Ice Overtopping of Embankments: Ice-Tank Experiments and Field Observations

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Abstract

Ice-sheet overtopping poses a problem for embankments adjoining large water bodies in cold regions. The problem is akin to wave loading and overtopping, though the water level is well below embankment crest level. Wind drives ice sheets, imparting large momentum, causing ice sheets to severely impact and possibly overtop embankments. Additionally, swift water currents in large rivers, especially during ice-cover break-up during spring weather, may drive ice against embankments such as flood-protection levees. Wind- or current-drive ice-sheets place unforeseen loads on embankments and the various erosion-protection methods intended to shield embankments. This paper briefly reviews the present state-of-knowledge regarding ice overtopping of embankments and reports the findings of ice-tank laboratory tests and field observations. Of interest are the influences of embankment geometry and ice-sheet properties on embankment overtopping. Also, of interest are the ice effects on riprap rock stability; and ice loads exerted against structures on embankments (e.g., a parapet wall).

1 Introduction

This paper draws together insights from ice-tank tests done thirty-five years ago and field observations taken at an embankment site over the past thirty-year period. The main concerns investigated using a model, riprap-protected sideslope placed in an ice tank were the stability of armor rocks (protecting the sideslope), ice overtopping of the embankment, and ice loads imposed against the sideslopes. Ice-sheet overtopping is a real concern for embankments adjoining large water bodies in cold regions – reservoirs, lakes and coasts. As elsewhere, embankments in cold regions are used extensively to form levees and dams, also causeways and breakwaters enclosing harbors. The overtopping problem is akin to wave loading and overtopping of embankments. However, instead of generating waves and wind-set-up, wind drives ice sheets formed on extensive surfaces of frigid water bodies. Wind drag may impart large momentum to floating ice sheets, causing them to severely impact and potentially overtop embankments. Also, swift water currents in large rivers, especially during ice-cover break-up during spring weather, may drive ice against embankments such as flood-protection levees. An important difference between liquid water and ice overtopping of embankments is that the latter can still occur when water levels are substantially below embankment-crest level. Wind- or current-drive ice-sheets place unforeseen loads on embankments and the various erosion-protection methods used at embankments. Presently, there is scant information on ice overtopping of embankments. This paper briefly reviews the present state-of-knowledge regarding ice overtopping and reports the findings of ice-tank laboratory tests showing how ice-sheet properties and embankment geometry affect overtopping, and how ice-impact and overtopping may affect the stability of riprap rock. Ice-tank observations are compared with field observations from an embankment site, an earthfill causeway used to form a harbor in Alaska.

2 Review

Whereas several design guides exist for rubble-mound embankments exposed to wave attack (e.g., Kamphuis 2000, CUR 1995, CERC 1984), essentially no design guides existed for addressing ice attack of embankments. There are several reviews of ice ride-up of coastal slopes (Barker and Timco 2005, Liedersdorf et al. 1996, Christensen 1994, Hocking et al. 1985), but they lack systematic insight into key factors influencing ride-up processes. At the time the ice-tank tests were done there were several studies investigating ice sheet impact with sloped planes (Croasdale 1980, Kovacs and Sodhi 1980, Lippsett and Gerard 1980, Yean et al. 1980, Ralston 1977, Tryde 1976). But little information existed (or exists) on ice effects on rock-armored slopes. Subsequently, Matheson (1988) had conducted an extensive field survey in this regard and reported that the predominant ice effects were freeze-thaw breakdown of armor rock, and the plucking and shoving of armor rock whose diameter was similar to ice-sheet thickness. Freeze-thaw breakdown occurred only for sedimentary rock and limestone, and plucking can occur when ice freezes around rock, reducing its effective weight and levering rock out of position. McDonald (1988) reviewed the few cases of armor rock used for slope protection in sheet-prone waters. Doyle (1988) and Wuebben (1995) mention various observations of ice-related damage to rock-armored banks of rivers, though typically the damage was attributable to ice-jam-related water scour of the toe of the banks and consequent geotechnical failure of banks. Only the study by Sodhi et al. (1996) involved ice-tank tests aimed at generating data on ice impact of rock-armored slopes. They placed a 1-vertical to 3-horizontal sideslope at one end of their 1.22m-wide ice tank. For such sideslopes, they concluded that maximum diameter of armor rock should be twice ice-sheet thickness; for steeper sideslopes, they recommend rock diameter be three times sheet thickness.

3 Ice-Tank Tests

The ice-tank tests were conducted at the University of Iowa using a 1:20-scale (model length/prototype length) physical model simulating approximately 100m lengths of a rock-armored embankment sideslope. The modeling was done in an ice tank 20m long, 5.0m wide and 1.3m deep. Ettema and Kennedy (1982) describe the main fea-tures of the ice tank and the urea-doped aqueous ice used as model ice. The model ice sheets simulated proto-type sheets 0.45km long, 100m wide and of varying thickness ranging from 0.1m to 0.8m. These thickness-value ranges were constrained by the similitude limitations of urea model ice (Zufelt and Ettema 1996). The model ice sheets were pushed at a constant speed toward the embankment models by means of the ice-tank's motorized carriage fitted with a push-blade. Figures 1 and 2 respectively show the ice tank and the model sideslope of an embankment.

The models comprised five modules of equal length (1.0m) and mounted on hinges. The three center modules were propped against load cells so as to measure the horizontal thrust and its lateral variation along the embank-ment. Additionally, three load cells in the push-blade measured the total force associated with moving the model ice sheet toward and onto the embankment. The face of the central sideslope module was recessed so as to con-tain three layers of Froude-scaled, 8-ton, rounded, randomly placed, armor rock, as Figure 2 shows. The surface of the sloped face of the central module was 1.0m wide by 1.4m long. One layer of armor rock was placed over the sloped faces of the other four modules. The boulders were loosely secured between nail studs. The natural angle of repose of the model rock was 38°. The sideslope had an inclination of 1H:1.5V. The crest elevation was varied from 6.0m to 9.0m above MLLW, and the water depths were varied from 4.5m to 10.5m. Water depths in the model were varied by means of a series of false-floor panels. Ice sheets with prototype lengths up to 361m were pushed against the sideslope.

Figure 1. A view of the ice-tank with ice sheet approaching the model embankment.

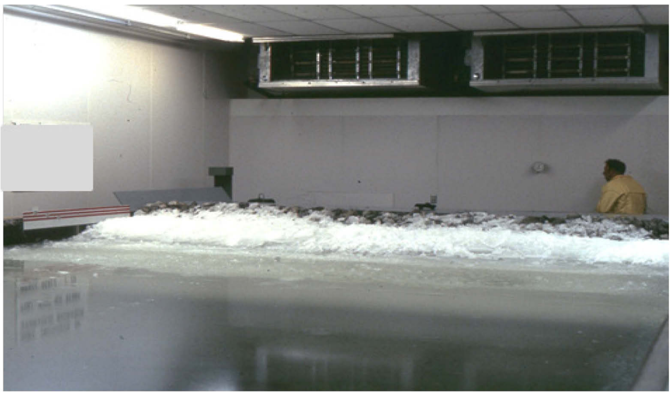


Figure 2. View of the model, 1:20-scale of an embankment sideslope in construction. The sideslope was layered with scaled armor rock and instrumented for force measurement. The Plexiglas base enabled viewing of ice movement from beneath the ice, and the false floor enable water depth to be varied.

4 Ice-Tank Findings

4.1 Observed Ride-up Processes

The observed ice ride-up processes can be briefly described as follows. The advancing ice sheet flexed upwards as it encroached onto the sideslope, and eventually failed in flexure. The resulting ice rubble consists of slabs whose size is proportional to the characteristic length, *l*, of the sheet; characteristic strength relates to the flexural failure of ice sheets (e.g., Zufelt and Ettema 1996). Measurements of ice-rubble length, *b*, from the leading edge of the sheet to the fracture line indicated that $b \approx 0.4$ to $0.6l$. Ice rubble was shoved up the sideslope until a second flexural failure occurred. The ice slabs were pushed up the sideslope by the advancing ice sheet, which all the while underwent flexural failure. Adequate contact is usually maintained at the fracture zones so that a train of ice slabs can be pushed up the slope by the driving ice-sheet. Eventually, the weight of ice slabs on the sideslope causes the leading edge of the sheet to flex downwards and fail. The ice slabs on the sideslope were then no longer underpinned by the ice sheet, and slide downwards; some ice rubble entered the water and slid beneath the advancing ice sheet. Other rubble remained on the lower portion of the sideslope. During subsequent impacts, the leading edge of the ice sheet pushed over the ice slabs in the water and slid over the slabs resting on the slope. The ride-up of ice onto the sideslope continued until once more the ice sheet flexed downwards and failed, causing the ice slabs up the slope to slip downwards. The ice slabs at the water line collect between the continuously advancing ice sheet and the submerged portion of the slope. After a number of ride-up cycles, the ice sheet formed a ramp, enabling ice slabs to ride fully up the slope, as Figure 3 shows.

The ice ramp greatly reduced the effective angle and roughness of the sideslope; the ice ramps typically developed a slope of about 1H:2.75V. The number of ride-up cycles required for ice to reach a certain elevation depended on water depth, the strength properties of the ice, and the 1ength of the slope. For ice sheets moving at about 0.2m/s, the tests indicated that the embankment's sideslopes could be over-topped by ice rubble in a prototype period of about 5 minutes. In due course, the distribution of ice rubble along the sideslope became sufficiently uneven that the impacting sheet failed irregularly and non-simultaneously along the sideslope. Portions of the sheet failed at different instances and, at times, under different failure mechanisms. At some locations, a sheet's leading edge was supported by ice rubble, which prevented the edge from flexing downwards. Instead, the ice sheet locally buckled against the sideslope. The irregular and non-simultaneous failure of the ice sheet is reflected in the measured time records of ice force exerted on the embankment. A major conclusion is that an impacting ice sheet forms its own ramp of ice rubble, upon which ice arriving later rides-up and possibly overtops the embankment.

Figure 3. Ice-sheet ride-up and overtopping of the model embankment sideslope. The model ice simulated a 0.9m-thick sheet moving at a speed of 0.2m/s.

4.2 Armor Rock Stability

The 8.3tonne, wave-protection rock sized armoring the embankment remained stably seated throughout the ride-up and pileup of ice rubble against the sideslope. The rock could be heard grinding against each other once ice rubble began pushing over them during the first one or two ride-up thrusts of sheets thicker about 0.6m. Occasionally, a less-well placed rock was dislodged from its seating. On average, only one rock in the tray of the model's center module was dislodged. The rocks most prone to be moved were seated in the sideslope crest, where rock had the least support. After the first ride-up push, rock in the lower part of the sideslope became covered by a protective layer of ice rubble. Thereafter, these rock experienced little direct contact from over-riding ice rubble. The sideslope was carefully cleared of ice rubble after each test, and its rock typically was found to have remained intact.

4.3 Influence of Ice-Sheet Thickness

Ice-sheet thickness was the most influential parameter affecting the height attained by ice ride-up of the sideslope. The likelihood that an ice sheet attained a certain ride-up height increased with sheet thickness. Several caveats to be considered, in this regard: the environmental thrust acting through the ice sheet is indeed large enough to drive ice up the slope; the ice sheet does not become extensively grounded offshore of the sideslope; and the sheet consists of strong ice. Figure 4 plots the heights attained at first ride-up of ice sheets moving up the sideslope. The present experiments showed that thicker ice more quickly formed a ramp of ice rubble extending upward from the water surface, and by means of the ramp enabled ice rubble to reach the crest of the sideslope.

The thicker ice sheets formed wider ice slabs, the fracture width being proportional to the characteristic length of the ice sheet, which in turn is proportional to $h^{0.75}$. These wider slabs were more effective in providing support for the leading edge of the ice sheet, and in flattening the sideslope angle, so that fewer slabs, or flexural failures, were required for the ice to reach the crest elevation. Once the sideslope crest had been over-topped by successive layers of ice rubble, the height of ice rubble on the crest of the sideslopes was proportional ice-sheet thickness. Figure 5 plots the height above water level of ice rubble on the crest of the model sideslope versus ice sheet thickness. The heights are not equilibrium heights of ice rubble for ice pile-up, because only 360m-long ice sheets were modelled. Also, much of the ice rubble was pushed off the leeward side of the crest during the ride-up of additional ice rubble on to the sideslope.

Figure 4. Maximum heights above water level attained during the first ride-up of ice

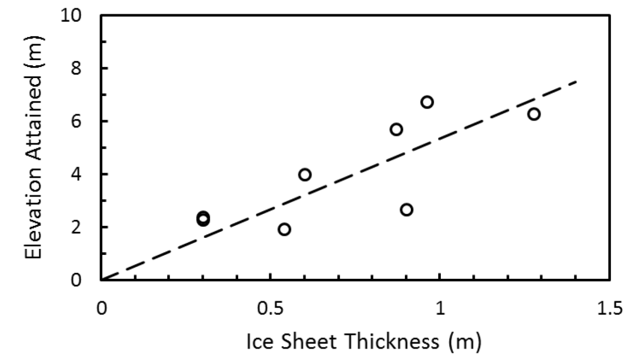
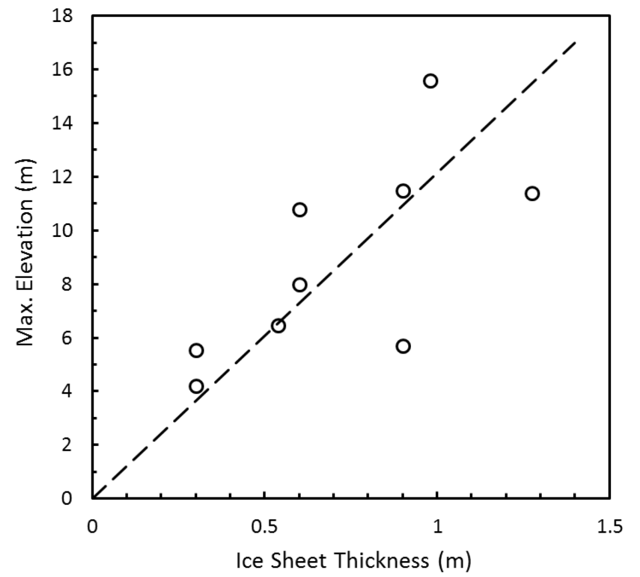


Figure 5. Maximum, final heights of ice rubble accumulation above Mean Low Low Water Level (MLLWL).



4.4 Influence of Ice-Sheet Strength

The experiments considered only a relatively narrow range of ice-sheet flexural strength. Nevertheless, the experiments indicate that the likelihood of ice over-ride increases, and the time to over-ride the crest decreases, with increasing flexural strength. Although the size of an ice slab broken from its parent ice sheet is not as strongly related to flexural strength as to ice thickness, the mass of ice slabs able to be supported on the slope by the ice sheet depended on the sheet's flexural strength. In a similar manner, when the ice sheet is prevented from downward flexural failure by accumulated rubble below it, then it is its crushing strength which determines the mass of ice slabs which can be supported on the slope.

4.5 Influence of Ice-Sheet Speed

Provided the ice sheet remains stable, less time is required for the faster moving sheets to drive ice slabs up to the embankment crest. The collision process is hastened with higher ice-sheet velocities. However, for relatively thin or weak sheets, higher velocities cause them to become unstable, thereby resulting in more irregular failure upon impact with the structure.

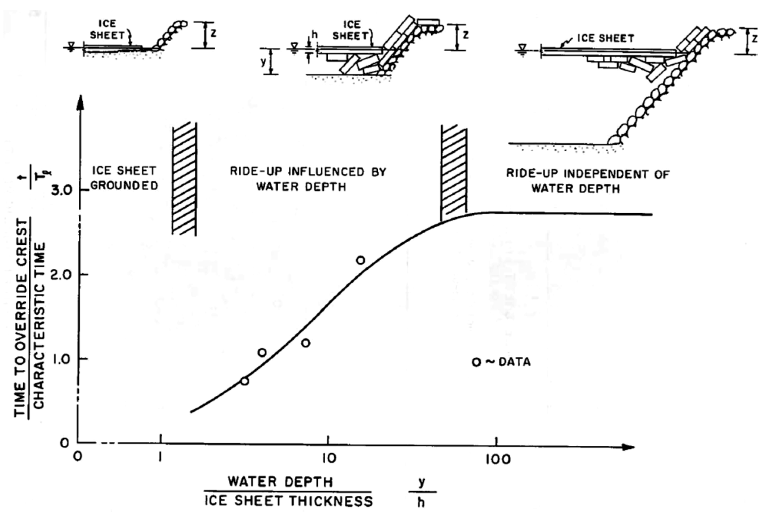
4.6 Influence of Water Depth

The experiments showed that a shallower water depth facilitates ice-sheet ride-up of the sideslope, provided the sheet does not become extensively grounded offshore of the slope. In deep water, ice rubble is less likely to become grounded at the toe of the slope, so that beyond a certain depth, which is possibly a function of ice-sheet thickness, water depth plays no significant role in ice ride-up. The influence of water depth on ice ride-up is indicated in Figure 6, in which water depth normalized by ice-sheet thickness is plotted against the time recorded for model ice sheets to reach the crest elevation of the embankment. The recorded time is normalized by a characteristic time, T_l, which is the characteristic length of the ice sheet divided by its velocity. Because the ice-slab sizes are proportional to the characteristic length of the ice sheet, the rate of ice-slab formation, or ice-sheet failure, is logically related to the characteristic time, T_l. The ends of the curve given in Figure 6 are extrapolated based on foregoing argument. The grounding of an ice sheet offshore of the structure may increase the resistance to ice-sheet ride-up and may cause an offshore pile-up of ice to occur.

Both reduced sideslope roughness and reduced sideslope inclination increase the distance an ice sheet can be driven up a slope. However, when the ice slabs on a slope are no longer propped up by the ice sheet, frictional resistance alone can act to support the ice slabs on the slope. Once over-ridden with ice, a rougher slope is more likely to remain covered in ice. Slope angle influences the elevation attained by ice rubble during the first ride-up event. Thereafter, the influence of slope angle is moderated by the accumulation of ice rubble and ice ramp formation.

The most extensive ride-up movements are the second or subsequent encroachments of the ice sheet onto the slope. The sheet then moves over ice slabs which pave the slope, reducing the frictional resistance to ice motion. Two tests were performed in which an ice sheet was driven onto a sideslope initially lined by a pile of ice rubble. The height of the initial pile was about 4.2m above water level (sideslope crest elevation was 6.0m above water level). The ice rubble produced during the collision of the 0.9m- thick ice sheet with the sideslope resulted in no ice over-ride of the crest. In another similar test, some ice rubble did manage to over-ride parts of the crest. The presence of a pile of ice rubble limits ice ride-up on a sideslope by, first, increasing the distance the ice rubble must be pushed in order to reach the higher elevations of the sideslope; second, by disrupting the train of ice slabs moving out of the water; and third, by providing a storage area for ice rubble between the pile and the sideslope crest.

Figure 6. Influence of water depth on time to overtop.



4.7 Influence of Embankment Roughness and Slope

Two tests were started with the leading edge of the ice sheet frozen to the boulders along the sideslope. In both cases, the ice sheet failed in buckling at the push-blade rather than at the sideslope. At the sideslope, the ice sheet was thicker and well anchored, whereas at the push-blade the ice sheet was freely supported. It is likely that the collision of an ice sheet with an ice sheet frozen fast to the sideslopes of the port will result in ice failure at the contact zone between the two sheets; the failure will be characterized by finger rafting of ice in the contact zone, particularly if the two ice sheets have different strength properties.

5 Field Observations and Conclusions

Since completion of the ice-tank experiments, the embankment causeway was built and about thirty years of observation were obtained. The observations are of a causeway extending out from the coast at Nome, Alaska. The field observations, by and large, support those from the ice tank, and apply to dam embankments, and coastal causeways and levees. Similar heights of ice overtopping have occurred, and indeed the riprap rock (sized for wave attack) has remained undisturbed. This latter point is important, as it confirms that embankment faces designed and armored for wave attack should fare well in ice-prone waters.

Ice floes riding-up embankments may impact parapet walls and other structures at the top of embankments. The resulting force exerted by ice relates to the thrust force acting through the ice flow, minus the horizontal component of frictional force associated with ice sliding up the embankment face (or ice-accumulation slope); or somewhat conservatively, the force exerted against a parapet wall is equivalent to the ice-thrust force per unit width of floe.

In response to the ice-overtopping events experienced the port has placed a protective breakwater to intercept and break up advancing ice sheets. This development also aligns with a recommendation from the ice-tank tests, which showed that a semi-continuous barrier placed suitably offshore of the embankment was effective in disrupting advancing ice sheets.

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References

CERC, (1984). *Shore Protection Manual*. Coastal Eng. Res. Center, U.S. Army Corps of Engineers, Vicksburg, MS.

Christensen, F.T., (1994). Ice Ride-up and Pile-up on Shores and Coastal Structures. *Journal of Coastal Research*, Vol. 10(3), pp 681-701.

Croasdale, K.R., (1980). Ice Forces on Fixed, Rigid Structures. In *Working Group on Ice Forces on Structures,* (Carstens, T., Ed.), Special Report 80-26, Cold Regions Research and Eng. Lab., U.S. Army Corps of Eng., , 34-106.

CUR, (1995). *Manual on the Use of Rock in Hydraulic Engineering*. Report 169, Centre for Civil Engineering Research and Codes, Rijkswaterstaat, Pub. By A.A. Balkema, Rotterdam, The Netherlands.

Doyle, P.E., (1988). Damage Resulting from a Sudden River Ice Breakup. *Canadian Journal of Civil Eng*., Vol. 15(4), 609-615.

Ettema, R. and Kennedy, J.F., (1982). *Ice Study for the Port of Nome, Alaska*. Limited Dist. Rept. 101, Iowa Inst. of Hydraulic Research, Univ. of Iowa, Iowa City, IA.

Hocking, G., Mustoe, G.W. and Williams, J.R., (1985). Influence of Artificial Island Side-Slopes on Ice Ride-Up and Pile-Up. Proc. *Civil Eng. in the Arctic Offshore*, American Society of Civil Engineering, Reston, VA., pp 185-192.

Kamphuis, J.W., (2000). *Introduction to Coastal Engineering and Management*. World Scientific Pub., River Edge, NJ.

Kovacs, A. and Sodhi, D.S., (1980). Shore Ice Pile-up and Ride-up: Field Observations, Models, Theoretical Analyses. *Cold Regions Science and Technology*, Vol. 2, 209-288.

Liedersdorf, C.B., Gadd, P.E. and Vaudrey, K.D., (1996). Design Considerations for Coastal Projects in Cold Regions. Proc. *Intl. Cong. on Coastal Eng*., pp 4397-4410.

McDonald, G.N., (1988). Riprap and Armor Stone. In *Arctic Coastal Processes and Slope Protection Design*, Eds. Chen, A.T. and Leidersdorf, C.B.). Tech. Council on Cold Regions Eng. Monograph, American Society of Civil Engineers, New York, p. 190-207.

Matheson, D.S., (1988). *Performance of Riprap in Northern Climates*. Rept. 625 G 571 Acres International Limited, Winnipeg, Manitoba, Canada, American Society of Civil Engineering, Reston, VA, pp.

Ralston, T., (1977). Ice Force Design Considerations for Conical Offshore Structures. Fourth *POAC Conference*, St. John's, Newfoundland, Canada, 741-752.

Sodhi, D.S., Borland, S. and Stanley, J.M., (1996). *Ice Action on Riprap*. Report 96-12, Cold Regions Research and Eng. Lab., U.S. Army Corps of Engineers, Hanover, NH.

Tryde, P., (1976). Ice Forces Acting on Inclined Wedges and Cones. *Ocean Eng*., Vol. 3, 311-316.

Wuebben, J.L., (1995). Ice Effects on Riprap. In *River, Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone*, edited by C.R. Thorne, Abt, S.T., Barends, F.B.F., Maynord, S.T. and Pilarczyk, K.W., Wiley, New York, NY, 513-530.

Yean, J.S., Tatinclaux, J.C. and Cook, A.G., (1980). *Ice Forces on Two-Dimensional Sloping Structures*. Report No. 230, Iowa Inst. of Hydraulic Research, Univ. of Iowa, Iowa City, IA.

Zufelt, J. and Ettema, R., (1996). *Model Ice Materials*. Report No. 96-1, Cold Regions Research and Engineering Laboratory, U.S. Army Corps of Engineers, Hanover, NH.