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Navigation Systems Research Program

Review of Ice-Induced Scour Impacts to Navigation and Structures

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Review of Ice-Induced Scour and Impacts to Navigation and Structures

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Abstract

Ice in navigation channels and around structures can cause significant damage that requires expensive repairs. This damage can also trigger delays that have the potential to disrupt the entire navigation system, well beyond the reach of the stretches of water directly impacted by ice. One example is upstream of Melvin Price Lock and Dam where ice-induced scour was repaired at a cost in excess of $1,000,000 and the scour hole reappeared within a year of the repair. Therefore, this report outlines the risks to navigation and structures, including a review of the available literature.

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Preface

This study was authorized by Headquarters, U.S. Army Corps of Engineers (USACE), where Mr. Jeffrey McKee was the Navigation Business Line Manager, and was conducted for the Navigation Systems Research Program under Work Item 9FDJ10, "Ice-Induced Scour." The Program Manager was Mr. Charles E. Wiggins, U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL).

The work was performed jointly by the Terrain and Ice Engineering Group (CEERD-RRC) of the Remote Sensing/GIS Center of Expertise (CEERD-RZR), ERDC Cold Regions Research and Engineering Laboratory (CRREL), and the River Engineering Branch (CEERD-HFR) of the Flood and Storm Protection Division (CEERD-HF), ERDC Coastal and Hydraulics Laboratory (CHL). At the time of publication, Mr. Stephen Newman was Chief, CEERD-RRC; Mr. David Finnegan was Chief, CEERD-RZR; Mr. Keith W. Flowers was Chief, CEERD-HFR; Dr. Cary A. Talbot was Chief, CEERD-HF; and Mr. W. Jeff Lillycrop was the Technical Director for Navigation. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Joseph L. Corriveau. The Deputy Director of ERDC-CHL was Mr. Jeffrey R. Eckstein, and the Director was Mr. José E. Sánchez.

COL Bryan Green was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
inches	0.0254	meters

1 Introduction

1.1 Background

Ice in navigation channels and around structures can cause significant damage that requires expensive repairs. This damage can also trigger navigation delays that have the potential to disrupt the entire shipping system, well beyond the reach of those stretches of water directly impacted by ice. One example that was detected and remedied before it could significantly disrupt navigation is upstream of Melvin Price Lock and Dam where ice-induced scour was repaired at a cost in excess of $1,000,000 and the scour hole reappeared within a year of the repair (Carr and Tuthill 2012).

1.2 Objectives

This report discusses possible mechanisms of ice scour, with an emphasis on those that may occur upstream of navigation structures. It also discusses example cases of ice scour at structures and observed ice-related scour in channels. This review lays the foundation for future study of the problem and possible mitigation alternatives.

1.3 Approach

Scour is generally considered a specific case of erosion caused by localized changes in a river. These changes can be the result of human activity, such as dams and bridge piers; natural phenomenon, like ice or sharp river bends; or a combination of factors. This report starts with a discussion of the U.S. Army Corps of Engineers (USACE) background and guidance on design and operation related to scour in channels and near dams. It briefly discusses ice scour in terms of design and measurements and reviews the structures affected by ice scour, including navigation locks and dams, hydropower, flood control and other dams, in-stream structures, and channels upstream of structures. Furthermore, the report reviews the mechanisms of ice scour, focusing first on general aggradation and degradation, looking specifically at ice hydraulic scour, and the effects of ice on transverse flow distribution. Bridge scour under ice, which has been more thoroughly explored than other mechanisms, is also discussed.

Finally, the types and sources of ice scour at structures are divided into ice hydraulic scour and direct scour. Ice hydraulic scour includes scour due to attached or pressurized ice covers, hanging dams, ice jams, and ice-jam release waves (also referred to as javes [Beltaos 2008b]). Direct scour includes anchor-ice releases and gouging of bed and banks by ice.

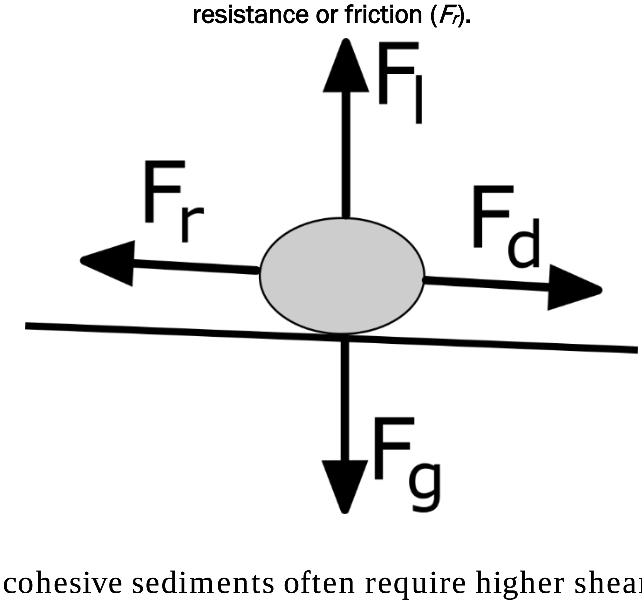
2 Scour Processes

2.1 Overview of sediment erosion

Erosion is the removal of soil and rock fragments (sediment) by the action of water (MacArthur and Hall 2008). Erosion of a streambed may result in a permanent change, or it may be episodic, depending on the sediment transport regime of the river.

Sediment transport occurs when the fluid-dynamic forces acting on sediment particles (lift and drag) overcome the resisting forces (gravity and friction). Figure 1 illustrates these forces. Depending on the site conditions, this could be caused by large, laminar flows or by turbulent eddies. It is common to think of these forces in terms of shear stresses, τ. Initiation of motion occurs once the shear stresses acting on the sediment exceed a critical shear stress, τ_c. The boundary shear stress acting on the sediment particles is a function of primarily velocity and water density. The critical shear stress is a function of the same variables, the kinematic viscosity of the water, and several particle-specific properties, including grain diameter, shape, and orientation.

Figure 1. Forces acting on a sediment particle resting on the streambed include gravity (F_g), lift (F_l), drag (F_d), and resistance or friction (F_r).



Fine-grained, cohesive sediments often require higher shear stresses to erode than coarser sediments. This is due to the additional chemical and molecular forces that act on them. Cohesive materials may erode both as individual particles and as larger chunks, often referred to as bed aggregates.

Temperature effects also play a role in sediment erosion, transport, and deposition. As water temperatures approach 0°C, viscosity increases, affecting settling velocities, shear stresses, and Reynolds numbers. In general, results from flume experiments show increasing sediment transport rates as water temperatures decrease, especially below 15°C (Ettema 2008). Fine-grained sediments, in particular, will remain in suspension much longer at colder temperatures, due to reduced settling rates.

2.2 Scour in channel and dam design

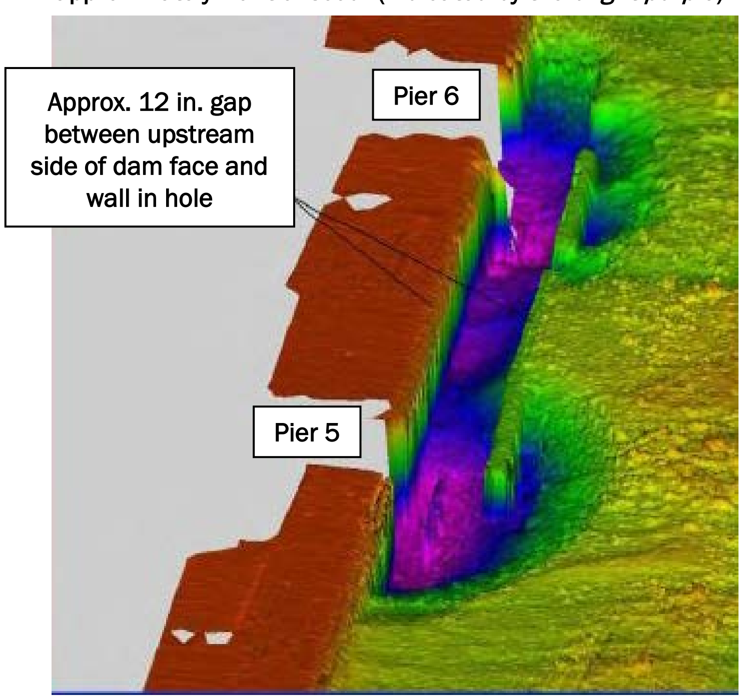
Scour is defined as a localized removal of bed or bank material by wind, water, or ice and is often associated with structures. This report focuses on scour due to the combination of water and ice near channel-spanning structures in rivers and reservoirs. Scour in rivers can be classified as either live-bed or clear-water scour. Live-bed scour occurs when material erodes but sediment from upstream settles out during the falling limb of a hydrograph and refills the scour hole. Clear-water scour occurs due to local erosion, but no upstream sediment is available to refill the scour hole.

Scour is most common in fine, cohesionless soils, with particle sizes ranging from fine sand to gravel (USACE 1994). To avoid scour in flood-control channels, the current USACE (1994) design guidance recommends maximum mean channel velocities that range from 2.0 fps for fine sands to 6.0 fps for fine gravels. Where it is not practical to limit velocities or there is likely to be significant turbulence, such as downstream of hydraulic structures, scour protection is needed. Scour protection for hydraulic structures often consists of riprap or concrete aprons. It is important to differentiate between local scour and deposition caused by a structure and general channel degradation caused by changes in the hydrograph and sediment transport due to the project because these may necessitate different protection measures (USACE 1987).

Designers of hydraulic structures also need to account for the operation of the structure when considering scour. Scour can occur below the spillway when gates are opened at low tailwater elevations. USACE (1992) guidance notes the risk for scour holes downstream of the gates during ice and debris passage operations but does not refer to upstream scour. Skimming, a procedure where surface ice is allowed to flow freely through open gates, is recommended to prevent this scour risk. This is only possible with submergible gates and when enough flow is available to cause the ice to overtop the gates. Single-gate operation results in jet flow that is constricted and can cause scour.

USACE (1987) design requirements are that riprap scour protection downstream of a dam must be sufficient to withstand fully open flow through any one gate. Ice passage should be considered in conjunction with this flow during design to conservatively size riprap (Hite 2008). Scour protection is also required upstream of a structure, especially during single gate operation. The upstream scour protection is usually determined by estimating the mean approach velocity and then using a standard formula for rock size and thickness, as described in EM 1110-2-1605 (USACE 1987). Limited lab experiments, including a model of Dam 2 on the Monongahela River, field measurements at Mel Price Lock and Dam on the Mississippi River, and an example model of a submerged low-head weir have shown scour immediately upstream of the face of structures (Figure 2) (Cooper 1995; Hite 2008; Melville 2014). Most experiments, however, focus on the scour downstream of structures.

Figure 2. Example of a scour hole upstream from gates at Mel Price Lock and Dam (Hite 2008). Flow is from right to left and there was approximately 10 ft of scour (indicated by the *bright purple*).



2.3 Ice scour

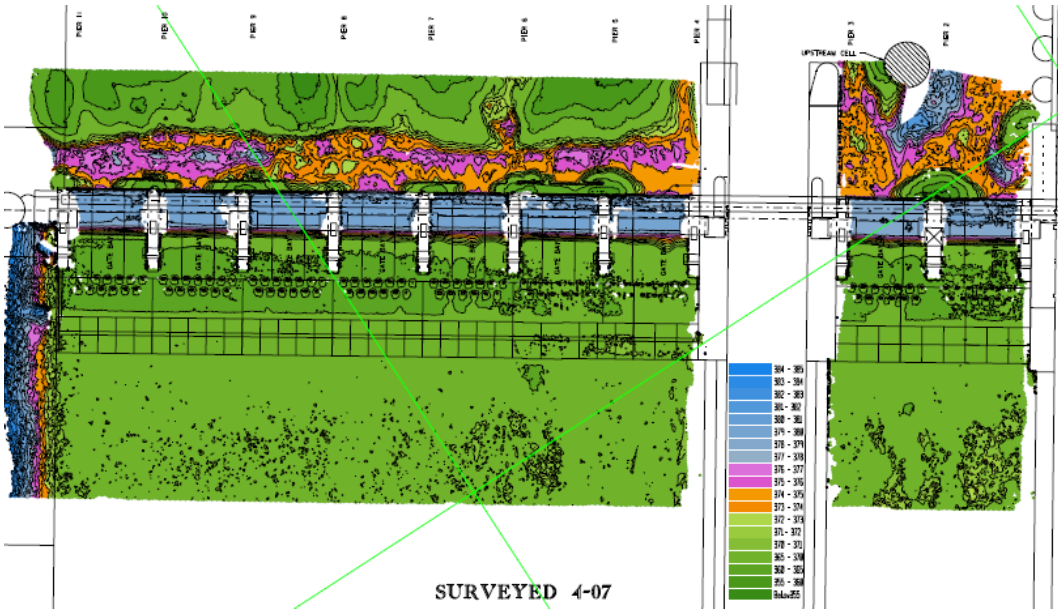
Local scour, which is the focus of this report, is scour due to an increase in turbulence and shear stress restricted to a small area, such as near a pier, abutment, or other flow obstruction (Beltaos et al. 2007). In the case of dams and navigation structures, this could include the toe of the spillway, the sill, a gate opening, or small areas of the bank and bed near the structure. Scour can occur under an ice cover due to several different mechanisms, including forcing the peak velocity in the velocity profile towards the bed and physical gouging or abrasion of the bed and banks by ice pieces or accumulations. General study of ice and ice-jam scour has been limited due to the inherent difficulty in collecting field data while ice is present and complications in lab measurements representing differing scales and temperature effects (Moore and Landrigan 1999).

Investigations of ice scour on riprap have primarily focused on protection from ice moving in the same direction as the primary river flow. Based on experimental work, Sodhi et al. (1996) have proposed rough guidelines for sizing riprap to withstand ice shoves. When the slope is shallow, they suggest doubling the rock size over that needed for open-water conditions and tripling the rock size for steep slopes. Because of the lack of field data, it is not certain if these guidelines are appropriate for ice scour. Measurement of ice scour during most ice events is difficult due to safety concerns and potential damage to instruments (Beltaos and Burrell 2015).

2.4 Structures affected by ice scour

Ice scour can affect structures and can cause structures to affect the adjacent river in many ways. This report focuses on the effect of ice on scour at river-spanning structures as opposed to narrow structures or along stream structures, such as bridge piers, abutments, revetments, or levees. Downstream scour risk due to low tailwater from ice passage in the winter has been a concern and was identified as the controlling case for downstream riprap protection after failure due to scour on Mississippi River navigation locks and dams (Hite 1987). Upstream scour protection was damaged and redesigned at two Mississippi Lock and Dam sites (Markussen and Wilhelms 1987; Carr and Tuthill 2012) (Figure 3). Historically, the USACE St. Louis District has reported navigation delays and maintenance costs due to ice and ice damages at the Mississippi River navigation locks and dams (Derrick 1991).

Figure 3. Bathymetric survey at Mel Price Lock and Dam in 2005, showing scour upstream of the central gates (Carr and Tuthill 2012). Flow is from top to bottom. The *orange* and *purple* areas indicate up to 5 ft of riprap is present upstream of the structure, while the *green* areas adjacent to the upstream side of the structure indicate that as much as 10 ft of material was scoured away.



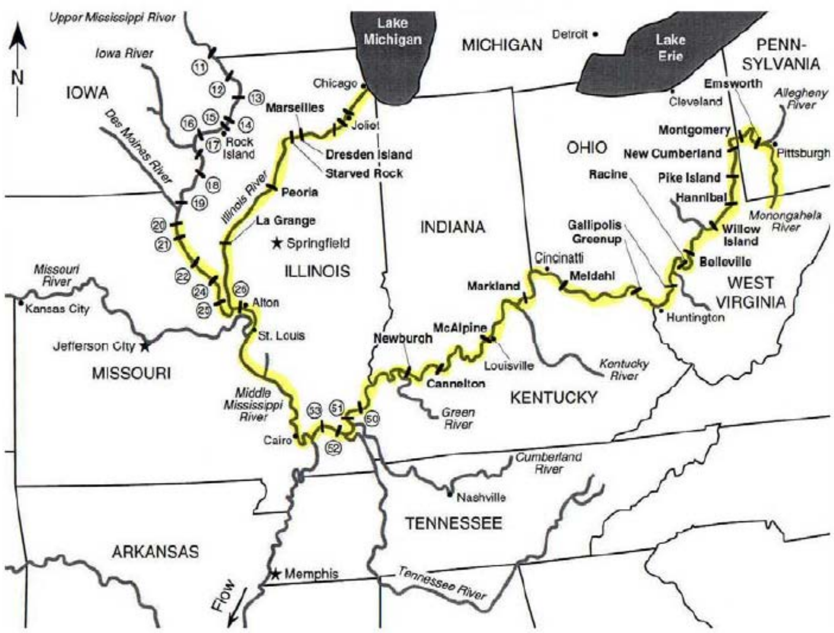
Ice scour has been a concern for other stream-crossing structures besides dams, including pipeline crossings, bridge piers, in-stream bank-protection structures, and ice-control structures (Wuebben 1995; Briggs 2003; Vuyovich et al. 2009). The failure of the bridge on the White River at White River Junction, Vermont, was attributed to ice scour after thorough observation and analysis indicating that scour and refilling of holes near structures can undermine their structural integrity (Zabilansky et al. 2006). Direct ice scour of banks and riprap protection at reservoirs is also a concern. On the Upper Mississippi River, dikes built to protect the upstream side of the Upper Saint Anthony Falls Lock and Dam have experienced damage due to direct ice action (Derrick 1991).

Ice jams can cause erosion and scour upstream of dams that retain contaminated sediments, resulting in the release of unexpected contaminants into an uncontaminated downstream reach (Moore and Landrigan 1999). An ice-jam release upstream of Montana's Milltown Dam on the Clark Fork River led to scouring of contaminated sediment when reservoir levels were dropped to protect the dam (Moore and Landrigan 1999). Erosion and scour on the lower Grasse River in Massena, New York, in March 2003 also transported contaminated sediment from a capped area downstream of the Power Canal Dam (Liu and Shen 2005).

2.4.1 Navigation dam operation and design for ice

Of 230 USACE-operated navigation structures, about one-third are ice-affected and reported problems related to ice in a 1985 survey (Tuthill 2002, 2003; Zufelt and Calkins 1985). Many of these structures can be found on the map of major ice-affected inland waterways in the United States shown in Figure 4 (Tuthill 2003). Furthermore, because reservoirs can act as sinks for sediment, the amount of material available for scour upstream of a dam is substantial and can be an environmental risk, if contaminated, and a risk to the structure itself if protection is dislodged (Petts and Gurnell 2005). Ice covers upstream of navigation structures can vary from a single layer of brash ice to accumulations many layers thick, depending on currents, wind, and navigation (Tuthill et al. 2004).

Figure 4. Major ice-affected inland waterway in the United States (Tuthill et al 2003).

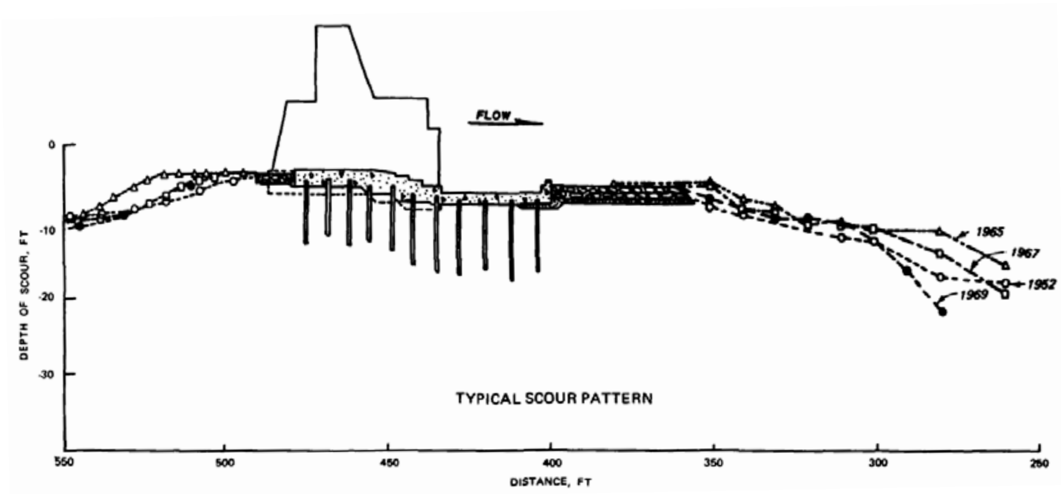


Low winter flows result in low velocities, and sheet ice often forms in front of navigation dams only to be broken up along the navigation channel by incoming tows (Tuthill and Daly 2002). Constant breaking of ice in the navigation channel upstream of a navigation lock and dam creates a continuous source of brash ice, an accumulation of broken ice pieces ranging from inches to feet in diameter (Figure 5) (Tuthill 2002, 2003). This ice drifts downstream or is pushed ahead of tows against the dam face and into lock approaches, blocking the entrance and causing difficulties for tows entering the lock (McCartney et al. 1998a).

Figure 5. A tow breaking through brash ice on the Ohio River (Tuthill et al. 2004).

Though technological advances, like bubblers that deflect ice from the lock, have helped keep ice from critical mechanical parts of navigation locks, the volume of ice constantly created is still a challenge to operators. Ice is often locked through the chamber as a tow would be to clear the brash ice and make room for actual tows (Haynes et al. 1992; Tuthill 2002). However, lockage of ice delays navigation and may present an opportunity for ice scour as multiple lockages bring brash ice repeatedly forward, causing jam-like conditions and increased near-bed velocities. Ice is also sometime diverted from the lock approach towards the dam gates (Zufelt et al. 1993). Ice may then be passed beneath tainter gates, which must be opened to a height equal to at least the ice thickness. To reduce downstream scour during low winter flows, gate opening are usually kept to a minimum to maintain pool depth (Tuthill and Daly 2002). Minimizing gate openings, however, produces a concentrated flow with high velocities routed through a few gates, with opportunities for scour upstream due to shear stress and abrasion and damage to downstream bed protection if not designed for this low tailwater condition (Hite 1987; Tuthill 2002). Scour of riprap both up and downstream of Lock and Dam 8 on the Mississippi River was attributed to large-opening, single-gate operation used to pass ice and debris (Figure 6) (Markussen and Wilhelms 1987). Scour upstream of Mel Price Dam was attributed to ice buildup and passage through a limited number of gates (Carr and Tuthill 2012).

Figure 6. Survey showing scour upstream and downstream of Lock and Dam 8 on the Mississippi River (Markussen and Wilhelms 1987).



In cases where low tailwater does not allow passage of ice from the upstream face of the dam, ice can build up behind the dam and increase the risk of upstream scour (Zufelt et al. 1993). Overflow of ice through emergency bulkheads or “skimming” over submergible gates is another alternative for moving ice from in front of the dam gates (Tuthill 2003; McCartney et al. 1998b). Periodic cycling of dam gates, meant to draw ice away from the lock approach, may also cause cases of repeated ice thickening in front of the gates, increasing the risk of scour (Tuthill 2002).

Another risk to upstream scour protection is brash ice that accumulates beneath barges as they navigate through ice-filled channels. Ice accumulated beneath barges has been estimated at as much as 8 ft thick and has been held responsible for damage to sills and riprap protection (Tuthill 2002). Towboat propellers can also increase the risk of scour in the channel upstream of the dam as they grind ice into small pieces that are jetted towards the streambed and cause direct scour (Miller and Siemsen 1987).

2.4.2 Hydropower, flood-control, and other dams

Hydropower, flood-control, and navigation dams that close for the winter are often drawn down during the late fall and quickly establish a sheet-ice cover. The seasonal drawdown may be conducted for a number of reasons, such as to provide flood storage capacity for the spring freshet or to encourage ice cover to reduce frazil-ice formation. The presence of this ice cover may suggest to operations personnel that structures are protected from upstream scour and potential damage to intake structures and other mechanical parts. This ice cover can, however, act like a lid, causing pressurized flow and increased risk of scour. Flume studies of gate releases have shown that scour depths and widths downstream of gates are the same size or larger when they occur under a simulated ice cover (Sui et al. 2009). This same effect could occur in other areas where ice jams or shore-fast ice have narrowed and concentrated the flow into a jet. Cracking of the ice near the dam, which can occur in a repetitive cycle, only temporarily relieves the pressure condition (Taras et al. 2011). If the dam is located below a frazil-producing reach, the slow flows and ample storage space in front of these dams provide a location for a hanging dam and the accompanying risk of scour.

Hydropower dams can play a positive role in reducing erosion that occurs under ice covers by changing the timing of freeze-up and breakup, creating smoother covers, capturing frazil ice in hanging dams, and reducing the risk and frequency of ice jams in shallow sections of the river that may have caused local scour (Wigle 1990). Because of the slow velocities in the backwater from hydropower dams, ice jams may preferentially form at the upstream end of a reservoir and cause erosion in an unprotected location, further reducing reservoir storage by adding to the sediment capture budget (Gebre et al. 2013). Furthermore, although hanging dams may protect the downstream reaches, they increase the risk of scour in the dam's reservoir and can release any contaminated sediments stored there.

2.4.3 In-stream structures

There is a limited amount of research studying the effects of ice and ice jamming on in-stream structures, such as those used to create fish habitat or control sediment erosion and ice jams. A rock-weir diversion structure in the White River in Colorado was reported to worsen the conditions of a freeze-up jam that formed upstream of it (Vuyovich et al. 2009). Laboratory tests of cross-vane structures (Vuyovich et al. 2009) found them to increase ice accumulation and be at risk for failure due to rock movement. Numerical studies of the same structure indicated a decrease in flow area during ice conditions, causing an increase in sediment transport above what would occur in the absence of ice (Knack et al. 2010). Hanging dams reduced pool volume and increased near-bed velocities at log-plunge structures on the South Cottonwood Creek, Wyoming, both of which increase the potential for scour (Barrineau et al. 2005). Ice-control structures meant to hold back ice jams in locations upstream of risk areas have been at risk for scour and erosion, including a structure on the Salmon River in Connecticut (Briggs 2003) and on Cazenovia Creek in New York (USACE 2015).

2.4.4 Upstream of structures

Scour in the reach or reservoir upstream of a structure can cause bed and bank erosion and shifting of the thalweg. These effects are likely to impact navigation channel and reservoir maintenance costs and to cause navigation delays for commercial tows (Ettema 2002). Structures can also have an effect on the ice regime of upstream areas themselves, increasing the risk or severity of ice jams and compounding any erosion affects (Knack et al. 2010). In 1984, an ice run on the Coldwater and Nicole Rivers in British Columbia damaged the riprap protection on seven bends due to impact scour (Doyle 1988).

2.5 Risks of ice scour near structures

Although much of the local ice scour that occurs upstream of structures is refilled during spring floods, there is a cumulative effect and potential for weakening both soils and structural stability (Hains and Zabilansky 2004). For example, scour at the White River Bridge Piers in White River Junction, Vermont, was occurring frequently, with fine, non-structural sediment refilling scour holes following scour events (Zabilansky 1996). Scour in front of a vertical sea wall has been shown to reduce passive resistance and the bearing capacity of the soil in front of a wall, which can cause a bearing failure and overturning, increasing the potential for failure of the structure (Hughes 2011). In the case of river-spanning structures, loss of soil or even weakening of soil due to loss in shear strength adjacent to the upstream face of the dam can in extreme cases cause settlement of the foundation or internal erosion of soil in embankment dams (Hoffmans and Verheij 1997). Erosion of the bed and banks upstream of a structure in a reservoir or approach channel can reduce bank strength, vegetation, and resistance to other erosive forces. It can also affect the location of the navigation channel and cause unexpected bars.

3 Mechanisms of Ice Scour

Ice can affect scour and deposition through multiple physical mechanisms. These processes can impact the general aggradation and degradation regime of a river or be restricted to localized effects of scour. Effects can be magnified by interactions with flow restrictions, such as bridge piers or gate openings. Ice can also be a source of flow restrictions, causing transverse shifting of preferential flow paths. A discussion of each of these mechanisms follows. Although studies on ice scour in front of structures that completely span the flow are limited, extensive studies of ice scour at bridge piers are discussed in detail as guidance for considering how the mechanisms of scour under ice could affect channel-spanning structures.

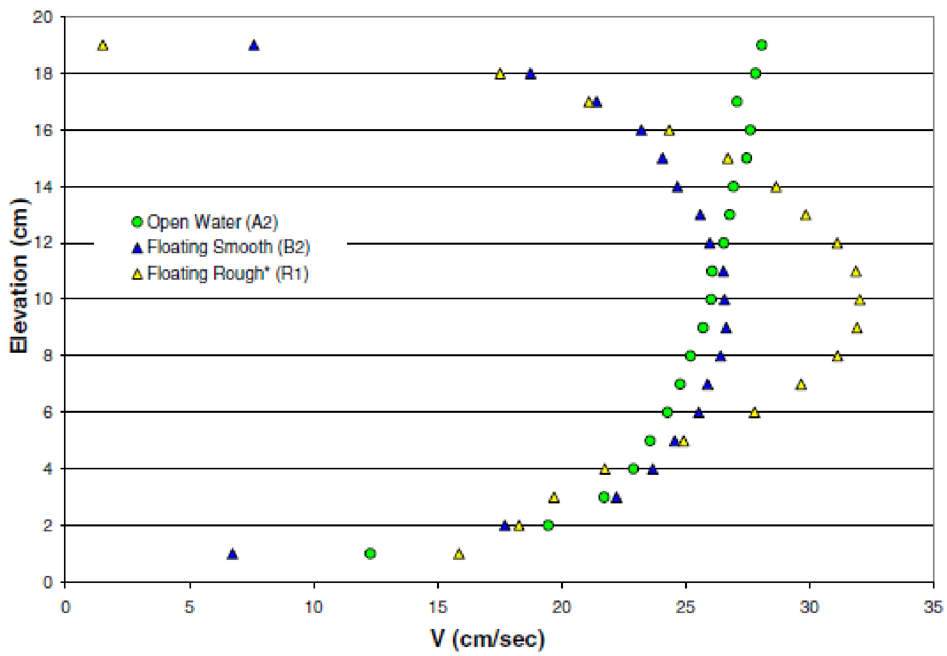
3.1 General aggradation and degradation

Ice cover can increase or decrease bed load and suspended sediment transport (Prowse 2001; Ettema and Kempema 2012). Even though the impact of ice cover on the annual sediment transport budget in cold regions can be significant (Lawson et al. 1986), it is often neglected in sediment budgets (Knack and Shen 2015).

If an ice cover is floating or a jam restricts flow, the drop in flow can reduce the transport of both suspended and bed-load sediment (Ettema and Kempema 2012), causing deposition. The magnitude of any sediment transport will depend on the how the ice affects the shear stress, particularly if it exceeds the critical shear stress for incipient motion. This critical shear stress is a function of both the bed sediment and the condition of the sediments (García 2008; Beltaos et al. 2011). Furthermore, under conditions where erosion occurs, the magnitude of erosion is a function of water depth, ice thickness, and ice roughness (Ettema and Kempema 2012). The impact of ice on sediment transport in a stream is typically most significant during ice formation and breakup (Ettema and Kempema 2012). Methods for estimating and modeling sediment transport under ice covers are usually appropriate for only floating ice conditions of standard thickness and do not well represent jams, javes, fixed bed covers, or other accumulations (Ettema et al. 2000). Recently, Manolidis and Katopodes (2014) introduced a model that better simulates changes in bed morphology during ice-jam releases, and Knack and Shen (2015) presented a model simulating bedload and suspended sediment load.

An ice cover changes the velocity profile in a river, with the ice acting as a flow boundary and rough surface that increases the wetted perimeter and the composite roughness (Tatinclaux 1998). The maximum velocity occurs between the bed and the bottom of the ice cover in a region dependent on the relative roughness of the two boundaries. The velocity drops to zero at each boundary due to the no-slip boundary condition, resulting in a parabola-shaped profile (Muste et al. 2000; Prowse 2001; Ettema and Daly 2004; Zabilansky et al. 2006) (Figure 7).

Figure 7. Velocity profile for open water and floating smooth and rough covers from experiments (Zabilansky et al. 2006).

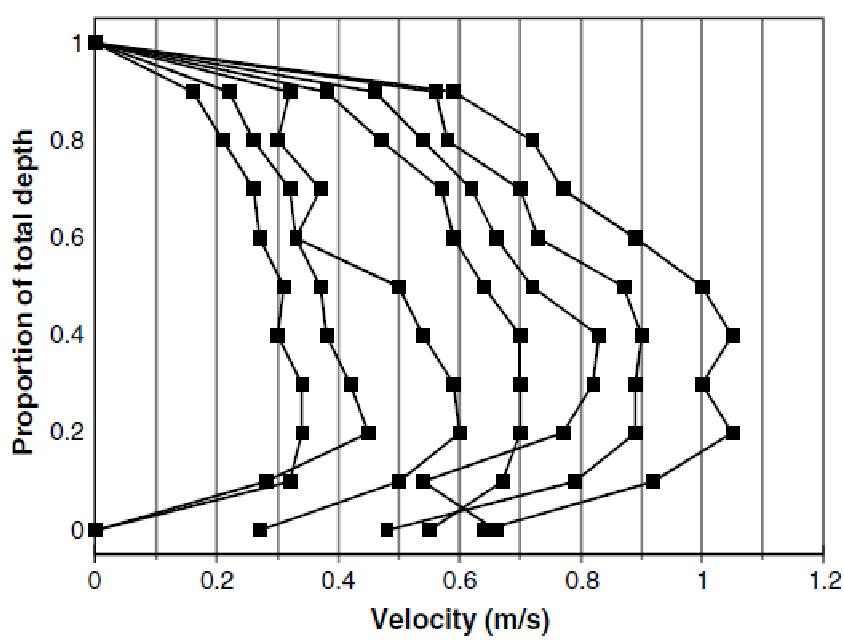


Observations in typical rivers support the consensus agreement in the discipline that most rivers and large streams have smooth, floating ice covers. This cover significantly increases the wetted perimeter, causing a decrease in velocity and lower bed shear stress that, in turn, result in a loss in sediment transport capacity (Ettema 2002; Turcotte et al. 2011). The magnitude of the loss in sediment transport capacity and the possibility of general or local scour, however, depend on the roughness, change in resistance near melt times, irregularity in thickness, depth of flow beneath ice that is jammed, whether the cover is attached to the shore, and the presence of structures (Wuebben 1995; Wang et al. 2008; Lawson et al. 1986). Muste et al. (2000) found that the presence of a rough cover in a flume decreased overall rates of sediment transport but increased the proportion of sediment moving in suspension. The presence of structures alone increases the risk for localized scour, and the impact of such localized erosion is an important factor to consider in design and operation of such structures (Beltaos and Burrell 2015).

3.2 Ice hydraulic scour

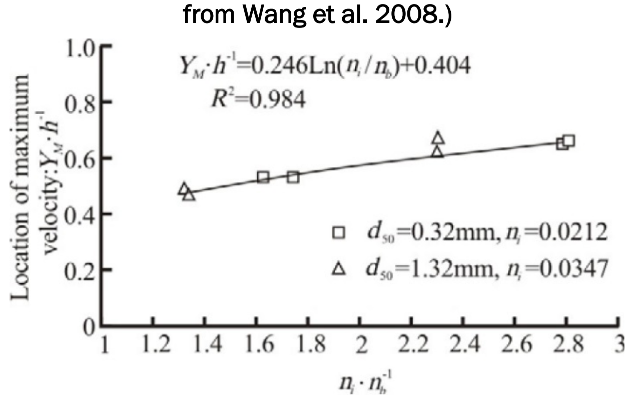
In the case of an attached cover, the restraint on the cross-sectional area causes increased velocity and sediment transport capacity with any increase in flow (Zabilansky 1996; Hirshfield and Sui 2011). The presence of ice cover also tends to shift the velocity maximum closer to the bed, increasing erosion (Zabilansky et al. 2006). Very rough ice can push the maximum velocity even further towards the bed in an attempt to reduce energy, causing scour (Hains and Zabilansky 2004). A study on the Hay River showed velocity profiles under ice with maximum velocities consistently below the midpoint, indicating ice roughness was more significant than bed roughness (Figure 8) (Milburn and Prowse 2002). The composite roughness of the bed and ice boundaries is also larger than either roughness alone, causing an increase in mean flow velocity (Wang et al. 2008). This indicates that a lower average velocity threshold is needed in an ice-covered flow, as compared to an open-water flow, to reach critical shear stress for bed deformation (Beltaos et al. 2007).

Figure 8. Velocity profiles observed on the Hay River, Station HR7, 1–17 April 1998. (Reprinted by permission from Millburn and Prowse 2002.) Each line represents a separate velocity profile measurement event at the same transect station.



Any altering of stream velocities and increased turbulence near the bed caused by an ice cover could cause localized scour, including around piers, abutments, and other hydraulic structures and through bridge openings, which can act like an open gate on a dam (Beltaos et al. 2007). Variation in thickness through an ice jam can lead to variations in sediment transport capacity and can affect general scour and deposition (Beltaos et al. 2007). An increase in velocity, and thus erosion, occurs at thickened parts of ice covers or jams and could lead to localized scour (Mercer and Cooper 1977). This was later verified as the shape of a jam, with a defined toe, was routinely observed in the field. Scour holes beneath ice-jam toes with deposition mounts downstream indicated conditions under which thickening occurred (Beltaos et al. 2007). Increases in jam length did not affect sediment transport capacity, as longer jams generally maintain an equilibrium thickness. Increased depth can lower the likelihood of erosion, as the maximum velocity will be farther away from the bed (Hirshfield and Sui 2011). Larger ice roughness also acts to push the maximum velocity closer to the bed, increasing the gradient between the maximum and minimum velocities and increasing scour (Hirshfield and Sui 2011) (Figure 9). Increased ice roughness can occur due to dynamic growth in steep, narrow rivers or due to undulations that can occur as ice covers remain in place through the winter season (Zabilansky et al. 2006).

Figure 9. Location of maximum velocity based on the ratio of the resistance of ice cover to that of the bed (water depth from ice cover). (Reprinted by permission from Wang et al. 2008.)



In addition to affecting the velocity profile in a stream, an ice cover affects vertical diffusivity, vertical distribution of suspended sediment, and the ratio between suspended load and bed load (Prowse 2001). Suspended sediment loads around 10 times that of open-water or ice-covered conditions were observed during breakup on the Liard, Saint John, and Lower Nelson Rivers in Canada (Prowse 1993; Moore et al. 2013).

Though much of the scour depth discussed in this report is rapidly refilled during spring floods, there is a cumulative effect and potential for weakening both soils and structural stability (Hains and Zabilansky 2004). While the standard engineering practice for designing bridge piers is to estimate the depth of scour by using an equation such as those in HEC-18 (Arneson et al. 2012) and then apply a factor of safety, most of these equations were not developed with considerations for ice. (HEC-18 acknowledges the possibility of ice scour but does not provide specific guidance on how to account for it.) Additionally, the refilling of scour holes with spring runoff sediment may disguise the existence and extent of any scour problems.

3.3 Transverse flow distribution

Ice covers also affect transverse flow distributions and velocities of secondary currents (Kämäri et al. 2015). These lateral flows can concentrate flows in an existing thalweg, shift the thalweg, or even divert water towards the bank, causing bank and bed erosion (Turcotte et al. 2011; Beltaos et al. 2007). Thalweg shifts can cause localized erosion that develops scour holes and then refills them as the thalweg moves again or may create permanent bed deformations (Ettema and Daly 2004). On the Missouri River in Culbertson, Montana, a thalweg shift from a primary flow channel to a secondary channel with different roughness led to erosion of both the bed and banks of the secondary channel (Zabilansky et al. 2006). Such shifts in flow towards an existing thalweg or to a different part of the cross section may also reduce velocities elsewhere and provide locations for frazil deposition (Ettema 2002) (Figure 10). Allard et al. (2011) found that 70% of measured cross sections in a pool on the Mitis River in Quebec were filled with frazil, and the depths of flow beneath the frazil layer varied throughout the pool. This frazil deposition will act to congest or choke off the flow, decreasing the area and increasing velocity and subsequent scour. Sui et al. (2006) found that scour was affected by the distribution of such frazil ice deposits and the reduction in composite area (Figure 11). Attachment to banks early in the season, paired with thalweg deepening and frazil deposition, can form “inner channels” that concentrate the flow and increase bed shear stress in a localized area (Prowse 2001). The effect of thalweg deepening is of particular concern for single-gate operation of dams to pass ice where any scour effect may be aggravated by flow concentration.

Figure 10. Riverbed scour under ice-covered condition at Hequ gaging station on the Yellow River (Sui et al. 2006) (a) 23 December 1982, (b) 13 January 1983, (c) 18 February 1983, and (d) 10 March 1983.

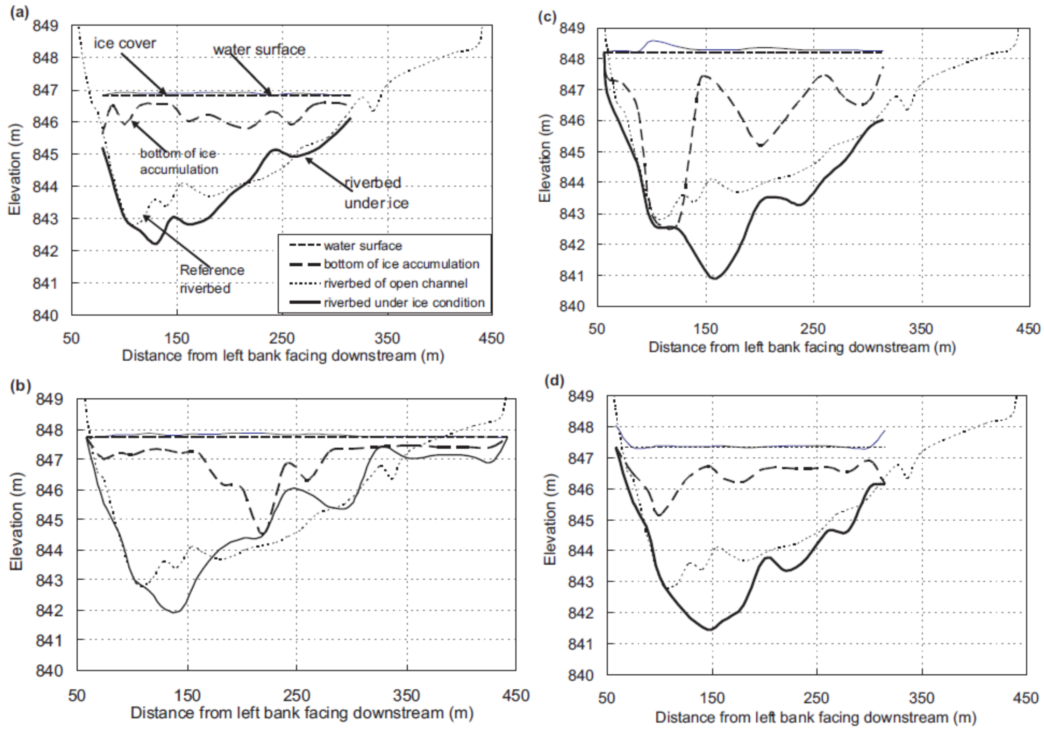
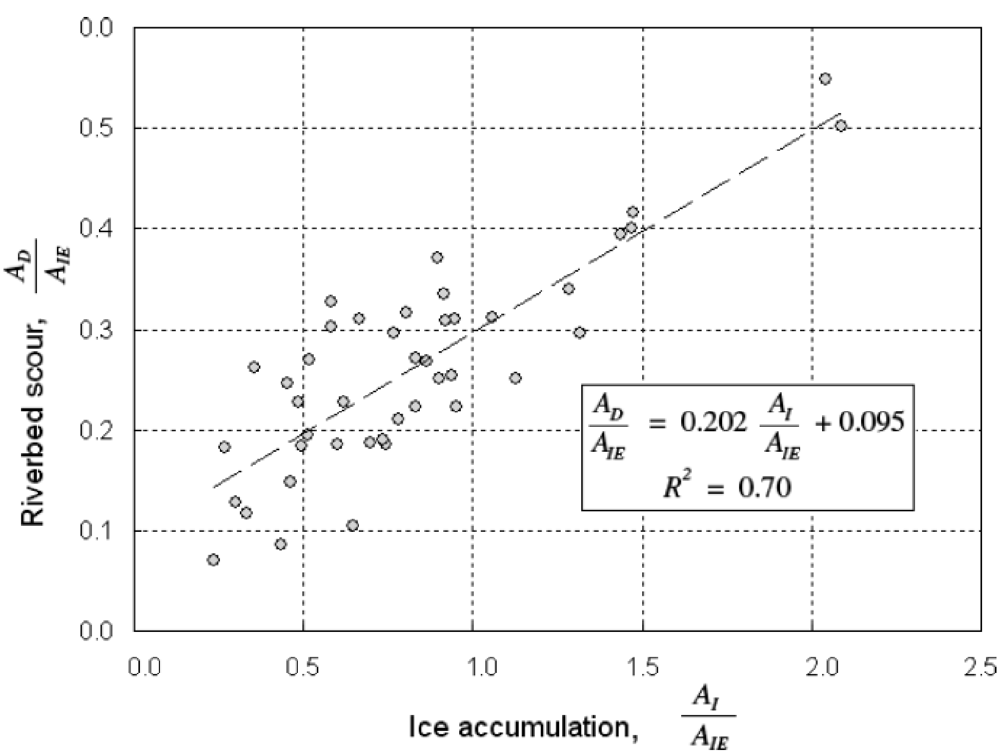


Figure 11. Riverbed scour as a function of ice accumulation at Hequ gaging station on the Yellow River (Sui et al. 2006).



3.4 Scour at bridges

The scour experienced by bridge piers and abutments, though different from the type of localized scour expected for a structure that occupies most of the channel cross section, has been studied extensively by transportation engineers. These studies of bridge pier scour provide some explanations of the mechanisms of ice scour. The presence of ice has been found to increase local clear-water scour depth at bridge piers by 10%–35% (Hains and Zabilansky 2004; Ackermann et al. 2002). For bridge abutments, flume experiments showed that with increasing ice cover roughness, scour increased (Wu et al. 2014). A bridge at White River Junction whose foundation failed was found to have weakened because of repeated scour and redeposition of non-structural fill (Zabilansky and White 2005). This case demonstrates why ice scour upstream of structures may not be recognized. By tracking scour, the investigators found that the scour hole beneath a restrained ice cover in front of a bridge pier (Figure 12) had been filled first with suspended sediment in the form of sand and then, as spring flow increased, topped with bedload gravel (Zabilansky 2002). It was also noted that the ice collar at the bridge pier was thickened due to thermal conductivity of the pier and was curved, forcing recirculation towards the bed, enhancing erosion (Figure 12). This is similar to the kind of ballycatter and crutch formation found in hydropower dams, which is thicker at the bed and may direct circulation towards the bed during higher flows (Figure 13) (Taras et al. 2011).

Figure 12. Restrained ice cover and sediment layers upstream of a bridge pier (Zabilansky 2002).

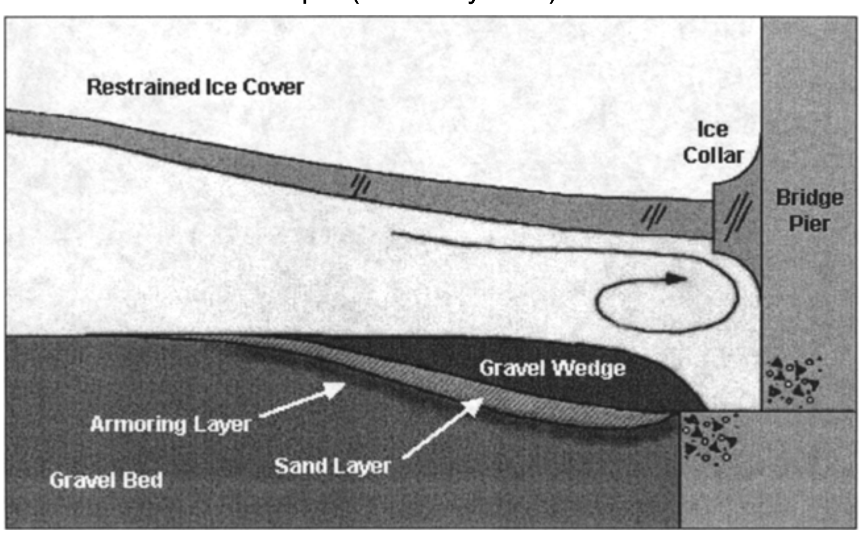
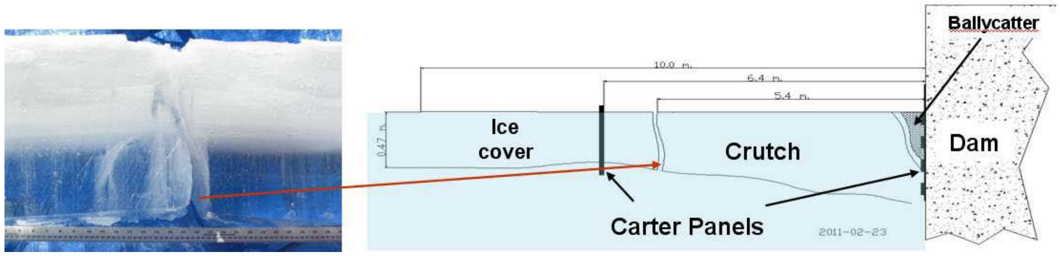


Figure 13. Ice thickness and crack profile at Barrett Chute (Taras et al. 2011).



4 Ice Scour in Reservoirs and near Structures

As rivers freeze-up, ice can form in several ways. Ice can bridge from the shore and form a smooth, thermal ice cover. Ice crystals, called frazil ice, can also develop in turbulent flows when temperatures drop slightly below 0°C. Frazil generation can occur in early winter during cold spells when flows are still high and can also occur in steep or fast-moving reaches that rarely form an ice cover during the winter. Frazil ice can accumulate into pans and floes and then juxtapose, shove, and underturn at an existing cover or constriction, forming a freeze-up jam. Alternatively, the frazil ice may move under an existing cover and deposit, forming a hanging dam and blocking a large area of the flow. As early as 1906, Barnes reported scour due to frazil ice deposition under ice cover at low winter flows (Collinson 1971). If frazil deposits on the bed, it forms anchor ice and may directly scour the bed by lifting sediment as temperatures rise (Kempema and Ettema 2011). All of these types of freeze-up ice generation and cover formation can occur upstream of a dam and bring specific risks for erosion and scour. Though ice scour is most often reported during the breakup season, local scour during low flows and specific freeze-up conditions can also induce scour (Tuthill and White 2005).

4.1 Ice hydraulic scour

4.1.1 Pressurized ice cover

A thermal ice cover, which develops in slow water, can cause erosion if it adheres to the bank and cannot respond to changes in water-surface elevation, causing pressurized flow that is similar to closed-conduit flow (Wuebben 1995; Hains and Zabilansky 2004). Though most ice accumulations in nature are assumed to be floating, a cover is more likely to adhere in deep, narrow sections under very steady discharge conditions and in locations where ice can easily adhere to banks. A river is considered narrow enough to experience pressurized flow if the distance between banks is less than 10 × *l*, the characteristic length (Hans and Zabilansky 2004). The characteristic length, *l*, is defined as $16 \times t_i^{3/4}$ where t_i is the ice thickness (Gold 1971). The ice may also attach to the shore during very cold spells (Ettema and Daly 2004). Frazil ice jams may also become bankfast, providing a pressurized ice cover that is very rough and more likely to affect velocities. An element of direct scour that can be attributed to an attached sheet-ice cover is bank material displacement as bankfast ice is released into the channel (Beltaos and Burrell 2015).

Pressurized flow restricts flow area, which causes an increase in velocity. In addition to forcing the maximum of the velocity profile closer to the bed, an ice cover or accumulation can move the main flow horizontally, shifting the thalweg or moving the path of deepest flow from one subchannel of a braided system to another. Erosion may even act as a relief of pressurized flow; if discharge rises above freeze-up levels, erosion provides a balance between the increased shear stress and the depth of the bed (Hains and Zabilansky 2004). Experiments also found that hydrostatic head in pressurized cases increased the maximum velocity in the profile, increasing scour (Zabilansky and White 2005). Narrow rivers, which are more prone to pressurized covers, are usually steep, suggesting dynamic ice cover formation. This results in a rougher cover and pushes the location of the maximum velocity closer to the bed, increasing the shear stress and erosion (Zabilansky and White 2005). Even though many dam operators are less concerned about scour upstream of the dam during low flow winter conditions, the simple presence of an attached ice cover may result in bed scour. Experiments found that fixed rough ice covers caused the largest bridge pier scour as compared to floating covers and smoother ice (Hains and Zabilansky 2005).

In pools upstream of flood-control and hydropower dams, water levels are usually drawn down and then kept steady in early winter to quickly form an ice cover and to prevent frazil accumulation near the dam and inlets. Movement of the ice sheet in the vertical direction and temporary periods of non-pressurized flow are possible but usually limited (Morse et al. 2009). The steady, low flows at which these structures are often operated in the winter are likely to keep or quickly restore any attached, pressurized condition (Ettema 2002).

Navigation locks typically have large depth-to-width ratios, making them more susceptible to pressurized flow (Liu et al. 2002). Therefore, navigation structures that are pressurized or experience periods during the winter where they are pressurized may be more likely locations for ice covers. Even under low winter flow and during brief periods of pressurized flow, ice upstream of dams can cause scour (Ettema 2008). Over the winter season, ice can become more adhered to the bank, increasing the strength of the cover and keeping flow pressurized as spring levels rise (Zabilansky 2002).

4.1.2 Hanging Dams

Hanging dams are large frazil deposits beneath an existing ice cover that can build to the point of grounding. Hanging dams can accumulate large volumes of ice, and the volume and thickness of such a jam is limited by the availability of frazil from upstream open reaches and by the amount of storage available in the pool (Beltaos 2008a; Beltaos et al. 2011). Hanging dams occur at locations of extremely low flow and can occur above a structure at the downstream end of a reservoir or at the upstream end of a reservoir where slopes change from steep to mild and deposition occurs (Prowse 2001). Ice deposits can be tens of meters thick (Beltaos et al. 2011), similar to large observed scour holes. Reported Froude numbers for hanging dams to begin forming range from 0.06 to 0.10 (Mercer and Cooper 1977; Sui et al. 2002).

Scour holes can cause an alternating cycle of scour and erosion beneath a hanging dam as the change in flow depth in the scour hole varies the ice transport capacity and as the hanging dam itself aggrades and degrades (Sui et al. 2000). Thus, if the source of frazil is unlimited, the larger the hanging dam grows and the larger the scour depth (Hirshfield and Sui 2011). For a case of scour under a hanging dam studied extensively on a reach of the Yellow River in China, investigators were able to find a site-specific relationship between cross-sectional scour area and the ratio of ice area in the hanging dam to water area beneath it (Sui et al. 2006). Literature reports that hanging dams can so fill reservoirs with ice such that hydropower production is affected (Ashton 2015).

If a source of frazil ice is present upstream, especially throughout the season, and an ice cover is present upstream of a structure, such as a hydropower or flood-control dam, hanging dams are likely and can lead to erosion upstream of a structure in several ways (Beltaos et al. 2011). Turcotte et al. (2011) indicate that the literature includes many cases where frazil ice blocks up to 40% of the cross section. As frazil blocks more and more of a channel, it can cause water to flow into secondary channels, which can lead to scour even at low flows (Tuthill and White 2005). The hanging dam itself pushes the maximum velocity closer to the bed, increasing shear stress in a usually deep pool and causing local scour (Prowse 2001).

4.1.3 Ice jams

Ice jams and their release can result in scour through several mechanisms, including direct scour from ice floes scraping on the bed, increased velocities beneath the toe of a jam, and increased velocities from the ice-jam release wave (Prowse 1993). Ice jams can occur throughout the winter due to differing causes. Freeze-up jams are formed by the accumulation and progressive juxtaposition and shoving of frazil ice, pans, and floes. Freeze-up jams occur in reaches with moderate velocities and could occur upstream of any of the structures discussed here. They can form early in the season and remain in place until breakup. Often, freeze-up jams occur at locations noted for breakup jams, being frozen so solidly in place that it is the physical feature that stops the breakup ice run and leads to the breakup jam. Ettema and Kempema (2012) cite six sources as reporting scour holes at the site of freeze-up jams.

Breakup jams occur when ice is released due to midwinter thaw, the onset of spring, or some other increase in flow. Breakup jams result from the mechanical breakup of an ice cover that is impeded by any number of physical features. The ice then forms into a jam similar in shape to a freeze-up jam, with a thick toe that causes flow concentration and scour. Breakup ice jams can occur near structures that can act as the impeding element or may have a strong sheet-ice cover or a hanging dam just upstream.

Brash ice, which accumulates constantly in front of active navigation structures (as discussed earlier), can act as a kind of jam with characteristics of both a freeze-up and a breakup ice jam. The ice can accumulate with a substantially thicker toe region in front of dam gates, particularly if brash is redirected from the lock approach or repeatedly broken up and redirected by tows. However, this ice buildup is not developed from frazil ice or hydraulic accumulation of breakup ice pieces. Furthermore, a brash ice buildup can repeatedly undergo partial release and rethickening as ice is passed through gates, and then more ice arrives as it is broken up by navigating tows. This is of particular concern because scour holes have been noted at sites of repeated ice jams in natural channels (Uunila and Church 2014)

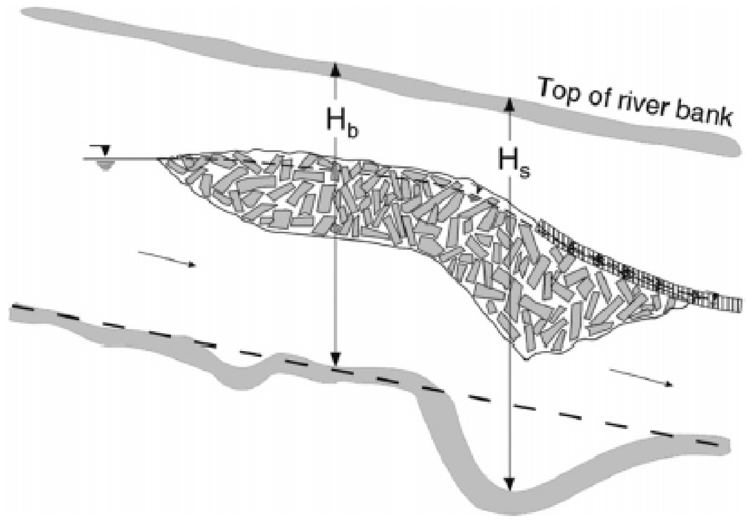
Significant scour and bed deformation, both erosion and deposition, are widely accepted as an effect of ice jams, with the ability to erode soft rocks and even create meander cutoffs within a single event (Boucher et al.

2009; Ettema 2002; Turcotte et al. 2011). The increase in velocity and shear stress caused by an ice jam can cause more erosion than scour caused under open-water flooding conditions (Hirshfield and Sui 2011). Initial estimates for maximum scour depth were similar to the ice-jam thickness (Mercer and Cooper 1977) but were found to exceed the ice thickness at Froude numbers greater than 1 (Wuebben 1988). For some rivers, the breakup and accompanying surge can be the largest annual sediment transport event (Tuthill and White 2005). Scoured sediment from beneath a breakup jam may not travel far, redepositing as the flow slows just downstream of the jam (Ettema and Daly 2004). Furthermore, following release of the jam, increased spring discharges (either due to snowmelt or spring precipitation) often increase sediment transport and can quickly refill scour holes developed during the ice-covered season (Hains and Zabilansky 2004). Therefore, one-time scour events due to ice may have no permanent effect on the morphology of a typical alluvial channel but could cause concern if they alter morphological structures, such as bars, or affect soil stability and composition near structures, such as bridges and dams (Ettema and Kempema 2012). Boucher et al. (2009) showed that at locations where the frequency of jams exceeds a certain threshold, ice scour and bed deformation due to ice jams tend to persist rather than disappear after the spring snowmelt event

The presence of an ice jam increases scour for several reasons: concentration of the flow at the toe, leading to an increase in velocity; movement of the velocity maximum closer to the bed due to the ice roughness; and deflection of flow towards the bed (Wuebben 1988; Zabilansky et al. 2006; Beltaos et al. 2007; Beltaos et al. 2011.). Scour and erosion at the toe progresses towards an equilibrium depth where the increased shear stress is balanced by the depth of the scour hole (Figure 14) (Beltaos et al. 2011). However, breakup jams are likely in place too briefly to reach an equilibrium state (Sui et al. 2000).

Upstream of the toe, where the thickness reaches an equilibrium value, scour is smaller although local scour can occur in any location where thickness is varied (Wuebben 1988). The head of the jam also results in an increase in velocity and shear stress, though it is quite small as compared to at the toe (Beltaos et al. 2007). Deposition is also known to occur downstream of the toe and in backwater regions of the jam where velocities drop sharply (Beltaos et al. 2011; Turcotte et al. 2011).

Figure 14. Schematic of a breakup ice-jam profile and riverbed morphology following scour (Beltaos et al. 2011). A deposition mount would be located downstream of the large scour hole.



4.1.4 Ice-jam release/javes

When an ice jam releases, there is a surge in ice and velocity as water surges downstream, referred to as a jave (Beltaos 2008a). These jam releases cause increased water depths and high velocities, forcing ice to abrade bed and banks and increasing velocities and shear stress, causing substantial erosion (Uunila and Church 2014). Velocities due to jam releases can be much larger than those produced during open-water events, and even a short surge can cause significant scour (Beltaos et al. 2003). An observed and measured pulse in suspended sediment also accompanies the jam release and further demonstrates the erosion capacity of the event (Beltaos 2015). The large sediment transport event that occurs at some point during the breakup is often attributed to the impact of the ice-jam release wave (Prowse 2001). An ice-jam release wave in the Red Deer River in Alberta in 1975 eroded a 2.4 × 7.6 m area of earth in a just a few minutes with channel velocities peaking at 2.4 m/s (Smith 1979).

4.2 Direct ice scour

4.2.1 Anchor-ice scavenging

Anchor ice is composed of frazil that has deposited on a streambed, usually on coarser-grained sediments in shallow flows where frazil concentration is well mixed in the vertical direction. Anchor ice often forms at night when temperature drops substantially and then releases as solar radiation increases during daylight (Kalke et al. 2015). Anchor ice that has lifted and carried sediment downstream accounts for the temporary movement of sediment and has been substantial in some cases (Ettema 2002). Because frazil usually develops at night, sediment can be picked up overnight during anchor-ice development and then rafted early in the morning, transporting sediment during each day of severe cold and open water (Ettema 2008).

Anchor-ice development, rafting, and displacement of sediment is likely only substantial in steep, shallow reaches (Turcotte et al. 2011). Large navigation locks and dams, therefore, may not experience these affects while hydropower or flood-control dams along steep rivers with coarse sediment may experience this kind of direct scour. Recent observations have shown that though the volume of sediment that could be rafted may not be large, anchor ice is able to move large gravel and cobble particles, which may affect stream stability (Kempema and Ettema 2011; Kalke et al. 2015).

4.2.2 Gouging

Gouging, or ice push, is the direct-impact scour caused by actual ice pieces scraping or rubbing against a normally stable bed or bank. Ice jams can increase in thickness so much that they impact the bed in a process called "grounding," which would likely cause gouging only during formation or shifting of the jam (Turcotte et al. 2011). The release of ice covers, ice jams, and ice runs can cause soil loss along the bed and shoreline of rivers and reservoirs by directly abrading the sediments (Prowse 2001). Grooves tend to occur in the streamwise direction with the main flow and can have a significant effect if they remove natural armor or riprap protection installed to protect a structure or the upstream channel (Prowse 2001). In a series of tests at the Canadian Hydraulics Centre, researchers demonstrated the effect that ice gouging can have on bed material (Barker and Timco 2002, 2003). The presence of direct scour on the bank can be identified by undercuts, high benches, and vegetation damage (Prowse 1993). Wuebben (1995) noted that engineers have attributed large gouges (1.5 × 0.3 m) in the embankments of rivers to river ice. Scientists have even identified furrows caused by ice pack in the rocky cliffs next to rivers in Siberia (Korzhavin 1962).

In reservoirs, the presence of an ice cover can protect banks from scour while frozen in place. On breakup, however, ice pieces can impact the bank, reducing existing protection from waves and the stability of sediments on the bank (Gatto 1988).

The breakup of upstream tributaries, which can occur before the main channel, can push large amounts of ice into the main channel and cause grounded jams in the pool upstream of the dam. This can delay navigation and also be a cause of scour upstream (Zufelt et al. 1993).

Channel stability and erosion protection design upstream of structures does not generally take into account the risk of direct ice scour on bed and banks and may lead to riprap failure, navigation-channel maintenance, and bank erosion. Ice-related damage to an inadequately designed structure may be significantly greater than the incremental cost of additional scour and ice protection (Tuthill 1995). For example, during a 1996 jam in Montana on the Clark Fork Pool of the Milltown Dam, the most substantial scour was due to ice impact and gouging of the bed and banks (Tuthill et al. 2007).

5 Further Research Needs

This literature review highlights the need for additional research into scour under ice, especially upstream of locks and dams.

There is a need to determine if scour has occurred after ice events and how deep the scour was. Currently, USACE requires scour surveys only downstream of structures and not on the upstream side. If surveys are conducted, they are typically collecting only bathymetry that will not indicate the actual depth of scour. Little information is available on the cumulative effects of ice scour over successive events and years. A comprehensive research effort to look for evidence of past scour near structures, including monitoring locks for brash-ice-induced scour, and to investigate the effects of changes in bed material may prove useful in guarding against future potential structural failures.

The current guidelines for sizing riprap under ice loads are limited to recommendations based on only a few case studies. It should be possible, through a combination of numerical and physical modeling, to improve on and formalize this guidance.

While there have been a few studies on the effects of ice on river training and river restoration structures, more research is needed to look at both the effects of ice on structures and the effects of the structures on ice-jam formation, growth, and scour. This may be especially important for the river restoration and habitat-creation techniques that use natural materials, such as root wads and engineered logjams, that may behave differently from traditional stone and concrete structures.

There is a need for a better understanding of the impact that the reduced-velocity threshold for scour due to bed shear under ice has on the currently available sediment transport equations. Most empirical sediment transport equations probably break down in these closed-channel environments. Even the transport equations that are based on excess shear calculations need to be verified against flume and field data due to the effects of increased viscosity at near-freezing temperatures. A related effort would include improving our understanding of the vertical distribution of suspended sediments under ice cover.

Numerical modeling routines for ice in the USACE hydraulic models have seen little improvement over the last 5 to 10 years. There is a need for continued improvement in these routines, including a move to more dynamic rather than static representations of ice and ice-jam locations. This is especially important if there is a desire to model the effects of ice cover and ice jams on scour and sediment transport. There is also a need to improve our estimates of under-ice roughness to support this modeling.

The estimates of Froude numbers that are required for the formation of hanging dams may represent an opportunity for preventive measures by altering the channel or placing structures to prevent flow from entering these ranges at critical locations.

There is an opportunity to estimate the maximum scour depth based on ice-jam thickness and toe depth. This could supplement design tools in use for estimating scour, such as the Federal Highways HEC-18 scour equations (Arneson 2012) for bridge piers, and act as a first-cut screening tool for in-channel structures.

More research into the relation of hanging dams and scour within reservoirs, including the potential interactions with contaminated sediment, would be useful for the navigation, flood control, and environmental fields. This work would also have system-wide implications because scour events have the potential to move sediment beyond the reservoir where it currently resides and into the downstream channel.

6 Summary

The presence of ice can have a significant effect on scour in rivers, lakes, and reservoirs. This is especially true near structures, such as dams and bridge piers. Failure of an individual structure, even temporarily, has the potential to interfere with the entire navigation system. The interruption in the movement of goods will continue until the problem is fixed or an alternative, often more expensive, means of transport is substituted.

Although there is a reasonable body of work regarding ice effects on bridge scour, research on other impacts of ice-induced scour is much sparser. In part, this is due to the difficulties of working in the field during river-ice conditions. Flume work in a laboratory setting, which is commonly used as a substitute for other sediment transport work, is complicated by the need to work in a refrigerated environment due to the temperature effects on the physical properties of water (e.g., kinematic viscosity and density).

The published literature regarding ice effects on sediment and scour indicates that there are many mechanisms at work. Ice can concentrate flow, both vertically and in the transverse direction, or cause flood waves (javes) when ice jams release. The ice can also directly cause erosion by anchor-ice scavenging or gouging of beds and banks.

It is also apparent from the literature that ice-induced scour may be more common than realized because the scoured areas are often replenished by fresh material brought downstream by high spring flows. This new material, however, does not necessarily have the same material characteristics and may not offer the same engineering properties as what was scoured. In situations where this is occurring, there would also be a period where scour holes exist; and they are a potential point of structural concern or failure in and of themselves.

More research, both in the field and in refrigerated flumes, is needed to fill in the gaps in scientific knowledge and to ensure that structures are safe throughout the winter months. Physical and numerical models present an opportunity to explore the sensitivities of ice-scour processes to both natural stream design and structure-design parameters and supplement data collected in the field. The results of such work would be useful in new construction and in rehabilitation of structures, navigation channels, and upstream erosion-control efforts.

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14. ABSTRACT
Ice in navigation channels and around structures can cause significant damage that requires expensive repairs. This damage can also trigger delays that have the potential to disrupt the entire navigation system, well beyond the reach of the stretches of water directly impacted by ice. One example is upstream of Melvin Price Lock and Dam where ice-induced scour was repaired at a cost in excess of $1,000,000 and the scour hole reappeared within a year of the repair. Therefore, this report outlines the risks to navigation and structures, including a review of the available literature.

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Channels (Hydraulic engineering); Dams, Ice; Ice jams; Ice on rivers, lakes, etc; Navigation; Scour; Sediment transport--Erosion

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