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Ice Model Tests of Caisson Platform in Shallow Water

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The purpose of the model tests performed in the Ice Tank of the Krylov Institute, St. Petersburg, Russia, was to study the effect of the closeness of the sea bottom on the ice pile-up in front of a caisson-type platform and on the ice loads acting onto the platform. Grounding of the ice rubble can lead to both a reduction and increase of the ice load. Both these phenomena were noted during the model tests in different stages of platform/ice interaction. The load increase was observed in the initial stage of the underwater pile-up formation, when its draft approached the water depth. In the later stage, when the stationary grounded pile-up against the platform was formed, ice load reduction was observed. The paper provides quantitative and qualitative analysis of the model test data.

INTRODUCTION

The Northern Caspian Sea has promising hydrocarbon fields, whose development either has started or is about to. The Korchagin Field is one of such deposits. Offshore structures intended for use during the development of this field should, among other things, be designed with consideration of natural features characteristic of the region, such as stable ice coverage in winter, relatively small water depths and significant water-level fluctuations.

One of the structures planned for installation on the Korchagin Field is the ice-resistant platform (IRP-1) being built based on the Shelf-7 semisubmersible. It consists of a caisson-type rectangle in-plane view, with sloping sides where the platform interacts with ice (Fig. 1).

Operating experience of caisson installations and artificial islands for well drilling in shallow water conditions—in particular, the Molikpaq platform in the Beaufort Sea and artificial island on the Kashagan Field in the Caspian Sea—indicates that in winter large rubble accumulations formed near these structures are in rather firm contact with the seafloor (Neth, 1991; Wright and Timco, 1994; Croasdale et al., 2004; Evers et al., 2001). If the above formations are not taken away in the event of ice drift changing, the structures turn out to be fully surrounded by ice piles. As theoretical studies and full-sized measurement records showed, the steady seabed-supported ice accumulations in front of the structures contribute to reducing the ice loads transferred to these structures by drift ice (Marshall et al., 1989, 1991). According to Marshall et al. (1991), the level of ice loads transferred to the installation through the ice formations can be diminished to zero depending on the extent of formed piles, consolidated layer thickness, physical and mechanical properties of their non-adfreezed part, and roughness of the seabed. This effect is used to construct artificial ice barriers near structures in shallow waters as was done at the time of the Sunkar drilling platform operation in the Caspian Sea (Croasdale et al., 2004).

Practically all the above parameters influencing the level of ice loads depend on the age of the accumulation. As the age increases, one can expect that the formation extent and consolidated layer thickness will go up. These 2 factors contribute to decreasing the ice loads acting on the structure. However, when predicting global ice loads, one should consider all probable scenarios of ice effects to select the one resulting in the greatest ice loads. Such scenarios are not always known in advance.

Model investigations were carried out in the Krylov ice basin to study how the IRP-1 platform interacts with surrounding ice under shallow water conditions. With the view of tracing the processes and measuring the levels of expected ice loads at the initial stage of ice formation generation, the scope of experimental modeling included some cases where ice and installation interacted without steady ice accumulations in front of the structure. At this stage it was found that the proximity of seabed and lack of stiff contact between ice formation and seafloor can bring greater ice loads onto the structure. This paper investigates the reasons for such an effect as recorded during the experiments.

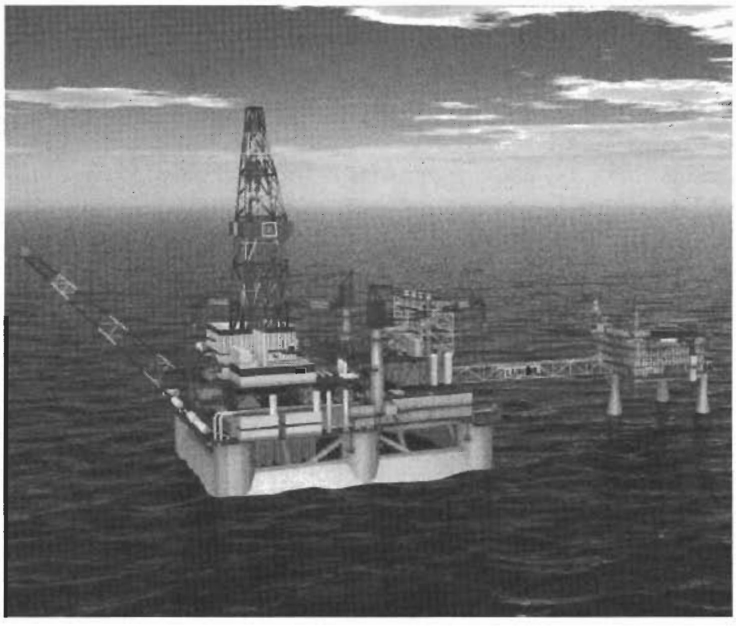

Fig. 1 Complex of offshore facilities for Korchagin Field

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KEY WORDS: Caisson platform, ice load, ice rubble, grounded rubble, shallow water.

In 2004, the Institute of Water Problems of the Russian Academy of Sciences in Moscow performed research such as, "History data about the Caspian multi-year water levels determined for design of surface installations on Korchagin Field." This included analysis of the Caspian Sea water-level fluctuations over 100 years and forecast probable sea-level changes in the 30-year platform operation lifetime. The design depths at the point of platform deployment are 12.2 m as a current depth within the field area, and 14.9 m and 7.8 m as, respectively, maximum/minimum likely water levels in the 30-year period. The sea levels as given above were modeled at the time of the experimental investigations.

DESCRIPTION OF EXPERIMENTAL INVESTIGATIONS

The model investigations were performed in the Krylov ice basin; its testing area measures 40 × 6 × 1.8 m, at a model test scale of about 1:60. Fig. 2 shows the general view of the IRP-1 model. The tests were conducted in 3 positionings of the platform model in such a way that its wide and narrow sides and diagonal were against the ice movement. This paper considers the only case of the platform orientation when its wide side was placed perpendicular to the drift direction from which the greatest ice loads can be expected. In this scenario the platform breadth on the waterline is 72.2 m at sea depths of 14.9 m and 12.2 m, and 74.8 m at a sea depth of 7.8 m.

The model investigations for the study of the interaction processes between offshore installations and drift ice formations can be realized in 2 ways: By towing an installation model rigidly secured to a towing carriage through an ice field (reversed-motion mode), or by advancing the ice field on the fixed installation model (direct-motion mode) that corresponds to field conditions. For the purpose of studying how the investigation modes influence the process of ice formations and ice load levels, some experiments were carried out in both modes. In those cases the same ice conditions were modeled (ice geometry, strength features and drift speed) as well as water depths.

Figs. 3 and 4 show a schematic and a general view of the testing facility used in the direct-motion mode.

A special seabed imitator was used to investigate the influence of sea depths on the interaction processes between platform and ice. The imitator was manufactured from tintless waterproof plywood, and its sizes were selected so that a sufficient area was provided for producing ice accumulations in front of the platform. Seafloor roughness and irregularities were not modeled during the experiments; the influence investigation was made of the seabed as a flat screen.

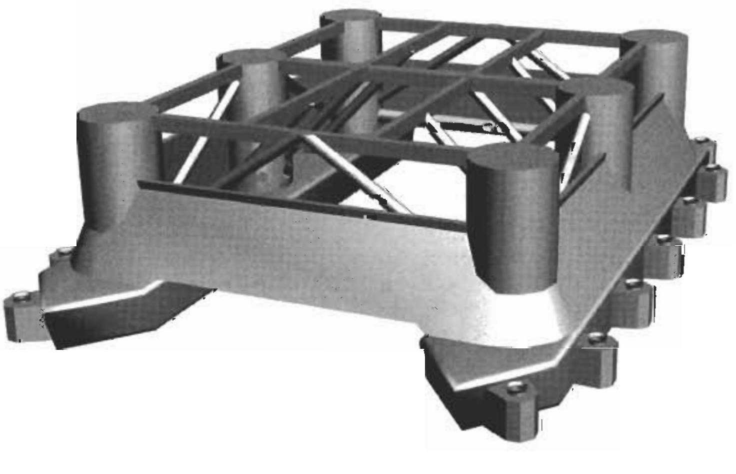


Fig. 2 General view of IRP-1 model

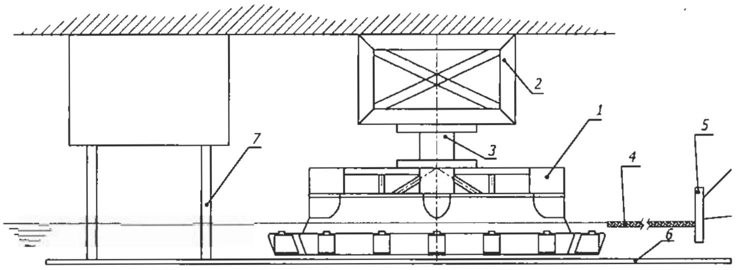


Fig. 3 Setup for direct-motion test mode: 1 = IRP-1 model; 2 = fixed frame; 3 = dynamometer; 4 = modeled ice feature; 5 = ice pusher; 6 = seabed imitator; 7 = supports for seabed imitator

In the case of both direct- and reversed-motion modes, the seabed imitator was not in contact with the model that was rigidly secured to a dynamometer. A small clearance between seafloor and model was made by cutting the model bottom to a size equal to the clearance. The seabed imitator fixed to the carriage was towed together with the model. The loads acting on the seafloor by ice formations were not recorded. The experimental task was to measure ice loads only on the structure model in the presence of the seabed.

The hummocked ridges modeled in the experiments correlated to natural hummocked ridges featuring a 0.8-m-thick consolidated layer and 5.3-m keel depth. The experiments were carried out at an ice speed of 0.5 m/s and a flexural strength of 0.6 MPa.

Table 1 shows the data on test modes and measured maximum horizontal ice force acting on the platform oriented with its wide side to the ice drift direction.

Fig. 5 shows the process of forming ice rubble accumulations with the level ice field advancing the platform model. Table 1 contains the amount of ice drift (or ice sheet extension) for each test run. The duration of runs was determined by a condition of obtaining a steady process of interaction, when (1) the ice rubble had achieved streamline contour; (2) ice breaking had transferred to the outer boundary of the rubble; and (3) mainly broken ice streamed the structure in the horizontal plane. After completion of a test run, the level ice in the vicinity of the rubble pile was carefully removed to estimate the size of underwater ice formations in front of the platform (Fig. 6). A video camera or special rod determined the moment when the ice piles were in contact with the bottom.

Because underwater currents that could have an impact on accumulation processes and ice load levels are partly modeled during

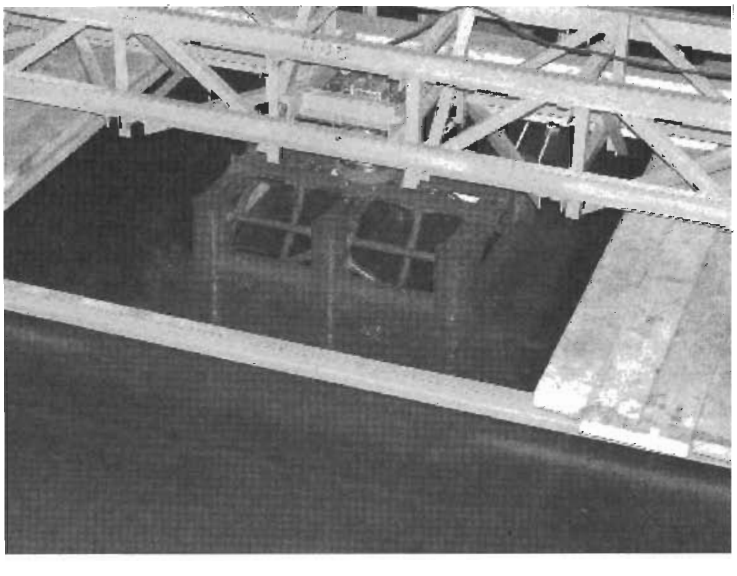


Fig. 4 General view of testing facility used in direct-motion mode

Run no.	Ice conditions	Water depth [m]	Test motion mode	Amount of ice drift [m]	Grounding rubble	Force [MN]
1	0.8 m level ice	12.2	direct	200	no	39
2	0.8 m level ice	7.8	direct	350	yes	59
3	0.8 m level ice	12.2	reversed	450	no	42
4	0.8 m level ice	7.8	reversed	450	yes	51
5	0.6 m level ice	12.2	reversed	400	no	20
6	1.2 m level ice	12.2	reversed	900	yes	84
7	Ridge	12.2	direct	350	no	44
8	Ridge	7.8	direct	300	yes	63

Table 1 Test modes selected for analysis (full-scale values)

towage of the platform model in the stationary field, one of the tasks of experimental investigations was to correlate the experimental results obtained through realizing both modes under the same conditions (runs 1 and 2, 3 and 4 in Table 1). Fig. 7 shows the time history of the horizontal ice force acting on the platform model in the course of runs 1 and 3; as is evident from this diagram, the records indicate quite a close correlation not only in the loads but also in the frequency of the processes in progress. The dips in the diagram correspond to a situation where the surface ice rubble in front of the platform was submerged resulting in an abrupt decrease in loads. The result obtained is of great practical value as it allows for the selection of the experimental plan that is best suited for investigating the interaction between structures and ice. It should be noted that the correlation might not be achieved with greater ice speeds.

Fig. 5 Forming ice rubble accumulations in front of IRP-1 model when pushing level ice sheet

Fig. 6 View of underwater portion of ice rubble after removing level ice sheet

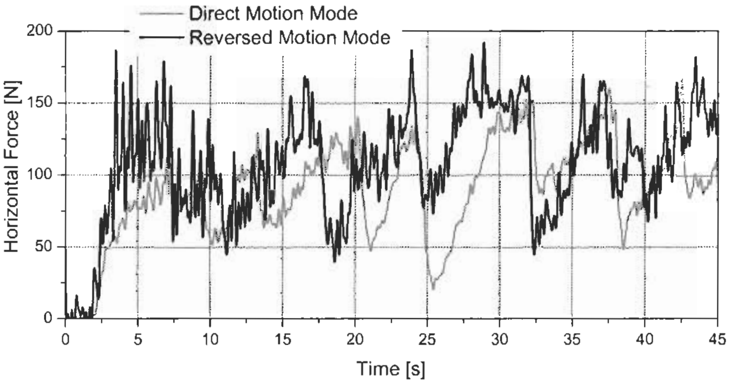


Fig. 7 Comparison of 2 time histories obtained in both direct- and reversed-motion modes

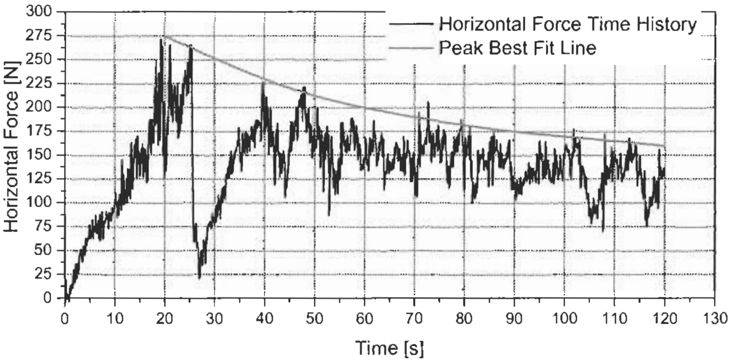


Fig. 8 Horizontal ice-force time history and peak best-fit line in case of formation of grounded rubble. (At time point ≈25 s, ice sheet has failed along whole width of structure model due to bending under weight of ice rubble, and sharp drop in ice load has occurred.)

Runs 2 and 4 differ from runs 1 and 3 by the interaction between the underwater portion of the ice rubble and the seabed imitator. Looking at the diagram in Fig. 8 (run 2), it can be seen that the ice force gains its maximum value at the initial stage of ice/bottom interaction, when the underwater piles only touch the seabed, but are not yet fixed to it. As the formations develop and the stable zone is firmly kept by the seafloor forms, the seabed begins to take some part of the load with the ice-breaking processes shifting to the rubble's outer boundary, and the peak best-fit line smoothly going down (Fig. 8).

ANALYSIS OF EXPERIMENTAL INVESTIGATION DATA

The findings of previous theoretical investigations (Alexeev and Karulina, 1999) showed that, considering the assigned thickness of level ice, there was a maximum depth of underwater rubble

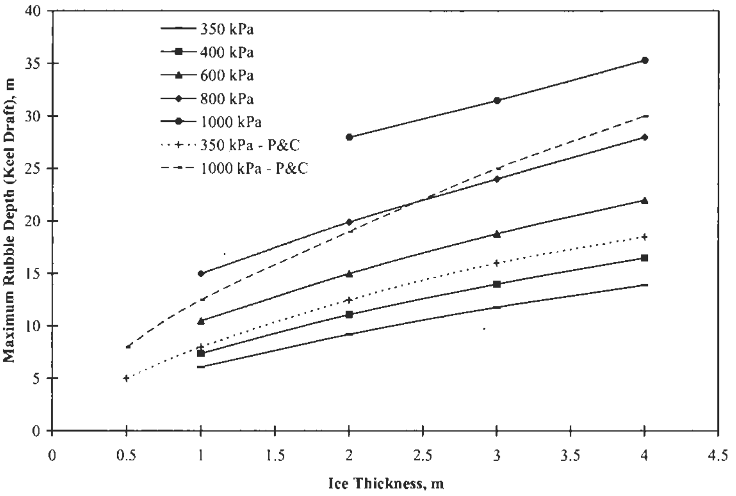


Fig. 9 Maximum rubble depth (or keel draft) vs. ice thickness and flexural strength (P&C = Parmeter and Coon, 1972)

accumulations in front of the wider piles (Fig. 9). Similar relationships were obtained by Parmerter and Coon (1972) for estimating the maximum depth of the ridge keel. Both curve series have rather accurate correlation.

With a modeled ice flexural strength of 0.6 MPa and level ice thicknesses of 0.6 m, 0.8 m and 1.2 m, the maximum rubble accumulation depth can be estimated at 8 m, 10 m and 12 m, respectively (Fig. 9). From the point of view of qualitative results, the performed experiments proved the theoretical estimations obtained. These showed that the rubble piles were in seabed contact under the modes where the water depth closely approached the maximum draft of rubble accumulation. Another scenario was obtained in test run 3, when the maximum draft of rubble (10 m) corresponding to the specified thickness of level ice (0.8 m) was less than the water depth (12.2 m), and there was no grounded rubble. The time record in Fig. 10 shows that, after significant floating ice-rubble accumulations in front of the structure had formed, the interaction looked like a steady process. Icebreaking occurred along the rubble's outer boundary, and broken ice flowed around the structure. So the maximum vertical dimensions of the ice rubble (height and draft) as well as the mean ice loads did not change. Such an interaction picture allows us to suppose that increasing the amount of ice drift in this test run would not lead to grounding of the ice rubble.

It is a rather complicated problem to quantitatively estimate the influence of seabed contact on the ice load taken by the structure. The maximum experimental horizontal force resulting from level ice effects on the platform may be grouped on the basis of the occurrence of grounding rubble formation (Fig. 11). It was found during the model investigations that the horizontal ice force had some increase at the initial stage of seabed contact. In order to study this phenomenon, consider the process diagram in Fig. 12.

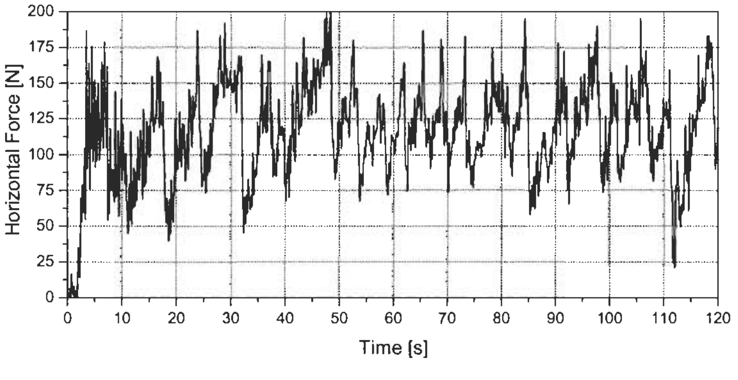


Fig. 10 Horizontal ice force's time history in case of formation of floating ice rubble in front of structure (test run 3)

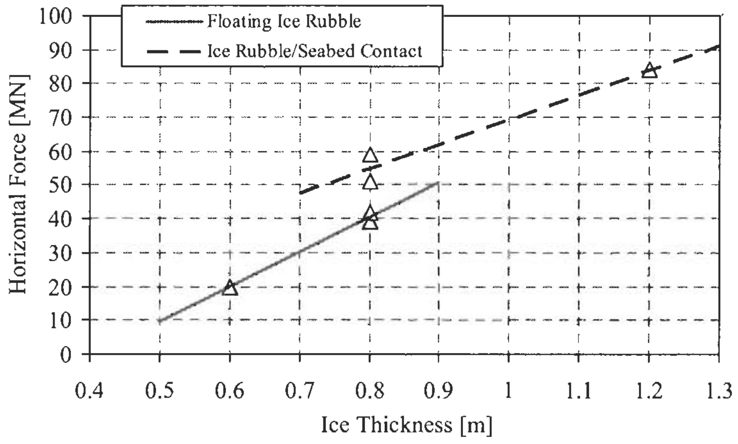


Fig. 11 Maximal horizontal ice forces measured in experiment

The subsea video records made of the model investigations of wide platforms in the ice basin showed that, at the initial stage of the underwater accumulation formation, its ice blocks are in constant motion. While going underwater, some ice blocks have a downward slide along the sloping surface; the effect is that the flotation force tends to bring them to the surface. In this case the blocks move along the trajectory close to a circular arc (Fig. 12a). As soon as the sinking ice formations reach bottom, their slide along the seabed will be accompanied by a friction force (Fig. 12b), increasing the total ice force on the structure. The friction force, F_{dyn}, can be estimated by the following expression:

$$F_{\text{dyn}} = \mu_{\text{dyn}}(W_{\text{sail}} - B_{\text{keel}}) \tag{1}$$

where μ_{dyn} is an ice/seabed dynamic friction coefficient; W_{sail}, a surface rubble accumulation whose effective weight is transferred to the seabed; B_{keel}, a flotation force acting on the submerged part of the rubble.

The following formulas can be used to approximately estimate W_{sail} and B_{keel}:

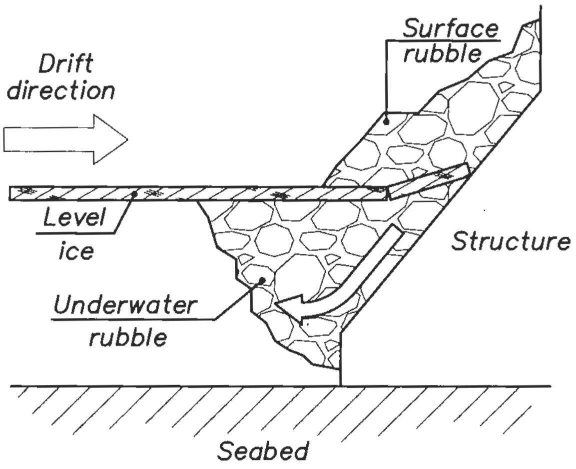
$$\begin{aligned} W_{\text{sail}} &= 0.5\rho_{\text{ice}}g(1-\nu_{\text{sail}})h_{\text{sail}}L_{\text{rubble}}D \\ &\quad - (\rho_w - \rho_{\text{ice}})gh_{\text{ice}}L_{\text{rubble}}D \end{aligned} \tag{2}$$

$$B_{\text{keel}} = (\rho_w - \rho_{\text{ice}})g(1-\nu_{\text{keel}})(d_w - h_{\text{ice}})L_{\text{rubble}}D \tag{3}$$

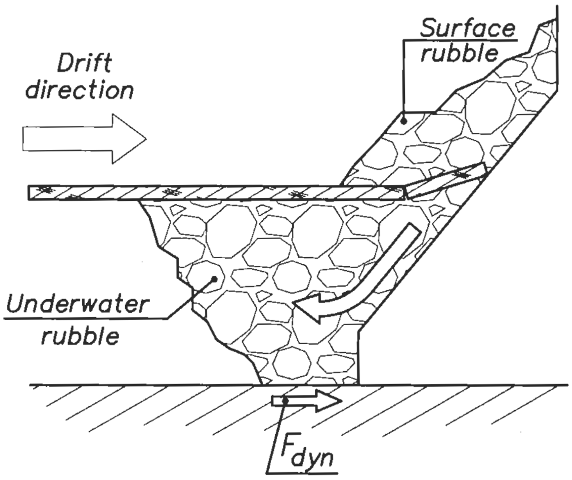
where $\rho_w g, \rho_{\text{ice}} g$ are water and ice unit weights, respectively; $\nu_{\text{sail}}, \nu_{\text{keel}}$ are sail and keel porosities; h_{sail}, a sail effective height; L_{rubble}, a rubble extent averaged over the structure's breadth; D, the structure's breadth on the waterline; h_{ice}, a level ice thickness; and d_w, a water depth.

The ice blocks' motion in the keel in front of the platform ceases as the ice rubble becomes bigger and icefield breaking shifts to the outer boundary of the ice accumulation. In front of the platform, the zone of steady bottom-connected grounding rubble forms (Fig. 12c). This case was theoretically investigated by Marshall et al. (1991); it was shown that some part of the ice loads would be taken by the seafloor, which served to reduce the total ice force acting on the platform. The load taken by the seabed can be estimated by using the above equations where μ_{dyn} in Eq. 1 changed for static friction coefficient μ_{st} as the rubble accumulation is stationary:

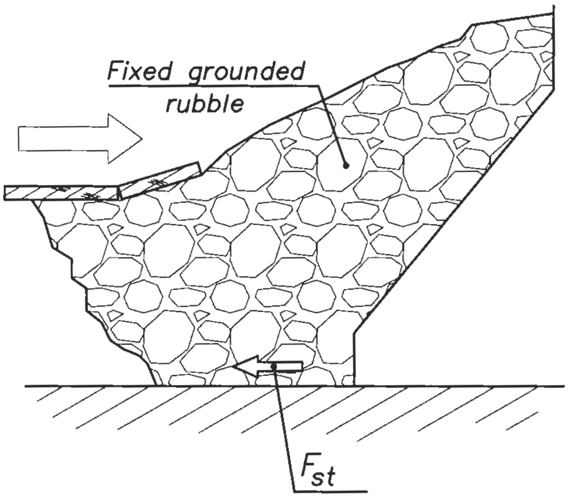
$$F_{st} = \mu_{st}(W_{\text{sail}} - B_{\text{keel}}) \tag{4}$$



(a) No rubble/seabed contact



(b) Rubble/seabed contact – initial stage



(c) Grounded rubble is formed

Fig. 12 Forming grounded ice rubble in front of platform

Let's take into account the following values corresponding to the conditions modeled in the experiment:

$h_{\text{ice}} = 0.8$ m; $h_{\text{sail}} = 8$ m; $L_{\text{rubble}} = 28$ m;

$\mu_{\text{dyn}} = 0.15$; $\mu_{st} = 0.3$;

$\rho_w g = 0.0101$ MN/m^3; $\rho_{\text{ice}} g = 0.0090$ MN/m^3;

$D = 74.8$ m; $d_w = 7.8$ m.

According to experimental investigations of the geometry and strength parameters of the ridges that were simulated in the Ice Tank of the Krylov Institute (Bitsulya et al., 2005), some mean value of ridge keel porosity equal to 0.2 may be accepted as a value of porosity of the underwater rubble, ν_{keel}. The same 0.2 value may be accepted for porosity of the surface rubble ν_{sail} on the basis of field data on the ridge sails' porosity that were obtained by the Arctic and Antarctic Research Institute (AARI) in Barents Sea.

From Eq. 1 we can further obtain the estimation indicating that, at the initial stage, the horizontal ice force on the platform increases by about 8MN because of the interaction between keel and seabed. Although a simple analytical model, this value allows the prediction of the order of growth of the ice force onto the platform in shallow water. Comparison of runs 1 and 2, 3 and 4 (from Table 1) shows that rubble/seabed contact at the water depth of 7.8 m has resulted in increasing the maximal ice force by 20MN in the former case and by 9MN in the latter.

It follows from Eqs. 1 and 4 that the influence of the seafloor on the ice loads directly depends on the ice block/bottom friction coefficient, μ. As a rule, an ice/surface static friction coefficient is twice as large, or even larger, than a dynamic friction coefficient. Thus, $F_{st} > F_{\text{dyn}}$, i.e. the loads transferred to the bottom after forming steady accumulations near the structure are higher than the additional ice loads on the platform resulting from the rubble/seabed contact at the initial stage of the structure/ice interaction. It follows from Fig. 8 that the loads transferred to the structure through the ice accumulation held by the seabed die down with time, and consequently with an increase in the extent of rubble accumulations in front of the platform. From the results of theoretical investigations by Marshall et al. (1991) it follows that these may be reduced to zero. However, this requires rather a significant time period of ice/structure interaction. This process was not simulated in the present model experiment.

In the process of interaction between the platform and a ridge with a keel depth close to water depth (run 8 in Table 1), the ice force was increased by approximately 1.5 times as compared to the force in the deep-water case (run 7). With the interaction between the ridge keel and the wide obstruction, the unfrozen ice blocks are pressed out in different directions. In the absence of an obstruction beneath, a portion of these ice blocks clear the structure, and the main portion remains in front of it without building up considerable loads. But if the seabed is rather close to the ridge bottom, the keel becomes more compressed in the zone between the consolidated layer and the bottom, which raises the keel stresses and ice loads on the structure.

Much like the interaction of the structure with level ice, the ridge force on the structure will be reduced at the expense of some load transfer to the seafloor in the presence of steadily grounded ice rubble in front of the platform. However, during run 8 (Table 1) such steadily grounded rubble was not formed before the structure/ridge interaction.

CONCLUSIONS

This paper presents the description of the IRP-1 model investigations in the Ice Tank of the Krylov Institute, St. Petersburg, Russia. The IRP-1 ice-resistant platform was being built based on the Shelf-7 semisubmersible. The primary conclusion drawn from the experimental findings is the necessity to take into account how the shallow water conditions characteristic of the Caspian region under discussion affect the platform/ice interactions and level of the expected ice loads.

In a qualitative sense, the shallow-water influence manifests itself in the formation, in front of the wider platform, of the ice accumulations reaching the seabed and firmly kept there.

In quantitative terms, the shallow-water influence, as compared with the results for deep waters, is patterned along changes in the ice loads on the platform exposed to drift ice formations. The experiments showed that, with that in mind, the shallows' influence is ambiguous, as both the reduction and enhancement of ice loads were obtained at different stages of ice interactions.

The model tests were done in 2 modes. In one mode, the platform model was towed through the stationary ice field. In the other, the ice feature was moved on the immobile platform model, making it possible to reveal the independence of both the qualitative and quantitative experimental results from the investigation modes.

The seabed influence on ice loads depends substantially on the nature of the seabed surface. The rougher it is, the more variations can be expected in the ice loads when the accumulations touch the seafloor. For this reason, before starting model investigations, it is important to obtain appropriate seabed data and use a seabed model with surface accounting for the actual ice/bottom friction coefficients.

The interaction scenario resulting in maximum ice loads on the platform is not always evident. All probable cases of ice impact on the platform should be considered.

ACKNOWLEDGEMENT

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REFERENCES

Alexeev, Ju N, and Karulina, MM (1999). "An Assessment of Pile-up Dimension in Front of Sloping Offshore Structures," *Proc Int Conf Port and Ocean Eng*, Helsinki, Vol 1, pp 396–405.

Bitsulya, AV, Karulin, EB, and Karulina, MM (2005). "Variance in Interpreting Results of Measurement of Mechanical Properties of Ridge Keel in Model Tests," *Proc Int Conf Port and Ocean Eng*, Potsdam, New York, Vol 3, pp 1039–1048.

Croasdale, KR, Comfort, G, Crocker, G, Metge, M, and Ritch, R (2004). "A Field Research Programme to Address Ice Engineering Issues for the North Caspian Sea," *Proc Int IAHR Symp on Ice*, St. Petersburg, Vol 3, pp 57–67.

Evers, K-U, Spring, W, Foulkes, J, Kuehnlein, W, and Jochmann, P (2001). "Ice Model Testing of an Exploration Platform for Shallow Waters in the North Caspian Sea," *Proc Int Conf Port and Ocean Eng*, Ottawa, Vol 1, pp 255–264.

Marshall, AR, Frederking, RM, Sayed, M, Nadreau, JP, Croasdale, KR, and Jordaan, IJ (1989). "Measurements of Load Transmission Through Grounded Ice Rubble," *Proc Int Conf Port and Ocean Eng*, Lulea, Sweden, Vol 1, pp 575–584.

Marshall, AR, Jordaan, IJ, and McKenna, RF (1991). "A Two-Dimensional Model of Grounded Ice Rubble," *Proc Int Conf Port and Ocean Eng*, St. John's, Canada, Vol 1, pp 428–444.

Neth, VW (1991). "Ice Rubble Formation Along the Molikpaq," *Proc Int Conf Port and Ocean Eng*, St. John's, Canada, Vol 1, pp 241–258.

Parmerter, RR, and Coon, MD (1972). "Model of Pressure Ridge Formation in Sea Ice," *J Geophys Res*, Vol 77, No 33, pp 6565–6575.

Wright, BD, and Timco, GW (1994). "A Review of Ice Force and Failure Modes on the Molikpaq," *Proc Int IAHR Symp on Ice*, Trondheim, Vol 2, pp 816–825.