DYNAMICS OF THE ICE SHEET INTERACTION WITH THE SLOPING STRUCTURE.

Karl Shkhinek, Ekaterina Uvarova
St.Petersburg State Technical University,Russia.
195250,St. Petersburg, Politechnitcheskaya 29, CEF,
(812)-247-59-54, Shkhinek@cef.spbstu.ru

ABSTRACT

Quasi-static approach is used usually in the problem of ice/sloping structure interaction. This approach is valid if ice speed is not too high. But ice speed in some regions (for instant at Sakhalin area) can be rather high. In this case ice sheet edge can not slide with sufficiently high velocity along the structure surface due to inertia, friction and rubble influence. Therefore ice sheet edge sliding along the structure surface is accompanied with its longitudinal compression. This compression induces longitudinal stress what changes whole pattern of interaction and loads level. Dynamics of ice interaction with slopes is considered in this paper. Results of analytical solution and numerical experiments are compared with physical experiments of Frederking and Schwarz, Law and Williams.

INTRODUCTION

Ice interaction with slopes or structures with the inclined planes was investigated in many of work. It is assumed that use of slopes for offshore structures is especially effective because they reduce the ice load.

Many experimental (Afanasiev, 1972; Edwards and Croasdale, 1977; Frederking and Schwarz, 1982; Lau and Williams, 1991; Lindholm et al, 1993; Maattanen, 1986; etc) as well as analytical (Croasdale, 1980; Croasdale and Cammaert, 1993; Frederking and Timco, 1985; Izumyama et al, 1993; Nevel, 1972, 1992; Ralston, 1977, 1979, etc) investigations deal with the problem of ice interaction with slopes or sloping structures. But still even in static there is no unique approach to define loads and scatter of results of different approaches is quite large.

At the present time methods suggested by Croasdale (1993), Ralston (1977, 1979) and Nevel (1972,1992) received the widest application to define ice loads on sloping structures. These methods are recommended by Codes of different countries. All these work consider quasi-static solution, but this solution can be considered only as a first approach. Dynamics (in particular the ice sheet velocity) influence the load was experimentally investigated in the recent years in work of Alexeev and Karulina (1998), Hoikkanen (1985), Frederking and Schwarz (1982), Kato et al (1999), Lau et al (1998, 1991). They show that effect of dynamics can be significant. Really ice sheet in static can slide along the slope without longitudinal deformation. So it will easy bend and fail by flexure. But the sheet inertia, friction, rubble on the slope will restrict sliding speed of the sheet edge in dynamics. Therefore if ice sheet moves with relatively great speed and if the slope inclination to the horizon is not low then the sheet will be additionally compressed in longitudinal direction. This phenomenon leads to load increase and can change the failure mode from flexure to compression.
The goal of our work was in investigation of the ice sheet speed influence on load on sloping structures.

STATEMENT OF THE PROBLEM

The process of interaction of (ice sheet)/(slope of limited length) consists of several stages. Radial cracks are caused by limited penetration of the structure on the first stage. The cracks confine the investigated part of the ice sheet. This part is considered later as a strip that is pushed on the slope by the whole ice sheet. It is assumed that the strip can undergo bending and longitudinal deformation. The next stage of interaction is formation of circumferential cracks, connected with bending of the strip during its sliding up the slope. According to experimental investigations of Hoikkanen (1985), Izumyama et al (1991), Saeki et al (1979) ice load onto the construction at the moment of these cracks development is much more than one corresponding to radial cracks formation. The third stage of interaction is subsequent division of the strip on pieces during the interaction. Initially the strip is long and easily can fail by bending on the two rather long pieces. The loads corresponding to this process are quite small. Later the piece at the contact with the structure breaks on the smaller pieces which form a rubble near the structure and at it surface. The maximal load usually corresponds to ice the piece interaction with the rubble and pushing it along the structure surface.

2D solution in vertical plane is considered in this paper. Similar approach in static is used quite often and gives satisfactorily results for small drift speeds. The ice strip with bending R_f and compressive R_c strengths is pushed against the slope with a constant horizontal speed v. It is proposed that this strip connected by a hinge with the sheet. Longitudinal deformation of the sheet at the contact with the strip is assumed to be much smaller than longitudinal deformation of the strip itself. So the sheet is considered as incompressible whereas the strip-compressible. Change of the form of the strip due to bending is neglected but all forces what induce bending moment and corresponding failure mode are considered. A reversion motion is investigated**.**

That is the following problem is examined (Fig 1): absolutely rigid plane inclined to the horizon at the angle α moves with the constant horizontal velocity v against the floating ice strip attached by the hinge to the semi-infinite sheet. Some rubble after previous interactions can be located on the structure surface. Maximal height z_r of the rubble is fixed. The ice strip is characterised by the length l_{ef}, width b and thickness h. Ice is considered as homogeneous elastic material with modulus of elasticity E and Poisson's ratio μ. The strip rotates at the angle φ around the hinge when the inclined plane moves, and can be compressed (longitudinal deformation ε can form). At the time moment assumed as the beginning of interaction ($t=0$) the longitudinal deformation and the angle of rotation are equal to zero.

Determination of the initial length l_{ef} in dynamics represents an independent task. This length is not a constant and can change its value depending on several parameters, for example, of mass of rubble on the structure slope, ice speed, etc. Experimental measurements demonstrate that this length can vary in wide range and should be considered as a random variable.

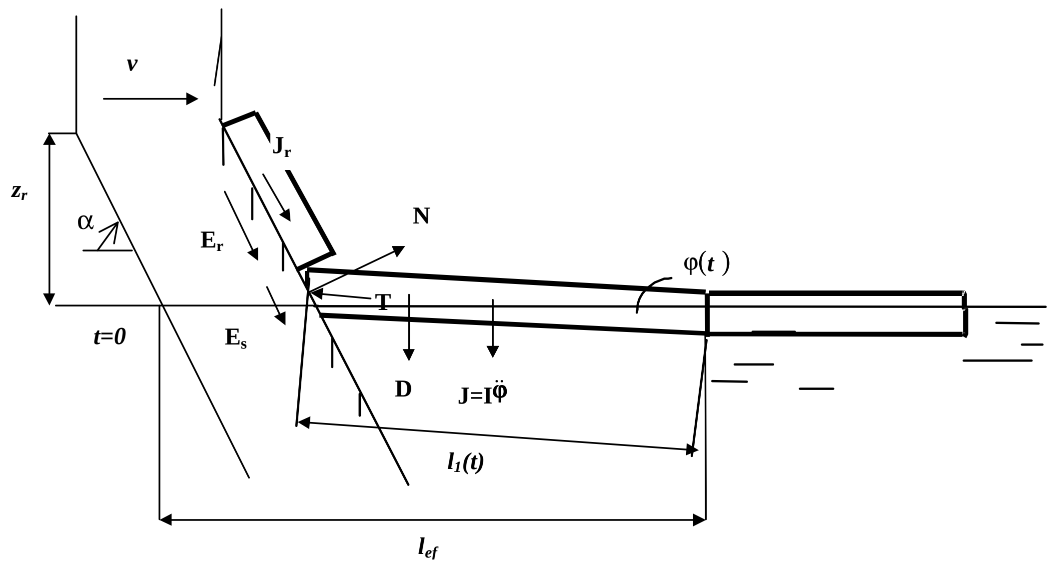

Figure 1.Scheme for computation.

The initial length as the first approach can be defined from the static solution. For example it can be assumed as the distance x_1 to the first crack that forms in the floating semi-infinite elastic beam in result of vertical displacement of its end. This distance is equal $x_1 = \pi\lambda / 4$ (where λ - characteristic length),

$$\lambda = \sqrt[4]{\frac{Eh^3}{12(1-\mu^2)k}} \qquad (1).$$

During the consequent numerical modelling value l_{ef} was varied in wide ranges.

THE MAIN STAGES OF DYNAMICS OF ICE/SLOPE INTERACTION.

In the course of the working out solution of ice/sloping structure interaction the following stages were considered:

- the initial stage of interaction when the strip moves against the slope and due to bending failure is divided on two pieces. These pieces are in the hinge contact. The far from the structure piece falls down to water after the crack formation; the nearest piece continues sliding along the surface, but position of the nearest part of the strip changes after failure crack formation, because both parts of the strip are in the hinge contact.
- subsequent motion of ice, rotation and sliding of the nearest to the structure piece of the strip and its division on smaller pieces;
- rubble formation on the slope and the ice piece interaction with rubble.

To define the strip movement, the stress in ice, the failure instant, the load at this instant etc. the differential equation of the strip and its pieces rotation was considered. The following forces were taken into account (see Fig.1):

- the inertia of the ice strip (or its piece) rotation, *J*;
- the deficit of buoyancy force due the strip(piece) moving up, *D*;
- the longitudinal force induced due to the strip (piece) compression during the structure motion, ***T***. This force consists of two parts: one is connected with projection on the longitudinal direction of the ice weight excess (due to deficit of buoyancy) and another with the piece compression (reason of this force formation was explained before).
- the damping of the ice strip (piece) oscillation, *De*;
- the force, exerted by the ice strip edge on the structure surface, *N*;
- the inertia of rubble located on the sloping surface, J_r;
- the forces due to the rubble and the ice sheet edge friction along the structure surface, E_r and E_s.

Determination of the mass of the ice rubble on the structure surface is connected with some difficulties: when the ice piece reaches the construction neck, it rotates and falls down, loading part of the ice beam near the structure. This can lead to additional uncertainties during the numerical modelling. To simplify consequent calculation it was supposed, that the rubble is located over the whole height of the inclined plane and the thickness of the rubble layer on the structure surface is constant and twice of a level ice.

As it was mentioned above, the process of interaction consists of some successive stages. Rotation equation on any stage (i+1) can be written in the form:

(2) $$\ddot{\varphi}_{i+1} + 2n\dot{\varphi}_{i+1} + w^2\varphi_{i+1} - Rt + c = 0$$

where *n*, *w*, *R* and *c* – constants, depending on l_{ef}, *b*, *h*, α, *v*, *E*, μ, γ_w, ρ_i (ice density), *f* (coefficient of dynamic friction of ice along the structure surface), η (porosity of the ice rubble on the slope).

Initial conditions at each step:

(3) $$t_{i+1}=0 \qquad \varphi_i = \varphi_0 ,$$

(4) $\dot{\varphi}(t=0) = f(v,\alpha,l_{ef})$,

where φ_0, $f(v,\alpha,l_{ef})$ are angle and velocity of rotation at the end of the foregoing step.

Integrating the equation (2) and substituting initial conditions (3,4) become possible to define angle of rotation at any time moment of interaction and correspondingly to estimate values of the horizontal N_h ($N_h = N\sin\alpha$) and the vertical N_v ($N_v = N\cos\alpha$) components of ice load onto the sloping structure.
The failure criterion of ice is used in the form:

(5) $$\sigma_{1,2} = -\frac{T}{bh} \mp \frac{6M^{max}}{bh^2},$$

where M^{max} – maximal bending moment in any section of the strip, $\sigma_{1,2}$ -maximal and minimal stress in the strip's cross-section (tensile stresses are positive). Equation (5) was checked step by step for every cross-section of the strip at the each time instant. The time moment, when the maximal stress in some section of the beam becomes equal to the compressive or tensile ice strengths, defines the failure instant. The load at this instant reaches intermediate maximum corresponding to the considered step.
The scheme described above was used for all stages of interaction. Subsequent the ice strip division, sliding, pushing the rabble, etc. repeated several times. The shorter is the piece (in result of division) the more is the stress component induced by compression. Cyclically repeating described above calculation procedure for the newly formed ice piece gives possibility to define absolutely maximal load on the construction and corresponding the ice failure mode. The following conditions were used as a criterion for the finalisation of the process of calculation:

1) the angle of rotation of the ice piece exceeds 10°
2) the length of the piece reached about 3 its thickness.

THE RESULTS OF CALCULATION

To run the numerical modelling the special computer program was developed on the base of the described above solution. This program gives possibility to determine the mode of ice failure and value of the maximal horizontal (vertical) load on the slope during all stages of interaction. The ice properties and the structure form were varied in the following ranges:

- the angle of slope inclination to the horizon α =30°-70°; ice thickness h= 0.5-2 m; the ice unconfined compressive and tensile strengths R_c =0.5-2 Mpa, R_f =0.3 R_c respectively; the ice drift velocity v = 0.05-0.8 m/s; the ice density and the Poisson's ratio 900 kg/m^3 and 0,3 respectively; the modulus of elasticity of the ice E= 5 Gpa; the coefficient of ice/slope friction f=0.2; the porosity of the ice rubble on the structure slope η =0.2, the damping of oscillations-5% of the critical.

It was ascertained in the computation that the effective length influences the process of ice/sloping structure interaction and the loads for the same other input data. That's why calculations were done for the 3 different values of the effective length derived by Eq.(1): $l_{ef} = 1.58\lambda$, $l_{ef} = \lambda$, $l_{ef} = 2\lambda$. During the analysis of the results the largest load value observed for different l_{ef} and the ice failure mode corresponding to this load (compression, flexure) were taken into account. In result of numerical modelling ice failure modes map and dependencies for ice load determination were suggested.

Initially the modelling of the ice/sloping structure interaction was performed without consideration of the ice rubble existence on the slope in order to define later the rubble influence on the ice load value and the ice failure mode. The ice failure modes map represented as the function of non-dimensional parameters $\frac{v^2}{gh}$ and $\frac{\rho_i gh}{R_c}$ (where g - the gravity acceleration) is shown in Fig.2. Input data in the area above each curve correspond to compressive failure for slope suitable to this curve. Otherwise to flexure failure. Increase of ice thickness or ice velocity leads according to this figure to transition ice failure mode to compression instead of flexure for the same other parameters. The more is the angle of structure inclination to the horizon the more is the probability of ice failure by compression.

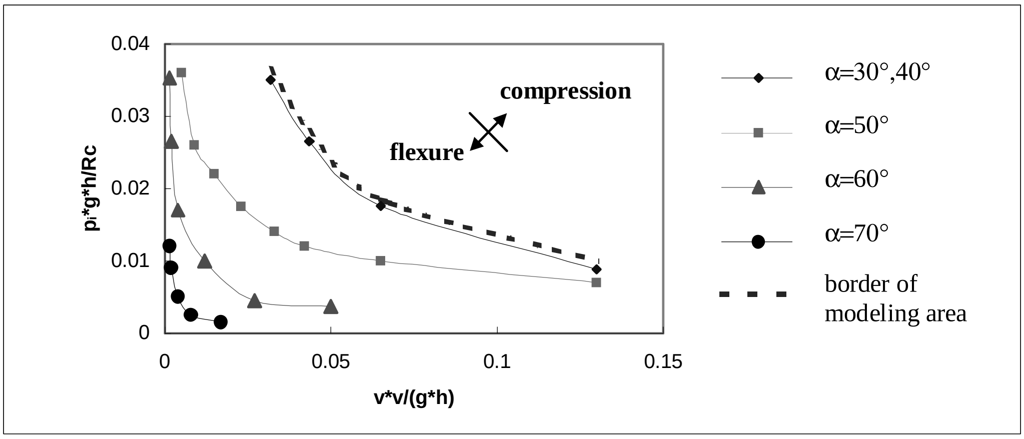

Figure 2. Ice failure modes map. Each curve represents the border of failure zones by compression and flexure for particular angle of the slope inclination.

In the result of the numerical modelling the ice load N_h dependence on the ice characteristics and the structure parameters can be represented by function of the non-dimensional parameter $N_h /(R_c bh)$ as the non-dimensional combination $\sqrt{\rho_i E} v / R_c$ for the given value of α.

α =30° $N_h /(R_c bh)$ =0.01+0.035$(\sqrt{\rho_i E} v / R_c)^{0.55}$

α =40° $N_h /(R_c bh)$ =0.02+0.07$(\sqrt{\rho_i E} v / R_c)^{0.55}$

α =50° $N_h /(R_c bh)$ =0.04+0.14$(\sqrt{\rho_i E} v / R_c)^{0.55}$

α =60° $N_h /(R_c bh)$ =0.08+0.25$(\sqrt{\rho_i E} v / R_c)^{0.55}$ for $0.05<(\sqrt{\rho_i E} v / R_c)<2$

$N_h/(R_c bh) = 0.425(\sqrt{\rho_i E}v/R_c)^{0.07}$ for $2<(\sqrt{\rho_i E}v/R_c)<3.4$

$\alpha=70^o$ $N_h/(R_c bh) = 0.16+0.45(\sqrt{\rho_i E}v/R_c)^{0.55}$ for $0.05<(\sqrt{\rho_i E}v/R_c)<1$

$N_h/(R_c bh) = 0.61(\sqrt{\rho_i E}v/R_c)^{0.07}$ for $1<(\sqrt{\rho_i E}v/R_c)<3.4$

The results for the parameter $\sqrt{\rho_i E}v/R_c$ value equal to 0.053 (what corresponds in nature to small drift speeds $v\approx0{,}05$m/s), were considered as a quasi-static. Then ratio of the non-dimensional load $N_h/(R_c bh)$ at any $\sqrt{\rho_i E}v/R_c$ value to the non-dimensional load corresponding to quasi-static solution will define the velocity influence on the ice load – so called velocity factor k_v. Velocity factor dependence on parameter $\sqrt{\rho_i E}v/R_c$ for different angles of inclination is depicted in Fig.3. Figure shows that the ice load essentially depends on the drift velocity, and can increase several times at high velocities.

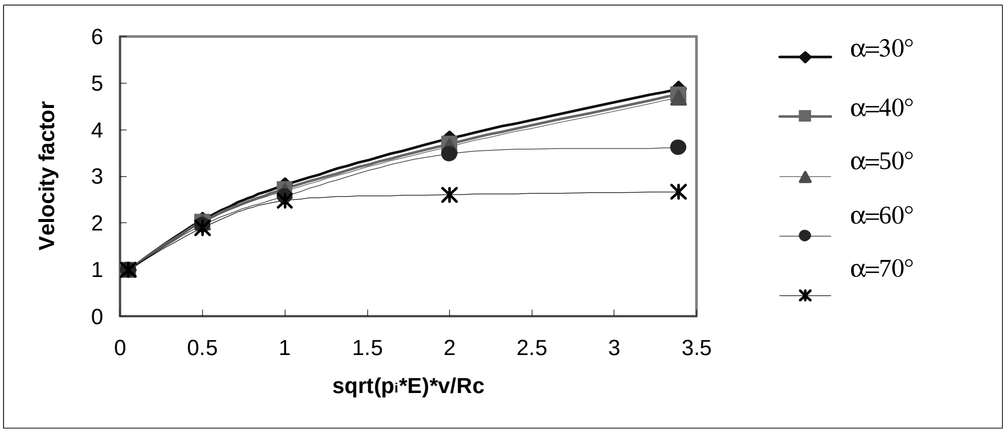

Figure 3. The velocity factor

Usually value of the velocity factor changes significantly when failure by flexure is replaced by compressive failure. This factor does not essentially depends on the angle of inclination for α=30-50^o and the parameter $\sqrt{\rho_i E}v/R_c$ variation at the whole considered range, because flexure is the main failure mode in this case. Significant increase of the velocity factor at high $\sqrt{\rho_i E}v/R_c$ is connected with influence of the longitudinal compression in Eq. (5). Due to this compression resistance to flexure failure increases. The velocity factor does not change for $\alpha=70^o$, $\sqrt{\rho_i E}v/R_c>1$ and $\alpha=60^o$, $\sqrt{\rho_i E}v/R_c>2$ because the compressive failure corresponds to all situations in this range. Actually great longitudinal compression in these situations enlarges the limit of flexure failure but do not change the limit of the compressive one. Therefore the whole pattern and the load remain the same independently on the ice speed.

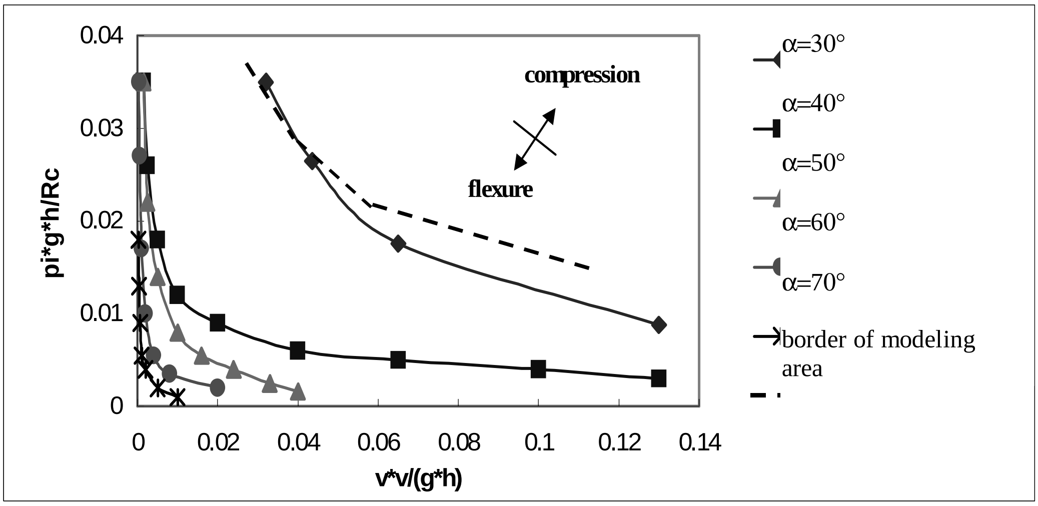

Figure 4. The ice failure modes map. The ice rubble exists on the slope.

Existence of the rubble on the slope essentially influences ice failure mode and ice load value. One can see comparing the ice failure modes maps given in Fig.2 and Fig.4.that the zone of failure by compression increases for the same combinations of the non-dimensional parameters $\frac{v^2}{gh}$ and $\frac{\rho_i gh}{R_c}$ if rubble is considered. Presence of ice rubble on slope also leads to the increase 1.5-2.0 times of the velocity factor for the same input data.

COMPARISON WITH THE RESULTS OF PHYSICAL EXPERIMENTS.

The velocity factors from the suggested solution and some physical experiments were compared. An example is demonstrated in Fig.5. The velocity factor defined on the base of experimental data of Frederking and Schwarz (1982) for the down-ward breaking cone and data obtained on the results of the numerical modeling are plotted in this figure. As the down-ward cone is considered, the rubble has not influence on loads. Therefore results of numerical experiments where the rubble was not considered are used.

The good correlation is evident. The same correlation was observed with some another experiments for instance of Lau and Williams (1991)

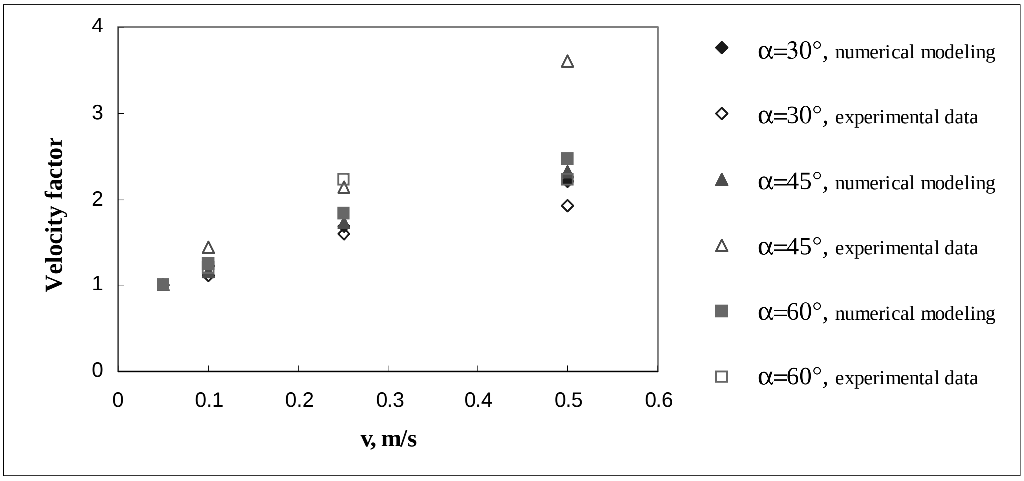

Figure 5. The velocity factor defined on the base of the experimental data given by Frederking and Schwarz (1982) and results of the conducted numerical modelling

CONCLUSION

Dynamics of ice / inclined plane interaction is considered in this paper. The analytical solution is obtained and wide numerical experiments are carried out. The results demonstrate possibility of transition ice failure mode from flexure to compression at high ice speeds and some of angles of slope inclination. This transition leads to loads increase. Especially significantly loads increase if rubble located on the slope. Influence of dynamics is characterised by the velocity factor equal to dynamic/static loads ratio. Dependence of this factor on the slope angle, velocity and ice properties is characterised by the special map obtained on the base of numerical experiments. Results of the suggested solution are in a good correlation with physical experiments of Frederking and Schwarz (1982), Law and Williams (1991) (do not shown here) and others.

ACKNOWLEDGEMENT

The work reported here was supported by the International Association for the Promotion of Cooperation with Scientists from New Independent States of the Former Soviet Union.(INTAS),Cooperation agreement INTAS-97-1665. Authors are grateful to this Association and coordinators of the project Dr.Karna (Finland) and Prof. Loset (Norway)

REFERENCES

Afanasiev V.P., Dolgopolov Y.V., Shvainshtein, Z.I. 1972. Ice Pressure on Separate Supporting Structures in the Sea. Proceedings of IAHR Symposium,.

Alexeev Y.N. and Karulina M.M. 1998, A Numerical Prediction Method for Ice Loads on Wide Sloping Offshore Structures. In the book 'Ice in surface waters', Shen (editor), Balkema, Rotterdam, pp.511-517.

Croasdale K.R. and Cammert A.B.(1993) Usovershenstvovanni method opredelenia ledovich nagrusok na naklonnie soorugenia. Proceedings of the RAO Conference. St. Petersburg, pp 158-165. (in Russian)

Edwards R.Y. and Croasdale K.R. 1977.Model Experiments to Determine Ice Forces on Conical Structures. Journal of Glaciology, 19(18), 660p.

Frederking R. Dynamic Ice Forces on an Inclined Structure. 1980, In: Physics and Mechanics of Ice, P.Tryde (Ed.), IUTAM Symp., Copenhagen, pp. 104-116.

Frederking R. and Schwarz J. 1982,Model Tests of Ice Forces on Fixed and Oscillating Cones. Journal 'Cold regions science and technology', vol. 6, pp. 61-72.

Frederking R.M.W., Timco G.W. 1985, Quantitative Analysis of Ice Sheet Failure Against an Inclined Plane. Proceedings of 4 OMAE Conference, v.2., pp.160-169.

Hoikkanen J. 1985, Measurements and Analysis of Ice Forces Against a Conical Offshore Structure. Proceedings of POAC Conference, vol.3.

Izumyama K. et al. 1991, On the Interaction Between a Conical Structure and Ice Sheet. Proceedings of POAC International Conference, vol.I, pp.155-166.

Izumyama K., Irani M.B., Timco G.W. 1993, Computation of Sheet Ice Floes on a Faceted Conical Structure. Proc. 12th Int. POACConf., vol.2, pp.517-526.

Kato S. et al, 1999. Study on Ice Loads Acting on Marine Structures. Proc. the 9th Int. Offshore and Polar Eng. Conf., pp. 483-490.

Lau M., Muggeridge D.B., Williams F.M. 1988.Model Tests of Downward Breaking Conical Structures in Ice. Proc. 7 OMAE Conference,

Lau M., Williams F.M. 1991, Model Ice Forces on a Downward Breaking Cone. Proc. POAC Conf., vol.I, pp.167-184.

Lindholm J.E., Makela K., Zheng C.B. 1993, Structure-Ice Interaction for a Bohai Bay Oil Production Project. Proc. 3th Int. Offshore and Polar Eng. Conf., pp. 538-547.

Maattanen M., Mustamaki K. 1985, Ice Forces Exerted on a Conical Structure in the Gulf of Bothnia. Proceedings of 'Offshore Technology Conference', pp.313-320.

Maattanen M,1986. Ice Sheet Failure Against an Inclined Wall. Proc. IAHR Symposium,.

Nevel, DE. 1972, The Ultimate Failure of Floating Ice Sheets. Proc. IAHR Symposium, pp.17-22.

Nevel D.E. 1992.Ice Forces on Cones from Floes. Proc. IAHR Ice Symposium,

Ralston T.D. 1977, Ice Force Design Considerations for Conical Offshore Structures. Proc. 4th Int. POA CConf., St.Johns, Newfoundland, vol.2, pp.741-752.

Ralston T.D. 1979,Plastic Limit Analysis of Sheet Ice Loads on Conical Structures. In: Physics and Mechanics of Ice, Per Tryde (Ed), IUTAM Symp., Copenhagen, pp.289-308.

Saeki H., Ono T., Ozaki A. 1979, Experimental Study of Ice Forces on a Cone-Shaped and on Inclined Pile Structures. Proc. POAC Conf., pp.1081-1095.

Numerical Simulation of the Ice-Structure Interaction in LS-DYNA. Hamid Daiyan* and BjÃ¸rnar Sand. Northern Research Institute (NORUT Narvik), P.O. Box 250, NO-8504 Narvik, Norway.Â As an ice sheet advances toward a conical or sloping structure, the ice load increases until the drifting ice sheet fails by bending and forms ice blocks. Following the failure of the ice cover, the failed ice blocks are pushed up the sloping structure or forms ice rubble in front of the structure. Predicting the correct failure modes (crushing, bending, and splitting or combined modes of failure) is desirable as well as the global force on the structure.