



A NEW ARCTIC PLATFORM DESIGN TOOL FOR SIMULATING ICE - STRUCTURE INTERACTION

Alexey Dudal ¹, Cyril Septseault ², Pierre-Antoine Beal ², Sébastien Le Yaouanq ²,
Brian Roberts ³

¹ Bureau Veritas, Neuilly-sur-Seine, France

² Cervval, Plouzané, France

³ Technip, Paris, France

ABSTRACT

A new type of ice simulator for offshore platform design is developing to deal with the complexity of ice behaviour and provide accurate results.

The need for an ice simulation tool for offshore platform design is twofold: the first is to simulate the flow of ice around a fixed or floating platform structure to ensure there is no excessive pile-up and encroachment on the topside facilities and the second is to predict the loadings on the structure so they can be minimized by design and to check they are consistent with the relevant codes and standards. The simulator is not envisaged to replace the verification stage of testing in an ice basin but to enable an optimization of the design on a standard PC which is then confirmed in an ice tank. Given the economic and environmental challenges of Arctic developments, any design optimization that minimizes cost and enhances safety is seen as vital.

The development program is nearing completion and the simulator is capable of simulating ice flows and calculating loads on conical or sloping walled structures where ice sheet fracture is dominated by bending. An ice crushing module is being finalized that enables ice interaction to be modelled with vertical structures such as tubular legs and artificial islands (where a safe ice encroachment distance can be determined).

This paper will illustrate the complexity of the simulator and how it treats each ice fragment individually, and the effect of current and the seabed. The results of selected simulations will be presented together with some examples of the verification runs performed that confirm the accuracy of the predicted loadings.

INTRODUCTION

The design of offshore structures for Arctic conditions is accompanied by a number of challenges related to complex phenomenon of ice failure and its interaction with rigid bodies. The phenomenon of ice interaction with offshore structures of different shapes has been investigated by many scientists using analytical and empirical techniques and numerical methods (FEM, DEM, PIC, etc). The methods, proposed by D.E. Nevel, T.D. Ralston, K.A. Croasdale, A.V. Marchenko, E.B. Karulin, M.M. Karulina and others, are widely used for the prediction of ice behaviour and ice loads exerted on offshore structures operating in ice-infested waters. Nevertheless, the prediction of ice loads is still a challenge, as ice may fail in different modes or in a combination of modes depending on the ice type, ice thickness, ice mechanical properties, structure geometry, interaction velocity, etc.

In June 2012, Technip signed an agreement with Cervval (a specialist software company in Brittany, France) and Bureau Veritas (BV) to develop an ice-modelling simulation program. The long term aim was for the simulator to predict the flow of ice around both fixed and floating offshore structures of different shapes using a multi-model approach.

The need for an ice simulation tool for offshore platform design is twofold: the first is to simulate the flow of ice around a fixed or floating platform structure to ensure there is no excessive pile-up and encroachment on the topside facilities and the second is to predict the loadings on the structure so they can be minimized by design and to check they are consistent with the relevant codes and standards. The simulator is not envisaged to replace the verification stage of testing in an ice basin but to enable an optimization of the design on a standard PC which is then confirmed in an ice tank. Given the economic and environmental challenges of Arctic developments, any design optimization that minimizes cost and enhances safety is seen as vital.

The development program is nearing completion and the simulator is capable of simulating ice flows and calculating loads on conical or sloping walled structures where ice sheet fracture is dominated by bending. An ice crushing module is being finalized that enables ice interaction to be modelled with vertical structures such as tubular legs and artificial islands (where a safe ice encroachment distance can be determined).

This paper will illustrate the complexity of the simulator and how it treats each ice fragment individually, and the effect of current and the seabed. The results of selected simulations will be presented together with some examples of the verification runs performed that confirm the accuracy of the predicted loadings.

ALGORITHM OF SIMULATION

The simulator allows modelling of reciprocal actions between the objects involved in interaction, such as: the offshore structure, ice sheet/ice floes, ice blocks due to ice sheet or ice floe failure, water, currents and seabed. The interaction between the objects is simulated by physical models selected according to the interaction scenario, the shape of the structure and the environmental conditions. The interaction process is presented in Figure 1.

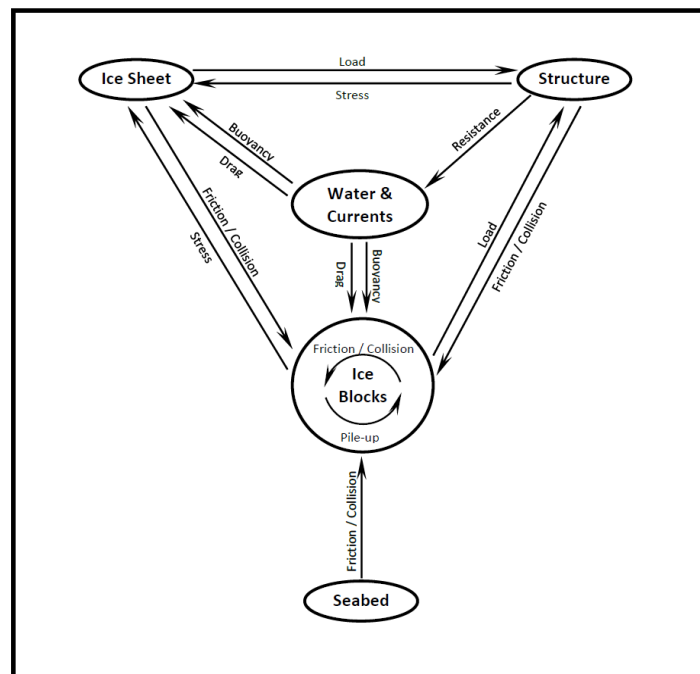


Figure 1. Simulation of the interaction process

A number of assumptions have been accepted for ice simulation:

1. The ice sheet is modeled as a homogenous semi-infinite plate.

2. The limit-stress mechanism is considered to simulate the ice sheet interaction with the offshore structure.
3. The ice sheet drifts with constant speed, envelops the structure and generates ice actions across its total width.
4. The ice sheet failure against the structure creates the ice blocks which are discretized with the volumetric element - voxel.

Rigid body interaction

The simulation of collision detection and rigid bodies dynamics build on The Bullet physics library. The Bullet software allows simulation of thousands of rigid bodies and soft bodies with discrete and continuous collision detection. The offshore structure, ice sheet, ice floe and ice blocks are considered as rigid bodies having six degrees of freedom (6 DOF). Each collision creates an impulse at the contact point and modifies the angular and linear velocity. A rigid body mass m is assumed to be distributed over its volume. The centroid of this distribution is the centre of mass. These assumptions allow application of the Newton's and Euler's equations for the task solution, which can be written as follows:

$$F = m\dot{v}$$

$$I\dot{\omega} + \omega \times I\omega = T$$

where v is the velocity of the body, I is the 3-by-3 inertia matrix of a body, ω is the rotational velocity of a body, F is the force exerted on a body and T is the moment exerted on a body.

Hydrodynamics

The ice collision with the offshore structure results in the accumulation of an ice rubble pile that significantly increases the global force. The program accounts for water buoyancy and currents to simulate the flow of ice blocks around the structure. The water current around the structure is pre-computed by the CFD software OpenFOAM.

The buoyancy force acting on each of the ice blocks is calculated accounting for both emerged and immersed parts and is applied on the centre of buoyancy. The buoyancy force F_b is calculated by the formula:

$$F_b = \rho_w V g$$

where ρ_w is the water density, V is the immersed volume and g is the gravity acceleration.

The drag force is calculated and applied on each voxel. The integration of all elementary forces results in a total drag force for each ice fragment. Figure 2 below shows a comparison of underwater ice behaviour during a simulation and an equivalent ice tank test.

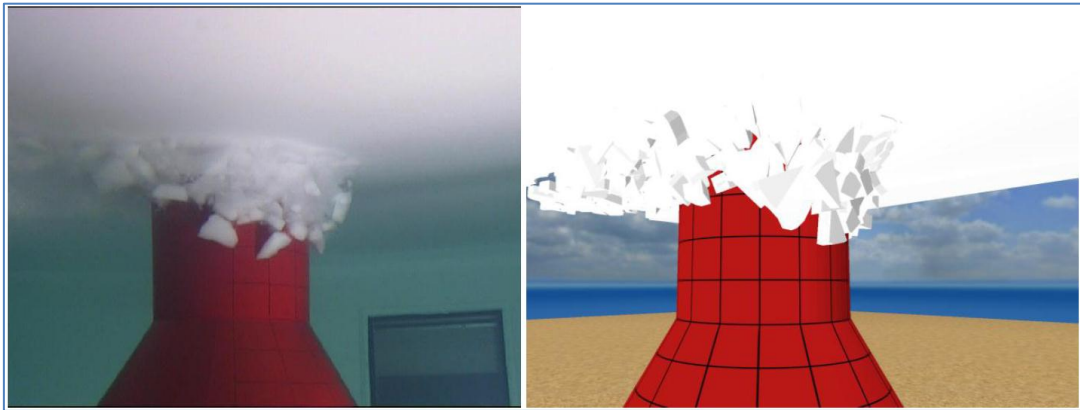


Figure 2. Modelling of underwater ice flow

ICE STRUCTURE INTERACTION

The multi-model approach used allows simulation of both bending and crushing ice failure modes depending on the interaction scenario and the shape of the structure, such as: conical structures, sloping and vertical wall structures, and cylindrical structures.

Bending ice failure

The program simulates bending ice failure for two main interaction scenario. At the initial stage of ice sheet interaction with the inclined surfaces of an offshore structures, the vertical forces exerted on edge of the ice field result in bending ice failure. For an up-breaking structure, the accumulation of ice rubble on the ice sheet surface in front of the structure is likely to create a gravity force exceeding the ice sheet bearing capacity.

The solution of the ice sheet bending failure problem builds on the solution of a semi-infinite plate on an elastic foundation.

$$D\nabla^2\nabla^2w + \rho_w gw = q(x,y)$$

where: $D = \frac{Eh^3}{12(1-\mu^2)}$ flexural rigidity of a plate, E is the Young's modulus of ice, μ is the Poisson's modulus of ice, h is the ice thickness, ρ_w is the water density, $w(x,y)$ is the ice sheet deflections and $q(x,y)$ is the external load.

This approach is used for prediction of the loads inducing critical stresses in the ice field. The critical stresses correspond to the ice flexural strength and initial formation of radial cracks. However, the prediction of crack numbers and their propagation requires implementation of a fracture mechanics concept, whereby the energy input from external loads is balanced by the energy dissipated in ice deformation and crack propagation.

The simulation of radial and circumferential crack formations is based on the method proposed by D.E. Nevel (1992). The elastic plate theory is transformed into the solution of the deflection of a wedge on an elastic foundation. A similar approach was presented in the work of R. Lubbad and S. Løset (2010). Figure 3 shows simulation of ice bending failure due to initial contact of ice field with conical structure and simulation of ice failure due to weight of ice rubble pile in front of the structure.

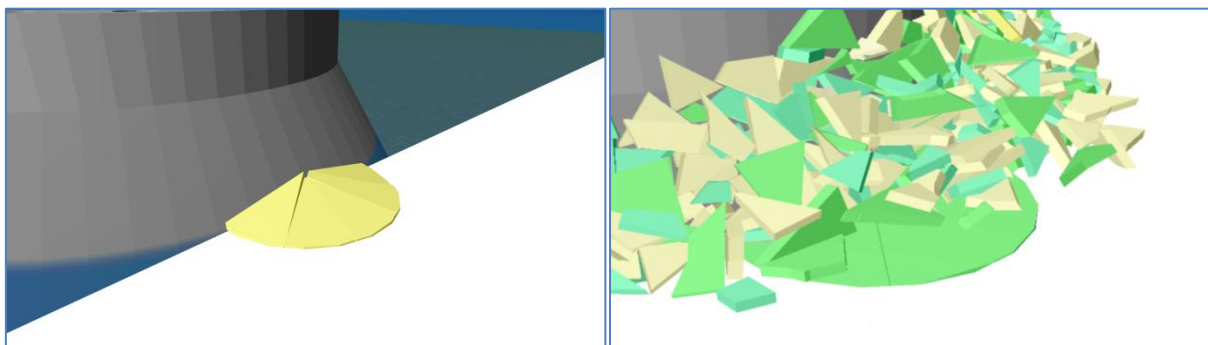


Figure 3. Simulation of ice bending failure due to contact with offshore structure and weight of rubble ice

One more model of bending ice failure implemented into the program builds on beam theory and is applied to the simulation of the secondary failure of ice blocks. The ice blocks are subjected to external forces from the structure, the ice sheet, the seabed and other ice blocks. The program computes the bending moment for each ice block accounting for its centre of gravity, the block's weight and the location of contact points where the external forces are

applied. The value of stress exerted on each individual ice block by external forces is compared with the flexural ice strength to determine the secondary block failure, as shown in Figure 4. The local crushing of ice blocks due to reciprocal actions is neglected.

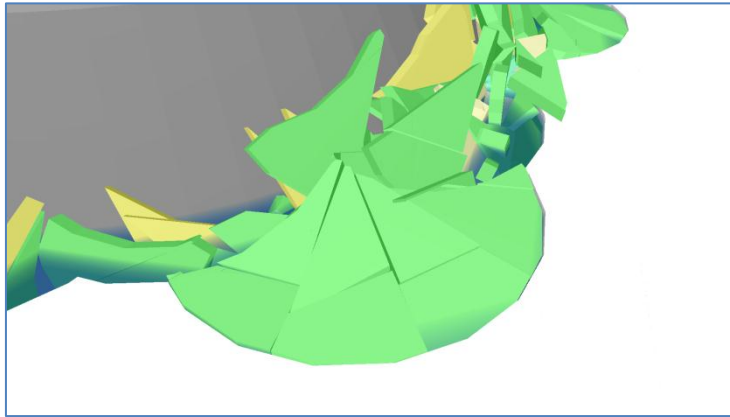


Figure 4. Simulation of secondary failure of ice blocks

Crushing failure

Due to ice interaction with cylindrical structures or vertical walls, ice more likely fails by a crushing mode. This brittle failure process model proposed by C. Daley (1991) was applied to the simulation of ice crushing failure. The simulator model is based on the assumption that the flakes occur due to external loads. The occurrence of a flake is determined by a local peak in the force time series and modifies the geometry of the ice edge. Daley's model does not consider the flakes and crushed ice after their formation. In the simulator however, the crushed ice and flakes are transformed into small ice blocks modelled by triangular prisms. This representation allows the simulation of two important phenomena:

1. the flow of crushed ice around the structure by currents or the formation of ice rubble in front of the structure
2. the accumulation of ice rubble on the surface of the ice sheet and its failure by bending due to the ice rubble weight, depicted in Figure 5

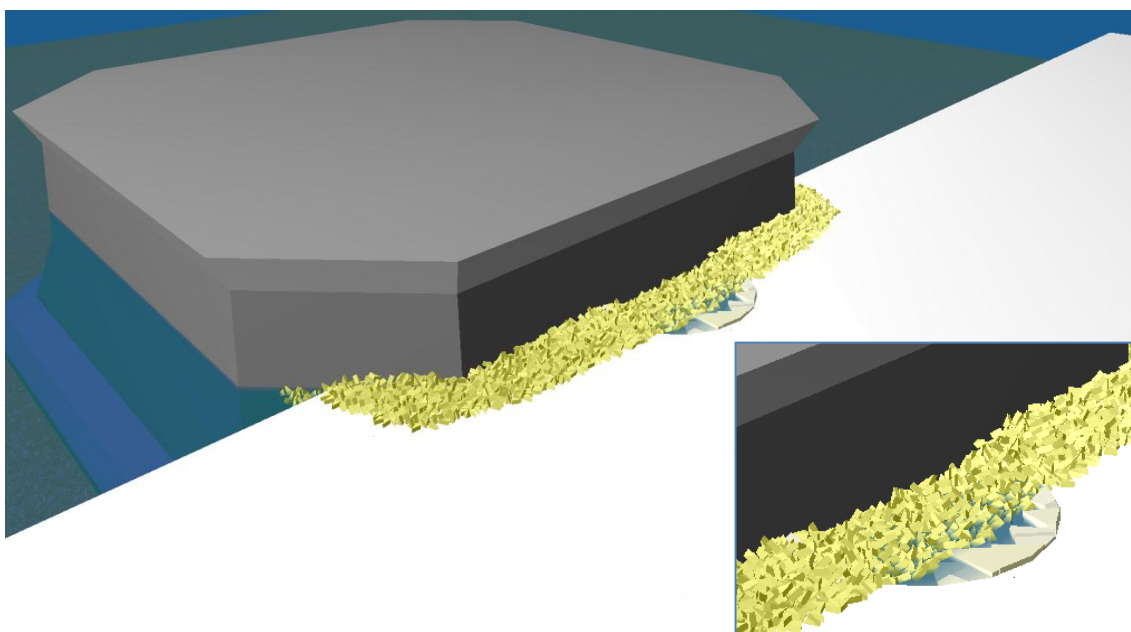


Figure 5. Simulation of ice crushing and bending failure due to interaction with vertical wall

VALIDATION AND RESULTS

The validation of the ice loads simulation builds on model tests conducted to estimate ice actions on conical structure and caisson structures with vertical and slopping sides.

A.V. Marchenko and E.B. Karulin (2005) published the results of experiment on ice motion against sloping wall. In model scale, the ice field of 35 mm thick hits the wall of 1.75 m width and slopping angle to be equal to 58 degrees. The ice-ice and ice-structure friction coefficients equal 0.35 and 0.15 respectively. The speed of ice field drift was 130 mm/s. The results of the ice model tests and simulation are presented in Figure 6.

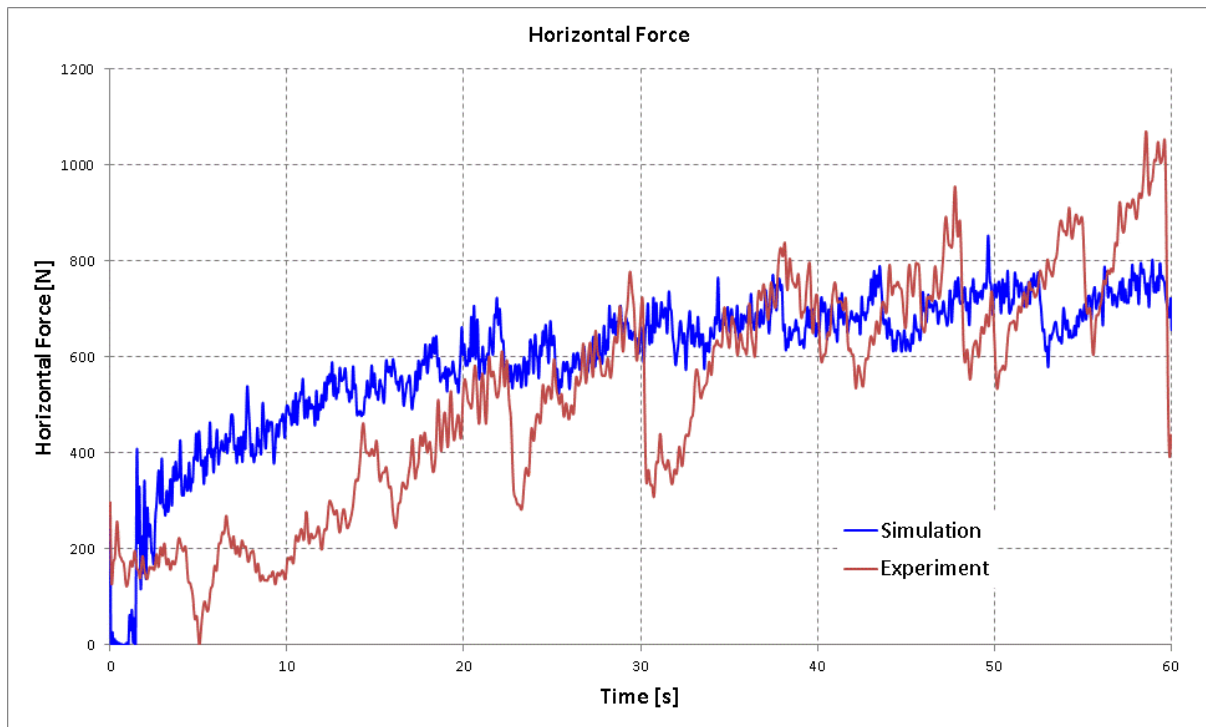


Figure 6. Results of experiment and numerical simulation of ice and sloping wall interaction

In spite of simulated horizontal force increases faster than the experimental one at the initial stage of the interaction, the mean values of the force are quite close.

The scenario of ice field interaction with conical structure was investigated using the data of joint university-industry program published by M.B. Irani and G. W. Timco (1993). The program was conducted to study ice loading on a multifaceted conical structure. The paper presents the results of more than 60 tests. About 40 tests were simulated for the validation. The difference between the mean values of the modelled and simulated ice loads does not exceed 20%. The comparative analysis of test C_006 is presented in Figure 7 and shows a good correlation between the results. The measured ice thickness and flexural strength were 37 mm and 166 kPa respectively. The speed of ice drift was 62 mm/s. The direct contact of ice edge with a sloping structure may result in local peaks, as the local crushing of ice edge is not considered yet.

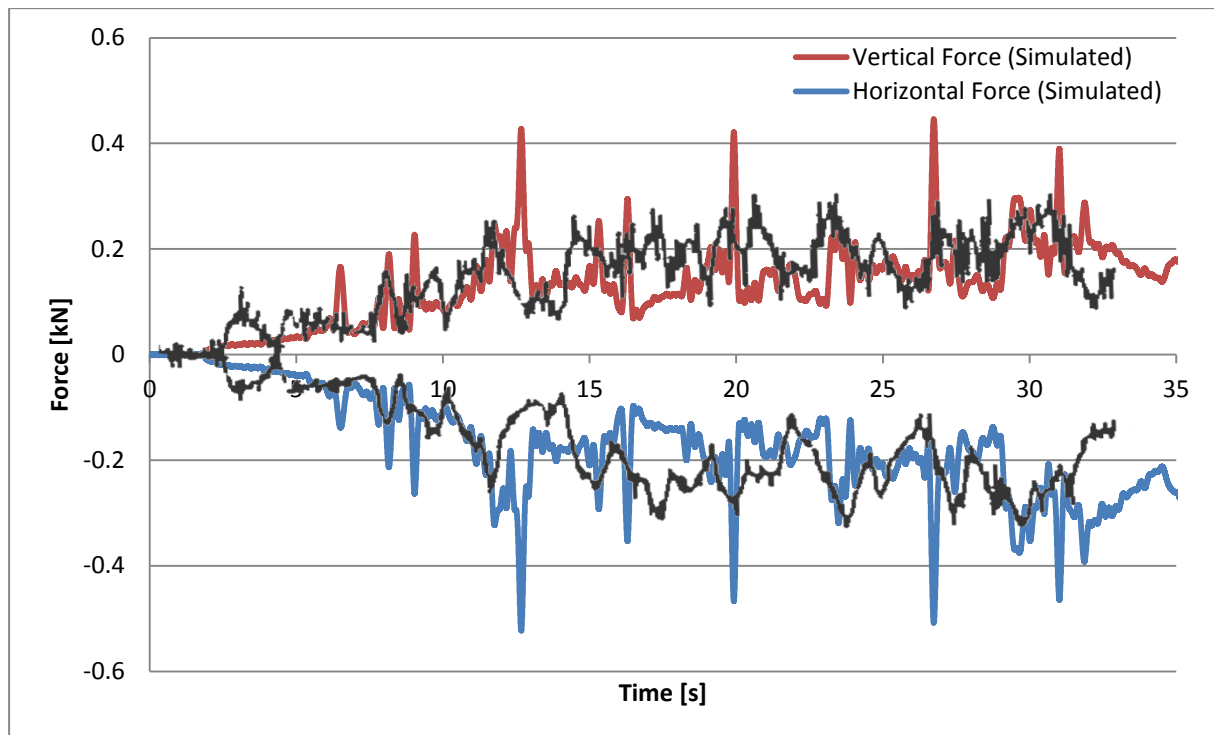


Figure 7. Comparative analysis of measured and simulated ice loads for the test C_006

CONCLUSION

A simulator program based on a multi-model approach has been developed to predict ice behaviour and loads exerted on offshore engineering structures accounting for water currents and the mutual reciprocal actions between an offshore structure, ice sheet/ice floes, ice blocks due to ice sheet or ice floes failure, water, currents and the seabed.

The program builds on methods widely used for the prediction of ice loads exerted on offshore structures and ice behaviour. The crack formation due to ice sheet bending failure is based on the model proposed by D. Nevel for cones and on classical theory of a semi-infinite plate on an elastic foundation (Nevel 1992). The crushing ice failure is simulated according to the model of C. Daley (1991).

The collision and dynamics of objects and the influence of water currents are simulated by professional open source Bullet Physics and CFD OpenFOAM softwares. The program performs the simulation of thousands of rigid and soft bodies with discrete and continuous collision detection.

The run time of simulation is not linear and mainly depends on ice failure mode and number of ice blocks and objects involved into the process. For instance, it takes about 10 minutes of real time to simulate 3 minutes of ice field interaction with conical structure and it may take 3 days to simulate 10 minutes of ice crushing failure with the structure of 100 meters wide.

The validation of the simulator builds on results of ice model tests and shows a good agreement with ice basin tests. Even though the simulator is not yet consider the local ice edge crushing and snow effects, the software is already able to simulate ice interaction with any type of structure shape (conical, cylindrical, sloping and vertical wall, artificial islands, etc.) considering ice failure due to bending, crushing or a combination of both and may be used for structures optimization, minimizing ice loadings & ice rubble build-up, prior to final verification in an ice test basin.

ACKNOWLEDGMENT

The authors express their appreciation to Dr. Marina M. Karulina for the technical expertise and support in modelling of ice behaviour.

REFERENCE

- Septseault, C., Beal, P-A., Le Yaouanq, S., Dudal, A., Roberts, B., 2014. A New Ice Simulation Tool Using a Multi-Model Program. Proceedings of Arctic Technology Conference, Houston, USA.
- Lubbad, R., Loset, S., 2011. A Numerical Model for Real-Time Simulation of Ship-Ice Interaction. Cold Regions Science and Technology, 65(2), Banff, Alberta, 111 – 127 pp.
- Marchenko, A.V., Karulin, E.B., 2005. A method for the calculation of ice loads by ice motion against wide structure. Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions, vol. 1, 441 – 452 pp.
- Marchenko, A.V., 2006. A method of calculating ice loads when ice piles up on a fixed wall. Journal of Applied Mathematics and Mechanics, 70(3), 387 – 398 pp.
- Nevel, D., 1992. Ice forces on cones from floes. Proceedings of IAHR International Symposium on Ice, vol. 3, 1391 – 1404 pp.
- Timco, G.W., Johnson. M., 2004. Ice Loads on the Caisson Structures in the Canadian Beaufort Sea. Journal of Cold Region Science and Technology 38, 185 – 209 pp.
- Daley, C.G., 1991. Ice Edge Contact – A Brittle Failure Process Model. Acta Polytechnica Scandinavica, Mechanical Engineering Series No. 100. Finnish Academy of Technology, 92 pp.
- Irani, M.B., Timco, G.W., 1993. Ice loading on a multifaceted conical structure. Journal of Offshore and Polar Engineering, vol 3, 313 -321 pp.