Chapter 18
Ice Control for Navigation

18-1. Introduction

Ice affects navigation when it is present in navigation channels, and it delays and interrupts navigation at locks and dams. Section I of this chapter focuses on ice in navigation channels. Many of the same nonstructural and structural techniques that were discussed in Chapter 3, *Ice Control for Reducing Flood Damages and Hydropower Operation*, are also discussed here. Ice problems at navigation locks and dams have been identified and grouped into 10 categories. These are discussed in Chapter 14. Floating brash ice hinders normal lock operations and can significantly delay barge movements into and through locks. Controlling brash ice is discussed in Section II of this chapter. Floating ice accumulations are often difficult to pass through dams to downstream reaches where the ice may pose fewer operational problems. Techniques for passing ice at navigation projects are discussed in Section III. Ice adhering to various lock surfaces interferes with the operation of lock machinery and can restrict the usable width of lock chambers. Techniques for removing and controlling ice adhesion are discussed in Section IV.

Section I
Ice Control in Navigation Channels

18-2. Nonstructural Ice Control in Navigation Channels

a. Introduction. Nonstructural ice control encompasses methods used for reducing the frequency and severity of damages from ice jams without use of a structure placed in the river. These were the first measures employed to prevent and breakup ice jams. The attraction of nonstructural ice control methods is that they are generally inexpensive. Also, these methods are popular because of the perception that they can be applied on short notice. Furthermore, the basic concept of not placing a structure into the river has appeal, as it does not create an obstacle for navigation. Most of the work that has been done in this area has concentrated on weakening or destroying the ice cover in advance of ice jam formation. However, some nonstructural methods have been used to breach ice jams. See Paragraph 3-1 for a more complete discussion.

b. Icebreaking Vessels

(1) *General.* Icebreaking vessels are limited to rivers that have sufficient draft for their passage. Also, river icebreaking vessels must have large power plants that not only can overcome ice–hull friction but also can produce large forward speeds (as much as 10 knots [5.14 m/s]) above the downstream water current (Bolsenga 1968). Underpowered icebreakers in swift flowing streams will not have enough speed, relative to the ice cover, to break the ice. Furthermore, intake designs for the engine cooling require special consideration to avoid blockage by the broken brash ice (Bolsenga 1968, Michel 1971). For breaking river ice, the following four types of vessels are typically used.

(*a*) Conventional icebreakers that break the ice in flexure by riding up on the ice cover.

(*b*) Ordinary towboats and towboats with reinforced frames and ice linings.

(*c*) Towboats or tugs that are fitted with icebreaking “plows” or prows designed for efficient icebreaking.

(*d*) Air Cushion vehicles.

(2) *Conventional Icebreakers.* Icebreakers are ships that have been designed specifically for traveling in ice-laden waters. This requires a hull that is stronger than those of conventional ships and constructed out of low temperature steel. The hull is shaped to facilitate the breaking of ice. Conventional hulls are designed to break the ice by riding the bow of the ship onto the ice, after which the ice breaks in flexure under the weight of the bow. Furthermore, to overcome the additional ice resistance, the propulsive power plants must be larger than what are used in conventional ships. Additional systems are also employed to improve the performance of the icebreaker, such as the following.

(*a*) Low friction hull coatings and cladding.

(*b*) Hull air lubrication systems.

(*c*) Hull heating at the waterline.

(*d*) Pitching systems that induce a rocking motion of the ship about the long axis of the hull.

(*e*) Water spray systems.

(*f*) Nonconventional hull forms to optimize icebreaking and clearing of a channel. Detailed discussion of these systems is beyond the scope of this Manual. A full treatment of icebreaker design is given in Sodhi (1995).

(3) *River Towboats.* Towboats are the mainstay of ice control on U.S. inland waterways, principally because they are on site when problems arise and they are very powerful (typically 2700–4600 kW [3600–8500 hp]). Ordinary towboats are limited to breaking ice thicknesses of 15 to 25 centimeters (5.9 to 9.8 inches) without damaging the hull (Bolsenga 1968). Thicker ice may be broken using explosives and then cleared using towboats. To extend the use of towboats in heavy ice, often 1.5-centimeter-thick (0.5-inch-thick) steel cladding is installed at the ice belt to reinforce the hull (Ashton et al. 1973).

(4) *Ice Prows.* The Dutch first used icebreaking prows in front of conventional ships for breaking ice on rivers and canals in the 1890s (Sodhi 1995). Ice prows have been used routinely since the early 1940s to break ice in Europe and the U.S. (Bolsenga 1968). In its simplest form, an ice prow can be a raked barge coupled to the front of a towboat (Figure 18-1). Typical prows are barges with the bow shaped to provide efficient icebreaking. The hull is also reinforced to withstand the ice forces.

(*a*) Icebreaking prows used in the former U.S.S.R. have knife edges at the front of the prow, and the hull shape pushes the ice to the side and under the adjacent ice cover (Tatinclaux and Martinson 1988). These are effective at creating a clear, smoothed edge channel, and can be used in both sheet and hummocked ice with reduced icebreaking power requirements.

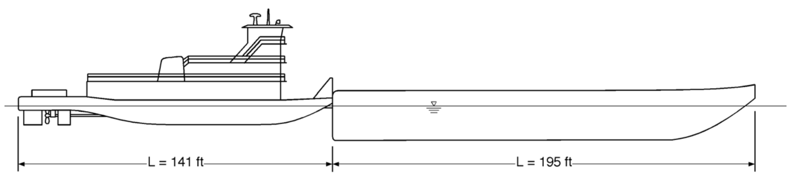


Figure 18-1. Tow with a raked barge used for breaking river ice.

(*b*) The Alexbow (Figure 18-2), designed by Scott Alexander in the 1960s, breaks the ice in uplift and deposits it on the adjacent ice cover. In field trials the bow form, pushed by a 1000-kW (1340-hp) tow, successfully broke ice up to 0.5 meters thick (1.6 feet think) at a speed of 2–3.5 knots (1.1-1.9 m/s) (Alexbow Ltd. 1967). However, field trials of the bow form conducted by the U.S. Coast Guard showed that it required considerably more power to break ice than conventional bow forms; trials in Canada, Europe, and the former U.S.S.R. confirmed these findings (Ashton 1986).

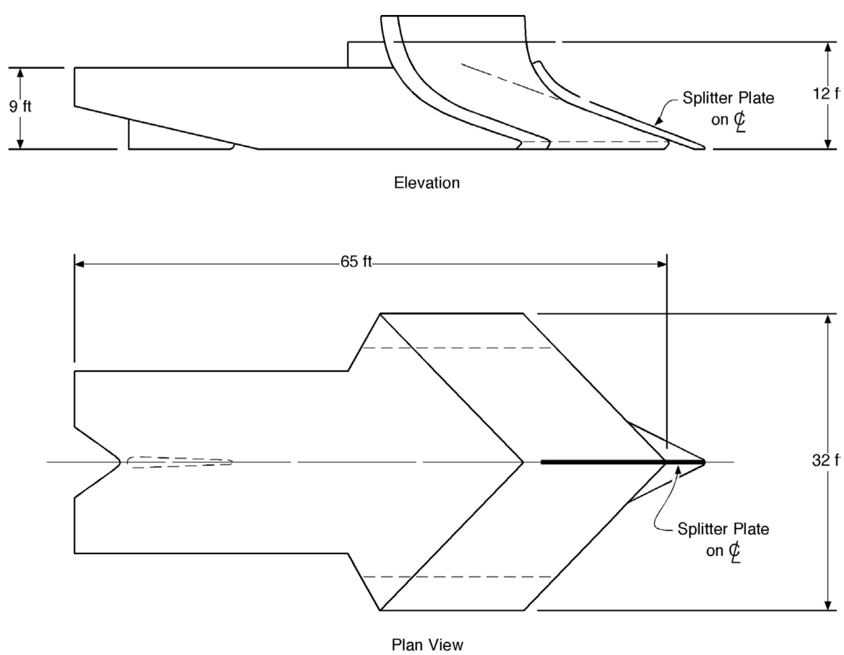


Figure 18-2. Alexbow ice prow.

(*c*) Air cushion vehicles (ACV) can also be pushed in front of a towboat to improve icebreaking capability. ACVs effectively reduce the icebreaking forces necessary when traveling through sheet ice, but they cannot be used in brash ice. Their great advantage is that they are not restricted by water depth and can break ice in shallow areas, such as river confluences.

(4) *Air Cushion Vehicles.* Air cushion vehicles (ACVs) are routinely used to break up river ice on tributaries to the St. Lawrence Waterway and on Lac St. Pierre. The ice can be broken by two mechanisms. Traveling at low speeds, the ACV pushes the supporting water out from under the ice, leaving the ice unsupported (Hinchley et al. 1991). The ice then fails under its own weight, and the broken swath is roughly equal to the beam of the craft. The maximum thickness

of ice that can be broken in this way is approximately 90% of the air cushion pressure, expressed as head of water. At higher speeds, the ACV sets up a standing wave about half the craft length astern in the ice cover, which moves with the speed of the craft, and breaks the ice at the crest of the wave. The resulting broken channel is considerably wider than the beam of the craft. The *Voyageur*—a 45-tonne (49.6 tons), 20-meter-long (66-foot-long) Canadian Coast Guard ACV with an air cushion pressure of 26 centimeters (10 inches) of water—traveling at a speed of 25 km/hr (15.5 mph)—is able to break sheet ice up to 1 meter (3 feet) thick on the tributaries to the St. Lawrence River. However, at low speeds the *Voyageur* is capable of breaking ice only 23 centimeters (9 inches) thick (Robertson 1975). ACVs are limited to breaking smooth sheet ice, because uneven ice surfaces damage the side skirts.

(*a*) Robertson (1975) conducted field tests using the *Voyageur* to break ice and reported this ACV was able to break over 250 ha/hr in 30- to 50-centimeter (12- to 20-inch) ice in open areas. In restrictive areas such as in harbors and around slips, the icebreaking rate was reduced to about 110,000 m^2/hr (1,184,000 ft^2/hr). The size of the resulting ice pieces was about 3 meters (10 feet) square.

(*b*) Though an ACV can open a track in an unbroken ice cover, the ice must be cleared by following vessels or water current (Tatinclaux and Martinson 1988). In long, narrow tracks running into the sheet, the ice can easily arch across the width, and water current alone cannot reliably clear the ice. Therefore, when ice clearing depends on water current alone, a more effective icebreaking strategy is to break the ice across the downstream edge of the cover by moving the ACV over the edge of the cover in circular motions, breaking off ice pieces that can then be carried away by the river current (Robertson 1975, Michel 1984).

c. Ice Bridging. Icebreaking vessels remove the ice cover. Ice bridging is a mechanical method that is used to change the way in which ice in a particular reach is formed or control the flow of ice into a problem reach. At the outlet to Soo Harbor an ice bridge is used to prevent ice from interfering with the Sugar Island ferry crossing on Little Rapids Cut. Historically, the ice from the Soo Harbor would jam on the lower end of the Little Rapids Cut and cause ice to back up to the ferry crossing. By placing a large ice floe at the entrance to the Little Rapids Cut, ice from the Soo Harbor does not enter the cut and ferry operation is unimpeded by ice. Paragraph 3-2*k* gives a complete discussion.

d. Thermal Suppression of Ice Growth. Ice covers deteriorate because of weakening and melting the ice cover owing to absorption of available thermal energy. Thermal weakening methods use available thermal energy to retard the growth or accelerate the deterioration of the ice cover by manipulating the absorption of thermal energy from one or more of these sources. For example, the effect that suppressing ice growth has on wintertime operation can be seen at two U.S. Army Corps of Engineer projects, Lock and Dam (L&D) 14 on the Upper Mississippi River and Dresden Island L&D on the Illinois River. Both projects report considerably reduced ice problems because of power plants and industry located upstream that discharge warm water into the river. To illustrate, on 5 December 1991 ice conditions on the Upper Mississippi stranded a tow pushing barges between L&Ds 15 and 16. That evening an ice jam formed on the pool of L&D 15 that brought river navigation to a standstill. It took 3 days for tows to break up the jam so shipping could resume. Meanwhile, only 17 kilometers (10.5 miles) upstream. L&D 14 was experiencing no ice problems. The warm water discharge from a nuclear power plant located about 40 kilometers (25 miles) upstream of L&D 14 significantly reduces the volume of ice produced above the project, resulting in open water or slight skim ice on the pool during much of the winter months. Paragraph 3-3 gives more information on this topic.

e. Discussion. Section I of Chapter 3 of this Manual contains a complete discussion of non-structural solutions to ice problems for flood control and hydropower production. Many of the options outlines there are applicable to navigation also.

18-3. Structural Ice Control in Navigation Channels

a. Introduction. Structural solutions exist for a wide range of river ice problems. Ice control research and development during the last three decades has concentrated on sheet ice retention methods. The difficult problem of breakup ice control has received less attention, particularly on larger rivers. Section II of Chapter 3 provides extensive background.

b. Ice Control on Rivers and Waterways with Winter-Long Navigation. On the lower St. Lawrence River, where winter-long navigation extends as far upstream as Montreal, the ice management program depends in part on structural methods to retain and stabilize sheet ice. Here, the ice control effort has the goals of preventing the ice jams that have historically flooded Montreal and of ensuring safe and efficient navigation to the port of Montreal. At Lake St. Peter, 65 kilometers (45 miles) downstream from Montreal, the St. Lawrence River widens and flattens, significantly reducing the river's ice conveyance capacity. Here, nine artificial islands effectively stabilize the ice between the shore and the centrally located, dredged navigation channel. These islands, constructed of quarried rock, have base diameters of 40 meters (130 feet) and are spaced 762 meters (2500 feet) apart. Figure 18-3 shows an ice island on Lake St. Peter retaining sheet ice during the early spring. Perham (1983), Appendix B of this Manual, and Lawrie (1972) provided more detailed information. The five islands on the south side of the navigation channel were constructed after 1985. Initial construction and maintenance of the ice islands are costly. The islands must periodically be topped off to compensate for continual settlement in the soft lake sediments. Upstream of Montreal, three similar islands in Lake St. Louis prevent floes from entering the navigation channel during the early part of the navigation season (Perham 1983).

(1) The four booms in the northeast corner of Lake St. Peter, depicted in Appendix B, were carried away in the late 1970s by a large floe that rotated up from the southwest quadrant of the lake; it was not replaced until the late 1990's. Upstream of Lake St. Peter, 700- and 1000-meter-long (2300- and 3300-foot-long) booms stabilize the ice cover along the river's left side at Lanoraie and Lavaltrie. Most of the original timber booms have been replaced by booms made of 76-centimeter-diameter (30-inch-diameter) cylindrical steel pontoons that greatly increase ice capture efficiency and reduce cost.

(2) The overall goal of the islands and booms is to allow as little ice as possible to enter the navigation channel. The structural measures make up only part of the overall ice management scheme, however. Continual ice breaking and flushing efforts, combined with routine airborne surveillance, are also critical.

a. Ice island along the northern edge of the navigation channel to stabilize shore ice.

b. Closeup of the ice island. It is constructed of quarried rock, the top diameter being roughly 40 feet.

Figure 18-3. Ice island on Lake St. Peter.

(3) The Montreal Harbor ice control structure (ICS), located at the upstream limit of winter navigation on the St. Lawrence, consists of a row of concrete piers, spaced at 27-meter (88-foot) centers, over a total width of 2 kilometers (1.3 miles). Figure 18-4 is an aerial view of the structure. Originally, steel pontoons (1.7 meters × 1.8 meters [5.5 × 5.8 feet] in cross section) floated in guide slots between the piers, with the goal of initiating an ice cover as early as possible. Later, the pontoons were found to be unnecessary, as the piers alone promoted the formation of a stable ice cover in Laprairie Basin, upstream of the structure. This discovery was fortunate, as operation and maintenance of the pontoons were costly and difficult. Once formed, the ice cover behind the structure prevents floes and brash from contributing to potential jams in the navigation channel downstream of the city. In addition, the cover behind the ICS traps and stores much of the frazil generated in the Lachine rapids upstream of Montreal. Before construction of the Montreal Harbor ICS, the ice cover on Laprairie Basin formed only after the natural ice cover had progressed from Lake St. Peter up to Montreal (Donnelly 1966). Should the cover progress as high as Montreal, the ICS was intended to capture arriving ice from upstream to reduce the ice

jam flood threat to the city. Owing to successful ice breaking and flushing efforts by the Canadian Coast Guard, the ice cover has not reached the city since winter-long navigation began in the mid-sixties, so the structure has never been tested in this worst-case scenario. At a cost of $16 million Canadian in 1965, the Montreal Harbor ICS is possibly the most expensive ice control structure ever built (Donnelly 1966, Lawrie 1972).

Figure 18-4. Montreal Harbor ice control structure. (From Lawrie 1972.)

(4) On the Trollhatte Canal in Sweden, ice booms, rock-filled cribs, and dolphins are used to stabilize sheet ice along the sides of the navigation channel. As with the lower St. Lawrence, winter-long navigation is the goal, from Sweden's west coast to ports on Lake Vanern. Ice breaking and flushing, bubblers, and lock wall heaters, along with airborne surveillance, complement the structural ice control methods (Solve 1986).

c. Ice Control at Lake-to-River Confluences and Channel Constrictions. Lake-to-river confluences present a special ice control problem. Although there is a tendency for ice arches to form naturally at these locations, wind and wave effects, as well as vessel passages, can disrupt arch formation, causing lake ice to enter and sometimes jam in the narrower channel downstream. A timber boom is located on the St. Marys River, south of the locks at Sault Ste. Marie, Michigan (Figure 18-5). Since its first installation in the winter of 1975–76, the boom has performed well, with only minor modifications (Perham 1977, 1978, 1984, 1985). The boom's centrally located navigation opening allows the passage of downbound vessels while limiting the ice volume entering the constricted channel at the Little Rapids Cut. For the same purpose, a four-span timber boom with a navigation opening was installed in 1976 at the Copeland Cut on the Wiley-Dondero Canal near Massena, New York. The boom performed well during its first season of use (Uzuner et al. 1977), but no recent information on the boom's performance has been obtained.

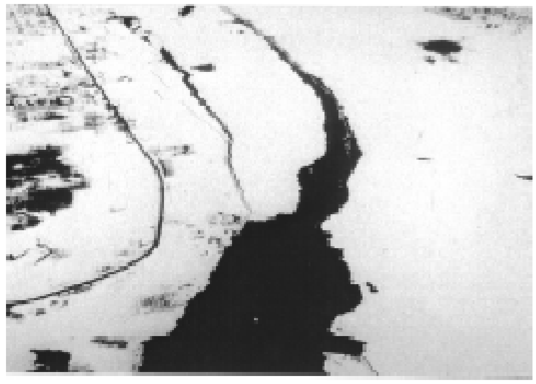


Figure 18-5. St. Marys River ice boom.

d. Sink-and-Float Ice Booms. Because the annual installation and removal of ice booms is costly, Fleet Technology, Inc. (2000) has developed a prototype sink-and-float boom. At the end of the ice season, the steel pipe pontoons are sunk in place for storage during the open-water season. To redeploy them, the pontoons are injected with compressed air, causing them to float back to the surface. An existing structure, similar in concept, protects the harbor entrance at Hokkaido, Japan, from drifting pack ice (Imaizumi et al. 1993). When there is no pack ice present, or during winter vessel transits in and out of the harbor, the pontoons lie on the seabed. The pontoons are refloated automatically by the injection of compressed air. Developed by Nishimura-Gumi Co., Ltd., the pontoons have a teardrop cross-sectional shape, minimizing the tendency for burial by deposition of sediment while resting on the bed.

e. Wiers. Submerged weir fields, known as bendway weirs, have been constructed on the Mississippi River. They direct flow towards the channel center, reducing erosion of the outside of the bend, and decreasing deposition in the channel, thus reducing the need to dredge. The St. Louis District has constructed weir fields on the middle Mississippi just below the Missouri River confluence and in the Dogtooth Bend upstream of the Ohio River confluence, both historical ice jam formation locations. Although observations are limited, these weir fields appear to have improved ice conveyance at these critical locations.

Section II
Floating Ice Dispersion

18-4. Introduction

The most notable problems with brash ice are its entry into lock chambers, often in heavy enough quantities to require separate ice lockages to pass the ice downstream, and its accumulation in miter gate recess areas, preventing the full opening of the gates. The most successful way to disperse ice is by means of high-flow air systems (Rand 1988). These systems may have up to three separate components, each with a specific function that increases the ease of lockage operations. (High-flow air systems are outgrowths of air bubbler systems intended to promote thermal thinning and weakening, i.e., melting, of ice.)

18-5. High-Flow Air Systems

a. Distributed Systems. Air manifolds should be placed in three specific locations around a lock to mitigate the problems of brash ice (Figure 18-6). First, a recess flusher should be placed in each gate recess; this will clear the recess area. The second manifold, called the screen, should be located just upstream of each set of miter gates. At the upstream edge of the gate forebays, there is typically a sill that runs across the lock chamber; place the screen on the downstream side of that sill. This screen helps prevent brash ice from entering the lock or, in the case of the downstream screen, clears ice from an area across the width of the chamber before the gate recess flushers are used. If there is some means for passing ice through or over a nearby spillway, the addition of a third type of manifold—a diagonal deflector in the upper lock approach—can be an effective way to direct the floating ice toward the spillway. This manifold is typically installed using divers and weights because the area cannot normally be dewatered.

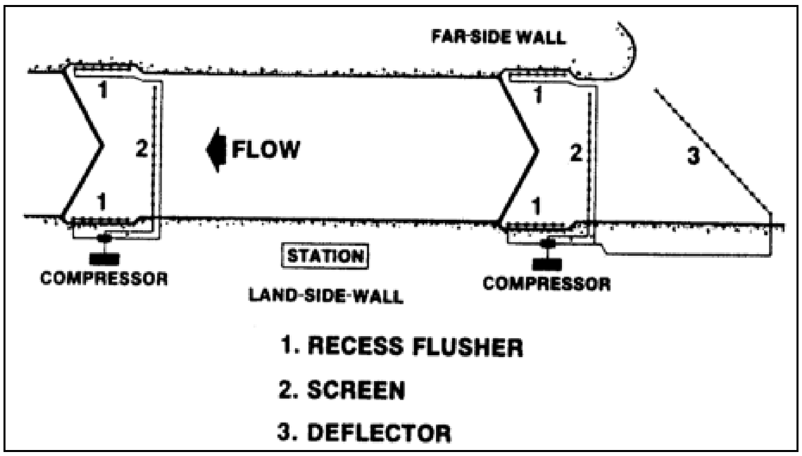


Figure 18-6. Schematic diagram of a complete high-flow air system, showing the locations for air manifolds at a typical lock. *Two compressors are shown, but one large compressor with long supply lines could also be used, assuming the supply lines are adequately sized.*

b. Single-point Systems. Single orifices can be placed on the back wall of a floating mooring bitt recess. A single air line discharging at the bottom of the recess provides sufficient water turbulence to prevent floating ice from being pushed and packed between the float and the recess walls.

c. Compressors. High flow are systems at Corps locks are typically supplied by compressors ranging in capacity from 200 to 1500 cfm (0.09 to 0.71 m^3/s), depending on the severity of the brash ice problems. Some systems have solenoid-activated valves, which allows the various manifolds to be controlled remotely.

18-6. Air System Components

Each of the major components of high-flow air systems are discussed to clarify what is required and to provide information on physical size and placement of the components.

a. Compressor. The air compressor of the size required is generally either diesel-powered or electrically operated. It can be either a permanent fixture or rented for the winter months. In a complete high-flow air system, the component requiring the most amount of air is the diagonal deflector. For a 33.5-meter-wide (110-foot-wide) chamber, a diagonal deflector manifold length of at least 61 meters (200 feet) is required. Design calculations (Paragraph 18-8) will indicate that a compressor of at least 21.2-m^3/min (750-ft^3/min) capacity must be available. No more than one manifold should be used at any one time.

b. Supply Lines.

(1) Pipes that run from a single, centrally located compressor to each end of the lock chamber must be large enough to handle the necessary air flow. One of the most common mistakes in designing an air system is undersizing the supply lines. Typically, at least a 7.6-centimeter-diameter (3-inch-diameter) schedule 40 pipe should be considered. If a supply length of over 152 meters (500 feet) is required, then a 10.2-centimeter (4-inch) pipe should be used for at least part of the total distance. Air control valves should be located at each end of the lock. Ideally, they should be remotely operated for easy use by the lock operator. The control valves allow the operator to selectively choose which air manifold to operate at any given time. An indicator should be provided to assure the operator that the valves are operating correctly.

(2) Supply lines from the control valves to the air manifolds submerged in the lock chamber vary in size, depending on the location of each manifold. The gate-recess flusher manifolds on the land wall require only a 5.1-centimeter (2-inch) pipe as a supply line (Figure 18-7). The gate-recess flusher manifold on the river wall, because of the added distance across the lock chamber to the manifold, needs to have at least a 7.6-centimeter-diameter (3-inch-diameter) supply line until the supply line reaches the far side of the lock chamber. The air screen going across the forebay sill requires at least a 7.6-centimeter (3-inch) supply line because of the volume of air being delivered (Figure 18-8). The location and placement of the supply lines may vary from lock to lock. It is best if the pipes can be located within the concrete walls, but if this is not possible, they should be located along the upstream edge of the gate-recess wall, protected from floating ice by steel plating.

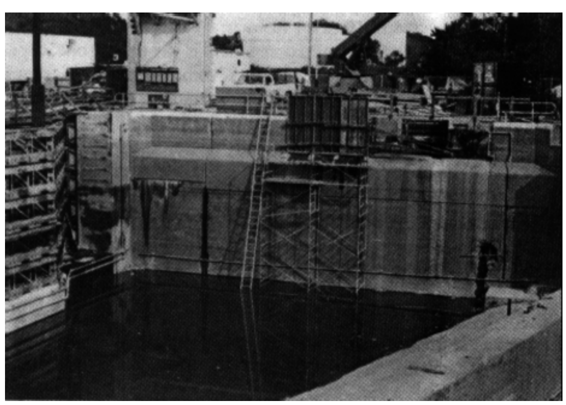


Figure 18-7. Flusher on the land wall of the upper gate recess composed of a supply line and manifold with orifices at Peoria Lock on the Illinois Waterway. *Note the vertical supply lines for the recess flusher of the river wall gate and for the cross-chamber air screen installed on the downstream-facing surface at the left (upper) end of the gate recess.*

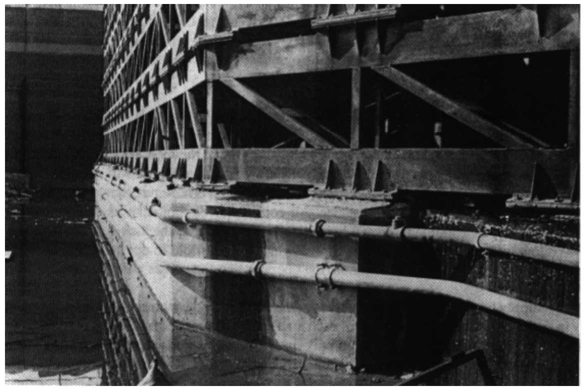


Figure 18-8. Downstream side of forebay sill, Peoria Lock.

c. Check Valves. At the bottom of the vertical leg of each supply line entering the lock chamber, an in-line, spring-loaded check valve should be installed to prevent water from passing into the manifold through the orifices, entering the supply pipe, and freezing near the water surface when the air lines are shut off. This check valve must be removable by divers for replacement or repair if required.

d. Manifolds. The manifolds for each of the systems vary with the number of orifices and the size of the pipe. The design of an air manifold should provide for an even and uniform air flow through its entire length. To achieve this goal, the total area of the orifices must be less than 25 percent of the cross-sectional area of the manifold.

e. Recess Flushers. The gate-recess flusher manifold differs from the other air manifolds because of the orifice spacing and pipe size. Laboratory and prototype analyses have shown that the spacing of the orifices should vary to provide more air near the quoin or pivot of the gate. The nominal spacings between orifices starting at the quoin end of the gate should be 1.2, 1.2, 1.2, 1.8, 2.4, 3, 3, and 3 meters (4, 4, 4, 6, 8, 10, 10, and 10 feet). The actual length of the manifold may vary because of lock constraints. Typically, in the locks on the Illinois Waterway, nine orifices are used.

f. Screens. The manifolds for the sill screens are designed with a 2.4-meter (8-foot) orifice spacing. For locks with a width of 33.5 meters (110 feet), a 29.3-meter-long (96-foot-long) manifold is used; 13 orifices are placed along that manifold.

g. Deflector. For a diagonal deflector in the upper lock approach area, a 61-meter (200-foot) manifold is recommended, with 26 orifices.

h. Orifices. Each orifice is a drilled hole in a hex-head stainless steel pipe plug, which is installed in a pipe tee in the manifold line. The inside of the plug is slightly chamfered, and there is a sharp edge at the outside surface. The orifices are aligned so that the air discharges vertically. Occasionally, the orifices might become plugged with silt, so the manifold should be regularly operated throughout the year to help the orifices remain free of dirt. The orifice diameter ultimately controls the amount of air discharged. From laboratory analysis, it is recommended that a design flow of 0.85 m^3/min (30 ft^3/min) be provided for each orifice. This will provide sufficient air to create the desired effect at the water surface. For all the systems installed on the Illinois

Waterway, 0.95-centimeter-diameter (3/8-inch-diameter) holes were drilled in the pipe plugs to serve as the orifices.

18-7. Effectiveness of the Air Systems

Experience gained from the use of complete high-flow air systems, as described above, has shown that the systems reduce winter lockage times, make for a safer operation, and keep the morale of lock personnel high. An average of 1 hour of compressor time is required to lock through an average tow. Some variation is experienced between individual operators, but all agree that a high-flow air system is an effective way to control floating ice problems at a lock (Figures 18-9 and 18-10).

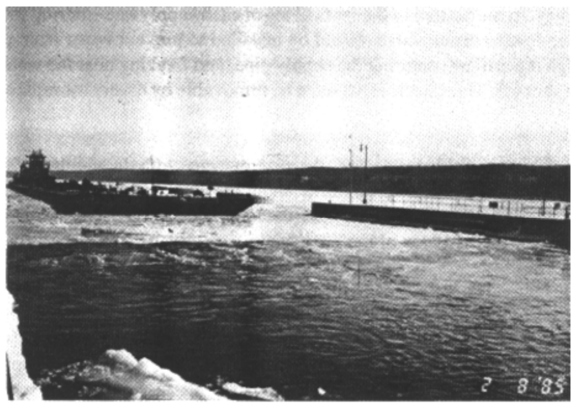


Figure 18-9. Upper screen in operation at Starved Rock Lock, Illinois Waterway.
Much brash ice is prevented from entering the lock chamber, even with the entry of downdbound tows.

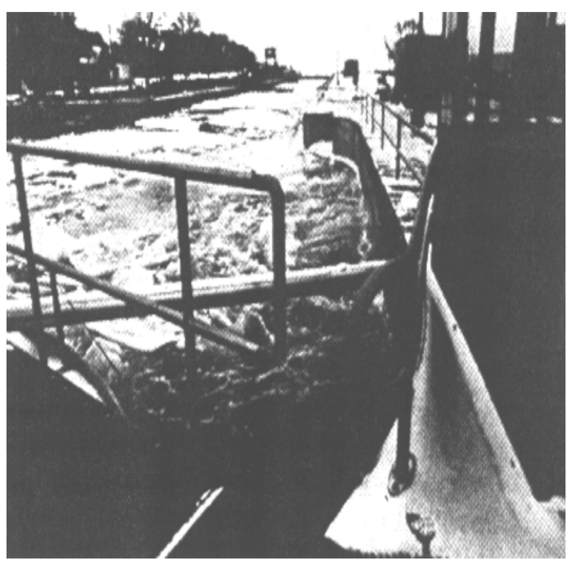


Figure 18-10. Gate-recess flusher in operation at Starved Rock Lock.
The ice is flushed away from the recess area, allowing the miter gate to be fully opened.

18-8. Design of a High-Flow Air System

The parameters affecting the design of a high flow air system include: air volume and pressure available; effective length and size of the supply line; length and size of manifold line; depth of submergence; and orifice size and spacing. The air system analysis determines air discharge rates from an orifice by an iterative scheme that starts with a trial dead-end pressure. The analysis calculates the orifice discharge and pressure, starting from the end and working toward the supply point. After all the orifices are analyzed, the supply line pressure and air flow are calculated. The compressor pressure and flow rate necessary to sustain the supply line pressure and air flow are then calculated. The calculated compressor output is compared to the actual compressor output. The trial dead-end pressure is then adjusted and the analysis scheme repeated until the calculated and specified compressor outputs differ by no more than 1 percent. Changes in system parameters are made until the optimum design is obtained.

a. The calculations for optimizing the air system parameters are provided below. The initial trial dead-end pressure (P_d) is taken as

$$P_d = P_w + \frac{(P_c - P_w)}{4} \tag{18-1}$$

where

P_c = true compressor pressure
P_w = $\rho_w\, g\, H$ = hydrostatic pressure
ρ_w = mass density of water
g = gravitational constant
H = submergence depth.

The subsequent trial dead-end pressure (P_d) is determined by

$$P_{d(new)} = P_w + \left(P_{d(old)} - P_w \right) \left(\frac{P_c - P_w}{P - P_w} \right) \tag{18-2}$$

where

P = calculated compressor pressure
$P_{d(old)}$ = old trial dead-end pressure
$P_{d(new)}$ = new trial dead-end pressure.

The air discharge rate (Q_o) from the orifices is calculated by the discharge equation

$$Q_o = C_d \frac{\pi d^2}{4} \sqrt{2\, \Delta P / \rho_a} \tag{18-3}$$

where

C_d = discharge coefficient, sharp-edged circular orifice

d = orifice diameter
ΔP = pressure difference between inside and outside of diffuser line
ρ_a = mass density of air.

Finally, the pressure drop attributable to friction between orifices and in the supply line (ΔP_f) is calculated using the friction loss equation for turbulent flow conditions

$$\Delta P_f = \frac{f \rho_a \ell v^2}{D 2 g} \tag{18-4}$$

where

f = friction factor
ℓ = equivalent length of pipe
v = air velocity
D = pipe diameter.

b. A computer program analyzing diffuser lines and nozzles gives a numerical simulation of air bubbler systems and is used for the air screen analysis. The input data include: diffuser line length and diameter, supply line length and diameter, orifice diameter and spacing, nominal compressor pressure, and submergence depth. The output from the program lists the following parameters: hydrostatic pressure, calculated output pressure, calculated compressor discharge, friction drop in diffuser line, friction drop in supply line, and excess dead-end pressure. To illustrate how changes in the system parameters affect the operating characteristics, Figures 18-11 and 18-12 show the effect on changes in the flow through an orifice with respect to changes in orifice diameters.

18-9. Example

A compressor with an output of 0.543 m^3/s (1150 ft^3/min) at 759 kPa (110 lb/in^2) was available for the high-flow air screen trials at the Soo Locks. Optimum air flow conditions could be obtained from a 5.1-centmeter-diameter (2-inch-diameter) manifold and supply line system with nozzles of 10-millimeter (0.40-inch diameter), spaced 3 meters (10 feet) apart. The manifold line was 5.1-centimeter (2-inch) galvanized pipe with 5.1- × 5.1- × 2.5-centimeter (2- × 2- × 1-inch) tee joints each 3 meters (10 feet) of pipe. A 2.5-centimeter (1-inch) stainless steel plug was mounted at each tee and each plug had a 10.3-millimeter (0.406-inch) hole drilled in it that acted as the nozzle or orifice. The supply line riser, which ran up the side of the lock, was also of 5.1-centimeter (2-inch) galvanized pipe. A flexible, quick-disconnect hose joined the bottom of the riser to the horizontal manifold line. Flexible hose was also used from the top of the riser to the compressor.

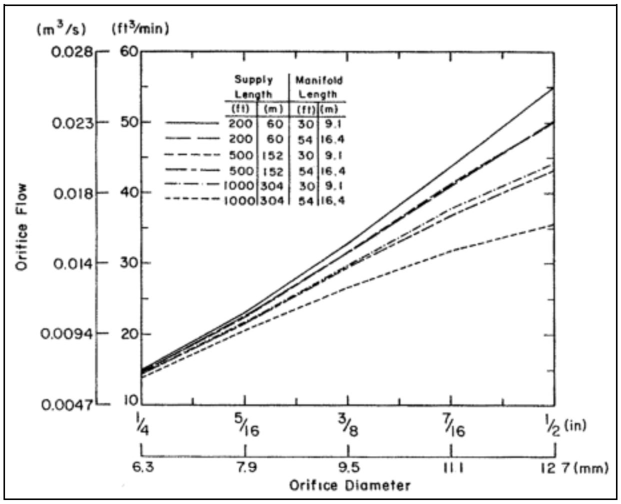


Figure 18-11. Performance curves for gate recess flushers, showing the average air discharge from each orifice plotted with respect to orifice diameter, for combinations of three supply-line lengths and at two manifold lengths. *The 5-centimeter (2-inch) diameter manifolds are either 9.1-meters (30-feet) nominal length for 17.1-meter (56-foot) wide locks, or 165-meters (54-feet) nominal length for 33.5-meter (110-foot) locks, submerged 6.1 meters (20 feet) below the water surface. Six orifices at nominal spacings of 1.2, 1.2, 1.2, 1.8 and 2.4 meters (4, 4, 4, 6, and 8 feet) are present in the 9.1-meter (30-foot) manifolds, and three additional orifices at nominal 3-meter (10-foot) spacings are present in the 16.4-meter (54-foot) manifolds.*

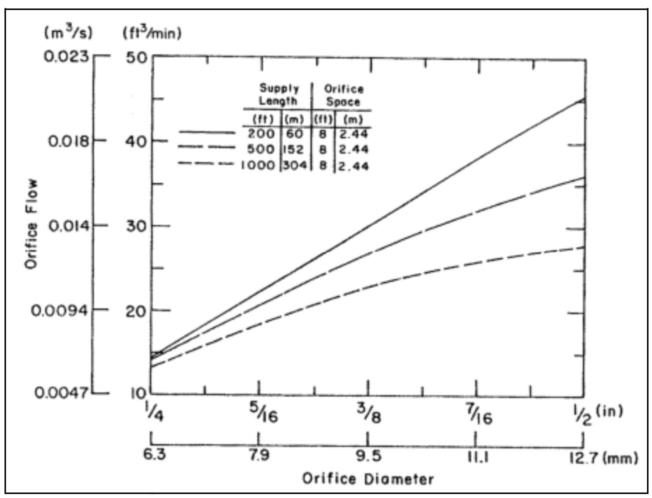


Figure 18-12. Performance curves for an air screen, showing the average air discharge from each orifice plotted with respect to orifice diameter, for three supply-line lengths. *The 6.4-centimeter (2.5-inch) diameter, 19.3-meter (96-foot) long manifold is typical for a 33.5-meter (110-foot) wide lock, and has 13 orifices at 2.4-meter (8-foot) spacings 6.1-meters (20-feet) below the water surface.*

a. The high-flow air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop-log gate sill. The sill is located about 61 meters (200 feet) above the lock gates. The riser line was installed in the stop-log recess in the wall. The width of the lock at this point is 33.5 meters (110 feet) and the height from the top of the sill to the top of the lock wall is 11.9 meters (39.2 feet).

b. The manifold line was installed at a depth of 10.5 meters (34.5 feet) in December 1977 and was assembled into four sections: two sections 8.46 meters (27.75 feet) long and two sections 7.47 meters (24.5 feet) long. Union connections joined the sections. The riser was assembled in one 11.7-meter (38.5-foot) section. The sections were light in weight; two to three people were able to move them by hand. All equipment for a hard-hat diver and the assembled pipes were placed on a 30.5-meter (100-foot) barge that acted as the working platform. The barge was positioned above the sill, and sections were lowered on ropes to the diver below who made the union connections and strapped the line to the concrete sill (Figures 18-13 and 18-14). One flexible hose coupling, from the diffuser to the riser, was also made underwater. The above-water installation process consisted of simply connecting a 15.2-meter (50-foot) flexible hose from the top of the riser line to the compressor. A 37,900-liter (10,000-gallon) fuel tank was placed beside the compressor to supply fuel (Figure 18-13) throughout the winter when delivery would be difficult.

Figure 18-13. Diver working to install air screen system.

c. The high-flow air screen was put into operation on 12 January 1978, when ice started to cause problems with lock operations. It was continuously available for service until 30 April 1978, except for a 5-day repair period in late March. By 1 May, ice no longer caused problems requiring the air screen, and the rented compressor was returned. During the 104 days of operation, the total running time on the compressor was 754 hours. Total consumption of No. 1 fuel oil was about 29,300 liters (7750 gallons).

d. The high-flow air screen demonstrated that it could hold back ice pushed ahead of downbound traffic. With ships in the 21.3-meter (70-foot) beam class, the ice was held back until the bow entered the air stream. The screen was not as effective with the wider 32-meter (105-foot) beam ships. Once the bow of a wider vessel passed the nose pier (about 40 meters [130 feet] upstream of the screen), the approach was just a little over 33.5 meters (110 feet) wide, so most of the ice remaining in the track was pushed into the lock by these larger ships. This problem possibly could have been solved by relocating the air screen upstream of the nose pier area and by providing some area for the ice to be pushed outside the vessel track.

e. The merits of the air screen cited by lock operating personnel, besides the reduction in vessel lockage time, were savings in wear and tear on the lock gate and operating mechanisms, and savings in the time and effort required to remove ice collars from the lock walls. (The ice collars at the Soo result in part from the vessels packing brash ice against the lock walls.)

18-10. Flow Inducers

A common technique to move ice in and around the lock is the use of a towboat's propeller wash to induce a flow that moves the brash ice. The towing industry assists itself and the Corps lock personnel on occasion; towboats break away from their tows and flush sections of a navigation project. Another type of flow inducer used in the past, a submergible mixer, develops a flow in the top layer of the water to aid in moving debris or floating ice. An example of this operation formerly existed at the Chicago Harbor Lock, where submergible mixers were attached near the sector gates. However, they have been removed. To prevent ice from accumulating in front of lock miter gates that are not functioning during the winter months, several Districts have made use of commercially available flow inducers designed for the marina industry for protecting docks. When ice is being locked, it is often difficult to flush brash from the area upstream of the filling and emptying ports. At the Soo Locks, this problem was solved by the construction of four 0.6-meter-diameter (2-foot-diameter) manifolds, located in the upper miter gates at the low pool level. With the chamber at low pool, the head differential creates surface jets that wash the ice downstream to an area where flow from the filling and emptying ports can move the ice the rest of the way out of the lock chamber.

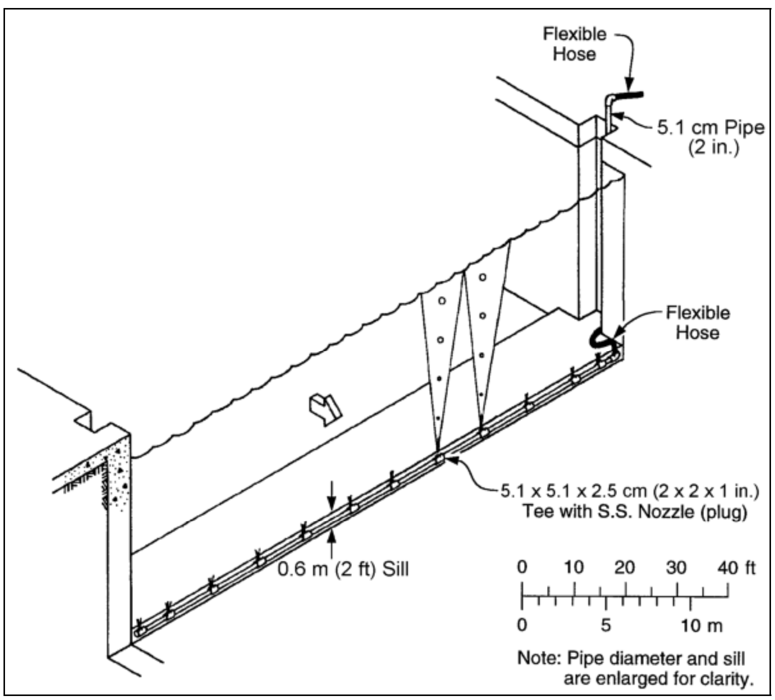


Figure 18-14. Schematic of an air screen.

Section III
Ice Passage Through Navigation Projects

18-11. Introduction

The question of holding ice or passing ice from one navigation project to the next is a subject of great concern on all river systems. A definitive position on this problem cannot be taken. It is clearly understood that growing a stable ice cover will reduce the overall quantity of ice grown because of the reduction in frazil generation. However, the broken ice within the frozen ship track has to be dealt with every time a vessel passes through. Just upstream of the locks is a particularly unfavorable spot to allow ice to accumulate. Almost every lockmaster will state that he wants to keep that zone above his lock clear. The specific policy, however, has to be addressed in each of the river systems.

18-12. Submergible Tainter Gates

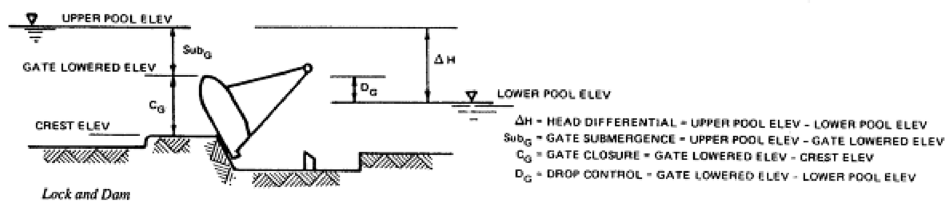
A case study of use of submergible gates at Corps projects was prepared by the Louisville District (U.S. Army 1985). Each of the project sites discussed in the study has a variety of dam gates. In the past, the use of submergible gates to pass ice in the former North Central Division was encouraged, whereas the former Ohio River Division did not allow the existing submergible gates to be operated. (These former separate divisions are now represented by the Great Lakes and Ohio River Division and by a portion of the Mississippi Valley Division.) The specific problems and comments regarding the varied use of submergible gates are well documented in the Louisville report. Figure 18-15 summarizes many of the submergible gates considered in the study. A 1989 rehabilitation project on the Illinois Waterway installed submergible gates at Marseilles Dam specifically for improving winter operations and ice passage. The major problem with passing ice is having sufficient water flow in the river system to open the gates, while maintaining adequate river stage. If broken ice is flowing toward the dam and the gates can be opened, a submergible gate will pass more ice than a nonsubmergible gate, given the same conditions. But it is more common that there is insufficient surface velocity to move ice toward the gate area. When this is true, the better ice passage characteristics of submergible gates provide no benefit. Moreover, ice bridging upstream of the gate, between the dam piers, is a common problem. However, a benefit of using submergible gates is that, because the gate is kept under the water, many gate freezeup problems are eliminated.

18-13. Roller Gates

Roller gates are used extensively on the Mississippi River. At most projects they are lowered to a fixed submerged setting in the late fall and are kept in that position for the duration of the winter. The pools are then maintained by adjusting tainter gates. At a few projects, the tainters are left to freeze in and the roller gates are adjusted, either submerged or with a bottom opening, to maintain upper pool stages. In the cases where the roller gates are used in the submerged mode in winter, they may assist in ice passage, functioning in the same manner as submergible tainter gates, but having the same limitations. Other problems associated with roller gates are largely related to the lifting mechanisms, in which ice interferes with lifting chains, guide channels, and gear racks. The side flanges of roller gates also tend to freeze to the concrete pier walls.

18-14. Conventional Tainter Gates

The openings required for ice passage at conventional tainter gates are usually quite large owing to the very high flow velocities needed to sweep floating ice downward to the bottom openings. As a result, except during periods of flood flow, these large openings normally cannot be used because of the likelihood of downstream scour at low tailwater stages. Thus, during the customary low-flow conditions of the winter season, ice passage at these gates is not feasible.



Lock and Dam (COE District)	*River*	*ΔH*	*Sub_G*	*C_G*	*D_G*	*Problem*	*Remarks*
Greenup (Huntington)	Ohio	32.0	7.0	28.0	25.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated, plans and specs for modification as of Dec 1978
Meldahl (Huntington)	Ohio	30.0	7.0	28.0	23.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated
Markland (Louisville)	Ohio	34.0	7.0	33.0	27.0	Yes	Problem: vibration and jet through stilling basin and across end sill Solution: gate stops added and spillway curve modified. Submerged operation eliminated
McAlpine (Louisville)	Ohio	37.0	7.0	12.0	30.0	Yes	Problem: bed-material abrasion of sill Solution: submerged operation eliminated, spillway curve modified
Cheatham (Nashville)	Cumberland	26.0	7.0	19.0	19.0	Yes	Problem: vibration Solution: submerged operation eliminated, design and modification being considered
New Cumberland (Pittsburgh)	Ohio	22.6	7.0	12.5	15.6	Yes	Problem: vibration, cavitation between gate and sill, and recreational craft hazard Solution: submerged operation eliminated
Pike Island (Pittsburgh)	Ohio	21.0	7.0	20.0	14.0	Yes	Problem: excessive leakage Solution: submerged operation eliminated
L&D no. 4 (Pittsburgh)	Monongahela	16.6	7.0	12.5	9.6	No	Movable crest or piggyback gate
Maxwell (Pittsburgh)	Monongahela	19.5	7.0	19.0	12.5	No	Movable crest or piggyback gate
L&D no. 11 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	13 gates
L&D no. 12 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	7 gates
L&D no. 13 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	10 gates
L&D no. 16 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	3 of 15 gates
L&D no. 17 (Rock Island)	Mississippi	8.0	8.0	8.0	0.0	No	8 gates
L&D no. 18 (Rock Island)	Mississippi	9.8	5.0	15.0	4.8	No	14 gates
L&D no. 20 (Rock Island)	Mississippi	10.0	3.0	17.0	7.0	No	6 of 40 gates
L&D no. 21 (Rock Island)	Mississippi	10.5	8.0	12.0	2.5	No	10 gates
L&D no. 22 (Rock Island)	Mississippi	10.5	8.0	17.0	2.5	No	1 of 10 gates
L&D no. 24 (St. Louis)	Mississippi	15.0	8.0	17.0	7.0	Yes	15-80 ft TG's, vibration, stress on trunion; submerged operation eliminated
L&D no. 25 (St. Louis)	Mississippi	16.0	7.0	18.0	9.0	Yes	14-60 ft TG's, vibration stress on trunion; submerged operation eliminated
L&D no. 26 (St. Louis)	Mississippi	24.0	3.0	27.0	21.0	No	30-40 ft TG's

Figure 18-15. Summary of submergible gates and their problems. *Many of these were considered in the Louisville District study of the use of submergible gates for passing ice (U.S. Army 1985).*

18-15. Gate Limitations in Winter

As detailed in Chapter 14, Paragraphs 14-4*g* through *i*, successful operation of dam gates in winter, regardless of types, is impeded by accumulated ice in the upstream pool, by ice buildup on gate and piers from spray and splashing, and by the freezing of leakage past gate seals. All of these factors combine to render ice passage through gate bays very difficult and unreliable, unless remedial measures, as discussed in the following, are employed.

18-16. Other Ice Passage Schemes

Ice can be successfully passed at some navigation locks having auxiliary lock chambers and bulkhead lift systems by skimming the ice over partially raised bulkheads. Figure 18-16 shows such an operation. This is an effective way to pass ice through the lock system, thus clearing the upper approach area.

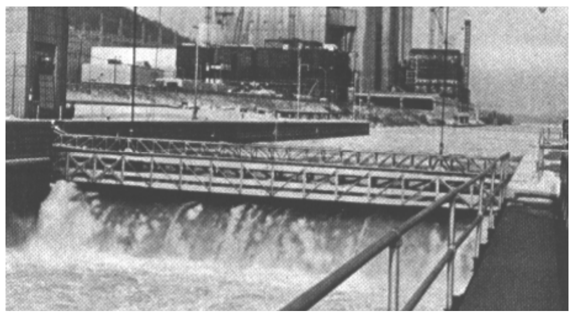


Figure 18-16. Ice passage at New Cumberland Lock on the Ohio River. *Raising the top bulkhead of the auxiliary lock chamber allows flow to carry ice out of the lock approach area.*

Section IV
Anti-Icing and Deicing at Navigation Projects

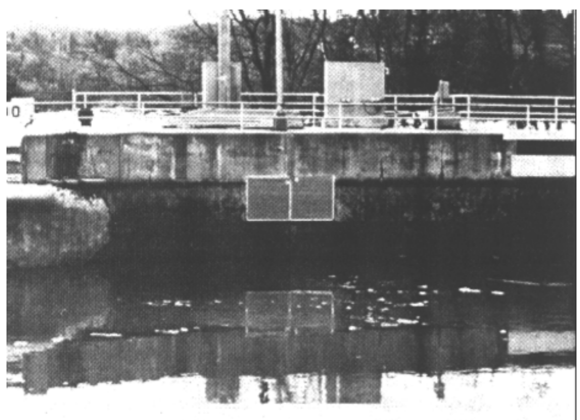
18-17. Introduction

As described in Chapter 14, the ice-related problems at navigation structures are severe during the winter months. Exposed mechanically operated systems may be frozen-in and become inoperable. The weight of ice formed on structures that need to be lifted or moved may become excessive so that the system becomes overloaded. Ice loads can also cause structural damage. Icing on the recess walls or gates of navigation locks prevents full opening of the gates. Ice formation on the chamber walls prevents full use of the lock width. Ice buildups on dam pier walls can obstruct the movement of the components of dam gates. Ice in any form causes safety hazards for personnel working on or near it. All of these ice problems involve ice formation on or adhesion to critical surfaces at locks and dams. Solutions to these ice problems at navigation projects currently are time-consuming and expensive. This section addresses several approaches to solving the problems of surface ice formation and adhesion.

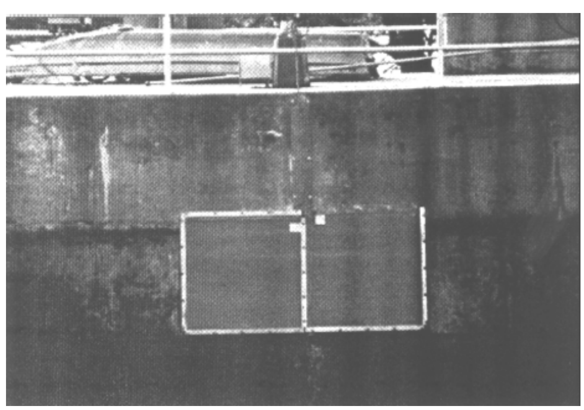
18-18. Electrical Heating of Lock and Dam Components

Ice adhesion on walls can be prevented by maintaining wall temperatures above 0°C (32°F), or ice collars can be shed periodically by raising the wall temperature intermittently. Possible arrangements include embedded (but removable) electrical heating cables within walls, direct placement of heat mats on walls, and heating dam gate side J-seals.

a. Embedded Electrical Heaters. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended.* Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. The recommendation for those areas where embedded heaters are needed is a replaceable heat tape as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 1.9-centimeter-diameter (3/4-inch-diameter) stainless steel pipes should be installed, 15 to 20 centimeters (6 to 8 inches) on center, with the bottom ends sealed. At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes are filled with glycol to act as a heat-transfer fluid, once the self-regulated heat tape is inserted into the pipe. The heat tape can be cut to specific lengths by project personnel and inserted into the pipe. The heat tape is self-regulating and has an output of 121 W/m at 0°C (37 W/ft at 32°F). In the control circuit, timers and thermostats can be added to limit power consumption. If a heat tape fails, then a new length of heat tape may be cut and installed. The cut end should be sealed using heat-shrink tubing, and a cold electrical lead is added to the upper end. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 7.5 to 10 centimeters (3 to 4 inches) deep in the wall.



a. General view.



b. Detail showing plate over vertical groove in wall (containing electrical leads) above heat mats.

Figure 18-17. Fiberglass-reincorced plastic heat mats installed on a miter gate recess wall at Starved Rock Lock on the Illinois Waterway.

b. Wall Heat Mats. Fiberglass-reinforced plastic heat mats have been placed directly on a vertical concrete wall at a lock to prevent ice from forming a collar in the gate recess area. The commercially available mats can be provided in any shape or size up to 1.2 × 2.4 meters (4 × 8 feet). Variable power ratings are also available. The mats shown in Figure 18-17 are 1076 W/m^2 (100 W/ft^2). These panels are each 1.2 × 1.2 meters × 0.6 centimeters (4 × 4 feet × 1/4 inch) thick. The mats are very effective in keeping the wall clear of ice. Material costs (1988) for such a mat material were about $753/m^2 ($70/ft^2).

c. Heated J-seals on Dam Gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold No. 3493 or equivalent).

(1) This in situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces, thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor “cindering” (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a recent dam rehabilitation.

(2) The self-regulating heat trace tape, 208 volts ac at 121 W/m at 0°C (37 W/ft at 32°F), was cut from a spool to a length of 5.5 meters (18 feet). The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal and the inserted heater are shown in Figure 18-18. The 1988 cost of Huntington J-seal Mold No. 3493 was $45.57/meter ($14.50/foot). The seal was manufactured as of 1988 by Buckhorn Rubber[*], The self-regulating heat trace tape is widely available at an approximate 1988 cost of $16.40/meter ($5/foot). If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is $2.24, assuming 1332 watts at $0.07/ kWhr.

(3) Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

[*] 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454).

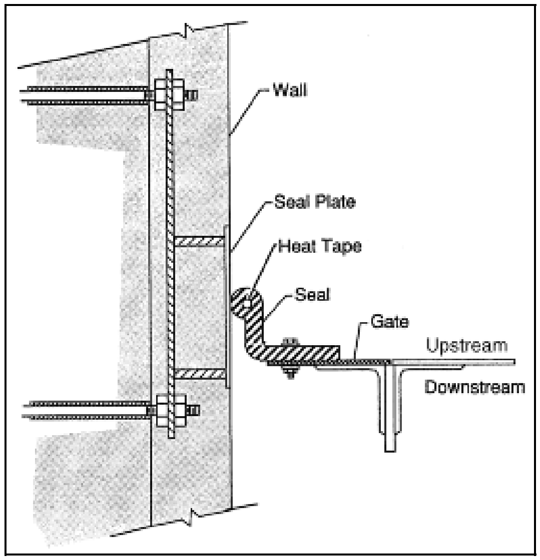


Figure 18-18. J-seal installation on a tainter gate

18-19. Providing Electricity for Heating to Locks and Dams

Electricity for the heating and deicing of lock and dam components can be supplied by the local electric utility. But since such energy is usually expensive, lower-cost sources of electricity are attractive. Two such alternatives are private hydropower projects installed at Corps navigation projects and, possibly, pre-packaged portable hydropower plants.

a. Installed Private Hydropower. It is the policy of the Corps of Engineers to cooperate with the Federal Energy Regulatory Commission in encouraging private interests to develop hydropower potentials at Corps navigation or flood-control dams. In these cases, the Corps usually has rights to certain portions of the power generated at no cost, as long as it is used for the benefit of navigation. In planning for use of this power, it is recommended that the power needs for ice control be considered and that the total power requirements for navigation be conveyed to parties exploring the feasibility of such private hydropower development.

b. Portable Prepackaged Hydropower. In those cases where private power development is not present or not likely to be developed, the use of dedicated, portable, packaged hydropower units as described below (if they are commercially available) should be investigated and compared to purchased power for meeting the needs of ice control at navigation locks and dams.

(1) A study conducted by the University of Iowa during the River Ice Management Program (Nakato et al. 1992) endorsed electrical heating as an attractive method for controlling ice, and suggested consideration of using a then-unconventional means of generating electricity on-site: prefabricated, portable, packaged power plants. The study described a concept in the development and demonstration stage (in 1988) for low-head micro-hydroelectric power plants. These packaged plants were of two sizes: one producing 500 kilowatts at a net head of 5.5 meters (18 feet) and a discharge of 11.3 m^3/s (400 ft^3/s), and the other a 1250-kilowatt unit operating with a 3.7-meter (12-foot) head and 42.5 m^3/s (1500 ft^3/s). These plants gain their portability by being barge-mounted. There is an anchored upstream barge providing the water intake, a siphon penstock, and a downstream barge that carries a submergible horizontal turbine. Trunnion-type

joints accommodate variations in upper and lower pool stages. There is no major construction involved for these devices to be installed; they can be placed in a variety of dam configurations, for example, in a gate bay of a navigation dam.

(2) Micro-hydroelectric power-plant output potentials, expressed in combinations of discharge, net head, and resulting power output, are listed in Table 18-1.

Table 18-1
Output Potential of Micro-hydroelectric Power Plants

Discharge m^3/s (ft^3/s)	Power Output (kW) (at 80% efficiency) at Net Heads of:			
	1.5 m (5 ft)	3.0 m (10 ft)	4.6 m (15 ft)	6.1m (20 ft)
7.1 (250)	85	170	255	340
14.2 (500)	170	340	510	680
28.3 (1000)	340	680	1015	1355
42.5 (1500)	510	1015	1525	2035
56.6 (2000)	680	1355	2035	2710

18-20. Mechanical Removal of Ice from Lock Walls

a. General. The experimental extension of the navigation season into the winter months on the Great Lakes created ice problems at the Soo Locks. Even under present operating-season schedules, ice poses many problems at the Soo Locks, as well as at many of the lock-and-dam projects on the Ohio River and its tributaries, on the Illinois Waterway, and on the Upper Mississippi River. Ice can adhere to lock walls, building up an ice collar at and below the high pool level, which can interfere with gate opening and closing and interfere with ship passage. For example, ice collars form at the 33.5-meter (110-foot) wide Poe Lock at Sault Ste. Marie, Michigan. Ships of the *Presque Isle* and *Roger Blough* class with their 32.0-meter (105-foot) beams encounter problems when the ice buildup along the walls becomes greater than 0.76 meters (2.5 feet) on each wall. Prior to the development of the ice cutting saw, discussed below, and the copolymer coating (discussed later in paragraph 18-19*a*), a number of methods were used with varying degrees of success to overcome this problem. Steam hoses work well but are extremely slow and require many man-hours. Backhoes have been used to scrape off the ice collar. This is faster then using steam, but still slow. Since the operator cannot see what he is doing he may miss some ice or scrape too deep and damage the lock wall. A high pressure water jet was able to cut off the ice, but the jet was noisy and somewhat dangerous, and the pressure pump was both expensive and difficult to maintain. The best solutions found to date used a copolymer coating, and an ice cutting saw. The ice cutting saw is discussed here.

b. Ice Cutting Saw. CRREL adapted a Bowdil coal saw (see Figure 18-19) to remove the ice collars (Garfield et al. 1976). The unit consisted of two parts: the cutting system, and the drive and propulsion system. The drive and propulsion system was a 48.5-kilowatt (65-horsepower) four-wheel-drive tractor, originally manufactured as a trencher (the tractor could be purchased without the trencher attachment). The drive line for the trencher was modified to accommodate the cutting system by extending the drive shaft and attaching a drive sprocket to its end. While in the cutting mode, the engine powered the shaft and sprocket directly and the drive wheels indirectly through a separate hydraulic drive system, so cutting power and propulsion power could be independently controlled. The system was deemed conditionally acceptable, with ice-collar cutting speeds in the range of 1.8 to 3.6 meters/minute (6 to 12 feet/minute).

Figure 18-19. Ice cutting saw at Poe Lock.

18-21. Surface Treatments to Reduce Ice Adhesion

There is a long history of study in this area for a variety of applications, but surface treatments that shed ice reliably and repeatedly have not yet emerged. The only chemical treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repetitive application of sodium chloride or calcium chloride. Another ice-control method is a permanent or semipermanent chemical coating that reduces the adhesive force between the coated surface and the ice that forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier. As an alternative to coatings to reduce ice adhesion, cladding surfaces with materials that shed ice more easily than concrete may be considered.

a. Copolymer Coatings. One successful material is a long-chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that have been tested is a solution of polycarbonatepolysiloxane compound, silicone oil, and toluene. The mixture is highly volatile and leaves a thin coat of the copolymer and silicone on the surface to which it is applied.

(1) The copolymer coating was not to be applied to a concrete surface unless it was certain that the concrete behind the coating could resist frost action in a critically saturated condition. Proper application guidance for surface coatings to concrete can be found in *Maintenance and Repair of Concrete and Concrete Structures,* EM 1110-2-2002. The surface to be coated must be clean and dry. For concrete and metal surfaces (bare and painted), steam cleaning is sufficient; however, a detergent may be added to the water of the steam cleaner. This was done, for example, in one case where navigation lock walls were heavily coated with oil and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system (Figure 18-20). A single pass will deposit a coat 25 to 51 micrometers (1 to 2 mils) thick. Three coats are recommended for a coating thickness of about 127 micrometers (5 mils). Achieving this final thickness requires about 24.4 liters/100 m^2 (6 gallons/1000 ft^2).

Figure 18-20. Application of copolymer coating.

(2) Care has to be taken when mixing the solution. Toluene is a combustible material, so no electrical motor-driven mixer should be used. An air-operated drill motor fitted with a rod with mixer blades has worked satisfactorily. The fumes may also be a health hazard, so that a well-ventilated mixing area should be used. A 208-liter (55-gallon) drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 151 liters (40 gallons) can easily be handled. The liquid portions, toluene and silicone oil, are placed in the container first. Then the mixer is started and the copolymer powder is slowly added. Mixing continues until all solids are dissolved. Then the solution can be transferred to a storage container.

(3) Tests to determine the merits of an undercoating for the copolymer (on concrete surfaces that are worn and rough) show that an epoxy-type coating that acts as a filler over the rough concrete provides a better surface to which the copolymer adheres. Trials of the undercoating and copolymer were done at the Poe Lock, at the St. Marys Falls Canal, at Sault Ste. Marie, Michigan, at Lock No. 4 on the Allegheny River, and at the Starved Rock Lock on the Illinois Waterway. Maintenance and frequency of recoating requirements were monitored. The coating remained in good condition for at least three years.

b. Epoxy Coatings. Commercially available two-part epoxy coatings, which can be applied in wet environments, have been tested for ice-phobic characteristics. Several of these coatings perform equally as well as the copolymer coating. They are far more durable because they are an epoxy resin and a polyamine-based curing agent. The epoxy coating gives concrete ideal protection against the ingress of chloride ions, carbon monoxide, and other corrosive agents over the design life. The hard, smooth finish provides a very low friction coefficient, thus reducing the bond strength between ice and substrate.

c. Claddings. Cladding of wall surfaces by materials that shed ice easier than concrete is another approach to solving the problem of ice adhesion. In a demonstration at Starved Rock Lock in Illinois, a 1.2- × 2.4-meter × 1.2-centimeter-thick (4- × 8-foot × 1/2-inch-thick) sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 0.5 meters (20 inches) on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about \$75/m^2 (\$7/ft^2).

18-22. References

a. Required Publications.

None.

b. Related Publications.

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