CHAPTER 101

ICE EFFECTS ON COASTAL STRUCTURES

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Introduction

Ice effects on coastal structures, and more particularly the maximum forces caused by ice action, depend on a number of factors, such as:-

(a) The physical properties of the ice encountered.
(b) The thickness of ice formations.
(c) The size of these formations, and their motion.
(d) The shape and size of the structures concerned.

Past history of ice accumulations is important too, not only in relation to ice properties (as when new ice and multi-year ice are found together at the one location), but also for instance when structures become frozen in, or when ice debris accumulates on sloping faces or when ice bustles form around piers. The very considerable difficulties in carrying out insitu experimental work, not only on the overall effects of interest to engineers such as ice thrust on fixed structures, but also on ice properties themselves, mean that there are still large gaps in our knowledge of the subject. Finally, the non-isotropic nature of the naturally occurring ice, and the broad spectrum of ice behaviour under loading (brittlc,ductile or, when creep pre-dominates, viscous), contribute still further to the complexity of the subject.

Physical Properties of the Ice Encountered

A sharp distinction should be made between freshwater ice, which exhibits brittle failure under commonly prevailing rates of load application, and sea ice, which is much more plastic. The added plasticity of the latter offsets the lower strength due to brine inclusions; sea ice in effect tends to mould itself around an obstacle producing higher crushing forces than when brittle behaviour prevals.

Ice masses which engineering structures must withstand differ in many respects from samples of ice studied in the laboratory. The use of carefully chosen small samples in evaluating the crushing resistance of ice overestimates the crushing strength of large masses of ice which naturally contain imperfections; the strength ratio, which is typically of the order of 2 : 1, cannot yet be estimated with high precision.

In the case of sea ice, brine pockets cause a reduction in strength. If the salinity is known, the brine volume may be found as a function of temperature. A reduction ratio may then be used to scale down the expected strength of the sea ice, as compared with that of freshwater ice at the same temperature; unfortunately, the reduction is not known with precision. It should be added that a rise in temperature leads to a reduction in strength of pure ice. This effect compounds the loss of strength suffered by sea ice on account of increasing brine volume at higher temperatures for a given salinity.

Much discussion has taken place in the past about the effect of rate of loading on the crushing resistance of ice. It has been inferred from past tests on sea ice specimens that a peak resistance occurs at a certain rate of loading, with strength reductions at either higher or lower rates. Our own re-evaluation of the earlier data referred to tallies with recent research (1) to the effect that while compressive strength drops off with a reduction in rate of strain, there is no peak value reached at a definite finite rate of loading. Highest strengths are found when impact is fastest, giving in effect brittle, rather than plastic failure.

<u>Thickness of Ice Formations</u>

The thickness of unbroken sheet ice forming on the sea or in bodies of freshwater can be estimated with adeuqate precision by a variety of formulae. One of the earliest of these formulae is Zubov's:

$$T^2 + 50T = -8\sum\theta$$

where T is the ice thickness attained in cm after $\sum\theta$ freezing ^{0}C - days, measured rather illogically for sea ice, from 0^{o}C down rather than from the actual freezing point of sea water. Later workers allow for snow cover, wind velocity, etc., but the results given do not vary much from Zubov's simple estimate based on average conditions for sea ice in the arctic.

Ice moving against an offshore structure may however have been subjected to prior crushing with the formation of rafted covers or of ridges. In the process, the original cover will have been fractured so that when recently formed, ridges or rafted formations may actually be weaker than the unbroken cover. For design purposes, however, it is essential to consider the effect of subsequent annealing. In the extreme case of multiyear arctic ice in which the annealing is caused by snowmelt water giving nearly pure ice of high strength, the resulting formations may present a formidable obstacle to shipping. Coastal structures, other than drilling rigs in exposed locations, will fortunately not have to cope with such extreme types of ice hazard in general. Partly-annealed ridges may have to be considered, though; we are only now acquiring reliable data (2) concerning not only the expected sail and keel shapes of ridges (which are generally not in isostatic equilibrium)but also the shear strength built up within the keel by the snowmelt water filtering down. This paucity of information is of course not surprising, in view of the experimental difficulties involved.

Close into shore in many regions hummocked ice is found which is thicker than elsewhere, principally on account of repeated crushing of floating ice against the ice fixed to the shore. Coastal structures will not be established in such zones. More importantly, the existence of such areas of ice may effectively bar winter access by icebreaker to harbours established within sheltered areas of the coast, e.g. in the mouths of rivers. An added source of ice thickening arises in this case too; fresh water brought down by the rivers will lead to thicker ice, as fresh water freezes more readily than salt. Problems of this nature plague the Hudson Bay shipping route, for example.

Thickness and age of an ice formation are two parameters from which expected salinities, so important in assessing crushing strength, may be assessed. As sea water freezes, brine is trapped between the surrounding ice crystals; however, with the passage of time, or by virtue of a melting and refreezing process occurring in multiyear arctic floes, the brine inclusions tend to disappear leaving much stronger ice behind.

The rate of thickening of ice, and the general conditions under which growth occurs, will affect the grain structure too. Though past tests have shown that grain orientation plays a very important role in relation to crushing strength (ice crystals growing parallel to one another in a typical thick sheet behave in rather the same way as lubricated bundles of rods), not enough is known yet to introduce grain orientation as an independent factor in crushing strength formulae for real, composite ice sheets as opposed to laboratory specimens.

Icebergs constitute a separate problem, fortunately in rather restricted areas of the globe. It is difficult to see as yet what means are available to cope with the iceberg danger as it affects fixed offshore structures, e.g. fixed rigs off the Labrador coast. The problem is not only one of the enormous masses of ice involved, but also of instability; icebergs may so readily overturn.

Size of Ice Formations, and their Motion

From the standpoint of structural design, a broad distinction serving to illustrate the principles involved may be made between two categories of ice:

(i) "Infinite" ice masses (sheets or icebergs)

These may or may not develop the maximum crushing force which the ice can in theory deliver, depending on the rate of movement of the ice. Generally a large ice floe moving against a fixed structure will do so at a velocity such that the maximum crushing force (brittle failure of the ice) occurs. The only possible relief from these high forces will result from substituting floating (non-fixed) structures for fixed ones wherever possible, e.g. by using barges instead of fixed offshore platforms for drilling. The floating structure will however be rendered unserviceable each time the ice hits.

Under this heading, the forces exerted by ice sheets undergoing thermal expansion, subsequent on a rise in air temperature, between fixed structures or obstacles may also be considered. It should be noted that the latter problem, despite much excellent research work (3), still sets the designer a difficult task; not only must the flexibility of the structure be allowed for, but also the transmission of shear between successive layers of the ice sheet must be considered, as these undergo differential expansion. Thus extensive ice sheets will predictably arch and crack, giving lower thermal forces than smaller sheets subjected to the same thermal effects.

In practice, it has been shown that successful engineering designs using light structures can be evolved by making proper use of flexibility.

(ii) Finite ice masses (small floes or growlers)

The maximum crushing force may or may not be developed in this case, depending on the momentum of the ice mass as it hits the structure; the flexibility of the latter also plays a minor role.

In designing against such ice impacts, considerable thought must be given to the probable size of the floes likely to occur at the site, the velocity of approach of the floes (depending for example on wind and durrents and to some extent on the roughness of the floe itself) as well as to the physical properties of the ice. Thus free-moving floes may only arise in the spring, when ice masses break loose and disintegrate; a careful estimate of probable ice temperature, salinity and residual thickness is required in such cases.

The Shape and Size of the Structures

Depending on whether the impact is delivered by a mass of ice of effectively infinite size, or by a mass of ice of finite size, one may have to consider respectively

(i) The effect of the ice impact over the whole exposed surface of the structures; or

(ii) Local effects occurring while the impacting mass is being brought to a standstill.

Of course, in case (1), the structure must be designed in such a way that local stresses occurring are also properly absorbed. Hence the case of an "infinite" ice mass is the more general one.

Structures, looked at as a whole (i.e. without reference to local effects) may be categorized in a number of ways. The simplest shape is that of a plane face, which may be vertical or sloping. In theory, at least, an ice sheet exerts far less force against a sloping face to which it does not adhere than against a vertical one. For reasons given at the outset, it is not proven that real benefits accrue from sloping faces as opposed to vertical ones, at least in the arctic.

Whereas, in the case of a plane face of considerable width struck by an ice mass, the proper crushing strength is that derived by compression testing of similar ice with due allowance for scale effects, temperature and salinity variations throughout the sheet, etc. the problem of choosing the correct equivalent crushing strength for the case of a cylindrical structure is somewhat more complicated, even if one assumes that prior to impact the ice sheet was preformed to the exact cylindrical shape in question. Part of the ice will shatter upwards, part downwards and obviously, in the case of a relatively slender cylinder at least, part will shatter out laterally. Certain rupture patterns can be devised in an effort to describe the impact phenomena; even if these are not perfectly coherent, and there are difficulites in developing a shatter mechanism that satisfies all the rules of logic, they should at least err on the safe side. Unpublished work has achieved this goal to a large extent, except in relation to one factor which must serve to reduce overall forces in the case of large engineering structures. This is the fact that, in considering the impact of ice masses not previously adhering to a structure, contact of the ice and subsequent failure at maximum stress will not occur at all points simultaneously over the face of the structure. A ratchet motion will in effect prevail, and this has been observed. The problem of determining just what scale-down factors should be used, without committing oneself to unsafe design, is as yet unsolved. Field tests of a particularly costly and difficult type are called for; some headway has been made, but only on thin, fast moving floes not typical of many locations (4).

In designing multileg offshore structures, to which category piled quaywalls belong, arbitrary allowance is generally made when studying overturning or sliding of the structure as a whole for the non-simultaneity of the forces acting on different legs or piles. Once again, more rational design procedures are desirable, but the problem is to obtain site data for this.

Reference has been made to the combination of failure modes, upward, downward and lateral, in the impact of ice on cylindrical structures. In the case of small ice formations, rather than of the large ones discussed hitherto, the gradual spreading of the contact zone as the ice hits the structure has to be considered. Various phases can be identified, e.g. in the case of a plane ice surface hitting a rounded structure. The local resistance of the structural plating or members affected must be checked against the force delivered by the ice. Local stresses can exceed the unconfined compressive strength of ice cylinders very markedly, while the contact zone is first expanding outwards. Subsequent phases of impact introduce the problem noted earlier: at how many points will contact develop simultaneously?

Overall forces in the case of very small floes or growlers may be restricted by splitting of the entire floe. The contact force in this case is limited by the tensile strength of ice, rather than by the compressive strength. High velocities of impact are the only ones of concern to the designer.

In the case of a floe of limited size hitting a large cylindrical structure, the ice may be brought to rest. The retardation of the floe as it comes to rest should be analyzed (5) in relation however to the limited momentum in the impacting ice, and possibly the give in the structure itself.

The added forces, if any, caused by unconsolidated ice ridges may be analyzed along fairly straightforward lines, at least in the case of simple cylindrical structure. Unpublished studies have shown that, to the extent that the ice sheet within such ridges may be thinner than elsewhere (on the assumption that ridging cannot occur in rafted and annealed ice, which is the most dangerous type of sheet), ridges may not exert supplemental forces on structures as compared with the surrounding cover. As previously noted, consolidation in ridges will present an entirely different problem.

The adhesion of ice to structures partly depends on the nature of the surface. Thus ice bustles, or ice accretions around piles brought about by tidal movement, occur on steel surfaces but not on creosoted timber ones. Freezing-in of structures will lead to a considerable increase (approximately to the doubling) of ice forces once the surrounding sheet begins to move. Finally many of the theories will be in default should adfreezing occur.

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