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NUMERICAL SIMULATION MODEL OF ICE-STRUCTURE INTERACTION

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ABSTRACT

Recently some oil/gas fields are being developed in the North-Eastern part of Sakhalin Island where ice drift velocity achieves 1.5 m/sec. High dynamics of ice cover and its considerable thickness cause higher requirements to reliability of offshore ice-resistant platforms (IRP).
The problem of estimation of design reliability of structure for development of offshore fields in northern seas is connected with development of methods of ice effects' determination and implementation of dynamic design calculation of structures for ice load effects, with investigation of marine ice as substance, and with mechanism of creation of ice regime and of structure loading regime.
Authors suggested a model of mechanical interaction between ice and IRP. The model is based on numerical simulation of the process when ice cover affects the structure.
The suggested model may determine following parameters of mechanical interaction between ice cover and a structure: quantity of load cycles, time of penetration, depth of penetration, and regime of ice load on structure.
Key words: ice, ice-structure interaction

INTRODUCTION

Results of research projects conducted by Russian and foreign scientists indicate that ice load formation is a complex problem. Variability of ice loads is determined by offshore ice regime, i.e. drifting ice dynamics, diversity of ice formations and variable material properties of seawater ice. Main factors influencing ice load value have occasional nature, but ice loads itself have clear-cut random nature.
Presently, there are many construction codes (SNiP, VSN, DNV, ISO, API) which define the rated value of ice load in terms of spontaneous failure of offshore hydraulic structure interacting with ice formation. Per contra, the practical experience gained throughout offshore IRP operations reveals the probability of bearing capacity failure (of entire structure or particular element) as a result of relatively moderate, but highly-frequent ice effects. However, the applicable norms and standards cover no recommendations for prediction of drifting ice load regime upon the structure to evaluate the structure's fatigue strength. Recommendations for ice abrasion evaluation are not available as well. Furthermore, the mere processes of ice formation / offshore hydraulic structure interaction, principles of ice load variations and probable load cases are not appropriately studied so far.

PROBLEM DEFINITION

Results of long-term surveys of ice cover and relevant abrasive effects suggest that proper ice load description requires to bring together the variability of ice regime parameters and the process of ice fracture at interaction with offshore structures. In this case, representation of the mathematical model of ice loads & effects formation as a simulation model is most feasible. Therefore, a probabilistic simulation model of ice-structure interaction based on applicable principles of simulation modelling was developed. This model is based on numerical formation of ice load distribution function and simulation of all probable situations featured with the accidental combination of input parameters values. For each particular situation the ice load is calculated using the authors' models of mechanical interaction process between the ice field and marine hydraulic structure. Probable characteristics of ice load, ice contact stress, mechanical effect path, structure's material abrasion path and depth are determined by numeric modelling and simulation of all possible situations throughout the entire period of marine offshore structure's operations.

ASSUMPTIONS

1 The sheet ice is an aggregation of ice formations equally distributed throughout the water area and characterized by the following parameters: thickness *h*, drift velocity per each direction *V*, diameter *D*, temperature *T*, ice consolidation *N*;
2 Parameters of sheet ice are independent random values and are shown as monthly distribution histograms based on of long-term observations in particular offshore area;
3 Duration of design situation is calculated by formula

$$t_k = P(V_k) \cdot P(D_k) \cdot P(h_k) \cdot P(T_k) \cdot P(N_k) \cdot P(Z_k) \qquad (1)$$

where $P(V_k)$, $P(D_k)$, $P(h_k)$, $P(t_k)$, $P(N_k)$, $P(Z_k)$ – occurrence probabilities of input parameters: ice drift speed, ice floe diameter, ice thickness and temperature, ice consolidation and sea level fluctuations respectively; t_s – design month of ice season.
4 Duration of design situation decreases subject to probability of ice collision with the structure.

$$t_c = t_k \cdot \frac{N}{10 \cdot D_k^2} (D_k + D) \cdot (L_0 + D) P(Z_k) \qquad (2)$$

where D – diameter of the structure; D_k – diameter of the ice floe; L_0 – initial spacing between ice formations; N – sheet ice consolidation.
5 Initial spacing between ice formations depends on diameter of ice formation D_k and sheet ice consolidation N_k and can be calculated by the following formula:

$$L_0 = \sqrt{\frac{D_k^2 \cdot 10}{N_k}} - D_k \qquad (3)$$

6 For proper calculation of ice loads, three basic groups of probable effects by drifting ice upon particular supports of hydraulic structure are specified depending on dimensions of ice formations (see fig.1):

- load by broken ice with dimensions up to ($D_k \leq 4d$, where D_k- diameter of ice formation, d– diameter of hydraulic structure's support)
- load by ice floes with dimensions up to ($4d < D_k \leq 500$m);
- load by ice fields ($D_k > 500$m);

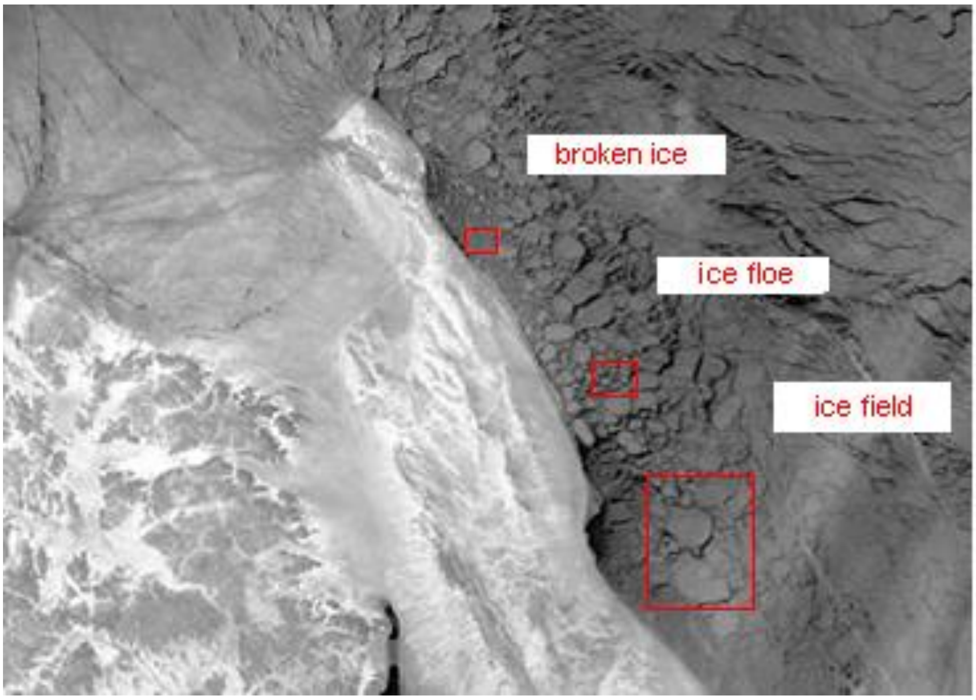

Figure 1 – Schematic diagram of ice formations

SIMULATION MODEL

Typical cases of ice field / hydraulic structure interaction are as follows:
B. Penetration of structure's supports into the ice field;
B.1 Penetration of the ice block, slowdown before the structure;
B.2 Penetration of the ice block with subsequent acceleration caused by another ice floe impact impulse;
B.3 Penetration of the ice block and shear of ice floe adjacent to structure;
C. Stand-still of the ice field before the structure;
C.1 Stand-still of the ice block and velocity slowdown;
C.2 Stand-still of the ice block with subsequent moving-off caused by another ice floe impact impulse;
D. Ice block buckling failure;
E. Open water in front of structure.
Block diagram of ice load generation is shown on fig. 2.
To properly describe the mechanism of kinematical process of interaction between the ice floes and the process of ice fields destruction in contact with the structure, the discrete approach was applied.
The calculation is primarily complicated by determination of time and path of ice floe / structure's base interaction. For the purpose of calculation, the law of momentum conservation and the principle of ice field's energy are applied.
B case describes the centric and completely inelastic impact, where all kinetic energy is equated to work of the contact force on structure's support along the ice penetration path.

$$\frac{M_{i+1} . V_{i+1}^2}{2} - \frac{M_i \cdot V_i^2}{2} = \sum W_k \qquad (4)$$

where Mi – weight of the ice floe at i-th phase, kg; Mi+1 – weight of the ice floe at next phase, kg; Vi - drift speed at i-th phase, m/s; Vi+1 – drift speed at next phase, m/s; ΣWk - total work of all forces effecting k-th situation.

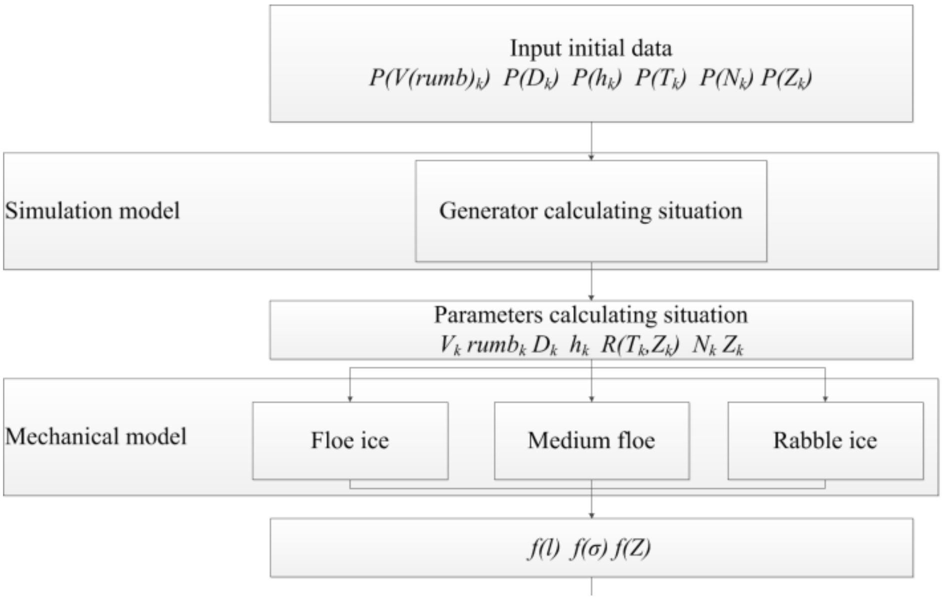

Figure 2 – Block diagram of ice load generation.

In this particular case, all kinetic energy of ice floe is equated to work of contact force on structure's support along the ice penetration path. Therefore, equation (4) can be assumed as

$$\int_0^x F_i \Delta x_i = \frac{M_{i+1} \cdot V_{i+1}^2}{2} - \frac{M_i \cdot V_i^2}{2} \qquad (5)$$

where Fi – ice force, MN; Δxi – path of mechanical interaction at i-th phase of particular situation, m

Length of ice field / structure mechanical interaction path at i-th phase can be calculated by the following formula:

$$\Delta x_i = V_i \cdot \Delta t \qquad (6)$$

where Δt – ice floe modeling time interval, sec

Offshore North-East Sakhalin, ice drift is 80% dependent on flood-tide stream. Therefore, proper allowance has to be made for the influence of seawater current onto the process of ice field / structure interaction.

Current velocity is assumed equal to ice drifting velocity, i.e. vw=vk. While dependency of ice penetration velocity variation subject to current force can be formulated as:

$$V_{i+1} = \sqrt{\frac{M_{i+1} \cdot V_{i+1}^2 + 2(F_i - F_w) \cdot V_i \cdot \Delta t}{M_{i+1}}} \qquad (7)$$

Once the kinetic energy of the ice field is nullified, the ice field will stand still, therefore ice block penetration velocity Vi=0; penetration time ti = ∑i·Δt; interaction path:

$$X_i = \sum \Delta x_i \qquad (8)$$

where Δxi – length of the ice field / structure interaction path at i-th phase.

Penetration process may be re-commenced once the subsequent ice floes impact the ice block standing still at structure support (cases **B.2** and **C.2**) with subsequent momentum transfer.

As per the law of momentum conservation, the system's total momentum is constant regardless of any internal processes. In turn, the total momentum of the whole system (ice block) can be calculated by summarizing momentums of all ice floes it is composed of. Then ice bock penetration velocity can be calculated by formula:

$$V_{i+1} = \frac{M_i V_i + M_0 V_k}{M_i + M_0} \qquad (9)$$

The sheet ice drift scenario subject to mechanical interaction with offshore structures assumed within the simulation model is as follows:

Initial ice / structure support contact will be one of five cases mentioned above (**A**,**B**,**C**,**D**,**E**). If the kinetic energy of ice floe is enough for penetration, the ice floe is penetrated by the structure upon impact (**B.1**, **B.2** cases), is penetrated and stopped (**C** case) or penetrated by structure and broken apart (**B.3** case).

When the ice floe penetration velocity changes from certain value V0=Vk (where Vk – ice floe drift velocity, m/sec) to Vi, velocity of structure support's penetration into the ice field is determined by formula (7). Upon the first contact, the ice block may either stand still before the structure (**C** case), or continue drifting under the condition that kinetic energy is sufficient (**B.1** case), or continue drifting with increased velocity being accelerated by another ice floe impact impulse (**B.2** case). When one (**C.1** case) or several ice fields stand still, concentration of ice floes before the structure increases, cumulation takes place. In this case, each subsequent ice floe will transfer its impulse to the ice block standing still before the structure, which may cause the penetration process to re-commence once the kinetic energy of impact impulse sufficient to move the ice block in front of the structure. The ice bock penetration velocity can be calculated by formula (9).

When the ice blocks have stopped and the load has been released (**C** case), the cycle will repeat upon arrival of new ice floes. Therewith, the distance between the ice block that stands still before the structure support and the next ice floe is calculated by the following formula:

$$L_{i+1} = L_i - V_k \Delta t + V_i \Delta t \qquad (10)$$

where Li – distance between the incoming ice floe and the outermost one standing still before the structure's support, m; Vk – ice floe drift velocity in k-th situation

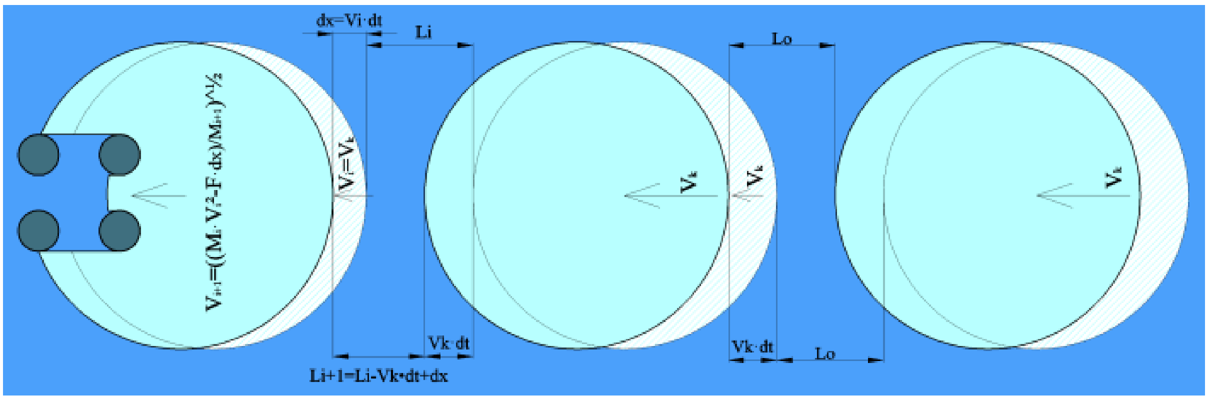

Figure 3 – Schematic diagram for calculation of distance between the ice floes

When the ice floe has impacted the ice block before the support, the number of ice floes within the system increases by one, Li will then be assumed equal to L0 and the entire cycle will repeat.

In case of ice field shear (**B.3** case) the distance between the structure and the first ice floe of the block (**E** case – open water) will be calculated as per the following:
Calculation continues unless the estimated time t is equal to design situation time tc subject to collision probability between ice formation / structure support.

CALCULATION PROCEDURE

Initial data for the calculation is as follows: parameters of structure (structure's diameter *d*, structure's support shape m) and properties of sheet ice.
1. Ice regime is modeled by exhaustive search of initial parameters: *h*, *D*, *N*, *T*, *V*, *Z* so that all design situations, i.e. all possible combinations of these parameters would be envisioned.
As a result of k-th combination of parameters, particular ice conditions will be modeled with the following parameters: h_k, D_k, N_k, T_k, V_k, Z_k. And occurrence probabilities will be determined respectively: $P(V_k)$, $P(D_k)$, $P(h_k)$, $P(T_k)$, $P(N_k)$, $P(Z_k)$, got as the result of field observations.
2. The lifetime of *k*-th combination of parameters of tc ice regime subject to collision probability between ice formation / structure support can be calculated by formula (2)
3. At each *i*-th phase of simulation calculation, the process of mechanical interaction between the ice fields / offshore hydraulic structures supports will be modeled considering the supports' thickness h_k, ice fields dimensions D_k, ice concentration N_k, ice temperature T_k, ice strength R_k, drift velocity V_k and sea level fluctuations Z_k. Duration of the analyzed process is t_k.
By modelling the process of mechanical interaction, ice load value F_i and range of sheet ice displacement at interaction with the structure X_i – interaction path – can be obtained.
4. The process should continue unless all probable combinations of ice regime parameters have been modeled.
The special «IceStrIn» (Ice Structure Interaction) software has been developed on the basis of author's calculation algorithm. This program is based on Microsoft.NET Framework 3.5 platform. Parallel Extensions library is also used for accelerating the calculation. The software complex «IceStrIn» enables calculation of ice load value, interaction path length, number of loading cycles and depth of lateral and vertical ice abrasion within the ice formation / structure contact area in any natural conditions. Given some minor upgrade, the software complex may be used for calculation of various types of structures (inclined supports, extended structures, etc.)

CALCULATION RESULTS

Calculations made with «IceStrIn» software complex have resulted in the following distribution of probabilistic features of ice abrasion process for North-East shelf of Sakhalin Island histogram of ice load for various ice fractures (see fig. 4).

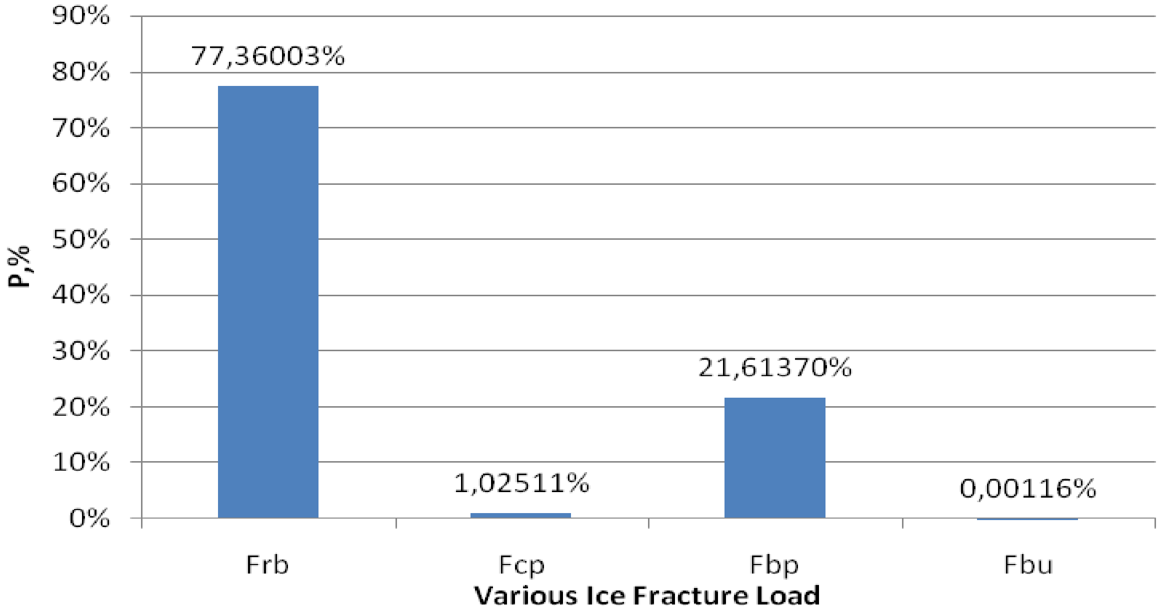

Figure 4 – simulation result of ice load for conditions of Sakhalin (ice field brittle fracture force Fbp; ice field standstill force Fcp; buckling failure force Fbu; broken ice force Frb)

CONCLUSION

Development of offshore oil & gas fields in northern seas requires a comprehensive allowance for specific features of ice regime within the construction area. Parameters of drifting ice should be considered in particular design solutions for supports of offshore hydraulic structures. They have considerable effect upon the dynamics, parameters and forms of ice field destruction at interaction with the structure. Complexity of this problem is aggravated by a large number of randomized natural factors with significant variation range and also by a great variety of ice fractures and design cases of their mechanical effects upon the structure.

The suggested model is purposed to identify the following parameters of mechanical interaction between sheet ice and offshore structure: number of load cycles, time of penetration, length of penetration way and load regime for the structure.

Numeric modelling enables determination of time dependence for parameters mentioned above, that may be used to obtain the dynamic characteristics of ice-structure interaction process, to calculate the fatigue strength of particular structural elements and/or to identify the depth of ice abrasion.

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