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Cold Regions Research & Engineering Laboratory

Ice Engineering

U.S. Army Engineer Research and Development Center, Hanover, New Hampshire

Ice Cover Effects on Scour in Narrow Rivers

The influence of an ice cover on a channel involves complex interactions among the ice cover, ice roughness, fluid flow, sediment, bed geometry, water depth, and channel geometry. This complex interaction can have a dramatic effect on sediment transport process (Fig. 1) and channel development, especially in narrow rivers. A river is considered narrow if the ice in the center of the channel is constrained from responding to changes in water level. In these situations, any increase in the discharge above the level at freezeup will necessarily be accompanied by an increase in the velocity under the ice cover.

Recent laboratory investigations of scour around bridge piers explored three surface conditions: open water, a floating ice cover, and a restrained ice cover with hydrostatic head conditions simulating discharge increased above freezeup level. The study concluded that increases in hydrostatic head caused an increase in the maximum velocity beneath the ice cover for the restrained case and also found that the velocity profile is shifted towards the smoother boundary. This technical note summarizes the more detailed descriptions of the experiments contained in Hains (2004), Hains and Zabilansky (2004), and Hains et al. (2004).

An ice cover approximately doubles the wetted perimeter of the river, adding to the flow resistance. When the ice cover becomes frozen to the riverbanks and bridge piers, the cover is restrained from freely responding to changes in discharge conditions. The ice cover forms at the stage corresponding to the freezeup discharge, defining the freezeup datum and subsequently the flow area for the remainder of the winter. Conveying a similar open-water discharge under a constrained ice cover requires an increase in stage, mean velocity, or both.

Figure 1. The formation, presence, and eventual breakup of ice covers, such as this one shown on the Yellowstone River in Montana, significantly influence sediment-transport dynamics.

For shallow rivers with thick ice, the change in discharge required to trigger breakup may be an order of magnitude greater than the freezeup discharge. A rule of thumb is that the corresponding open water stage has to increase two to four times the ice thickness to initiate breakup of the ice cover (Donchenko 1975). Furthermore, if the discharge is above the freezeup datum, but below the breakup threshold, a moveable bed will tend to erode to restore the balance between the shear stress and the erodibility of the bed material. Roughness on the underside of the ice also has a role in the scour process. This process also results in resuspension of contaminated sediments. Although ice impacts on sediment transport can be significant in cold regions, the effect of a fixed ice cover has yet to be considered in sediment transport processes.

Experimental study

The investigation into scour under ice was triggered by the collapse in 1990 of a bridge over the White River in White River Junction, Vermont. During its service life the bridge survived more dramatic ice and flood events (Fig. 2) than the one that led to the failure of the pile foundation (Fig. 3). The anecdotal evidence indicated that the foundation had deteriorated because of multiple bridge pier scour cycles (Zabilansky 1996). However, no method existed to quantify and verify this conclusion. The first step in correlating hydraulic and ice conditions with scour required the development of a robust real-time scour monitor that could operate in ice-covered rivers. CRREL developed and tested Time Domain Reflectometry (TDR) technology for this purpose (Zabilansky and Yankielun 2000). Three TDRs were installed upstream of a bridge pier in the White River, Vermont. These measurements were augmented with hydraulic and meteorological data and visual documentation of the ice conditions. The unique TDR instruments were incorporated into two additional projects to monitor sediment transport process during the winter: the Missouri River in eastern Montana and the Mississippi River near Rock Island, Illinois. Zabilansky (2002) summarized the observations from the three case studies.

Figure 2. Bridge Street Bridge, White River Junction, Vermont, 1969.

The next step in the investigation of scour under fixed ice covers was to begin laboratory testing of scour for similar conditions to those observed in the field. The experiments reported herein were designed primarily to determine the effects of two critical parameters—pressure flow and ice cover roughness—on the sediment transport process (pressure flow is assumed to occur when the ice cover is fixed). Depth of scour around a model cylindrical bridge pier and velocity profiles were used to assess the influence of these parameters. The influence of the ice cover condition (fixed or not) and roughness on the velocity profile is directly related to the stability of the sediments beneath the ice cover in a narrow river (Tuthill and White 2005). All tests were designed to be in the clear-water scour regime, where the mean velocity, V_{avg}, was less than critical velocity, defined as the threshold for general bed movement, V_c. Table 1 lists general testing conditions in terms of cover condition and relative cover roughness for the tests.

Figure 3. Collapse of the Bridge Street Bridge, White River Junction, Vermont, 26 January 1990.

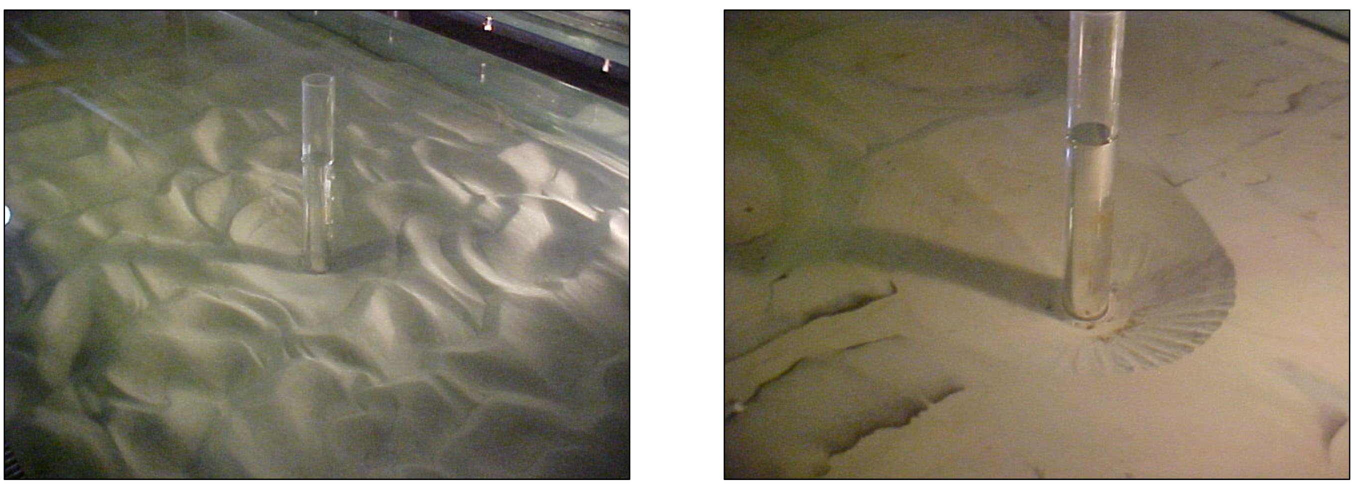
Table 1. Test conditions.		
Number of tests	**Cover condition**	**Relative cover roughness**
6	Open water/free surface	N/A
5	Floating	Smooth
1	Floating	Rough
6	Fixed	Smooth
2	Fixed	Rough

Experimental setup

The experiments used the recirculating tilting bed flume housed in a coldroom in the Ice Engineering Facility at CRREL. The flume is 36.58 m long, 1.22 m wide, and 0.61 m deep and can be tilted from a +1° to a –2° slope. To avoid experimental effects caused by variations in thermally grown ice covers, simulated ice with stable engineering properties was used for these initial tests. The water temperature was maintained at 1.6°C to obtain values of density and viscosity typical of an ice-covered channel. Downstream of the final entrance transition section, the flume was filled to a depth of 19.05 cm with uniform sand with a median grain diameter of 0.13 mm and a sediment uniformity coefficient of 1.41. The ice cover was simulated using Styrofoam insulation panels, with the natural finish used as the smooth cover (with an estimated Manning's *n* of approximately 0.010). For the rough cover, a geotextile open mat (Enkamat, manufactured by Maccaferri) with a Manning's *n* of 0.303 (Maccaferri Engineering 2002) was attached to the Styrofoam.

For the fixed cover tests, the simulated ice was fixed vertically for 15.24 m around the pier (12.19 m upstream to 3.05 m downstream) to maintain a water depth of 22.86 cm. To simulate an upstream ice jam that creates a hydrostatic head under the fixed cover section, an 11.58-m-long transition section was extended immediately upstream of the rough fixed cover. The simulated ice in the transition section followed a linear slope from the fixed elevation to the hydrostatic head elevation.

Velocity measurements were taken 3.66 m upstream of the pier on the centerline and at locations 25.5 cm left and right of the centerline. Vertical velocity profiles were taken using a two-dimensional Acoustic Doppler Velocimeter (ADV) with a 1-s sample rate for two minutes at 1-cm increments between the bed and water surface or underside of the cover. A complete description of the experimental setup and procedure can be found in Hains (2004) and Hains and Zabilansky (2004).



a. Rough ice cover. *b. Smooth ice cover.*

Figure 4. Scour tests: Live bed versus clear water scour.

Results and discussion

The analyses were conducted on the relative velocity, which is the average velocity normalized by the critical velocity (27.43 cm/s for the test sediment). The majority of tests were conducted at a relative velocity of 0.86. The effects of ice cover roughness on the velocity profile are evident in Figures 4 and 5. The open water profile is logarithmic in shape, as would normally be expected. For the floating smooth cover, the profile is gradual, with the maximum velocity approximately at the mid-depth, indicating that the roughness of the Styrofoam and bed are similar. For the floating rough cover, the maximum velocity is also at mid-depth but is about 20% greater than the smooth ice profile. The steeper velocity gradient is responsible for the live-bed scour that was observed under the floating rough cover.

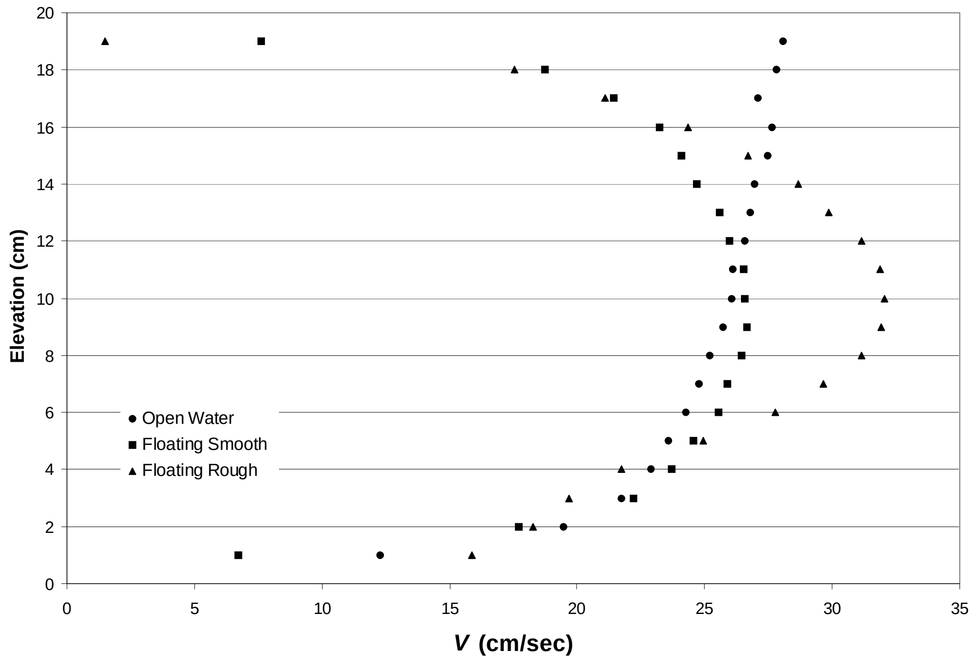


Figure 5. Velocity profiles for open water and floating smooth and rough ice covers. V_{avg} *= 23.56 cm/s,* V_{avg}/V_c *= 0.8589.*

The effects of the pressurized flow test condition are not significant when the smooth ice cover is fixed (Fig. 6). Here, the depth of flow on the ordinate axis has been non-dimensionalized to allow comparisons between tests with different depths of flow. More significant changes in the velocity profile are observed with a fixed rough cover (Fig. 6). The maximum velocity for the fixed cover with the pressurized condition was higher than for the floating cover condition. For the smooth fixed cover tests, the velocity profile was nearly symmetrical about the mid-depth. The velocity profile for the rough fixed cover test shifted dramatically towards the bed, the smoother of the two boundaries. The steeper velocity gradient near the bed and the associated increased shear stresses along the bed resulted in live-bed scour.

The velocity profile shift toward the smooth cover is more pronounced when the relative velocity is increased to 0.9278, and it is especially pronounced for the higher pressure head (Fig. 7). Moreover, at this relative velocity, the maximum velocity for both pressurized tests was greater than those of the floating cover tests. The live-bed scour that occurred under these test conditions is likely a result of the greater maximum velocity.

Theoretically, V_{avg}/V_c must be greater than one for live-bed scour to occur for the open water condition. However, these test results indicate that, although the average velocity may be an acceptable indicator for the type of scour (clear-water versus live-bed) for open water conditions, it is not acceptable for ice-covered water, especially when a pressurized or rough cover exists. This is demonstrated by Figure 8 as the hydrostatic pressure increases from zero in the floating condition to 15.2 cm in the fixed condition, the velocity profile shifts towards the smoother boundary. This profile shift will subject the bed to higher shear stresses and accelerated scour.

Conclusion

The field observations and flume study indicate that an ice cover is an active participant in the sediment transport process for narrow rivers, for which ice cover movement is constrained. The roughness of the ice cover and the pressurized flow condition must be considered in determining the stability of contaminated sediments in narrow rivers. If the ice cover forms from dynamic processes, typical of steep, narrow rivers, the bottom surface of the ice may be rougher than the bed. When the discharge increases above the freezeup datum, the pressurized flow condition, combined with the rough underside of the ice, will cause the maximum velocity in the flow to both increase and shift closer to the bed. The result will be increased shear stresses on the bed and lowering the ratio of V_{avg}/V_c that results in live-bed scour. The increase in shear stress on the bed due to the ice cover accelerates the scour around bridge piers and the contaminated sediment becomes unstable as well.

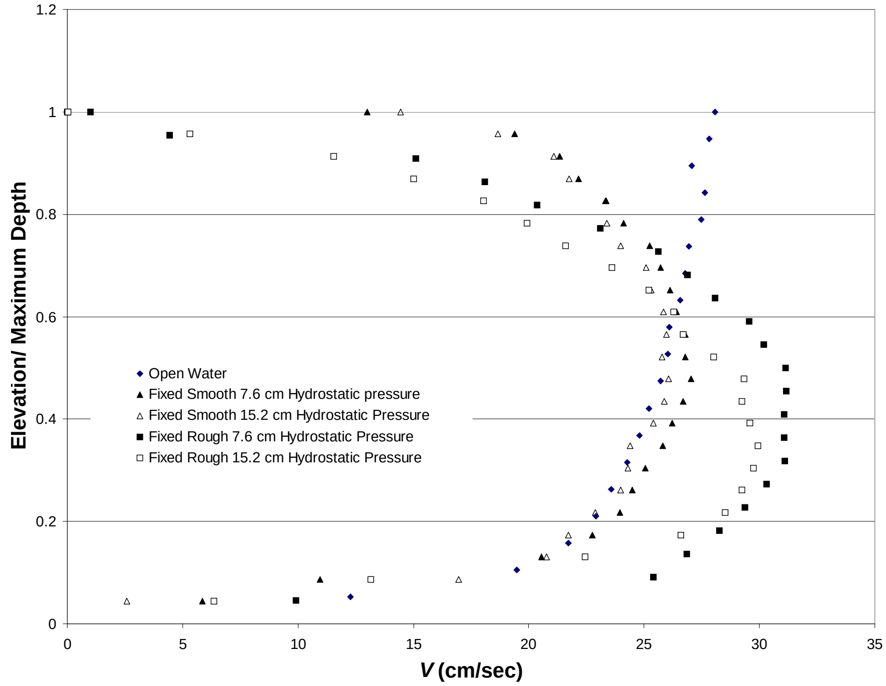


Figure 6. Velocity profiles for open water and fixed smooth and rough ice covers with hydrostatic heads of 7.6 and 15.2 cm. V_{avg} *= 23.56 cm/s,* V_{avg}/V_c *= 0.8589.*

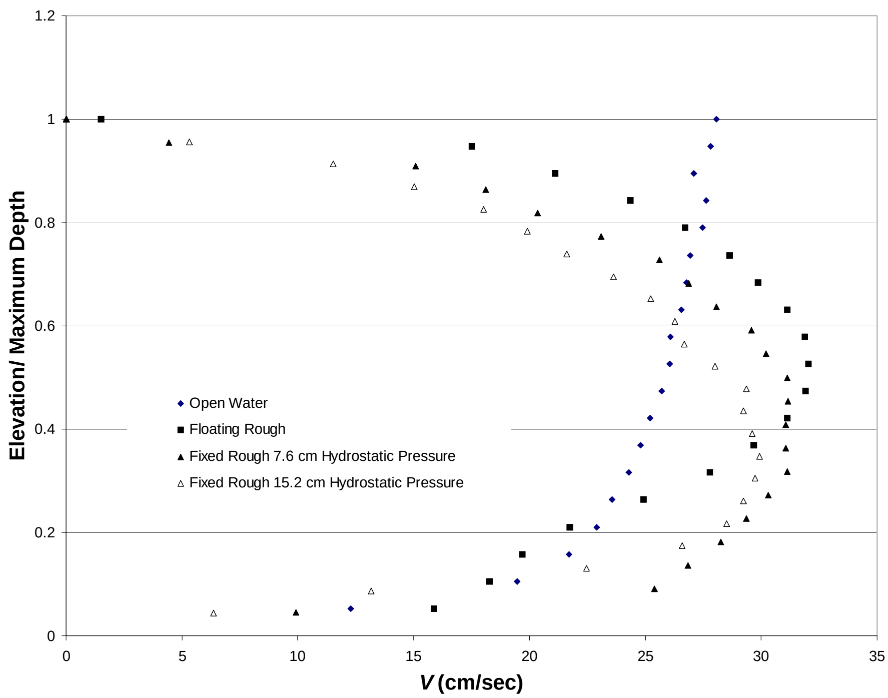


Figure 7. Velocity profiles for open water and restrained smooth and rough ice covers with hydrostatic heads of 7.6 and 15.2 cm. V_{avg} *= 23.56 cm/s (0.773 fps),* V_{avg}/V_c *= 0.8589.*

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