MODEL COMPUTATION RESULTS FOR A FIRST-YEAR ICE RIDGE PENETRATING THE SEABED

S.A. Vershinin[1], P.A. Truskov[2], K.V. Kouzmitchev[3]

ABSTRACT

Theoretical model (A GOUGING MODEL FOR A FIRST-YEAR ICE RIDGE PENETRATING THE SEABED S.A. Vershinin, P.A. Truskov, and K.V. Kouzmitchev) was computed for pressure ice ridges of low recurrence probability (based on the statistics of hummock parameters observed offshore Sakhalin (Sandwell report for the Sakhalin II project).

Input data for hummocks of low recurrence probability

The thickness of hummock-forming ice rubble (5% exceedance probability), $h = 1$ m

The keel top width (mean rubble thickness = 1 m), $B_t = 62$ m.

The front face slope angle is 45 deg. (average over min. and max. values)

The keel depth (exceedance probability = 10^{-5} to 10^{-7}), $H_k = 31$ m

The hummock is 2 months old.

The level ice floe thickness
(1% exceedance probability, hummock age observed) = 1.2 m.

The hummock has been formed at a floe mean temperature of −5°C.

The ultimate bearing force of floe hummocking
(per meter of hummock width) $F_{lim} = 0.43\ P_{ult} = 0.5$ MN/m (Vershinin et al. 2003a)

The ice pressure ridge length is 100 m.

Ice floe velocity (1% exceedance probability), $V = 1$ m/s

Bottom soil data

Bottom soil is composed by fine-grained and medium-grained sands. We assume that the sand in the rampant prism has the same density as undisturbed soil (other density may be taken into account). The sand angle of internal friction $\phi = 32$ deg. and its angle of repose are assumed to be equal.

[1] Morneftegasproect, Moscow, Russia
[2] Sakhalin Energy, Moscow, Russia
[3] Rosneft, Moscow, Russia

The cohesion of undisturbed bottom soil is c = 5 kPa. The soil void volume ratio is ε = 0.64. The porosity of sand of natural occurrence is n = 0.3 to 0.45; calculations give 0.39.

Modeling the hummock keel by a 2-3 m wide punch, we assume the subgrade reaction of 1000 ton-force/m2 (the stiffness of springs modeling the yield of bottom soil and keel).

The bottom slope is 1 deg.

Hummock strength parameters

The cohesion, $C(z)$, of hummock's keel [in ton-force/m^2] is determined by fitting the keel strength data by a model of frozen ice rubble keel treated as a discrete medium [2] with an angle of internal friction of 20 deg.

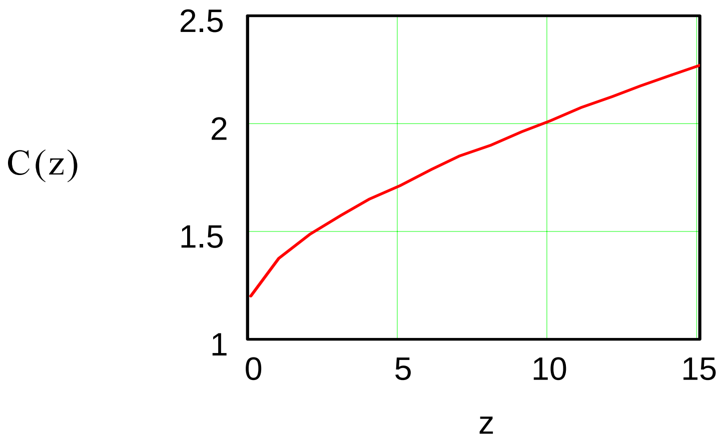

Fig. 1. Cohesion $C(z)$ [in ton-force/m^2] of hummock keel as a function of distance (z) from the keel bottom

In this model analysis, we assume an axially symmetric hummock of height H_k = 31 m. A symmetric truncated-cone geometry is equivalent to the prismatic geometry provided both hummock models have identical face slopes of 45 deg. (measured as a local slope in the vertical section) and volumes. The diameter of equivalent hummock (keel top section diameter D_t = 84 m, and base diameter D_b = 22 m, and volume of 76,240 cubic meters).

Calculations indicate that the hummock of a given keel strength crushes layer by layer (in 6 steps with layer height of 2h) when it penetrates into the seabed.

Until it stops completely (step 7) the hummock suffers a shear of 12-m thick layer of its body in the bottom part. At each shearing step, the hummock velocity decreases down to a certain value; but having lost a certain layer of ice, the hummock gains speed to the initial velocity V. We assume that the resistance of the seabed falls to zero; otherwise, the initial velocity could be recovered. The gouge bottom profile is a step geometry, changing from zero depth to a maximum in steps. The results of the calculations are summarized in Table 1.

In horizontal shear, the slope of bottom soil wedge a is half or one third as large as the angle of passive knockout wedge sliding due to Coulomb $(\pi/2-\varphi/2)$. This proportion is explained by the effect of ice-on-ground friction and loading of soil rampart knocked out of gouge.

Table 1. Calculations of hummock keel – seabed interaction

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
Gouge depth (H), m	0.46	0.54	0.59	0.77	0.71	0.73	0.75
Gouge width (B_t), m	22	26	30	34	38	42	46
Gouge length (S), m	27	30	33	45	42	43	47
Hummock's center of mass uplift, cm	24	28	46	58	64	83	88
Hummock roll angle (ψ), radians	0.016	0.019	0.017	0.017	0.15	0.17	0.011
Initial velocity (V), m/s	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Finite velocity (V_s), m/s	0.58	0.40	0.32	0.20	0.11	0.01	halt
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
Horizontal component of soil knockout wedge (F_r), t-f	646	1010	1255	1658	2260	2928	3380
Resistance to hummock gouging (horizontal component) (P_{ult}), t-f	869	1214	1554	2296	2667	3654	4129
Hummock's vertical load on soil due to overturning roll on keel footprint (F_c), t-f	288	482	582	751	742	945	765
Soil contact area ($L \times D_t$), m^2	28	36	45	55	76	72	83
Friction force of hummock bottom on soil ($F_c \times f$), ton-force	201	337	407	526	520	661	535
Average contact pressure over the keel footprint (distribution over triangle) (P_n), t-f/m^2	11	13	13	14	12	15	10
Minimum ultimate normal resistance of soil over keel bottom (P_n*), t-f/m^2	18	22	24				
	Feasible shear in a narrow zone			30	30	30	30
Keel crushing pattern	Shear	Shear	Shear	Shear	Shear	Shear	none
Keel height after crushing (H_k), m	29	27	25	23	21	19	19
Hummock mass with entrained water, M, ton-force s^2/m	7773	7673	7529	7344	7113	6830	6491
Resistance to horizontal shear (P_{sh}), t-f	847	1286	1766	2351	2982	3762	4552
Maximum bearing (floe drive) force on the hummock $F_{lim}[1-V(S)/V]^2$, t-f	818	1624	1954	2571	3347	4141	4225
Maximum ice bearing force(F_{lim}), t-f	818	1624	1954	2571	3347	4141	4225

This model was computed for the energy integral of equation. The results were compared with the solution of the differential equation of hummock motion. The results differed at most by 5%. Figure 2 illustrates the solution of the differential equation for step 1 of hummock penetration into bottom soil.

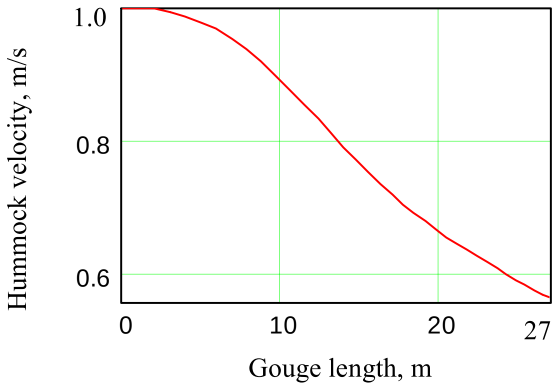

Fig. 2. Hummock velocity [m/s] in gouging computed for step 1 of keel bottom shear over a gouge length of 27 m and gouge depth H = 0.46 m

Once the bottom layer of the keel is sheared off, the resistance to hummock motion decreases and the hummock velocity increases as driven by floe bearing forces. This process occurs at each step of keel shear and brings about a self-oscillatory motion for hummocks interacting with the seabed (oscillation about some center of mass moving at an average speed).

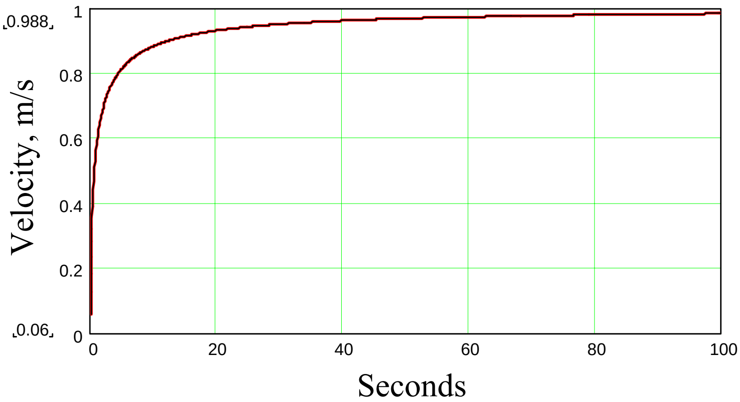

Fig. 3. Recovery of initial hummock velocity after shearing of keel's bottom layer

Assuming an unlimited strength of the keel ice, we estimate the upper bound for gouge length and width at step 1 of gouging

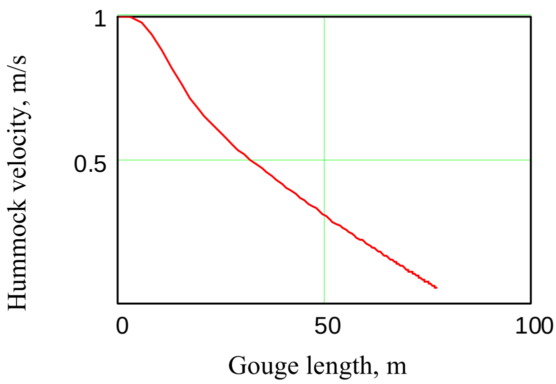

Fig. 4. Hummock velocity [m/s] in gouging at step 1 computed for an unlimited strength of the keel bottom part for a gouge length of 80 m at the moment of halt as driven by floe bearing limited by hummocking of 1.2-m thick floe ice

For a bottom slope of 1 deg., the gouge depth is H = 1.43 m.
The maximum feasible length and depth of a gouge may be obtained by assuming an unlimited strength of hummock's keel and an ultimate bearing force of ice floe corresponding to the strength of 1.2-m thick ice (Vershinin et al., 2003b). Derived as a function of keel top section width D_t, it is

$$\max F_{\lim} = 116.3 \cdot D_{\mathrm{t}}$$

Under this assumption, the hummock digs a gouge about 150 m long and 2.7 m deep.

CONCLUSION

Hummock penetration into the bottom proceeds in cycles as the keel crushes under bottom soil resistance. A penetration model should not overlook the friction of the keel against the bottom soil.
The gouge depth estimated on the condition of unlimited keel strength may be 1.5-2.0 times as large as the gouge depth estimated with allowance for keel bottom destruction under the effect of gouging forces. The maximum feasible gouge depth is about 2.5 m.

REFERENCES

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