LAND–ICE INTERACTION: ICE PILE UP AND RIDE UP ON LAND

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Summary

In the cold regions, it is common for a floating ice sheet, driven by wind and/or water drag forces, to ride up or pile up on the shores of rivers, lakes and seas. In a pile–up event, an intact ice sheet shoves itself into a pile of ice blocks, resulting in breaking of ice sheet into blocks and deformation of rubble pile. Observations of ice pile up and ride up have been recorded for a long time, and sometimes such ice movements have damaged structures and riprap shore protection.

Early efforts to estimate forces required to form an ice pile up dealt with mass balance and increase in gravitational potential energy, and simple models were presented to estimate forces to overcome frictional forces. Advances made in numerical methods, such as discrete element modeling (DEM) and particle–in–cell (PIC), led to detailed accounting of breakage of intact ice sheet and frictional forces in a rubble pile. Results from DEM indicate that the total energy is 7–10 times the increase in gravitational potential energy during formation of an ice–rubble pile. Comparisons of results from DEM and physical modeling are good, except for more accumulation of ice blocks under water in DEM in comparison to that in physical modeling.

Small–scale, physical tests were conducted to assess the damage to riprap shore protection by the shoving action and the shearing action of an advancing ice sheet. Two type of stone placement have been tested: (a) random and (b) selective. For random placement of stones, there was no damage observed during a ride–up event, which occurred for shallow–slope (1V:3H) banks. Most of the damage took place during ice pile up on steep–slope banks, when the incoming ice sheet moved into the rubble pile, causing much displacement of riprap stones. The results of shoving tests indicate that

the maximum size of rocks needs to be two times the ice thickness for shallow slopes (1V:3H), and three times the ice thickness for steep slopes (2V:3H), to sustain no damage to riprap shore protection. For shearing action against random placement of rocks, riprap failure always took place when the ice thickness was equal to, or more than, the median size of rocks. Some minor damage took place when the median size of rocks was 2–3 times the ice thickness. Results from later tests indicate that selective placement of rocks offers greater degree of stability during ice shoves than that for random placement of rocks. Though selective placement of stones is a more expensive method of construction compared to random placement of stones, it requires smaller stone size and provides greater resistance to ice shoving action.

1. Introduction

Ice movement on to the land, also known as ice shove or *ivus* in Inuit, can occur along shores of lakes, rivers and seas. An ice movement is caused by wind forces acting on the top surface of an ice cover, and/or by water drag forces on the bottom surface. At times, changes in water level caused by tides and storm surges can transport an ice sheet a long distance inland. In small lakes and reservoirs, thermal expansion of an ice cover can lead to an ice cover moving onshore or against structures during spring warm up. Coastal protection is designed and constructed to avoid erosion and to protect other man-made structure. The action of an ice sheet being pushed to land and forming a rubble pile is similar to formation of pressure ridges at the boundary of two ice floes, being pushed against each other in the middle of an ice cover. Because of these similarities, there is some overlap of discussion on formation of pressure ridges, grounded rubble pile and pile up of ice on shores.

The process of rubble formation is complex in which an intact ice sheet is pushed into a pile of ice blocks, and the interaction between these two results in breaking of ice sheet into blocks and deformation or rearrangement of ice pile. The energy required to push an ice sheet into an ice pile is dissipated by increase in gravitational potential energy of an ice pile and work done to overcome frictional forces that are activated during deformation of an ice pile. Sometimes, an ice pile up can protect a shore or a structure by forming consolidated grounded rubble during early winter, thus providing protection from further ice action. Events of ice shoves during spring breakup can potentially lead to erosion of shores, damage to riprap and destruction of structures. At present, there is little guidance for design of armor stone structure to resist damage from ice action. Advances made in numerical modeling in the last two decades have increased our understanding of the processes and the magnitude of forces. The objectives here are to present a review of observations related to ice pile up and ride up, efforts to understand the forces involved during these events, and results of theoretical simulations and physical model tests.

2. Observations of Ice Pile up and Ride Up

2.1. Thermal Expansion

Thermally induced expansion of ice sheets is a slow process and generally results in ice movements of a few meters onto a shore. While thermal expansion results in compressive stresses being developed in an ice cover, creep deformation of ice relaxes thermally–induced stresses. Sanderson (1988) discusses the ice forces that are generated as a result of thermal expansion of ice being confined between a structure and steep shores. Alestalo and Häikiö (1979) give a detailed account of thermally induced movement of ice onto shores of many lakes in central Finland. In April 1985 at one location in Mackenzie Bay in Canada, the land–fast, sea–ice cover moved about 10 m seaward, and the full–thickness stress was estimated from the stress–sensor data to be about 300 kPa (Johnson et al. 1985). This amount of internal stress is sufficient to cause ice ride up onto a sloping structure. The forces active during thermal expansion of ice can result in offshore boulders being gradually pushed onto the land to form boulder ridges, the displacement of armor blocks, the destruction of docks and progressive failure of dams and piers (Kovacs and Sodhi 1988, Summerville and Burns 1968).

2.2. Wind and Water Driven Ice Shoves

On rivers, large lakes and seas, wind and water induce the main driving force to push ice onto shores, overwhelming thermally–induced motion. Material being pushed by ice on shores can reach heights of 10–15 m and be "sufficiently continuous to impede drainage of small streams into the lake and to produce marshes inland of the ice–shoved ridges" (Bird 1967). Kraus (1930) gives an account of an onshore movement that occurred in Estonia in April 1868: "The ice at the time was about 0.4 m thick, but along the shore it had melted back some 15 m. Strong wind developed over a period of a few hours, and the water level rose. Suddenly the ice moved against the land, pushing rocks and debris before it and making loud noises. These sounds wakened a man in his house just in time to allow him to escape before the ice destroyed the structure. A nearby inn was partially destroyed. This event appears to have occurred in less than fifteen minutes." Similar onshore ice shoves, such as one shown in Figure 1, take place on shores, and some of these have damaged structures and riprap shore protection in Canada and the United States (e. g. Boyd 1981, Tsang 1974, Kovacs and Sodhi 1980, Sodhi and Kovacs 1984, Becker et al. 1986, Kovacs 1983, Kovacs 1984, Kovacs and Sodhi 1988, Gawne 1999). Keyserling (1863), Alestalo and Häikiö (1975), Girjatowicz (in press) and many others have described ride up and pile up events that have taken place in northern Europe. Recently, events of ice ride up and pile up in the United States can be seen in the video at the following URL: http://www.huffingtonpost.com/2013/05/12/lake-mille-lacs-ice-minnesota-izatys_n_3263630.html

Large boulders up to 2 m in diameter can be pushed across shallow water sediments, plowing through them as they go, and this process can results in the formation of onshore boulder pavements of heights of about 7 m (Bird 1967, Dione 1979, Mackay and Mackay 1977). Boulder pavements are generally found along shores exposed to wind or current driven ice movements. This occurrence demonstrates that onshore ice movement can provide boulder armor to protect a shore, and also that ice can remove shoreline armor. Bruun and Johannesson (1971), Tryde (1972), Danys (1979), Christensen (1994) and others have reported on considerable damage to man–made armor of coastal structures caused by onshore movement of ice.

Figure 1. An ice pile up formed in January 2006 at Barrow, Alaska.(from www.gi.alaska.edu/snowice/sea-lake-ice/images/ice_events.html)

In general, the shallower the slope of a beach, more susceptible it is for ice to ride up. Rough, irregular or steeply sloping shores will tend to initiate an ice pile up. The forces required to initiate onshore ice movement are much reduced if the water level rises as a result of tides or storm surge. Under such condition, the ice is lifted free of the seabed or elevated at the tide crack and then easily driven onto the shore (Kovacs and Sodhi 1988).

Pile up and ride up along the banks of a river take place during breakup of ice, when the flow rate and water level are high, sometimes leading to ice jams. A breakup of ice on rivers leads to fast moving ice, and it can push ice blocks diagonally up the river banks or drive against islands or shoreline obstacle. Ten–meter–high pile up of ice on shore have been observed in northern rivers. In the case of ice jams, flooding in a populated area cause much damage. Significant bank modification, uprooting of trees, gouging of topsoil and destruction of structures are some of the common devastations caused by river ice (Samochkin 1961, Bolsenga 1968).

The random sequence of ice failures in buckling, bending and fracturing leads to a pile of rubble ice. The moving ice sometimes rides over the rubble or goes through the rubble pile at other times, increasing in the height and the extent of an ice pile. The angle between the sloping surface of an ice pile and the horizon ranges from 30º to 45º with an average of 37º. Some of the highest pile up is reported to be about 15 m (Kovacs and Sodhi 1988). A history of ice pile up or ride up events along a coastline may provide information to indicate locations where these events are frequent or severe (Harper and Owen 1981). In general, more exposed a shore is to drift ice, the greater is the possibility that an ice impingement against the shore is likely to happen.

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Biographical Sketches

Devinder S. Sodhi did his undergraduate studies at Indian Institute of Technology, Kharagpur, India, and graduate studies at University of Toronto, Toronto, Canada. He was an Associate Professor in the Faculty of Engineering and Applied Science at Memorial University of Newfoundland from 1972 to 1978. He joined Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire, in 1978, and retired as Senior Research Scientist in 2001. His contributions in the field of ice mechanics are ice forces on structures, dynamic ice–structure interaction, breakthrough loads of floating ice sheets, buckling forces of a floating ice sheet, splitting failure of ice floes, simultaneous and non–simultaneous crushing of ice during dynamic ice–structure interaction and various other topics. For his master's thesis, he worked on large, in–extensional deformation of thin shells (Journal of Applied Mechanics, 43[E1]: 69-74). From 1993 to 1994, he was chairman of Offshore Mechanics and Arctic Engineering (OMAE), a division of American Society of Mechanical Engineers (ASME). In 2013, he became an ASME Fellow for his contributions in the field of ice mechanics. Currently in retirement, he is engaged in consulting work within and outside CRREL.