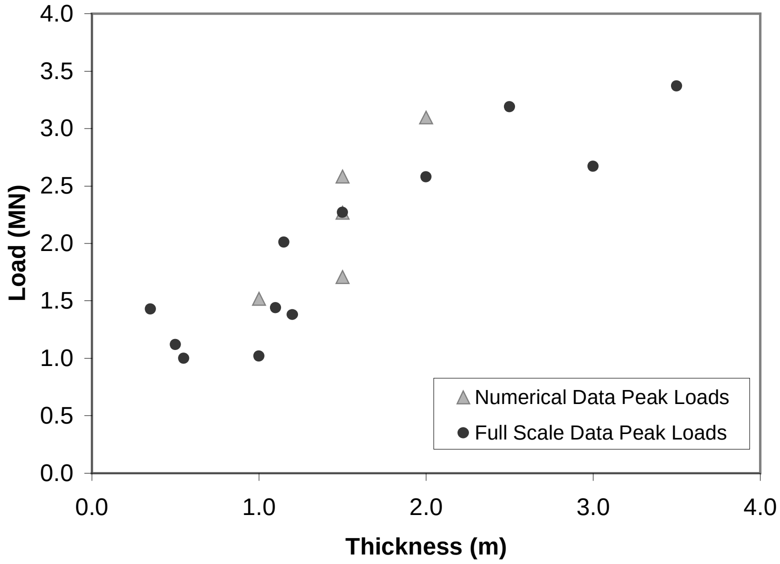

Figure 5 Numerical load versus initial ice thickness, for ϕ=27°, c=0.95

The output from the numerical program simulations produces force-time data as well as ice thickness, concentration, pressure and velocity data at specific time steps. For example, Figure 6 shows a "snapshot" of the ice concentration around the Kulluk for the base case, 300 seconds after the start of the run. This can be compared to the schematic of the rubble wedge build-up around the Kulluk that was experienced in the field (Figure 3), after Wright (1999).

CONCLUSIONS

The full-scale data that was examined was obtained from conditions involving tight, managed ice. The upper bound to the peak loads observed at the Kulluk in these conditions is defined by the equation L_p=0.86h+0.91, as developed by Wright (1999). The numerical model used for this study showed good agreement with the full-scale data. Using ϕ=27°, a linear relationship was observed between thickness and peak load. A linear relationship with ice velocity was found, but not indicated by full-scale data. Future analysis using this technique can be used to obtain information on loads on moored vessels for a wide range of conditions.

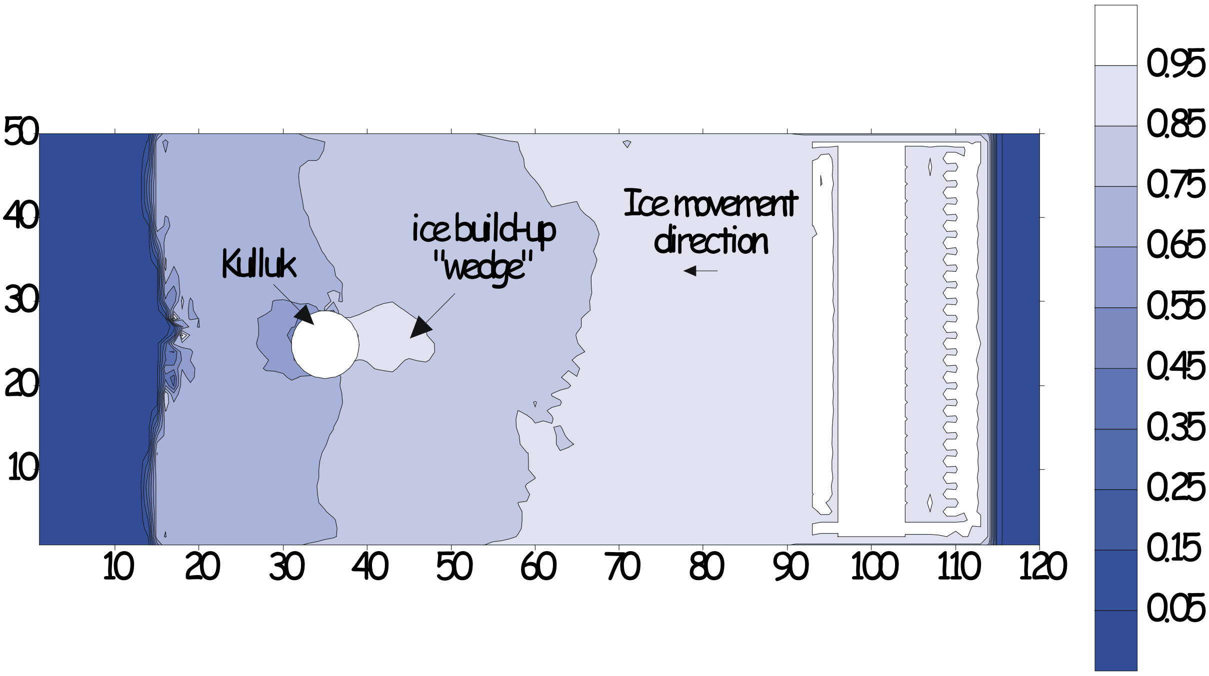

Figure 6 Ice concentration profile around Kulluk generated from a numerical simulation showing the ice build-up in front of the Kulluk.

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