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ICE CONDITIONS INFLUENCE ON THE DESIGN AND CONSTRUCTION OF ICE-RESISTANT STRUCTURES FOR OIL AND GAS PRODUCTION ON THE ARCTIC SHELF

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If consider promising tendencies in the policy of Russian oil and gas industry the most important factor of its further development is industrial exploitation of continental shelf hydrocarbon resources, where several dozens of large deposits and even provinces are predicted.
As a result of 20-25 year long period of oil and gas exploration work carried out by the geological survey and fuel-energy departments on the shelf the total oil-gas potential reserve of the Russian shelf is estimated exceeding 100 billion tons (85 % of the resources belongs to the interiors of the Arctic seas and 14 % - to the seas of the Far East). It is planned by the federal programme of the Russian Federation source of raw materials development to mine 25 – 28 million tons of oil and 30 – 35 billion cubic meters of gas in 2006 – 2007 and in 2020 – 65-70 million tons and 135 – 140 billion cubic meters correspondingly (Alekseev Y. N. et al, 2001).

The Barents Sea province which resources are estimated as 1/3 of the total shelf resources is the matter of top-priority interest. There 56 promising fields have been revealed and 8 oil and gas deposits have been established The productive boreholes for the Barents Sea fields exceed 70 %. The fields and deposits are situated in comparatively favourable geographical conditions and also in acceptable distance from the North-East Russian consumer centres infrastructure. To put it differently the provinces are ready for its industrial developing. The area of western Arctic with the regions of the Barents, Pechorsk and Cara Seas is one of the most promising concerning hydrocarbon resources and its role in developing of the fuel energetic industry is very important all in Russia, Europe and in the whole world. Large provinces have been revealed and 10 large deposits on different depth both in freezing and unfreezing water areas have been discovered here for a few years. Among them large Prilazlomniy oil deposit (the shallow area of the Pechorsk Sea) and super giant Stockman gas condensate deposit (deep-water area of the Barets Sea) should be noted particularly. If consider oil and gas industry shallow areas of the Cara and Pechorsk Seas present great interest in its devel-

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opment, where by geophysical exploratory methods on the sea depth down to 50 meters a number of large provinces were revealed to make trial boreholes. Those areas are the sea continuation of the large land provinces – Western Siberia and Timan-Pechora where unique deposits were revealed and constructed (Fig. 1) (Alekseev Y. N. et al, 2001).

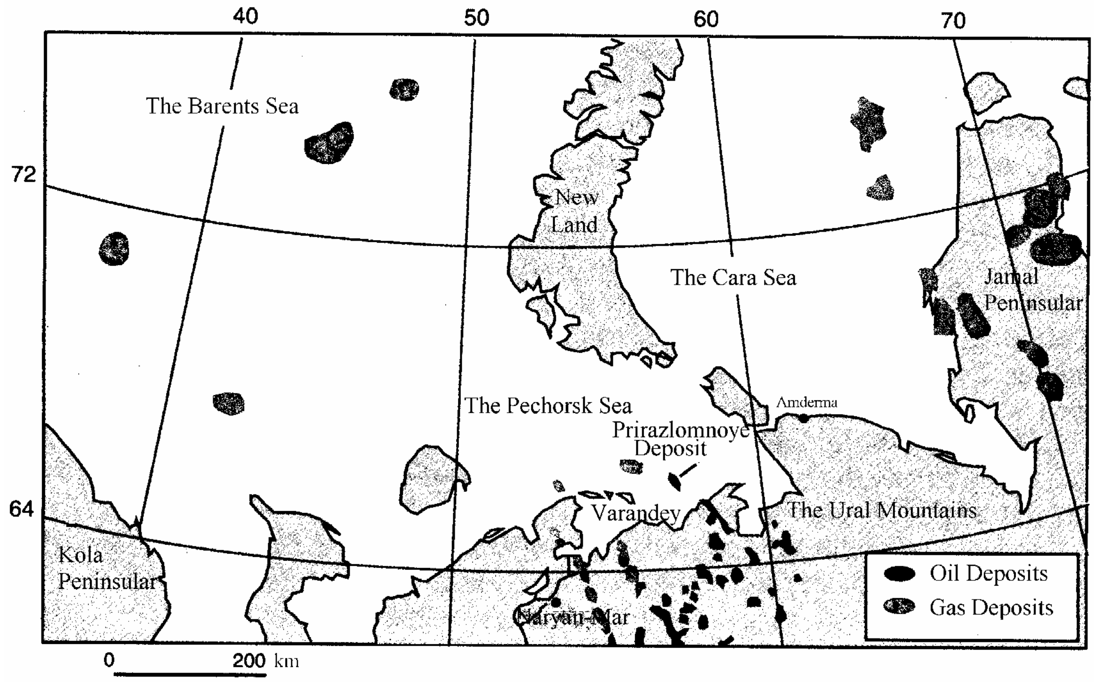

Fig. 1. The Map of Oil and Gas Content in the area of the Barents, Pechorsk and Cara Seas

The general approach to the development of the Eastern Arctic shelf is the following - the Laptev, Western Siberian and Chukotsk Seas require more detailed consideration but are very promising as a reserve of large oil deposits.

Concerning the critical condition of the energy supply of the Far East the priority course in the region occupies the development of oil-gas resources of the Bering and Okhotsk Seas (the Sakhalin shelf in particular) as practically the only alternative to satisfy the fuel-energy necessity of the region (Fig. 2.).

One of the main problems in creating boring technology for development of the shelf deposits is the design and construction of ice-resistant platforms (substructures) (Alekseev Y. N. et al, 2001). The type of the ice-resistant structures is determined by their functional purpose, region ice regime characteristics, the depth of the sea and other specific conditions. The state of the market, the quality and quantity of the technological equipment, the production capacity available and the development of the infrastructure, the distance from the industrial regions and from the supply bases all play a great part (Vershinin, 1983).

When developing oil deposits on the shelfs of the freezing seas, the problem of the transportation of the raw materials to the user arises. In the overwhelming majority cases there are not any trunk pipelines or stationary port structures near the deposits under development, which could be used to transport oil in the traditional way. The economical feasibility analysis of building new pipelines leading from the deposit (or group of deposits) to the trunk pipelines on the shore, building of the stationary trans-shipment port or building of the offshore ice protected terminal for loading the oil on tankers should be performed.

In the seas with severe ice conditions, which include the seas of the Arctic and sub Arctic shelfs, there is not an oil loading terminal under operation. There are only project proposals, patent ideas or general recommendations. Under these circumstances the possibility of using in the freezing seas the available types of terminals, constructed in the non-freezing seas would be appropriate for consideration to estimate the restrictions on the terminal structure operated in ice conditions.

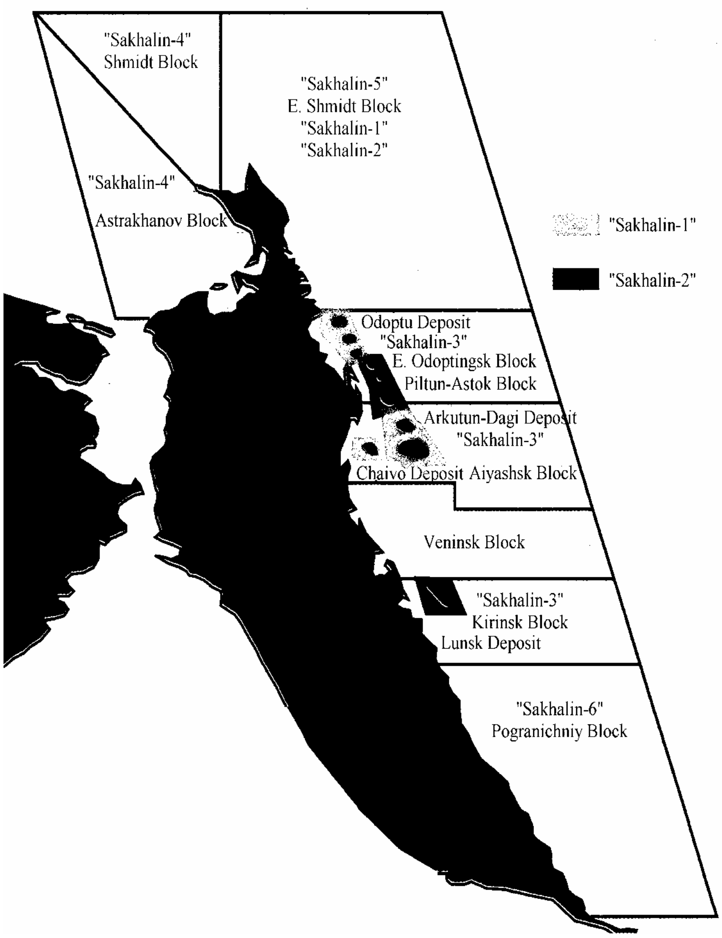

Fig. 2. The Review of the Sakhalin Projects (Alekseev Y. N. et al, 2001)

In the freezing seas the terminal and the tanker moored to it suffer from ice loads along with wave, wind and current loads. According to the operation conditions the ice loads can be either commensurable with the wave loads or be larger than them considerably.

To solve technical problems of construction on the Russian Arctic and Far East shelfs complex studies of the ice regime in the regions of oil and gas deposits are started.

The programme of ice regime studies in the region of the structure includes:

- historical data on the ice regime;
- probabilistic estimation of ice conditions;

- description of ice cover parameters including ice cover thickness and ice hummockness;
- geometrical characteristics of ice cover;
- morph metrical structure of ice cover;
- ice drift;
- physical and mechanical ice characteristics;

The results estimation of the complex programme of studies has to be the basis for design of ice protected structures on the Russian Arctic and Far East shelfs.

It is convenient to present this data in the form of local technical conditions (LTC) on ice regime elements for every particular deposit.

The nomenclature of the ice regime characteristics presented is corresponding to the list of standards (VSN, STN 00-93, SNiP) and in some sections exceeds them. The order of the account is determined by VSN (from sea freezing to ice melting). As a rule in the table the following characteristics are presented: 50 % and 1 % probability of exceeding, the maximum value and the return period 1 per 100 years. 1 % probability of exceeding of the presented characteristics means that 1% in the number of observations (expedition, one time aerial surveying etc) is equal to or exceeds the given value. The maximum value of the characteristics was received by means of the selection from the number of episodic or long term observations. The values of the return period 1 per 100 years were received by means of the extrapolation to the range of rare repetitions on the basis received statistical laws. If there is not a value in the table corresponding to the return period 1 per 100 years, the estimated value should be taken from the "Max" column, and from the column "1 % probability of exceeding value" if that is not given either.

The local technical conditions consist of:

State of the ice cover

The dates of steady ice formation
The dates water area cleaning from ice
The length of the ice period in the region (days)
The probability of ice presence in the months November-July, %
The ice conditions of the whole Barents Sea, %
The ice concentration, points
The age structure of different ice kinds (February –June)
Young ice, points
Thin first-year ice, points
First year ice of average thickness, points
Thick first-year ice, points
The thickness of the large ice fields for the period of the maximum development (April), m
The diameters of the ice fields, km
The area of the ice fields, km
The snow thickness on the even drifting ice, sm
The snow thickness in hummocks, sm

Hummocks

The hummockness of the drifting ice (April), points
The height of the hummock sails, m

The length of the hummock ridge, m (the joint length in the case of the ridge hummockness)
The width of the hummock sails, m
The width of the hummock keel, m
The calculated keel settlement, m
The porosity of the above water part of the hummocks,%
The porosity of the under water part of the hummocks,%
The inclination of the sail, degrees
The inclination of the keel, degrees
The dimensions of the hummock blocks, m
The average thickness, m;
The average length, m;
The field diameter of the 5-pointed hummockness, m
The thickness of the consolidated layer on the 100-meter front

Ice drift

The total ice drift velocity of 1% probability of exceeding, in m/sec
The (climatic) velocity of the general ice drift, the direction – 160^o, m/sec
The velocity of the wind ice drift, the direction NNE, m/sec
The length of the unbroken period with zero (0 – 0,05 m/sec) drift velocities, hours;
The amplitude of the tide ice drift velocity, m/sec in the directions 12^o– 192^o

Physical and mechanical ice characteristics

The average temperature over the ice thickness, ^oC (January – March)
The average consolidated layer temperature over the ice thickness, ^oC (April)
The average salinity over the ice thickness, pro mil (April)
The average density of even ice over the thickness, kg/m^3
The density of hummock ice, kg/m^3
The compression strength limit of even ice attributed to the whole ice cover thickness (the load is parallel to the surface), MPa
The compression strength limit of the hummock ice, MPa
The bend strength limit of the even and layered ice, MPa

Icebergs

The maximum dimensions of the iceberg above-water parts (height, length, width, m)
The iceberg mass, million tons
The maximum iceberg drift velocity, m/sec
The average radius of circulation due to the tide, km
The average iceberg ice density, kg/m^3
The maximum iceberg ice compression strength, MPa
The character of the ice conditions can be presented with the data of Fig. 3 – 6.

This data characterize the thickness of the consolidated hummock parts, the compression strength of the ice plate, the liquid phase quantity in the ice.

On the basis of LTU using scenarios of acting global and local loads are being worked out.

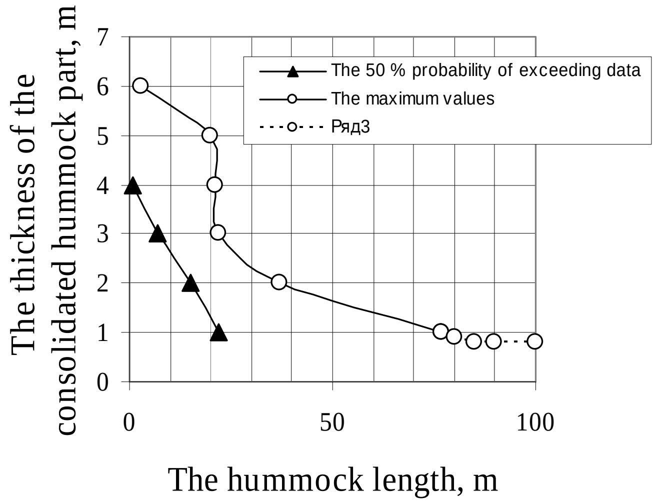

Fig. 3. The thickness of the consolidated hummock part depending of its dimension

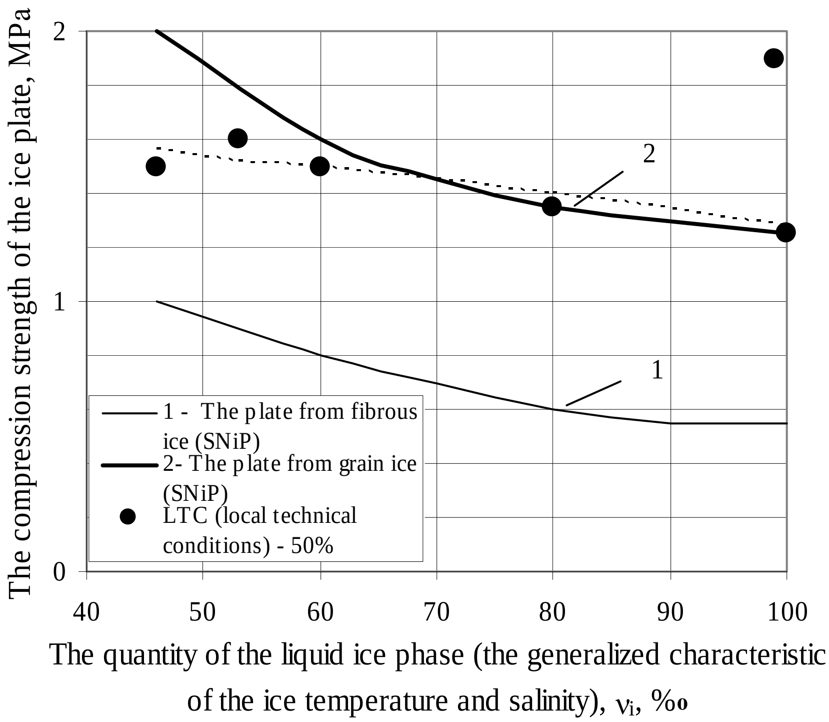

Fig. 4. The compression strength of the ice plate depending on the fluid phase content in ice comparing with 50 % probability of exceeding data

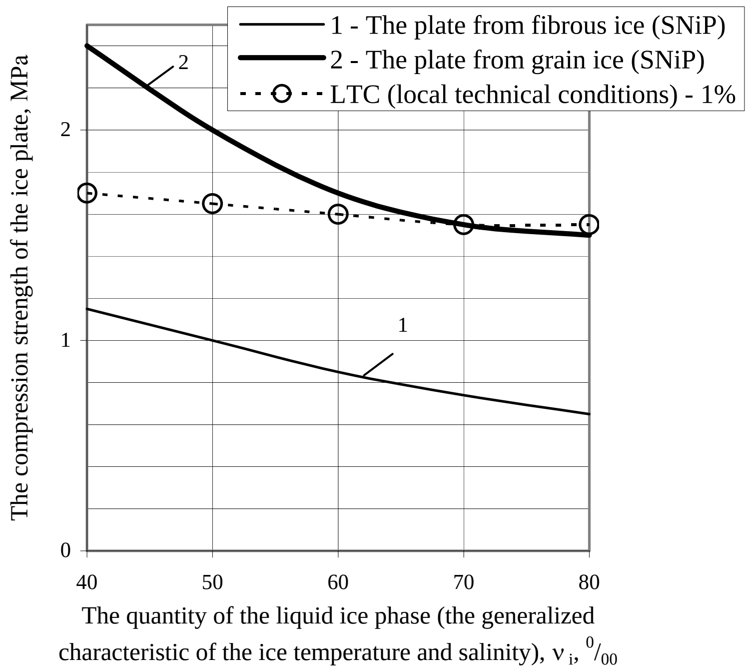

Fig. 5. The compression strength of the ice plate depending on the fluid phase content in ice comparing with 1 % probability of exceeding data

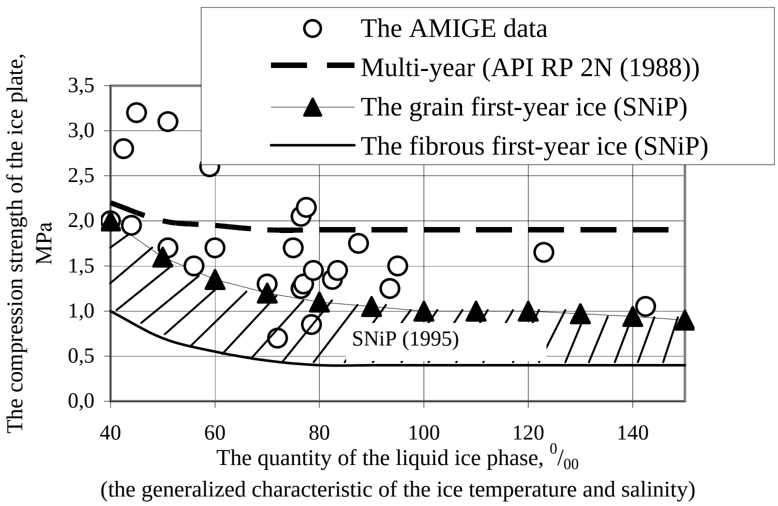

Fig. 6. Comparing of the in-situ data (AMIGE, 1998) with the SNiP (Russia) and American Petroleum Institute (API) data

The deterministic or semi-deterministic methods of ice loads calculation are the most widespread, when the values of the main physical-mechanical and morphological characteristics of ice included in the design equations are specified with this or that probability of exceeding. These methods including the ones used in (SNiP, 1995; APIRP 2N, 1992; VSN, 1998) give conservative estimations (sufficient as a rule for the ensuring surplus reliability) of indefinite repetition and take into account the most unfavourable scenarios of ice massifs – structure interactions –the scenarios of the limit stress and of the limit force. The first scenario assumes that with the large enough kinetic energy of the moving ice massif the ice stresses in the area of its contact with the structure reach the limit values and the ice load becomes maximum. The second scenario can take place when immovable or frozen to the structure ice massif presses down on the structure due to the shearing of the surrounding ice. This scenario assumes that wind, current and coming new ice fields loads act on this ice massif. The interaction of the ice surrounding the structure and the new coming ice fields causes additional efforts because of the hummocking on their boundaries. As a result the total load on the structure due to the listed factors increases and can reach the load corresponding to the scenario of the limit stress.

It should be noted that in case of freezing the ice with the structure the absolute contact on the ice-structure boundary takes place and intensive ice massif near the structure is observed; the ice thickness near the structure can become 1.5 times greater than the thickness of the ice massif frozen to the structure (SNiP, 1995). These factors lead to substantial increase of the ice load –for the vertical walls the load increases twice or so, and for the cones – in 3 – 5 times. It is clear now that freezing to the platforms on the tension piles must be excluded with help of appropriate technical measures.

The deterministic approach is used for determining of the maximum (the greatest possible) loads for the early stage of projecting when there is scanty information on the source data concerning ice conditions in the region of building.

The problem of ice load repetition is the most important one for creating both safe and economical structures and it is solved in the context probabilistic methodology, allowing to determine the distribution law of the loads and according to this law use the load of any given probability, including the return period 1 per 100 years set by CAN/CSA and recommended by ARIRP 2N for ice loads on the structures in Arctic.

The probabilistic approach can be used in the latest projecting stages if there is the data on the long-term distribution of the main ice massif characteristics.

The analysis of the known approaches to the ice loads calculation in respect to their application for the platforms with tension links

It is essential to suppose, that using compliant structures (platforms with tension links for example) can have considerable effect on the value of upcoming structure-ice massif interaction forces. The ice massif when meeting with the structure of this kind uses the kinetic energy it has for the ice destruction work and the structure deformation work. That is why the more compliant the structure is the smaller will be the ice load.

This situation however (as shown in (Korzhavin K. N., 1962)) is only correct for the scenario of the restricted kinematical energy in which assumed that after the resource of the energy is exhausted not being enough for reaching the limit stresses in the ice in the area of its interaction with the structure, the ice massif will stop. If an ice massif (or a group of them pressing on each other due to the wind and water current) is large enough as it is the case in the sea then its energy will be without doubt enough all for the structure deformation (displacement of the floating platform), the overcoming the friction forces along the lower surface of the ice massif and giving the maximum pressure on the structure. That is the reason why the scenario with the limited kinematical energy is not taken into account in (APIRP 2N, 1988) and cannot have any practical application for platforms with tension links.

The platforms with tension links are constructed in the way that only their stabilizing columns can bear the ice pressure: the single column which is also a pontoon; a group of as a rule of 3 or 4 columns connecting the upper site and the pontoon. The columns can have conical parts directed up or down on the level of the water line or lower/upper in the area of ice forces. Hence the calculation of the ice loads on the considered platforms comes to the calculations of the load on the single vertical or conical supports and on the structures consisted of the group of columns.

The present–day practice of the ice loads calculation on the mentioned above supports and structures can be described as follows.

1. The ice load on the single vertical support is determined according to the generally used in the world this or that modification of the K. N. Korzhavin‘s formula (Korzhavin K. N., 1962) as a multiplication of the strength ice compression characteristic by the width of the support along the front, by the thickness of the ice massif and by the coefficients taking into account the real contact conditions between the ice and the support, the support shape, the ice stress condition and etc.

The change of the support shape can change considerably the character of the stress-strain condition and therefore the conditions of the destruction of the ice interacting with the support and because of this the value of the interaction forces.

For ascertaining of influence of the support shape on the interaction forces K. N. Korzhavin had tests of pressing different shape stamps and seams to have estimated these forces for the first time in the context of the plasticity theory, having solved for ice the 2-D Sokolovskiy problem on the pressing of the bulging stiff stamp in the plastic isotropic medium. As a result the coefficients of the support in the plan were received ($m \le 1$) and the relationship of the maximum (limit) stress in the ice in the area of its interacting with the stamp (support) to the one axis compression ice strength – crushing coefficient ($k_b \ge 1$).

The dependence of the ice load from the support width in plan (b) and the thickness of the ice massif (h) K. N. Korzhavin offered to take into account with help of the imperfect ice-structure touch coefficient (a kind of scale coefficient) ($k \le 1$), reducing along with the reduction of the relation b/h.

The coefficients proposed by K. N. Korzhavin m, k_b and k are used nowadays practically in all Russian and abroad methods of ice loads calculations, the coefficient m being called in the abroad practice in the same way as according to K. N. Korzhavin – shape coefficient; and the coefficients k_b and k are called pressing coefficient and contact coefficient respectively. However the values of the coefficient are different from the K. N. Korzhavin’s ones in one or the other direction. It is connected with the different ways of determination of the maximum (limit) ice stresses.

So for instance in SNiP the coefficients values m and k_b received by the method of the limit load are used (Gladkov M. G.,1989; 1994). The following should be noted here: the value of the coefficient k_b given in the SNiP table 30 is the multiplication of the normalized limit ice stresses at the relationship $b/h \le 0{,}3$ (which is correspondent to the plane strain condition) and at the relationship $b/h \ge 0{,}3$ (correspondent to the plane stress condition) by the coefficient k at the different values b/h. The value b/h used in SNiP with help of expert estimation , to which plane stress condition can correspond, is characteristic to the ice with the thickness of 1,5 m or less – which is due to the fact that SNiP traditionally concerns more river than sea structures. As far as we can see the plane stress condition can take place when $b / h \geq 1$.

In VSN the values of the coefficients m, b, k_b, received as a result of the tests of rushing of the support models in the ice basin are used (Vershinina,1983), and in APIRP 2N and CAN/CSA it is recommended to use the values of the coefficients received both by the methods of the upper and lower estimation of the limit load and as a result of the tests in the ice basin (Ralston T. D., 1978)

As for the ice compression strength either average values of the maximum one axis compression (which are observed at the critical deformation velocities corresponding to the boundary from the plastic ice destruction to the fragile) are used in 10 (Ralston, 1977, Vershinin, 1983) or 3 and more (Gladkov M. G., 1994) ice massif layers taking into account the temperature, salinity, structure and porosity distribution along thickness, or the concrete numerical value of the ice strength of uncertain structure independent of the temperature regime or hydro chemical analysis (Michel, 1978) is used.

Except this SNiP proposes to take into account the effect of the ice massif velocity on the load value on it.

However in spite of the mentioned differences, the approaches presently used to the calculations of the ice loads on the singular supports give at the similar external conditions comparable results.

2. The ice load on the singular conic support SNiP and API RP 2N recommend to determine as the sum of the contributions from the force necessary for the break of the ice massif coming to the support and forming in it circular and radiant cracks as a result of the foundation (water) reaction, of the sliding along the cone crashed ice and of the friction forces acting on the surface ice-cone (Ralston T.D., 1978). Such an approach is possible both for the up and down directed cone but only at the slow velocities of the ice massif when the ice is destructed plastically and its velocity does not practically influence on the ice load.

Now it seams to be possible to expand the using of this approach to the fragile ice destruction where along with increasing of the ice massif velocity (or in other words with the increasing of the loading velocity) there is a tendency of increasing the forth necessary for its breaking (Gladkov M. G. et al, 1984: Uvarova E. V., 1999), and therefore to the increasing of the ice load on the conical support. For this purpose the coefficient of the influence of the ice velocity on the load value from it ca be used, received as a result of the numerical modeling of the ice action on the structure with the sloping front side (Uvarova E. V. 1999).

In CAN/CSA at the determining of the loads on the inclined (including conical) structures it is recommended to take into account the ice destruction along with the formation of the radial and the circular cracks, the ice rotation after the destruction the ice crawling over or its sliding, hydro dynamical and inertial forces (Frederking R. M. W., 1979) – essentially the same factors as in SNiP and APIRP 2N.

The VSN recommendation on the determination of the ice load on the conical support are worked out as a result of the tests on the pushing large scale support models in the ice cover of the Okhotsk Sea (the Kuibyshev MISI, MGSU now) In those recommendations only the force necessary for the break of the ice cover and the friction force on the surface ice-cone are taken into account. It is clear that if consider the degree of the factors having effect on the ice load value on the conical support taken into account the VSN recommendations are inferior to the SNiP, API RP 2N and CAN/CSA recommendations.

Except this, in API RP 2N and CAN/CSA the calculation methods based in the frame of the beam on the elastic foundation theory (Croasdale K. R. et al, 1994: Nevel D. E., 1992) and the corresponding computer programmes are recommended. Those methods give less conservative estimations of the ice loads on the conical structure (comparing with the method (Ralston T. D., 1977).

3. The total ice load on the structure consistent of the group of columns is usually determined as a product of the maximum load on the singular column, the number of the interacting with ice columns and the coefficient, taking into account the mutual column influence (depending from its front width and the distance between the neighbour column axes) and 3-D ice strength heterogeneity (SNiP, 1995; VSN, 1988; Bhat et al, 1995; Gladkov M. G., 2000).

4. For the platforms constructed in the Arctic and Far East seas the problems of the influence of the hum mocked ice massifs and dynamic ice loads are extremely important.

The load from the hummock massif is determined now either by the multiplication of the maximum ice field load by the constant coefficient of ice hummocking (SNiP, 1995; VSN, 1988), or as the sum of the consolidated part and the keel loads (APIRP 2N, 1995; CAN/CSA, 1992; Bellendir E. N., 2000). In the latter approach the sail load is neglected because of its comparative smallness. This approach to the determination of the hummock field load seams to be more substantiated.

The problem of taking into account the ice dynamic load as it is indicated in CAN/CSA requires a special consideration at the frequency of the cyclic loading 0,3 – 3 Hertz, which is characteristic for the real frequencies of the natural oscillations of the different types and dimensions structures constructed on the sea bottom. It is also noted there that the piers of bridges and narrow structures are more sensitive to the cyclic loading than the massive broad structures. It can be supposed from this that the platforms on the tension piles are more sensitive to the dynamical loading to a greater extent. For them the frequencies 0,01 – 0,1 Hertz could be dangerous.

On the basis of the premises taking into account the experience received by the experts during the work on the projects of the stationary sea platforms (including TLP of the Shtokman gaseous condensate deposit) the following conclusions can be proposed:

1. The ice loads on the platforms with tension links are calculated as on rigid structures.

2. The known approaches used in SNiP, APIRP 2N and CAN/CSA are applicable for the platforms with tension links.

3. The values of the global ice loads accounting the compliance of the TLP platforms has to be determined either with help of physical modelling performed on the equipment of competent organizations or with mathematical modelling using the programmes approved by MPS.

The ice loads have to be determined on the basis of the archival statistical physical and mechanical data on ice properties, hydro-meteorological and ice regimes in the region of the structure and also in-situ data received during the at least 5-year-long period of observations and investigations.

Depending on the stage of the structure projecting, the degree of the knowledge about the ice conditions and the group of the limit conditions in question, the deterministic or statistic approaches to determine ice loads should to be used.

The deterministic approach is used for the determining of the maximum ice loads in the earliest projecting stages when the information on the ice massifs parameters distribution laws during the structure life is limited. The defining parameters in this calculation are the characteristics of the ice massif (thickness, strength, air temperature, velocity, etc.) of the 1 % probability of exceeding for 100 years. The mutual parameters time correlation has to be taken into account (e. g. month correlation). The combination of the calculating parameters should be real and lead to the largest possible calculating load.

The statistical approach is recommended to use during the final projecting stages if there is data on the probabilistic long-term distribution laws of the main parameters in the considered time period. If there is no data concerning all the periods the most dangerous of them is permitted to use.

The statistical approach is used to determine the ice loads with the repeatability once in 100 years and also to determine all the stresses in the construction occurring during its life time when the fatigue calculations are carried out.

The value of the global loads accounting the compliance of the platforms with tension links has to be determined with help of the physical modelling on the base of the competent organizations or with mathematical modelling using programme products approved by MPS.

The ice freezing to the platforms with the tension links has to be excluded with help of the corresponding technical measures.

The determination of the ice loads on the stationery constructions is regulated by a number of standards (e. g. by SNiP 2.06.04-82* currently in force). However the construction of the new types of platforms and terminals requires special elaboration of the standard base.

First-year hummock loads

Hummock load is the most dangerous for hydraulic structures and therefore in the current practice it is determined either as the multiplication of the maximum even ice load by the constant hummock coefficient, without considering morphological or hummock physic-mechanical characteristics (VSN, 1988, P, 2001, SNiP, 1995), or as the sum of the hummock sail (or the above water ice conglomeration of the extensive structure), the consolidated layer and the keel loads (P 31.3.07-01, 2001, Wright, 1998).The latter approach seems to be more grounded. It is clear that using the hummock coefficient without taking into account the keel load can lead to a considerable error both in the value of the hummock load and the value of the overturning moment. It particularly concerns the hummocks with the advanced under-water part and the extensive structures.

A modification of the known abroad as Dolgopolov's method (Afanasiev, 1970) for the determination of the hummock keel load on the structure with the vertical front side (API RP2N, 1995, Croasdale, 1996) and a new method of the calculation of the hummock load without using the hummock coefficient are presented here. The description of the methods is followed by an example of hummock load determining for Prilazlomnaya platform with the comparison of the keel loads received by the described methods and the recommendations P 31.3.07-01 (P 31.3.07-01, 2001),

The modification of the Dolgopolov's method

The keel load on the structure with the vertical front side (as the international design experience of the sea ice resistant stationary platform (SIRSP) has shown) is usually estimated abroad by Dolgopolov's and Mellor's methods (Dolgopolov, 1975, Mellor, 1993). The average value received by these methods is used as the normative value. Such an approach seams to be correct for the early design stages, when as a rule the specialists have only expert estimations of the morphological hummock characteristics in the region of the structure.

Dolgopolov's method is also used with Croasdale's method (Croasdale, 1996)for the estimation of the hummock keel load on the structure with the sloping front side (Wright, 1998).

This fact shows in our opinion that Dolgopolov's method reflects the physical aspect of the hummock keel-structure interaction more adequate if compare with the other used methods (Bellendir, 2002). The known from model investigations (Afanasiev, 1970) and in-situ observations (Leperanta, 1992) fact that the keel increases in size during the interaction with the structure is taken into account in this method.

However the using of the increased keel thickness in the second term of Dolgopolov's formula doesn't seem to be quite correct because the ice smashed in hummock-structure interaction, which accumulates in front of the structure and leads to the keel thickness increase does not appear to have the same cohesion as the original keel. To overcome this inaccuracy Dolgopolov's formula can be used in the following form:

$$F_k = \left[0{,}5 \cdot 10^{-6} (\rho_w - \rho_i) g (1 - \rho_k) b_{k,m} (h_{k,m} - h_c)^2 tg^2 \left(\frac{\pi}{4} + \frac{\varphi_k}{2} \right) + 2\overline{C}_k (h_{k,0} - h_c) \times \times tg \left(\frac{\pi}{4} + \frac{\varphi_k}{2} \right) \right] b_{u,0} k_0 , \quad (1)$$

where ρ_w – the water density, kg/m^3; ρ_i – the ice density, kg/m^3; g – the acceleration of gravity, equal to 9.81 m/sec^2; ρ_k – the keel porosity; $b_{k,m}$ – the average front structure width at the moment of the maximum hummock load; $h_{k,m \le d}$ – the maximum keel depth at the moment of the maximum hummock load, calculated according to the formula:

$$h_{k,m} = h_{k,0} + j b_{k,0} ; \quad (2)$$

$h_{k,0}$ – the original keel depth, m; j – the coefficient of active structure width, taken (if $b_{k,0} / (h_{k,0} - h_c) > 2$) equal to 0,2 for the flat wall; $b_{k,0}$ – the average front structure width at the zone of the keel action with the keel depth $h_{k,0}$, m; d – the water depth at the structure, m; h_c – the thickness of the consolidated layer, m; φ_k – the keel internal friction angle, deg.; $\overline{C}_k$ – the average keel cohesion, MPa; k_0 – the coefficient accounting the 3-D character of the medium destruction when using the plane deformation model, determined as:

$$k_0 = 1 + \frac{2\left(h_{k,0} - h_c\right)}{3b_{k,0}} . \qquad (3)$$

The proposed modification of Dolgopolov's method as shown in (Afanasiev, 1970) does not lead to the considerable load change, but it makes the mentioned method more adequate.

Recommendation P 31.3.07 on determination of the hummock keel load on the structure with a vertical front side

According to (P 31.3.07-01, 2001) the hummock keel load on the structure is determined when $0,2 \le h_b \le 0,8$ m,(where h_b – the thickness of the ice pieces, m) as the multiplication of the even ice load by the hummock coefficient, or when $h_b > 0,8$ m according to the formula:

$$F_k = kR_k b_{k,0}\left(h_{k,0} - h_c\right), \qquad (4)$$

where k – the coefficient accounting incompleteness of the ice-structure contact (Korzhavin, 1969) taken dependent on the ratio $b_{k,0}/\left(h_{k,0} - h_c\right)$ by the recommendations of (SNiP, 1995); R_k – the overall keel compression strength, MPa, calculated as

$$R_k = 0,37\, exp\left(-6,6\rho_k\right) R_c ; \qquad (5)$$

R_c – the ice one axis compression strength, MPa, determined according to the relation:

$$R_c = -2,60\, ln\sqrt{10^{-3}\nu_i} - 2,32 ; \qquad (6)$$

ν_i - liquid phase quantity in the ice, ‰, calculated by the formula:

$$\nu_i = s_i\left(0,532 - \frac{49,185}{\bar{t}_i}\right); \qquad (7)$$

s_i – ice salinity, ‰; $\bar{t}_i$ – the average ice temperature, °C; $b_{k,0}$, $h_{k,0}$, h_c – the same symbols as in formula (1).

The proposed method of hummock load determination

The proposed method of hummock load determination, worked out in the frame of the problem of the passive pressure on the retaining wall with the friction forces taken into account and known in soil mechanics, is described bellow.

The hummock load is determined as the sum of the above water ice conglomeration, the consolidated layer and the keel loads (Figs. 7 and 8).

$$F_r = F_u + F_c + F_k . \qquad (8)$$

The above water ice conglomeration load is calculated by the formulas:

a) the horizontal load projection $F_{u,h}$, MN:

$$F_{u,h} = 0,5[10^{-6}\rho_i g(1-\rho_u)h_u^2 k_{u,\varphi} + c_u ctg\varphi_u\,(k_{u,c} - 1)h_u]\, b_u ; \qquad (9)$$

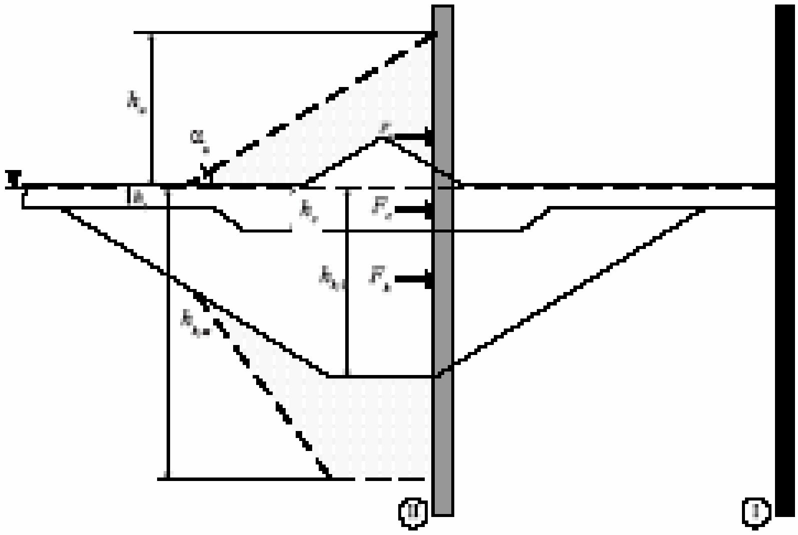

Fig. 7. The principle drawing of the hummock-vertical wall interaction:
I – the hummock cross-section before its interaction with the wall;
II – the hummock cross-section at the moment of the maximum load

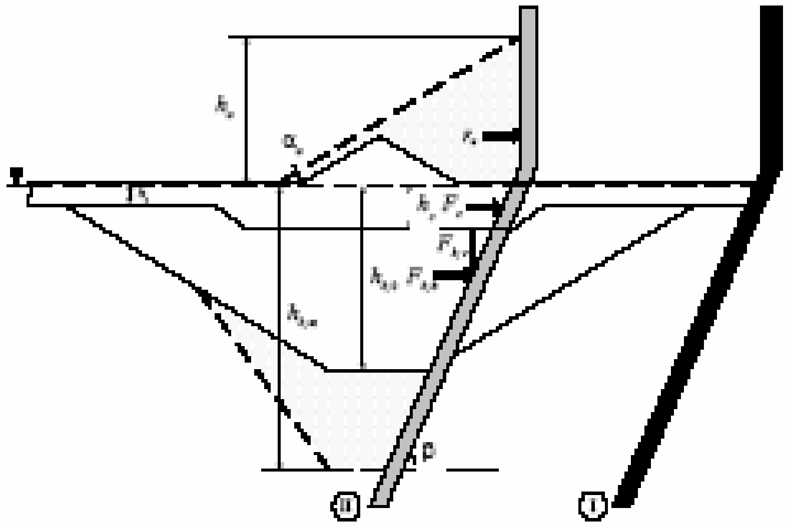

Fig. 8. The principle drawing of the interaction between the hummock and the wall having both vertical and inclined parts:
I – the hummock cross-section before its interaction with the wall;
II – the hummock cross-section at the moment of the maximum load

b) the vertical load projection $F_{u,v}$ MN:

$$F_{u,v} = F_{u,h} tg(90 - \beta - \alpha_f) - 0{,}5 c_u ctg\varphi_u tg\alpha_f b_u h_u . \qquad (10)$$

Where ρ_u – the ice conglomeration porosity; h_u – the height of the ice conglomeration determined by the relation (Vershinin et al, 2003)

$$h_u = 9{,}1 h_i^{0,4} , \qquad (11)$$

h_i – the thickness of the even ice around the hummock, m; C_u – the ice pieces cohesion, MPa; φ_u - ice conglomeration internal friction angle, deg.; b_u – the average structure front width at the zone of the ice conglomeration action, m; $k_{u,\varphi}$ and $k_{u,c}$ – the coefficients of the horizontal passive pressure projection, calculated according to the formulas:

$$k_{u,\varphi} = \left[\frac{cos(\varphi_u + 90 - \beta)}{cos(90 - \beta)(1 - \sqrt{k_1})} \right]^2 ; \qquad (12)$$

$$k_{u,c} = \left[\frac{cos(\varphi_u + 90 - \beta + \alpha_u)}{cos(90 - \beta)(1 - \sqrt{k_2})} \right]^2 k_3 ; \qquad (13)$$

$$k_1 = \frac{sin(\varphi_u + \alpha_f) sin(\varphi_u - \alpha_u)}{cos(90 - \beta - \alpha_f) cos(90 - \beta + \alpha_u)} ; \qquad (14)$$

$$k_2 = \frac{sin(\varphi_u + \alpha_f) sin\varphi_u}{cos(90 - \beta - \alpha_f + \alpha_u) cos(90 - \beta + \alpha_u)} ; \qquad (15)$$

$$k_3 = \frac{cos(90 - \beta) cos(90 - \beta + \alpha_f)}{cos(90 - \beta - \alpha_f + \alpha_u) cos(90 - \beta + \alpha_u)} ; \qquad (16)$$

$\alpha_f = arctg\ f$ – the internal friction angle; f – the ice-structure friction coefficient; $\alpha_u \le \varphi_u$ – the ice conglomeration slope angle, deg.; β – the structure front side inclination angle, deg.; ρ_i and g – the same symbols as in formula (1).

The hummock consolidated layer load F_c, MPa is determined according to the relation (Gladkov, 2002) in the following form:

$$F_c = r_c[(s_i^2 / 120 - 0{,}15 s_i + 0{,}79)\ |\bar{t}_i| + 1{,}39]\ (b_c / h_c)^{-0,4} b_c h_c . \qquad (17)$$

Where r_c – the reduction coefficient (the ratio of the consolidated layer and the even ice strength limits in the similar conditions); b_c – the average structure front width at the zone of the consolidated layer action, m; h_c, s_i, $\bar{t}_i$ – the same symbols as in formulas (1), (4) and (7).

The hummock keel load is calculated by the formulas (Bellendir E. N., Gladkov M. G., 2000) in the following form:

a) the horizontal load projection $F_{k,h}$, MN;

$$F_{k,h} = 0{,}5[10^{-6}(\rho_w - \rho_i)g(1-\rho_k)b_{k,m}(h_{k,m} - h_c)^2 k_k + C_k ctg\varphi_k (k_k - 1)b_{k,0}(h_{k,0} - h_c)]; \tag{18}$$

b) the vertical load projection $F_{k,v}$, MN:

$$F_{k,v} = F_{k,h} tg(90 - \beta - \alpha_f) - 0{,}5 C_k ctg\varphi_k tg\alpha_f b_{k,0}(h_{k,0} - h_c). \tag{19}$$

Where C_k – the consolidated layer-keel cohesion, MPa; φ_k – the keel internal friction angle, deg; k_k – the coefficient of the keel horizontal passive pressure projection, calculated by the formulas:

$$k_k = \left[\frac{cos(\varphi_k + 90 - \beta)}{cos(90-\beta)(1-\sqrt{k_4})}\right]^2; \tag{20}$$

$$k_4 = \frac{sin(\alpha_k + \alpha_f)sin\,\varphi_k}{cos(90 - \beta - \alpha_f)cos(90-\beta)}; \tag{21}$$

ρ_w, ρ_i, g, $b_{k,m}$, $b_{k,0}$, $h_{k,m}$, $h_{k,0}$, h_c, φ_k – the same symbols as in formula (1); β – the same symbol as in formulas (12) – (16); α_f – the same symbol as in formulas (14) – (16).

Notes.

1. The loads $F_{u,h}$ and $F_{k,h}$ on the structure with the vertical front side are determined with $\beta = 90^o$.

2. The loads $F_{u,v}$ and $F_{k,v}$ on the structure with the sloping front side with $75 < \beta \le 90^o$ are equal to 0.

A numerical example

The hummock loads on SIRSP Prilazlomnaya (the above-water side of which is vertical and the under-water side has the inclination angle $\beta = 58^o$) calculated according to the described method are given in table 1. These loads were obtained with the original data reflected in table 2.

Table 1

f	0	0,1	0,2	0,3
F_u, MH	55,2	59,6	64,1	69,1
F_c, MH	187,8			
$F_{k,h}$, MH	38,2	51,7	64,1	76,7
$F_{r,h}$, MH	281,2	299,1	316,0	333,6

Table 2

Hummock part	Original data element			Reference
	Symbol	Dimension	Value	
Above-water ice conglomeration	b_u	m	101,0	SIRSP design
	ρ_i h_i	kg/m^3 m	918 1,45	(LTU, 2000)
	ρ_u α_u	 deg.	0,3 30	(Korzhavin, 1969)
	φ_u c_u	deg. MPa	40 0,005	(Vershinin, 2003)
Consolidated layer	b_c			
	h_c $\bar{t}_i$ s_i r_c	m ^{0}C ‰ 	2,91 -6,5 4,2 0,76	(LTU, 2000)
Keel	ρ_w	kg/m^3	1025	(APIRP 2N, 1995)
	ρ_k $h_{k,0}$	 m	0,32 13,0	(LTU, 2000)
	d β $b_{k,0}$ $b_{k,m}$	m deg. m m	20 58 1,09 17,09	SIRSP design
	φ_k C_k	deg. MPa	15 0,03	(Gladkov, 2000)

It should be noted here that the hummock loads (with the friction angle f = 0,1 – 0,3) $F_{r,h}$ (table 1) are very close to the foreign experts recommendations concerning the unfactored loads on SIRSP Prilazlomnaya with the return period 1 per 100 years: 300 – 335 MN (Bellendir E. N., Gladkov M. G., 2000).

For comparing in table 3 the hummock keel loads calculations according to the proposed method (with β = 90^o and f = 0) and the loads calculated by Dolgopolov's method and by the recommendation P 31.3.07-01 are presented.

Table 3

Load, MN		
Proposed method	Modified Dolgopolov's method	Recommendation P 31.3.07-01
65,6	65,5	69,0

You can see from table 3 that the proposed method gives the same results (concerning the hummock keel loads on the vertical wall with the friction coefficient f = 0) as both Dolgopolov's method and the Recommendation P 31.3.07-01. It is also clear, that along with the nowadays most popular methods using the internal angle and the ice shivers cohesion as the main hummock keel parameters, the methods using strength compression and other deformational keel characteristics can be used (Astafiev et al, 1997, CAN/CSA – S 471-92, Bellendir E. N., Gladkov M. G., 2002).

Furthermore on the basis of large-scale tests and in-situ observation results simple empiric expressions concerning the dependence of the effective pressure of both the above-water ice conglomeration and the hummock keel from their contact area with the structure should be found, as it is the case for even ice (Masterson, 1993, Sanderson, 1988). In this case the morphometrical hummock characteristics will be determinant and the attention of the organisations specialised in sampling and analysing of hydro meteorological data in ice conditions in the regions of the structures will be given to the obtaining such characteristics.

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