ICE JAMMING BETWEEN THE LEGS OF MULTI-LEG PLATFORMS

Andrew Palmer [1], Bai Wei [1], Poh Leong Hien [1], Yap Kim Thow [2]

1 National University of Singapore, Civil and Environmental Engineering
2 Keppel Offshore and Marine Technology Centre, Singapore

ABSTRACT

Ice jamming occurs when ice fills the space between the legs of a multi-legged structure. The jammed ice often has sufficient strength and size not easily to clear away from the legs, and the legs and the jammed ice may then act as a single structural unit. There are many analogous phenomena in the flow of fragmented solids through gaps. Relationships between ice jamming, leg dimension and leg-leg spacing are discussed in ISO 19906. The choice of leg diameter and leg spacing is an important design decision that affects the commercial value of the structure. The primary objective of the present study is to develop a deeper understanding of ice jamming events, in order better to formulate design loads on a multi-leg structure.

INTRODUCTION

An option for a fixed Arctic platform structure that will operate in ice-covered seas is to base the structure on three or more legs. The structure is relatively simple, and can be constructed like a conventional platform away from the Arctic, taking advantage of a well-understood and straightforward technology. A jackup structure is one example: it can be lifted out of the water by jacking on the legs. The legs can be made slender, so that ice, wave and current forces are minimised. Moreover, those ice forces can be calculated with greater confidence than can ice forces on wide structures, because ice forces on narrow structures are better understood than forces on wide structures (Palmer, 2011; Palmer and Croasdale, 2012) and can be calculated more reliably.

A potential difficulty is that broken ice can accumulate between the legs. The presence of that ice build-up is undesirable: it markedly increases the effective breadth of the structure at the waterline, so that the total ice force on the platform will correspond to the total breadth rather than to the diameters of two separate legs. In addition, the presence of the ice build-up makes it difficult to drill from the platform.

CONDITIONS UNDER WHICH ICE BUILD-UP MIGHT OCCUR

The mechanism by which ice builds up between the platform legs depends on the relative dimensions of the ice fragments and the gap between the platform legs.

If the fragments are larger than the gap, a single fragment can bridge between two legs (Figure 1(a)). Once that has happened, the current can carry other fragments against the first one, even if those fragments are smaller than the first, and a jam can begin to accumulate.

If the fragments are smaller than the gap, but the gap can be bridged by a small number of fragments, the fragments can accumulate to form an arch between two legs (Figure 1(b)). The stability of that arch will depend on the current, on the presence or absence of waves, on friction between the fragments and between the fragments and the platform legs, and on any adhesion created by additional freezing or snow accumulation.

If the fragments are much smaller than the gap, they may still be able to form an arch and initiate build-up (Figure 1(c)). The accumulated ice is thicker than a single fragment, and the ice and current force on the fragments increases the horizontal stress and tends to increase the stability of the arch. Friction between the fragments has become more important to the stability of the arch and the shape of the fragments is more significant.

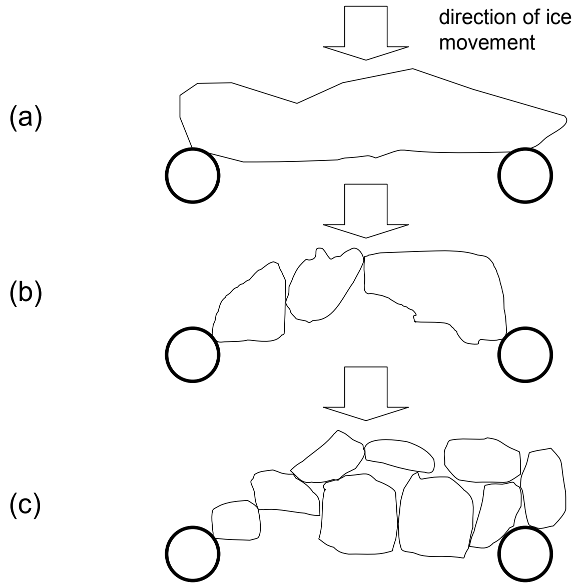

Figure 1 Jamming modes

It is widely agreed to be desirable to install cones at the water surface. Whereas a cylinder with vertical or near-vertical sides breaks the ice in crushing, a cone angled to the horizontal at 50° (say) causes the mode of fracture of the ice to switch to bending. The ice forces are then substantially reduced, and in addition those forces are easier to predict. That strategy has been applied to multi-leg platforms in the Bohai Sea and to the multi-pier Confederation Bridge in Canada, and has real advantages (Tian and Palmer, 2014). It is not known whether the cone option makes ice jamming more or less likely. On the one hand, the fragments formed by breakage in bending are larger those formed by crushing, and those fragments will form arches more easily. The presence of cones reduces the gap between the legs. On the other hand, the flow of ice around a structure appears to be smoother if cones are present, and that ought to be a positive factor that reduces the likelihood of arch formation.

RELATED PHENOMENA

Similar phenomena occur in other contexts when solid particles flow through gaps. Beltaos (1995) describes the formation and break-up of ice jams on rivers. The IAHR (International Association for Hydraulic Research) defines an ice jam as ‘a stationary accumulation of fragment ice or frazil that restricts flow’, a definition that covers the ice jams this paper concerns. The book includes spectacular photographs of jams hundreds of metres across, and of the destruction that follows when the jams break. The photographs make clear that the fragments are usually quite small, far smaller than the breadth of the river. Not much is said about the conditions that initiate a jam, but sharp turns, narrowing and the presence of obstructions such as bridge piers play a part. Figure 2 from Beltaos' book shows an ice jam at a bend. The river surface may be further constricted by stationary ice formed along the banks. Sometimes the jam is only one fragment thick ("surface jam") but more often fragments that reach the upstream edge are pushed under the ice that has accumulated earlier, constricting the flow between the river bed and the bottom of the jam and slowing the flow.

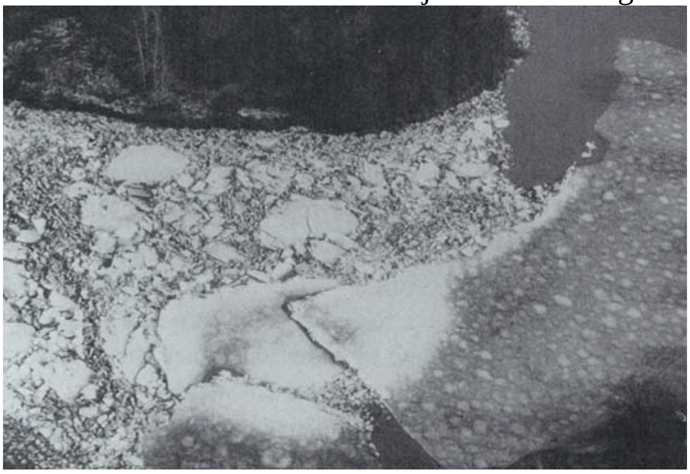

Figure 2. River ice jam (from Beltaos (1995))

All these effects may be expected to be significant to jamming in multi-leg structures.

Beltaos reviewed the many physical models that have been experimented with, and has a list of the many materials that have been tried. If only the hydraulics is important, the ice can be modelled by unbreakable particles. If additionally the mechanical properties are thought to be important, the ice can be simulated by a breakable material, or by 'real' ice modified to reduce its strength: the difficulties with that option are discussed elsewhere (Palmer and Croasdale, 2012; Palmer and Dempsey (2009). That approach has produced useful results about arching (Calkins and Ashton, 1975) and Tatinclaux and Lee (1978). Ettema (1990) did experiments with square blocks one-seventh of the flume width, and found that jamming occurred when the surface concentration was 0.5. The significance of surface concentration is discussed below.

River ice jam flooding can be mitigated by placing breakup ice control structures (ICS) to arrest breakup ice. These ice control structures are typically vertical cylindrical piers placed upstream of an ice jam-prone area at equal spacing perpendicular to flow direction. Parallels may be drawn with the experience-based design of multi-legged structures in ice – to prevent ice jamming in a multi-legged structure, the ratio between the clear spacing and leg diameter, *L/w,* is made greater than a threshold value at which ice jamming is expected to occur – this is described later in this paper.

A related and technologically difficult and important problem occurs when a bulk solid flows downward under gravity out of a bunker (Woodcock and Mason, 1987). Almost always, the mid-section of the bunker is larger in diameter than the exit, and the exit is necessarily larger than the solid particles. The flow converges as it approaches the exit, and can form a stable arch that blocks further flow.

Bulk solids theory makes a distinction between 'mass flow' and 'core flow' (Figure 3). In mass flow all the particles move towards the outlet. In core flow, only a central region flows downward, and around that region the material is stationary. Core flow is almost always undesirable, because the material that arrived first is last out and because the flow is often highly variable. In core flow, the stagnant region can persist after the flow stops, leaving a 'pipe' or 'rathole'. In mass flow, the flow can stop because a cohesive arch has formed, and there the stress within the bulk solid allows the arch to support itself and the solid above it.

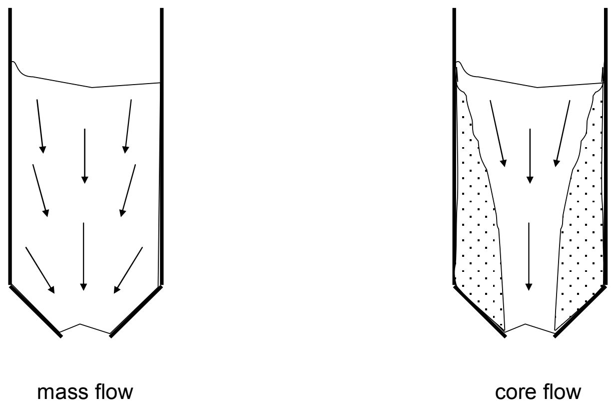

Figure 3 Flow in bunkers

Woodcock defines a flow function, a relationship between the unconfined yield stress of a bulk solid and the major consolidating stress, in geotechnics language the most compressive principal effective stress. He says that the information can be obtained from a shear box test, though that ignores the well-known difficulty that the stresses in a shear box are highly nonuniform. He then plots a flow factor on the same diagram, and asserts that the condition for no flow to occur and for an arch to form is that the flow factor be less than the flow function. He goes on to apply the theory proposed by Jenike (1964), which asserts that 'a bulk solid will flow provided that the strength which it develops is less than the strength which would exist in a stable obstruction to flow'. In the context of the build-up problem, this is equivalent to saying that the ice fragments will form an arch if they are strong enough to do so.

It is not clear how far these ideas can be applied to ice jamming, and that will be explored. An immediate difficulty is that the definition of the flow function is uncertain (and open to criticism if the function is determined by a shear box test). The required data for ice fragments are not readily available, though they could perhaps be estimated by interpretation of published tests on unconsolidated pressure ridges (Palmer and Croasdale, 2012). Alternatively, it would be possible to carry out tests on ice rubble. Those tests would be difficult to do in a laboratory, and would be better and more realistic in the field, but that would be complicated and expensive.

Rotter (2001) says that

> ‘…mechanical arching is prevented by the choice of an outlet diameter *B* in excess of 8 times the maximum particle diameter, but this may be raised to 10 in the case of very rough angular particles (crushed rock and coal) or long stick-like particles…’

but that conclusion disagrees with Beltaos’ observations about ice jams.

The formation of stable arches within the stored material is a serious problem for bunkers, and much thought has been given to it, as witnessed by the amount of space given to it in Woodcock’s book. Something can be done by careful design of the bunker, but often it is found necessary to introduce active devices that destabilise arches. That might be a practical option for multileg structures in ice.

A third thought-provoking analogy is with arches in masonry. The analogy is by no means precise: a masonry arch is of course designed and assembled by human beings, who choose the shape of the component blocks that make up the arch and choose the stone they are made from. In the case of ice jamming, on the other hand, the material is necessarily ice and Nature forms the components by an irregular and haphazard process of repeated fracture.

The stability of a masonry arch depends on the form of the arch as a whole, on the forms of the individual components, and on the friction between the components. In contrast, and at first sight surprisingly, the strength of the stone has little or no importance, because in masonry the stresses are almost invariably much lower than the strength of the stone (Heyman, 1961, 1998). That conclusion applies equally to an ice arch formed naturally between the legs of a multi-leg structure. Imagine, for example, an ice arch that spans 15 m between the legs of a structure, as in Figure 3, and suppose that the rise of the arch is 2 m, that the arch is composed of floating 1 m cubes of 900 kg/m^3 ice, and that the arch as a whole is loaded by a 1 m/s (2 knots) current. Taking the drag coefficient as 1, the hydrodynamic force on the ice arch is 1.8 kN/m, the thrust in the arch is roughly 25 kN, and the corresponding mean stress is 25 kPa. Even if non-uniformity and eccentric loading were to increase that stress by a factor of 10, the resulting 0.25 MPa is far lower than the compressive strength of ice (Palmer and Croasdale, 2012).

That calculation confirms that the stability of an ice jam is governed by the shape of the fragments that make it up, and by the strength of the interfaces between them, rather than by the internal strength of the fragments themselves. Ice jams will not usually break up by fracture of the ice. It is however possible that a jam of fragments could form an arch, and then a continuous ice sheet might drift against the arch, and then the force in the arch might be much larger.

A fourth analogy is sieving. Sieving is used the separate small particles from large. The small particles fall through the gaps between the grid of wires that forms the sieve, and the large particles remain behind. It could happen that the small particles form an arch wider than the gaps, but that is often prevented by constantly shaking the grid.

ISO 19906 RECOMMENDATIONS ON ICE JAMMING

ISO 19906 (2010) recommends ice load calculation based mainly on model test findings. The global limit stress action is given as:

$$F_G = k_s \, k_m \, k_j \, F_1 \qquad (1)$$

where

F_1 is ice action on one leg

k_s is a coefficient accounting for interference and sheltering effects

k_n is a coefficient accounting for non-simultaneous failure

k_j is a coefficient accounting for ice jamming

For a typical multi-leg structure with four legs, ISO 19906 states that the maximum factor k_s ranges from 3.0 to 3.5. The factor k_n is suggested by ISO 19906 to be assumed as 0.9. Regarding the ice jamming effect, ISO 19906 states that ice jamming can, but not necessarily always, lead to an increase in ice action.

When the legs of a structure are far apart they may act as independent, isolated legs in ice, but when the legs are close they influence the ice loads and failure mechanisms. This closeness effect has been studied based on model test results by Kato and Sodhi (1983), Timco and Pratte (1985) and Timco (1986).

This effect is accounted for by the ratio between clear spacing and diameter, *L/w*, considering a line of piles perpendicular to ice movement. The model test results suggest that the piles act independently if the ratio *L/w* is greater than approximately 5. Observations at the Confederation Bridge suggest that the piers act independently when the ratio *L/w* is greater than approximately 10.For *L/w* less than approximately 5, Timco (1986) found that the ice moving between legs is broken into smaller pieces, suggesting that the length of each ice piece is a function of the clear leg spacing. Based on unpublished model tests, Timco suggested that a closer leg spacing may have an advantage in overall clearing of ice pieces under the structure, due to the fact that the ice is broken into smaller pieces.

Observations from model tests and full-scale structures provide some indications when ice jamming occurs. Kato et al. (1994) carried out model tests on two structures with four conical legs spaced at L/w = 3.8 at the waterline, one with downward-breaking conical legs and the other with upward breaking conical legs. Kato et al. (1994) observed that ice jamming usually occurred for the downward breaking conical legs, never for the upward breaking conical legs.

Field observations at the Chinese JZ-20 platform in the Liao Dong Bay, with four cylindrical legs with diameter of about 1.7 m to 2 m, and L/w of approximately 3, indicate that ice jamming occurred between the platform legs and the jam accumulated to a thickness between 4 m and 7 m (Løset et al. 2006). The ice thickness at the site is about 0.35 m in moderate winters, and can go up to 0.70 m in severe winters (Johnston et al. 2000).

ANALYSIS

Bringing these observations together, the probability of jamming in a multi-leg platform depends on the size of the fragments, on the gaps between the legs, on the surface concentration (the fraction of the water surface occupied by fragments), and on the water and fragment velocities within and around the platform. Larger fragments and narrower gaps induce jams more readily, but a jam can still occur even if the gap is many times larger than the fragments. High surface concentrations jam more easily. Simple models indicate that there may be a trade-off between gap and fragment size, so that larger fragments jam in narrower gaps.

Following from the earlier discussions on breakup ice control structures (ICS), but in the context of river ice, Tuthill and Lever (2006) point out that Calkins and Ashton's (1975) experiments showed that for surface concentrations greater than about 30 per cent, moving ice will arch between piers when the ratio of the gaps width *L* to the floe diameter *D* was less than about 4. Lever et al. (1997) found that a sloping-block ICS would arrest a dynamic ice run and hold the resulting dam when *L/D* was less than about 6. Typically, they said, the average diameter of breakup ice floes is 3 to 4 times the ice thickness *h.* If *L/D* ought to be less than 5 and *D/h* is about 3, then L/h<15 should give good ice arrest and holding.

This would appear to be a good practical guide to the conditions in which ice will jam in multi-leg structures. However, it needs to be kept in mind that in the ICS context that Tuthill and Lever are talking about, it is *desirable* that the ice jams, whereas in multi-leg structures it highly undesirable.

MITIGATION

Design measures might be adopted to minimize the risk of formation of an ice jam, and with actions that might be taken to destabilize an arch. Tuthill and Lever (2006) explore the general problem of the design of passive ICS.

An arch is least stable when it is first formed, and becomes more stable when ice accumulates and the compressive forces across the arch have increased. The best option is to do everything possible to avoid the initial formation. Close to the waterline, the structure should be as simple and smooth as possible, with no protuberances such as brackets and clamps that ice might lodge against. The surfaces that might be contacted by ice should be smooth and low-friction. Much effort has been given to the development of special paint for icebreaking ships, and that paint would be a good option.

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