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DESIGN OF SELF-STABILIZING ICE BARRIER

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ABSTRACT

Ice barriers installed in close vicinity to offshore platforms are designed to take the main loads resulting from floating ice by breaking the ice and piling-up the rubble ice. Platforms and equipment protected by ice barriers can be dimensioned considering only low ice loads and can thus be constructed more economically. Also, the safety of the platforms increases. One objective of the research project MATRA is to design suitable ice barriers for exploration and oil production in ice-covered, shallow-water areas. Several concepts were investigated, e.g. vertical and inclined piles as well as barges equipped with piles. Model tests were carried out under varying conditions in order to evaluate the design alternatives and to provide the design loads resulting from floating ice. The most suitable structure is a light-weight ice barrier with an inclined roof structure mounted on a barge which collects early, thin ice inside the structure, stabilizes itself by the piled-up rubble ice and by this later can withstand thicker ice. The measured loads were analysed and compared with loads theoretically derived from existing approaches. At the first stage, when the structure fills with ice, bending is the dominant failure mode. Once a rubble pile has built-up in front of the structure, other failure modes may become significant comprising buckling and crushing. The load-time curve shows a scattering behaviour and has very high load peaks of short duration, especially for thick ice. The analysis comprises a statistical evaluation of the loads, taking the site conditions in the Caspian Sea as reference. Design loads for different load-cases were derived, which are the basis for the stability analysis of the ice barrier. On the basis of the results of the stability analysis and considering the requirement that the structure shall be self-floating for transport, the structure was optimized and the detail design was carried out.

INTRODUCTION

Existing ice barriers which are designed to withstand the ice forces without the stabilizing effect of the ice itself have to be anchored in the sea bottom or must have an extremely high weight. In the latter case, the ice forces are transferred to the sea bottom through bottom friction. Those ice barriers are expensive and it can be difficult to install them in shallow waters.

The idea of the research project MATRA is to design modular ice barriers which catch early, thin ice, stabilize themselves by this ice and can withstand thick ice later in the ice season. The ice barriers can be removed in summer and thus do not hinder shipping traffic in ice-free seasons. The following criteria shall be fulfilled by the structure to be developed:

- Self-stabilizing of structure by piled up rubble ice,
- Self-floating for transport,
- Fast and environmentally sound installation and de-installation,
- Cost efficiency in fabrication, transport and maintenance,
- Flexibility, adjustability to specific site conditions,
- Safety, reliability,
- Good availability of construction material under consideration of local fabrication facilities.

For the design of the structure, model tests with different structures under varying conditions were carried out at the Hamburg Ship Model Basin (HSVA).

ICE PROPERTIES

For the statistical evaluation of the forces, the site conditions in the Caspian Sea are taken as reference.

In average years, ice starts to form by mid-November in the shallow waters of the North Caspian. In February, the ice has reached its maximum thickness. In March, the ice extent starts to decrease, and by early to mid April, the region is free of ice. In extremely severe winters, ice develops already in October and reaches its maximum thickness and extent in the time span between end of November and beginning of December.

Two ice thicknesses, 0.1 m and 0.5 m, were investigated.

The mechanical properties, i.e. the flexural strength and the modulus of elasticity, of the model ice were measured by cantilever beam tests. The following values, converted to full scale, have been reported (EVERS, KÜHNLEIN, 2001):

- Flexural strength: s_f = 750 kPa
- Elasticity modulus: E = 148 MPa

RESULTS OF MODEL TESTS

The model tests were carried out by the Hamburg Ship Model Basin (HSVA) at a scale of 1:16. All values in this paper are given at full scale. The ice velocity of 1 kt and the water depth of 4 m were kept for all model test configurations.

The ice thickness of 0.1 m is referred to as “thin ice”, while the ice thickness of 0.5 m is referred to as “thick ice” in the following.

During phase I of the model tests, the following structures were investigated:

- vertical piles installed in a row,
- inclined piles installed in a row,
- barge equipped with two oppositely arranged rows of vertical piles,
- barge equipped with two oppositely arranged rows of inclined piles,
- barge with closed, inclined sidewalls,
- inclined piles with inclination against the ice direction.

The structures were equipped with load cells measuring horizontal and vertical loads.

First, the groups of vertical and inclined piles installed in a row were investigated. The pile distance was varied. Ice rubble was generated by all pile groups with the thin ice, yet the pile groups with large distances between the piles were not able to generate ice rubble with the thick ice. Also, pile-up occurred only at the pile groups with small distances between the piles. At the end of the tests, the rubble piles had grounded to some extent. Pile-up was more effective at the inclined piles.

Second, the barges and the inclined piles with inclination against the ice direction were investigated. The inclined piles generated ice rubble only with the thick ice. At the barges, ice rubble was generated and moved into the structure. The ice rubble also piled up in front of the barges. With the thin ice, no ride up occurred into the barge with closed side walls. Not any barge was completely filled with ice, so that the foundation of a grounded rubble pile is likely only at the upstream walls of the structures.

During phase II, the following structures were investigated:

- two oppositely arranged rows of inclined piles,
- one row of vertical piles,
- inclined roof structure.

The vertical piles generated ice rubble only with the thick ice. At the other two structures, ice rubble was generated with thin and with thick ice and the ice rubble moved into the structures. Inside the structure, the ice rubble grounded, but the structures were completely filled only with the thick ice. Neither the vertical nor inclined piles were able to prevent the thick ice from moving downstream.

During phase III, the inclined roof structure was further investigated concerning the arrangement of several modules of the structure and concerning the variation of the ice drift angle.

The results of the model tests are described in detail in (EVERS, KÜHNLEIN, 2001).

The following conclusions can be taken from the model test results.

- If using piles as ice barrier, the distance between piles should be less than 4·d for inclined piles and than 6·d for vertical piles. Piles at larger distances only generate ice rubble when the ice grounds, i.e. at low water levels.
- Piles do not prevent the rubble ice from floating further downstream. Significant pile up only occurs for small distances between piles.
- The piles on the barges act in principle as the stand-alone piles. Due to the height of the barge, the effective water depth is smaller and thus, grounding starts earlier. This is more favourable for the pile-up process.
- Significant ride-up only occurs for the barge-based structures and for the inclined roof structure. Ride-up depends mainly on the inclination angle, so that it can be expected that the barge with closed side walls and the inclined roof structure would act in the same way if the inclination angles were the same.

For the structure to be designed, the following criteria can be derived from the results of the model tests:

- The structure shall be sloped with a sloping angle of not more than 30°.
- The structure shall preferably be closed sided.
- Two structures of the same type shall be oppositely arranged. The distance between the structures is dependent on the rubble grounding process inside the structure.

As, in addition to the above mentioned criteria, the structure shall be self-floating and adjustable to different site conditions, two oppositely arranged inclined roof structures mounted on barges are assumed to be the best alternative. Between the piles, nets are arranged which support catching the rubble ice.

The inclined roof structure is shown in the following figure 1.

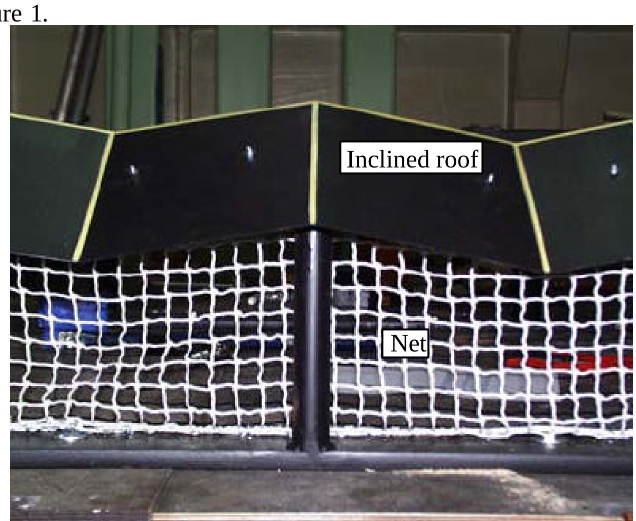

Figure 1: Ice barrier with inclined roof

In the following paragraphs, the inclined roof structure and its loading is further investigated.

SELF-STABILIZING PROCESS

At the beginning of the ice impact, ice rides up on the inclined roof of the front structure. The ice rubble inside the structure is not grounded yet. After a certain time, the rubble inside the structure partly starts to ground. The structure is stabilized by the ice rubble and vertical forces increase. The shape of the grounded rubble ice is not known exactly, but can be approximately derived from the known ice volume inside the structure and from documentation of the model tests. The following shape is assumed:

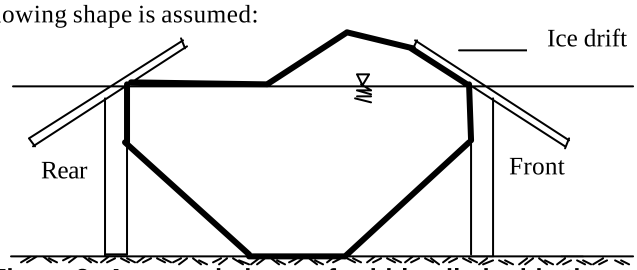

Figure 2: Assumed shape of rubble pile inside the structure 800 s after beginning of the model test with thin ice

When the grounded rubble has reached a certain height, the ice is not able anymore to ride into the structure. A rubble field forms and the ice starts to pile-up in front of the structure. The maximum ride-up length depends on the ratio of driving force and slope resistance.

Initially, the rubble pile in front of the structure is supported by the advancing ice sheet and the advancing ice continues to be pushed through the rubble surcharge to fail against the slope of the structure. This process gives very high horizontal forces. The maximum penetration of the impacting ice depends on its kinetic energy and the rate at which this energy is dissipated during the impact process. Later, the rubble surcharge breaks the advancing ice sheet due to its weight. As the ice barrier is wide, the rubble does not clear and the advancing ice fails against the ice rubble in a random rubble building process (CROASDALE et al., 1994).

The rubble field formation mechanism is a complicated phenomenon involving e.g. the dynamic and inherently random interactions between the individual ice pieces. Development of a detailed theoretical model of rubble field formation is still subject of research. Recently, approaches for three-dimensional finite element modelling of rubble pile build-up have been made (e.g. BARKER, TIMCO, 2001).

The presence of the rubble pile in front of the structure does not only result in additional ice forces, but it can also alter the failure mode of the ice sheet from bending to buckling or crushing (IZUMIYAMA et al., 1993).

When the ice rubble in front of the structure is grounded, it enhances the weight of the whole system and thus contributes to the overall stability of the ice-steel-structure. As an example, the sail of the rubble pile measured at the end of the model tests with the thick ice is shown in the following figure 3.

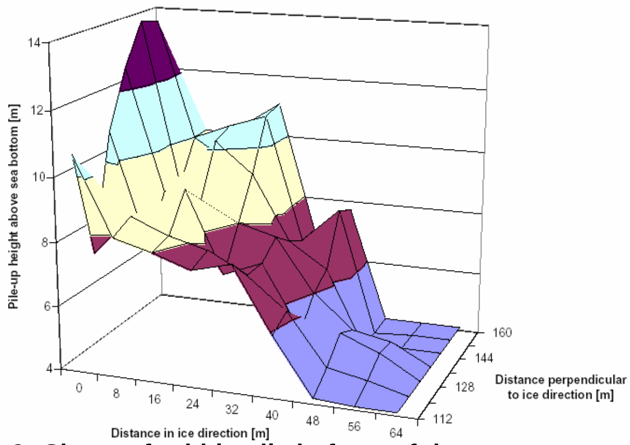

Figure 3: Shape of rubble pile in front of the structure at the end of the model test with thick ice

DERIVATION OF DESIGN LOADS

Horizontal loads

As discussed in the previous paragraph, the following processes of the ice-structure interaction can be observed resulting in different calculation approaches for the design loads:

- Ride-up over front roof,
- Rubble built-up in front of structure; pushing of ice sheets through rubble pile,
- Random rubble forming process.

These processes will be further described in the following. The load resulting from the ride-up process consists of:

- Force necessary to break the ice sheet by bending,
- Force necessary to push the ice sheet up the inclined roof.

The breaking force is calculated by relating the moment capacity of the ice sheet to the vertical force required to initiate failure. Once the ice has failed, the broken pieces start to ride up the inclined roof and an additional force is experienced by the structure. The corresponding total force on the structure is calculated from the CROASDALE-model (CROASDALE, 1978 in: SANDERSON, 1983).

The static friction coefficient is slightly dependent on the ice temperature and increases at lower temperatures. For the given conditions, a rather high friction coefficient at the beginning of the model tests is assumed.

The horizontal forces at the very beginning of the ice-structure interaction are expected to give the ruling load case because the structure has not yet been self-stabilized at that time. The forces were calculated by the CROASDALE-model for thin and for thick ice and compared to the measured values.

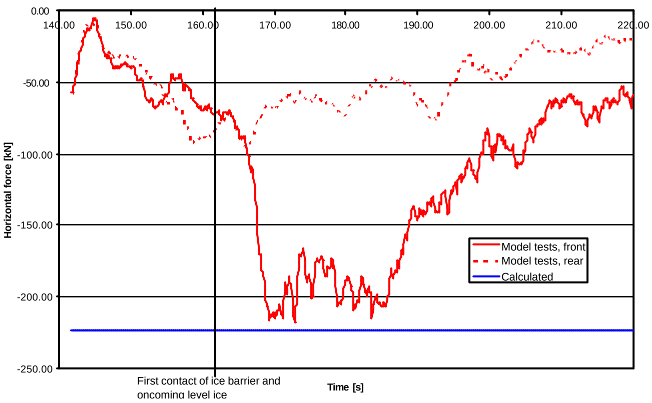

Figure 4: Horizontal forces on inclined roof at the beginning of the model tests with thin ice

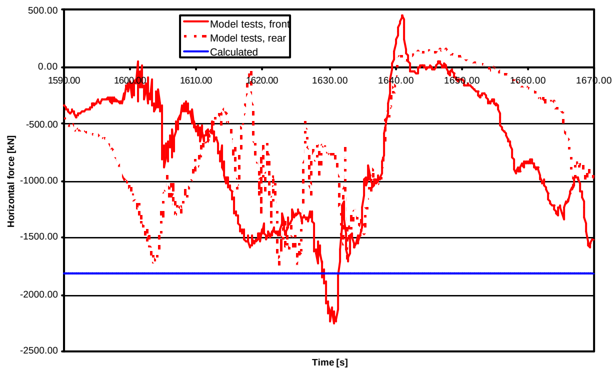

Figure 5: Horizontal forces on inclined roof at the beginning of the model tests with thick ice

The calculated forces agree with the measured forces in the order of magnitude. The CROASDALE-model can thus be used for dimensioning the structure.

After the first contact, the horizontal forces decrease quickly. This can be explained by reaction forces from ice inside the structure. The reaction forces may result from momentum applied to the ice inside the structure when the up-ridden ice falls into the structure and strikes the surrounding ice sheets which drift to the sides. The reaction forces increase with time and therewith with ice mass inside the structure. Also, the friction coefficient decreases after the first up-riding of the level ice due to the lubrication effect.

Once a rubble pile starts to form in front of the structure, ice sheets may still be able to push through. For the model tests, this was only the case for the thick ice. The thin ice did obviously not have enough kinetic energy. Even though the structure has already started to self-stabilize, the extremely high horizontal forces resulting from the ice sheet being pushed through the ice rubble may also become the ruling load case for the stability analysis.

Assuming an ice sheet being pushed completely through the ice rubble and fails in bending at the inclined roof, the following forces due to the presence of the ice rubble have to be applied in addition to the forces caused by bending failure (CROASDALE et al., 1994):

- Force necessary to push the advancing ice sheet through the ice rubble,
- Force necessary to push the ice blocks up the slope through the ice rubble,
- Force necessary to lift and to shear the ice rubble on top of the ice sheet (before it can be pushed up to fail in bending).

To calculate the total ice force, the force components have to be superimposed. The result of the calculation compared to the measured horizontal forces is shown in the following figure 6.

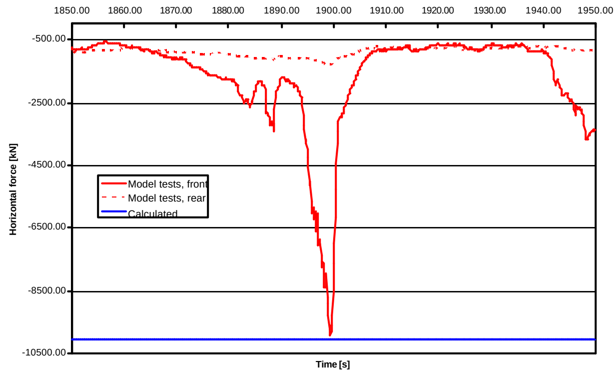

Figure 6: Peak load on inclined roof resulting from ice sheet being pushed through rubble pile

The calculated force agrees with the measured force in the order of magnitude. The extended CROASDALE-model can thus be used for dimensioning the structure. The result is, however, very sensitive to a variation of the rubble pile inclination angle and of the rubble pile height.

With further growth of the ice rubble in front of the structure, other failure modes may become significant. The loads applied to the structure during this phase of ice-structure interaction can be described by the following mechanisms.

There are several possibilities for ice sheet failure against a rubble pile. In some cases, the ice forms a ramp for the oncoming ice sheet and the ice sheet fails in bending. At other times, the ice sheet penetrates the ice rubble to a certain distance and then also fails in bending due to buoyancy and the weight of the rubble pile. Eventually, the ice sheet starts to fail in crushing leading to much higher ice loads applied to the structure (CAMMAERT, MUGGERIDGE, 1988). Also, multimodal failure (simultaneous bending, crushing and shearing) may occur over multiple zones. The forces are not completely transmitted to the structure but are reduced due to the energy-absorption capacity of the ice rubble (ALLYN, CARPENTIER, 1982).

The multimodal or crushing failure behaviour over multiple zones leads to cyclic loads which may cause the structure to vibrate and thus magnify the deflections and stresses in the structure. The measured loads are shown in the following figures 7 and 8.

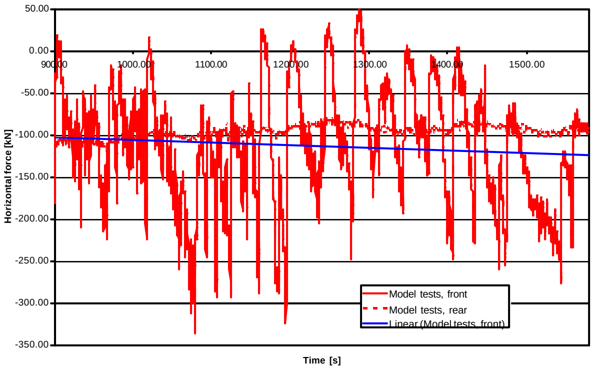

Figure 7: Horizontal forces on inclined roof after a rubble pile has formed in front of the structure, thin ice

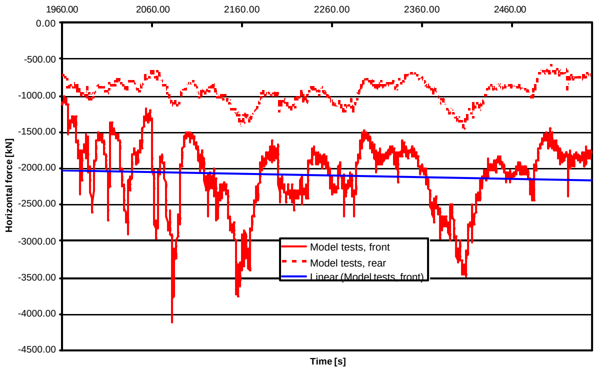

Figure 8: Horizontal forces on inclined roof after a rubble pile has formed in front of the structure, thick ice

From figures 7 and 8, it can be seen, that the horizontal force in front of the structure increases significantly when compared to the initial forces applied by bending failure and ride up. It is yet much lower than the force applied by the ice sheet being pushed through the rubble pile. The load time curves show a scattering behaviour.

The trend curves in the above figures 7 and 8 show slightly increasing loads while the maximum values decrease and the minimum values also increase. This behaviour shows the damping effect of the ice rubble on the loads applied to the structure. The distance between load peaks is about 40 s giving a load frequency of 0.025 Hz. This value is much lower than the eigenfrequency of the structure.

The horizontal forces applied to the structure by the thick ice do not show those large deflections as the horizontal forces applied by the thin ice. The rubble grows further for the thick ice and thus the load damping effect is stronger.

The forces depend on random hits of the ice pieces against the ice rubble. They were statistically evaluated. The following figure 9 shows the quantiles of the load distribution.

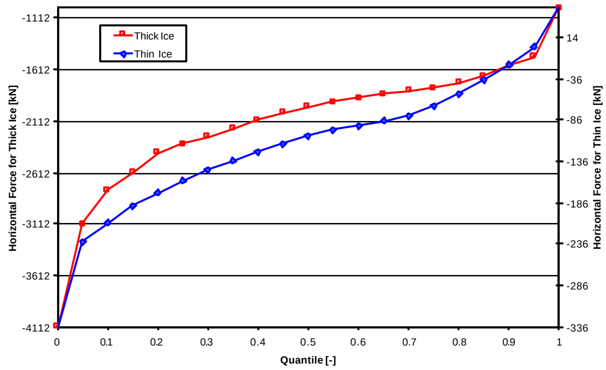

Figure 9: Quantiles of horizontal forces

The above figure 9 can be used to derive design loads for a specific safety level.

As can also be seen from the trends, the loads are not normally distributed but show a skew to the lower loads. The skew is greater for the thick ice. This load distribution may be described statistically e.g. by a GUMBEL-distribution.

Vertical loads

For the ride-up process, the forces in vertical direction can be calculated from the horizontal forces by applying the CROASDALE-model.

The vertical forces were calculated using the measured horizontal forces in ice direction. The following figures 10 and 11 show the calculated vertical forces compared to the measured vertical forces on the front structure.

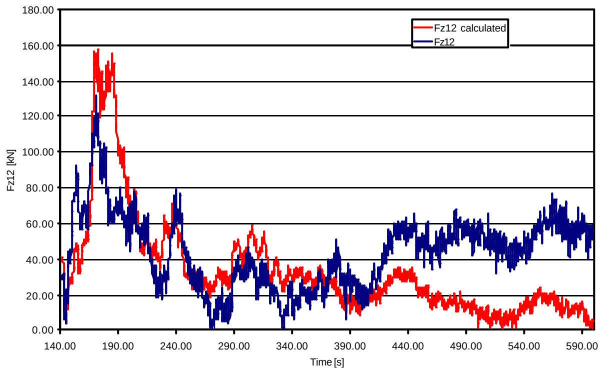

Figure 10: Measured and calculated vertical forces at the beginning of the model tests for thin ice

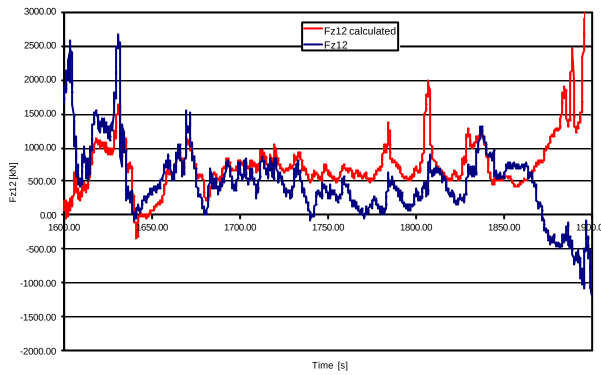

Figure 11: Measured and calculated vertical forces at the beginning of the model tests for thick ice

Figures 10 and 11 show a similar behaviour of measured and calculated vertical forces and therewith of measured vertical and measured horizontal forces at the beginning of the model tests. For the thin ice, the time, when the structure starts to stabilize can clearly be seen. It is at about 400 s from the beginning of the test, when the measured vertical forces significantly start to exceed the calculated vertical forces.

For the model tests with the thick ice, the situation is more complicated. At the beginning of the model test, the ice rubble inside the structure formed during the model test with the thin ice was still present, while the ice rubble in front of the structure was removed. After about 1850 s from the beginning of the model tests, the measured vertical forces decrease and even have an uplifting effect on the structure. The uplifting effect is probably caused by the keel of the rubble pile in front of the structure being pushed against the structure, when the oncoming ice sheet penetrates the rubble pile. The resulting force from this process is directed upwards.

SAFETY AGAINST SLIDING AND OVERTURNING MOMENT

As discussed in the previous paragraph, two load cases may become the ruling load case for dimensioning the structure:

- First contact of ice and structure at the beginning of the ice season when the structure has not yet been self-stabilized,
- Ice pieces being pushed through the rubble pile in front of the structure in combination with uplifting vertical forces.

For the first case, the forces according to the CROASDALE-model are applied to the structure. The limit overturning moment is a function of the resulting force calculated from the horizontal and the vertical component. The following figure 12 shows the angle of the resulting force to the horizontal as a function of the ice thickness.

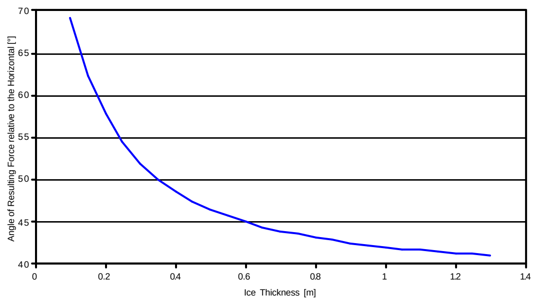

Figure 12: Angle of resulting force relative to the horizontal as a function of ice thickness

An inclined tube with an inclination angle of 45° shall be part of the structure which takes the resulting force up to an ice thickness of 0.6 m.

For sliding resistance, it is assumed, that the internal friction angle of the soil is 30°. If skirts are arranged at the bottom of the barge, the friction angle can fully be applied. The following figure 13 shows the safety factor against sliding in dependency on the ice thickness.

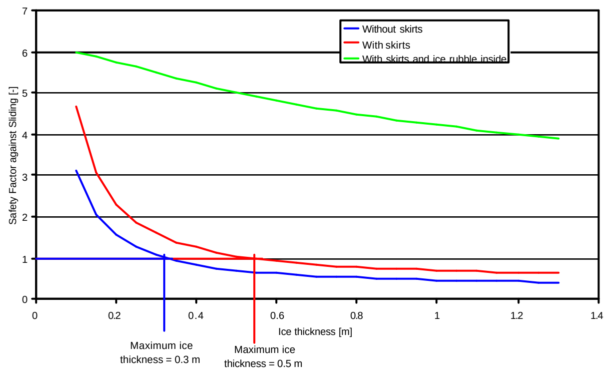

Figure 13: Safety factor against sliding as a function of ice thickness without rubble ice in front of structure

Figure 13 shows that sliding stability is guaranteed for ice thicknesses up to 0.5 m if skirts are arranged. Without skirts, the structure can still withstand force from ice not thicker than 0.3 m. The green line shows the stabilizing effect of the grounded rubble inside the structure for comparison.

For the second load case, the stabilizing effect of the ice rubbles inside the structure and in front of the structure ice is taken into consideration. The sliding stability analysis comprises the calculation of the overall resistance of the grounded rubbles to a net horizontal driving force. The weight of the rubble sail that is not compensated by the buoyant forces on the keel generates a frictional force that must be exceeded before the rubble can be moved. It is assumed that failure of the rubbles will occur at the seabed. Further, it is assumed that the rubble piles and both oppositely arranged inclined roofs act as one structure. Failure because of overturning moment is not significant for this case and is thus neglected. The sliding resistance of the structure can be calculated to:

$$R = \left(G_S + F_{z,f} + F_{z,b}\right)\cdot \mu + \left(G_{r,i} + G_{r,f}\right)\cdot \mu_i$$

R is the sliding resistance, G_S is the weight under buoyancy of the ice barrier, $F_{z,f}$ is the vertical component of the ice force on the front structure, $F_{z,b}$ is the vertical component of the ice force on the rear structure, $G_{r,I}$ is the weight under buoyancy of the rubble pile inside the structure, $G_{r,f}$ is the weight under buoyancy of the rubble pile in front of the structure, μ is the steel-soil friction coefficient and μ_i is the rubble-soil friction coefficient.

The dimensions of the rubble piles are derived from measurements at the end of the model tests, volume balance considerations and from the video documentation of the model tests as described in the previous paragraphs. The dimensions of the rubble pile in front of the structure correspond to the dimensions assumed for the CROASDALE model applied to calculate the peak load. Therewith the rubble piles apply a significant stabilizing vertical force which is much greater than the weight of the structure.

The sliding resistance of the structure is compared to the measured horizontal forces applied to the structure. If the sliding resistance is smaller than the total of the horizontal forces displacement of the structure occurs which can approximately be quantified by a dynamic load balance. The results are shown in the following figure 14.

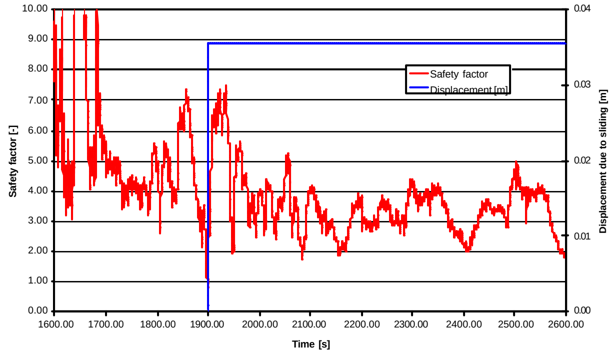

Figure 14: Safety factor against sliding and displacement due to sliding with rubble ice in front of structure

Figure 14 shows that the safety factor is below 1.0 only for the peak load which is applied to the structure over 1.6 s. The load balance gives a displacement of 3.5 cm. This value seems to be acceptable. Also, it is necessary in most cases to arrange several ice barriers around the structure to be protected. The ice barriers can be interconnected and therewith have a higher overall sliding resistance.

ARRANGEMENT OF ICE BARRIERS

In general, the inclined roof ice barriers will be arranged at small distance from the structure to be protected. Several ice barriers may mostly be necessary to guarantee that ice from varying directions does not reach the structure to be protected.

The ice barriers are connected by a tube construction in a simple guiding system. This construction allows to arrange the ice barriers in varying angles from 0° to 90°. Structures of arbitrary size can therewith be protected.

In the following figure 15, a typical arrangement is shown.

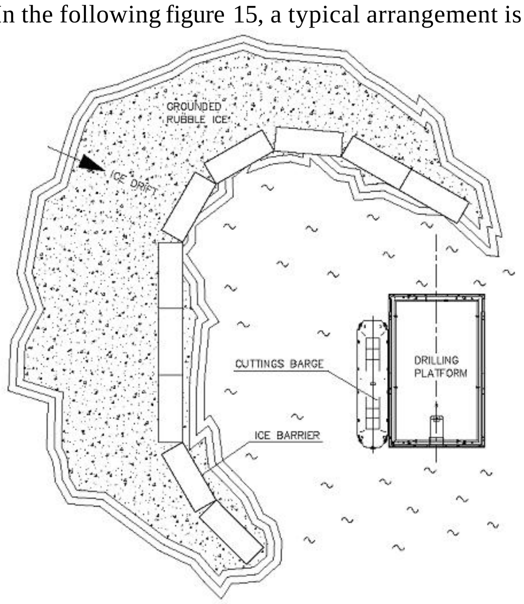

Figure 15: Typical arrangement of ice barriers at one side of a drilling platform

The inclined roof ice barriers can also be arranged directly at the structure to be protected. The maximum additional force applied to the structure results from load peaks when an ice sheet is pushed through the ice rubble in front of the ice barrier and the ice barrier intends to slide. This force is small when compared to the weight of the structure to be protected, so that no significant negative effects are to be expected.

The inclined roof structure can also be adjusted to specific site conditions concerning available pre-fabricated parts. E.g., it can be easily mounted on existing barges.

As can be seen the structure has a great flexibility and can be easily adjusted to varying site conditions.

CONCLUSIONS

The investigations show that the newly developed ice barrier is suitable to protect offshore structures from high loads caused by floating ice. Due to the relatively low roof inclination angle, the forces acting on the structure are caused by bending of the ice sheet applying much lower loads than it would be the case if the ice failed by crushing. Once rubble piles have built-up inside and in front of the structure, other failure modes may occur. Due to the self-stabilizing effect of the rubble piles, these loads do not put the stability of the structure at risk. Only for very high peak loads resulting from an ice sheet being pushed through the rubble pile, the structure starts to slide. If several ice barriers are arranged and connected, the sliding can probably be avoided.

Further work is required to investigate the dynamic loads applied to the structure when the rubble pile in front of the structure has built-up. A finite element model will be developed for this purpose.

ACKNOWLEDGMENTS

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REFERENCES

AGIPKCO (2001): Design Specification for Ice. Kashagan East Early Oil Development, Platforms for the North Caspian Sea.

Allyn, N, Charpentier, K. (1982): Modelling Ice Rubble Fields Around Arctic Offshore Structures. Proceedings OTC, Houston, pp. 501-508.

Barker, A., Timco, G. (2001): Three-dimensional numerical simulation of ice pile-up evolution along shorelines. In: Coastal Science and Engineering, challenge for the new Millenium. Canadian Coastal Conference.

Cammaert, A. B., Muggeridge, D. B. (1988): Ice Interaction with Offshore Structures. Van Nostrand Reinhold, New York.

Croasdale, K. R., Cammaert, A. B., Metge, M. (1994): A Method for the Calculation of Sheet Ice Loads on Sloping Structures. IAHR Ice Symposium, Trondheim, Norway.

Evers, K.-U., Kühnlein, W. (2001): Model Tests of Ice Barriers in Shallow Water. HSVA-Report E 311-01.

Izumiyama, K., Irani, M.B., Timco, W. G. (1993): Computation of Sheet Ice Forces on a Faceted Conical Structure. 12th International Conference on Port and Ocean Engineering (POAC), Hamburg.

Sanderson, T. J. O. (1983): Ice Mechanics. Risks to Offshore Structures.Graham & Trotman, London, Dordrecht, Boston.

