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DESIGN AND MODEL TESTING OF ICE BARRIERS FOR PROTECTION OF OFFSHORE STRUCTURES IN SHALLOW WATERS DURING WINTER

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ABSTRACT

In order to increase the safety of platforms in shallow water, ice barriers are designed to take main loads from floating ice sheets. Platforms and equipment protected by ice barriers can be dimensioned and constructed more economically, when ice barriers are present. Several concepts were investigated and for promising concepts ice model tests were carried out in the Large Ice Model Basin of the Hamburgische Schiffbau-Versuchsanstalt (HSVA) in order to establish the design ice loads and to prove that the design force for offshore structures can be reduced significantly by using ice barriers. Model tests were conducted in different ice conditions in order to investigate the ice rubble formation process, to evaluate the design alternatives and to establish design loads. The measured ice loads were analysed and compared with loads theoretically derived by use of existing methods. The analysis comprises a statistical evaluation of the ice loads related to site conditions in the North Caspian Sea.

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INTRODUCTION

Existing ice barriers which are designed to withstand ice loads without the stabilizing effect of the ice itself have to be anchored in the sea bottom or must have extremely high weight to transfer forces to the sea bottom through bottom friction. Different concepts of ice barrier types for shallow water areas are developed by IMPaC Offshore Engineering, HSVA and the shipyard Lindenau GmbH. The main objective of this study is to design economically and simplified ice barriers, which can be installed on site easily in order to initiate an ice rubble pile up in the vicinity of the offshore structure. The presence of such an ice rubble pile up may protect an offshore structure (e.g. exploration platform, drilling rig, etc.) with respect to ice load reduction. The idea of the research project is to design modular ice rubble generators (IRG's), which are able to catch early thin broken ice, stabilize themselves due to the added weight and can withstand thicker ice later in the winter season. The IRG's can be removed during ice free seasons and shall fulfill the criteria: self-floating for transport, self stabilizing during rubble formation, fast and environmentally sound installation and deinstallation, cost efficiency regarding fabrication, transport and maintenance, flexibility, safety and reliability, sufficient availability of construction material and participation of local fabrication facilities. The design of different IRGs is verified by ice model tests in the Large Ice Model Basin at HSVA.

ICE MODEL TESTS

The ice model tests are carried out at a model scale of $\lambda = 16$ with different types of shallow water ice barriers in the Large Ice Model Basin at the Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA) in two experimental phases. According to ice conditions typically for the North Caspian Sea, the ice thickness varies from 0.1 m to 1.3 m (full scale = f.s.), and the ice bending strength is about 750 kPa (f.s.). Ice drift angles (90°, 60° and 30°) and the configuration of ice barriers are varied during the tests. The design water level in the model tests is about 4 m (f.s.).

The main objectives of the tests are:

- to determine ice loads acting on individual piles and barges with ice rubble generators, and
- to investigate the formation ice rubble along the ice barriers

MODEL TEST SET – UP

Phase I – Vertical and inclined ice protection piles

Groups of vertical and inclined protection piles of about 480 mm diameter (f.s.) are installed in a row. The pile distance , i.e. the center to center distance varied from 2 times diameter to 8 times diameter, i.e. 2*d to 8*d (Fig.1). At least one pile of each pile group is instrumented with a triaxial load cell (KISTLER type) in order to measure the ice force on this individual pile.

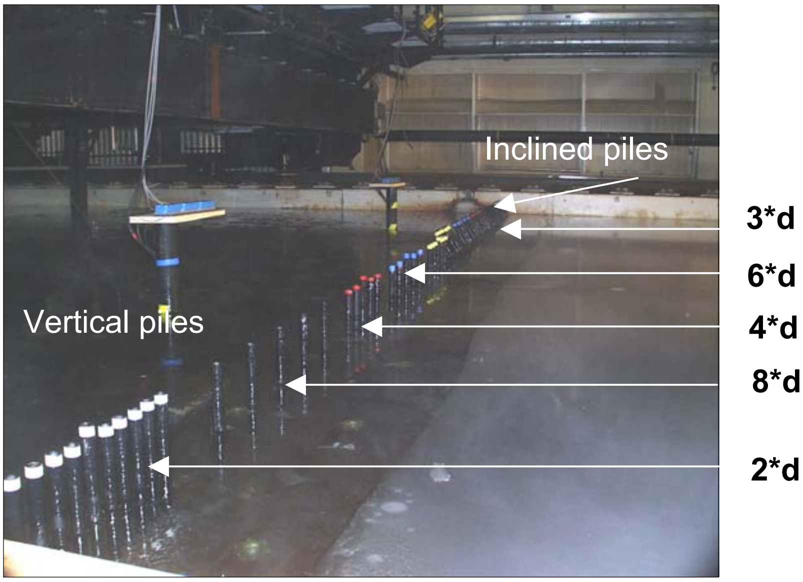

Fig. 1 Arrangement of vertical and inclined protection piles

The vertical ice protection piles cut the 0.1 m (f.s.) thick ice sheet into strips which passes the structure downstream. No ice rubble formation is observed along the vertical piles and at the end of the test run only some ice rubble is observed along the inclined piles. For the 0.5 m (f.s.) thick ice sheet the ice fails by upward bending along the inclined piles with a small pile to pile spacing. In the transition area between inclined and vertical piles ice rubble starts with subsequent ice bridging to both sides. At the end of the test ice rubble is grounded to some extent.

Phase I – Inclined ice protection piles and barges

As a result of previous tests the vertical ice protection piles seem not to be efficient with respect to rubble formation, thus these piles are replaced by barges. Three barges with

two parallel vertical pile rows (structure A), two inclined pile rows (structure B) and two parallel inclined sidewalls (structure C) are investigated (Fig.2). The angle of inclination in all cases is 60° to the horizontal. Each individual barge is instrumented with one triaxial load cell KISTLER type) and two uniaxial load cells (U9b type).
Besides the barges inclined protection piles of about 480 mm diameter (f.s.) are installed in a row. A 60°-inclination of the piles is chosen to initiate downward bending failure of the ice sheet.

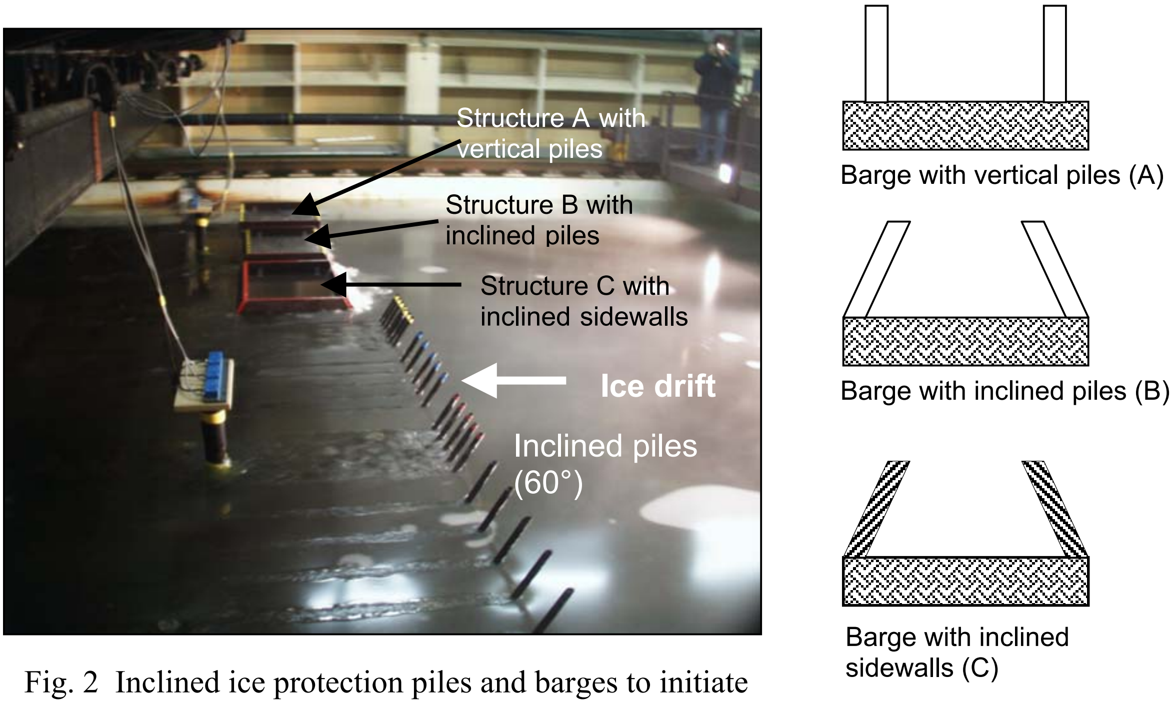

Fig. 2 Inclined ice protection piles and barges to initiate ice rubble formation

In the 0.1 m (f.s.) thin ice sheet ice rubble occurs at first on the barge with inclined sidewalls, however no ride-up is observed. In front of the barges with installed piles (B an C) ice rubble occurs and broken ice blocks are caught. Along the row of inclined piles the ice is cut into strips and drifts downstream without any accumulation Fig. 3).
In the 0.5 m (f.s.) thick ice sheet ice ride up is observed simultaneously on all barges. At the beginning the broken ice is cleared downstream between the barges until ice bridging starts and the space between the barges is subsequently filled with broken ice.
The extent of ice rubble towards upstream side of the barge is slightly higher than the ice rubble collected in the barges (Fig. 4).

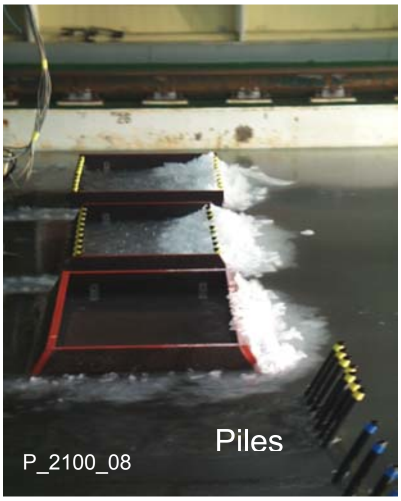

Fig. 3 Ice rubble on barges, ice thickness is 0.1 m (f.s.)

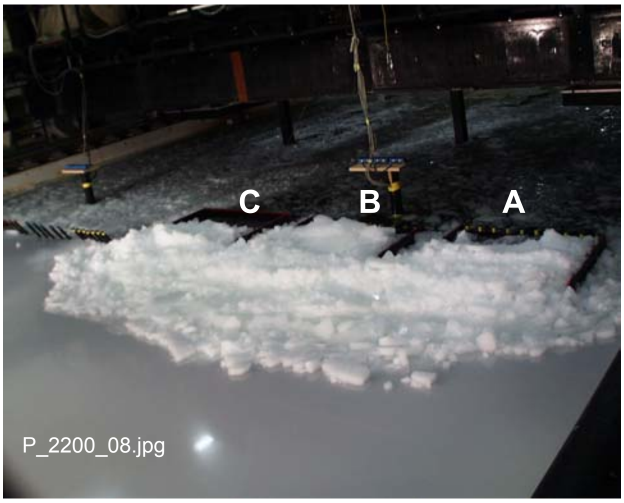

Fig. 4 Ice rubble on barges, ice thickness is 0.5 m (f.s.)

Phase II - Ice rubble generators (IRG's)

From the results achieved in Phase I the use of barges in combination with IRG's seems to be very efficient with respect to ice rubble formation.

IRG's are installed on barges, which can be moved to a certain location and then lowered to the seafloor. The barges are instrumented with triaxial (KISTLER type) and two uniaxial load cells (U 9b type) in order to measure the entire ice force on each barge. The test set-up consists of a configuration of three different IRG's. Two parallel rows of 30° inclined piles with a pile distance of 4*diameter are installed. The inclined piles initiate upward bending ice failure. One row of vertical piles with pile distance of 4*diameter is installed as well as a 'roof structure'. The latter consists of a pleated steel sheet mounted on piles. Between the piles an 'ice catcher' consisting of a Nylon® net of about 0.3 m (f.s.) mesh width is stretched in order to keep the broken ice floes inside the 'roof structure' (Fig.5). A schematic of the 'roof structure' which is fixed on the barge is shown in Fig. 6.

The 'roof structure' elements are arranged as shown in Fig. 7. The ice sheet encounters with an oblique angle of 60°. Three components of the 'ice catcher' are instrumented (A, B and C) with two triaxial load cells each, whilst additional 'roof structure elements' (D, E and F) are installed without instrumentation. Between 'roof structure' elements D and F a bulkhead is installed, in order to avoid that broken ice floes are drifting downstream. Fig. 8 shows the IRG's filled with broken ice blocks after a test.

Fig. 5 ‘Roof type’ structure with a net between vertical piles

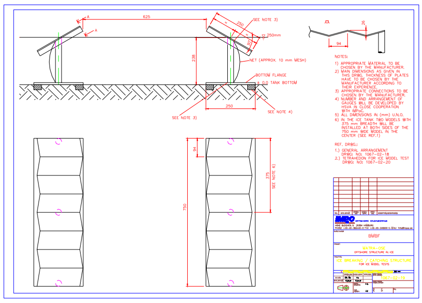

Fig. 6 Schematic of the ‘roof type’ structure

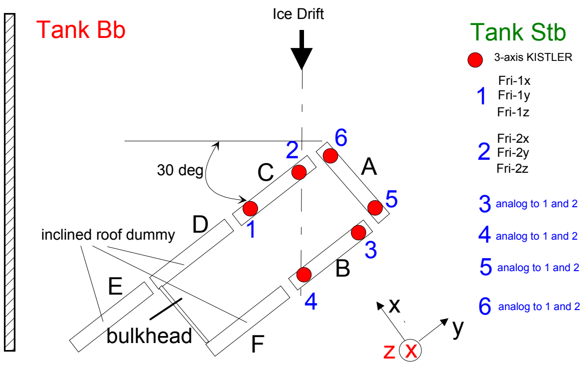

Fig. 7 Schematic of ‘roof type” structure arrangement and instrumentation

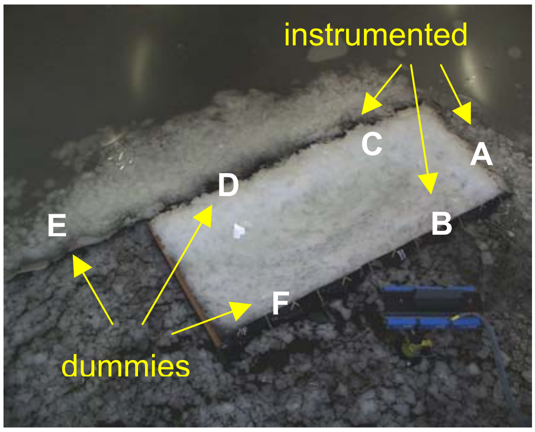

Fig. 8 ‘Roof type” structure filled with broken ice

When the ice drift angle is 60°, the 0.1m (f.s.) thick ice sheet fails along the short and long side of the structure by bending and the broken ice floes ride up on the inclined roof and fill its inner part. After a steady state is achieved, the filling process stops and ice rubble formation starts at the long side of the structure. When the ice drift angle is 30°, the ice rubble formation process is similar.

When a 0.5 m thick ice sheet encounters under 60° drift angle, the IRG’s are filled with ice blocks and an existing rubble is in front of the structure, the ice fails by bending on the existing rubble without ice over-ride. During the ice breaking process the ice rubble extends in upstream direction. When the ice drift angle is 30°, the ice rubble formation process on an existing rubble starts and subsequent ice over-ride occurs. The structure is completely filled with ice blocks and without accumulation of broken ice along the sides of the structure. No grounded ice rubble is observed.

DESIGN ICE FORCES

The following processes of the ice-structure interaction can be observed for all IRG's resulting in different calculation approaches for the design loads:

- Filling of IRG with ice blocks,
- Ice rubble formation in front of IRG; pushing of ice sheets through rubble pile,
- Random rubble forming process.

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 an analytical model for the 0.1 m thick ice and for the 0.5 m thick ice and compared to the measured values. The results for the inclined roof structure are shown in Fig. 9.

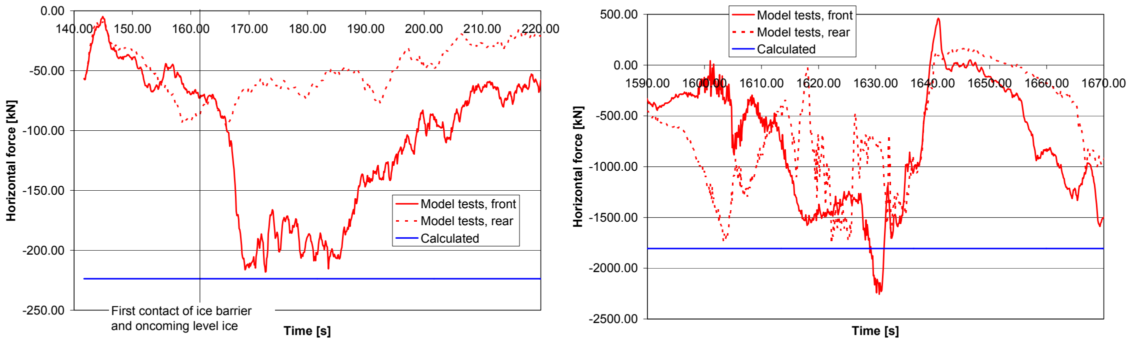

Fig. 9 Horizontal forces on inclined roof at the beginning of the model tests

The calculated forces agree with the measured forces in the order of magnitude. Once a rubble pile starts to form in front of the structure, ice sheets may still be able to push through. 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. The result of the calculation with the analytical model is, however, very sensitive to a variation of the rubble pile inclination angle and of the rubble pile height (CROASDALE et al., 1994). 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 may even result from multimodal failure (simultaneous bending, crushing and shearing) occurring over multiple zones (CAMMAERT, MUGGERIDGE, 1988). 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). An example of measured loads for the IRG with inclined roof is shown in Fig. 10.

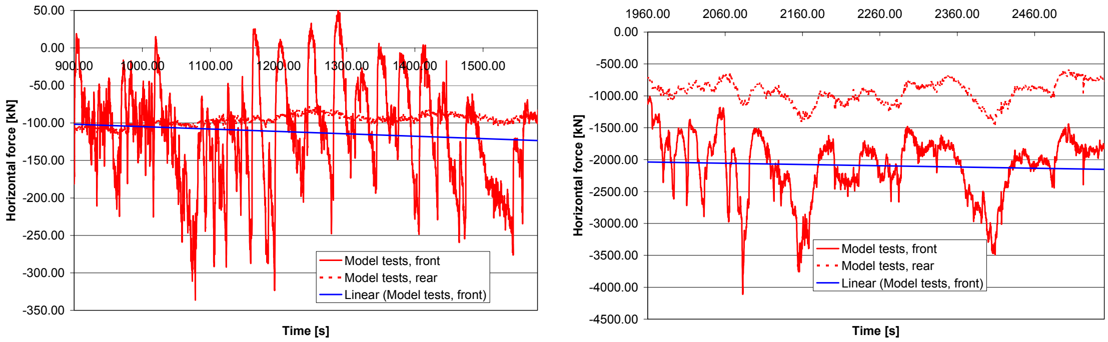

Fig. 10 Horizontal forces after a rubble pile has formed in front of the structure

From Fig. 10, 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 trend curves in Fig. 10 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 measured forces were statistically evaluated. Fig. 11 shows the quantiles of the load distribution.

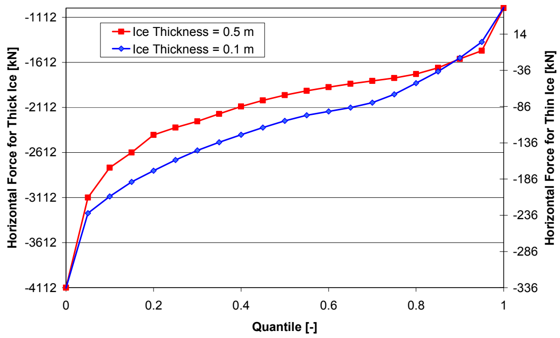

Fig. 11 Quantiles of horizontal forces for 0.1 m thick ice and for 0.5 m thick ice.

Fig. 11 can be used to derive design loads for a specific safety level. The load distribution may be described statistically e.g. by a GUMBEL-distribution.

SAFETY ASPECTS

The stability analysis was carried out for the structure with inclined roof. For the first contact of ice and structure at the beginning of the ice season when the structure has not yet been self-stabilized the 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 ruling load case results from ice pieces being pushed through the rubble pile in front of the structure leading to high peaks of the horizontal loads. The stabilizing effect of the ice rubbles inside the structure and in front of the structure ice has to be taken into consideration in this case. 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. The rubble piles apply a significant stabilizing vertical force which is much greater than the weight of the structure.

The dimensions of the rubble piles are derived from measurements at the end of the model tests and from volume balance considerations (see Fig. 12). The sliding resistance of the structure is compared to the measured horizontal forces applied to the structure. The displacement of the structure can approximately be quantified by a dynamic load balance. The results are shown in the Fig. 13.

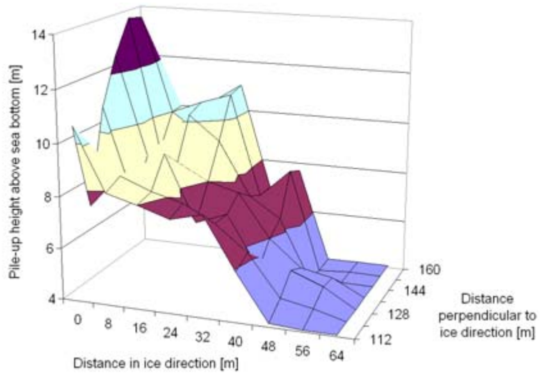

Fig. 12 Shape of rubble pile

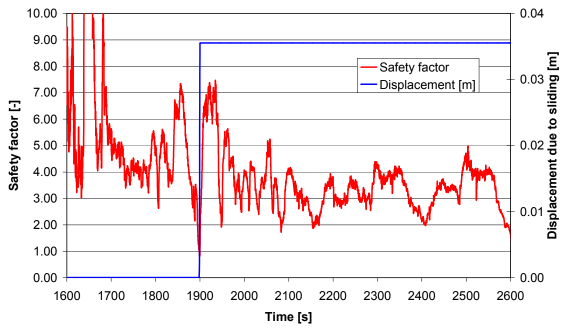

Fig. 13 Safety factor against sliding

Fig. 13 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.

CONCLUSIONS

From the results of the model tests design criteria for IRG's can be derived. The investigations on ice loads and stability show that the IRG with inclined roof is suitable to protect offshore structures from high loads caused by floating ice. 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, displacements can probably be avoided.

ACKNOWLEDGEMENT

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