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Ice Engineering

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire

Advances in Icing Control at Corps Hydraulic Structures

Adhesion of ice to surfaces creates problems for many industries, including hydropower and navigation. At present, ice removal techniques are costly, hazardous, and time-consuming. Andersson and Andersson (1992) reported that at one hydropower station in Sweden, ice-related costs averaged $0.2 million per year over a 10-year period. At Corps of Engineer projects, annual maintenance costs resulting from ice problems were estimated to be $33 million in 1992 (Haynes et al. 1993). Recent advances in deicing and anti-icing technologies have been evaluated in the laboratory and the field to assess their applicability for use at hydraulic structures operated by the U.S. Army Corps of Engineers. At Corps projects, considerable resources are expended annually to keep ice off steel and concrete structures to maintain operations through the winter months. Comparisons of the performance of these new technologies with current practice are given herein.

Heat panels

Heat has been used to control icing at hydraulic structures for years. Typical methods include steam lances, heat tracing embedded in concrete walls, and mineral-insulated (MI) heaters installed under steel side-seal rub plates. Though these have proven effective, they all have demonstrated limitations. Steam lances pose the same problems as pike poles and other manual methods in that they are very labor-intensive and slow, and frequently place personnel in hazardous locations on the lock or dam. Using heat tracing to place heat where it is needed is desirable, but the practice of embedding heat tracing in concrete typically provides only a very short-term benefit because the heaters burn out relatively quickly and cannot easily be replaced.

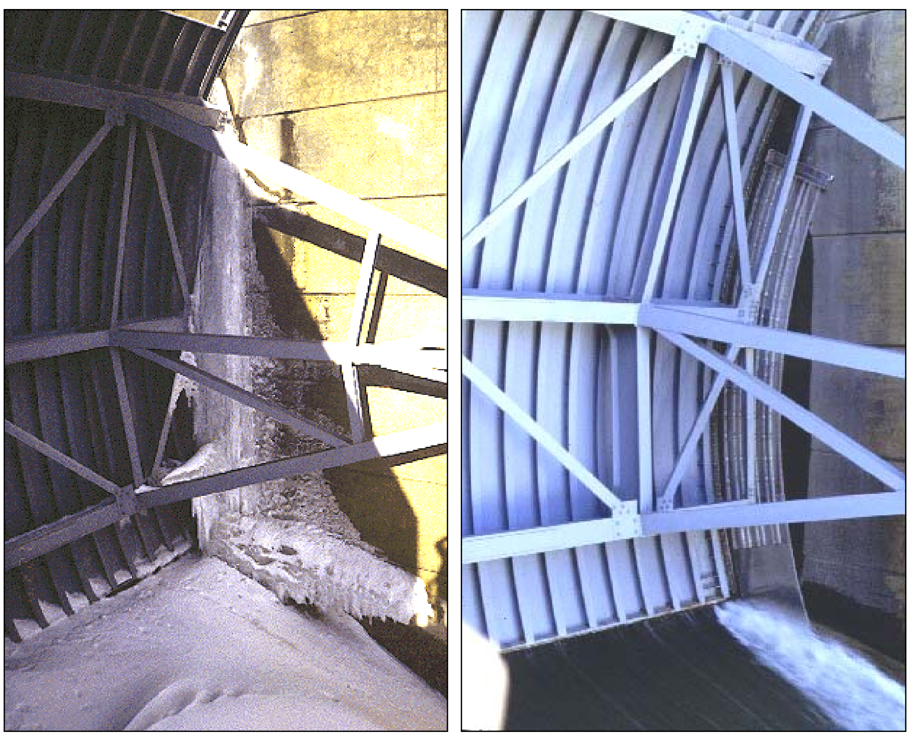

Figure 1. Icing on a tainter gate at Gavins Point project, Yankton, South Dakota, prior to heater panel installation (left) and after installation on the pier wall (right) showing the panel's outer covering removed. (Parallel white lines are troughs for the heater tracing.)

Placing side-seal rub plate heaters that have replaceable electric elements on dam gates was beneficial, but the limited area that was heated did not entirely prevent the gates from freezing shut. For example, Figure 1 shows ice accumulation on the downstream side of a tainter gate at the Gavins Point project in Yankton, South Dakota. These gates have heaters to prevent the side seal from freezing to the steel rub plate. However, because the surrounding concrete is a poor heat conductor, the heat from the 10-kW elements remains confined to the vicinity of the rub plate. Thus, water leaking by the side seal freezes and then bridges the gate and pier wall, freezing the gate solidly in place. To prevent the gate from freezing, the heater needs to extend over an area large enough to melt most, if not all, of the ice from the wall and gate. The enclosure for the heater must have high conductivity (e.g., aluminum) so that the heat is distributed uniformly over the area. Furthermore, provision for easily replacing failed heater elements must be designed into the enclosure. The heaters could be turned on in the fall and thermostatically controlled throughout the winter.

The first proof-of-concept heater panel was installed in 1993 on a miter gate recess on Starved Rock Lock and Dam at Ottawa, Illinois. Self-regulating heat cable was installed in this 0.91-m (3-ft) × 2.4-m (8-ft) aluminum panel. This initial design proved to be robust and successfully kept a protected portion of the wall ice-free throughout the winter (Haynes et al. 1997). Figure 1 shows an aluminum heater panel installed in 1997 at the Gavins Point project.

A similar heater panel was installed in 2001 on the spillway gates of the Turner Falls project, Montague, Massachusetts (Haehnel 2001). For both the Gavins Point and Turner Falls projects, ice formation on the pier wall and gate was a persistent problem caused by water leaking past the tainter gate side seal, making the gate inoperable.

At the Heywood Generating Station, St. Catherines, Ontario, Canada, the submerged tainter gates freeze in place because of frazil ice accumulation in the upstream bypass channel. In this case, heaters installed on the gate face and sides were needed to keep the gate from freezing in place. In this design, the heaters were protected by steel enclosures that were an integral part of the gate. Table 1 summarizes the details of these three installations.

Table 1. Summary of heater panel installations.

Location	Year installed	Heater type	Total power per gate *(kW)*	Approximate power density *(kW/m²)*
Gavins Point Yankton, South Dakota	1997	MI	16	0.7
Heywood Station St. Catharines, Ontario	1998	MI (immersion-type)	40	4.4
Turner Falls Montague, Massachusetts	2001	MI	16.8	0.57

Electrolytic shedding

Recent work (Petrenko and Qi 1999, Petrenko and Courville 2000, Haehnel et al. in review) shows that low DC voltages applied through ice can cause it to release by electrolytic decomposition of the ice. Laboratory experiments show that as few as six volts cause the ice to separate into atomic oxygen and hydrogen. These gases coalesce into bubbles at the electrode, and over time the bubbles cover a significant portion of the ice–substrate contact area. Given sufficient time, all of the ice in contact with the substrate is completely converted to gas and the bond is eliminated. Petrenko and Qi (1999) and Haehnel et al. (in review) found that with a voltage application of only one minute, the ice bond strength to stainless steel could be reduced by 60–80% or more. Figure 2 shows an electrode configuration used to remove ice from a flat surface (Petrenko and Courville 2000).

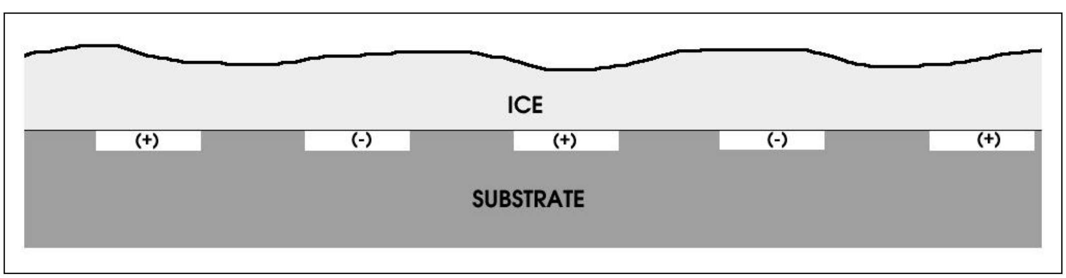

Figure 2. Electrode configuration used for removing ice from a flat surface by electrolysis.

This technology relies on the conductivity of the ice to complete the circuit between the two electrodes. For saline ice, the conductivity is quite high, and the electrode spacing can be quite large (1 cm or more). As the purity of the ice increases, its conductivity declines and electrode spacing must be reduced, or the applied voltage increased, for the electrolyzing circuit to be completed. Haehnel et al. (in review) found that, for ice formed from Mississippi River water, the electrode spacing needed to be as small as 0.51 mm (0.020 in.). Using an electrode spacing of 100 µm, Petrenko and Courville (2000) were able to produce the effect in pure ice; in these experiments micro-grids had to be transferred onto an insulating substrate using printed circuit board techniques. Table 2 provides a comparison of the power requirements to produce electrolysis in these experiments.

Table 2. Power requirements for electrolytic shedding with various electrode spacings and water types.

	Water type	Applied voltage *(VDC)*	Electrode spacing *(cm)*	Power density *(kW/m²)*
Petrenko and Qi (1999)	Saline 0.5%	21	1	0.7
Haehnel et al. (in review)	Saline 0.1%	20–30	0.25	3
Haehnel et al. (in review)	Mississippi River	20–60	0.051	3–6
Petrenko and Courville (2000)	Pure	10–30	0.01	0.2–0.8

Haehnel et al. (in review) observed corrosion of their stainless steel electrodes as a result of the electrolytic process, which was more pronounced when saline ice was tested. Petrenko and Courville (2000) were able to eliminate corrosion by plating their electrodes with gold. Future work requires developing robust micro-grid systems that can withstand the rigors of abrasion and impact in a field application.

Electro-expulsive shedding

Another method for shedding ice—electro-expulsive separation or EES—applies a short burst of current (approximately 3 ms in duration) in opposite field directions through adjacent conductors (Embry and Friedman 1989, Haslim and Embry 1989). This produces opposing electromagnetic fields in the conductors, rapidly forcing them apart. The conductor configuration can be enclosed within low-profile, flexible panels and mounted on a surface needing protection from ice buildup. Ice that accumulates on the panel surface is fractured and released when the panel skin flexes. The burst of current is provided from a bank of capacitors, which are charged to approximately 500 V and then rapidly discharged into the copper foil conductors, expanding the blanket and shattering the ice. This cycle can be repeated until all of the ice is completely removed from the EES blanket. It has been used for deicing ship hatch covers and removing ice from the leading edge of airplane wings. Power consumption for the EES system is on the order of 700 W/m^2 (during the 15 seconds it takes to charge the capacitors) and has successfully dislodged ice accumulations up to 4–5 cm thick (Embry and Friedman 1989). At present, the durability of this system for hydraulic structures is unknown.

Laboratory tests at CRREL evaluated the use of an EES system to shed ice grown on a vertical lock wall. In these tests a 1.22-m × 1.04-m flat EES panel was mounted to a concrete wall on one side of a 2.48-m-long × 0.89-m-wide × 1.22-m-deep chamber located in a coldroom (air temperature maintained at –10°C). Water was pumped into and out of the chamber to simulate the cyclical wetting and freezing on a lock wall. These tests showed that the EES panel was effective at removing a 2.5-cm-thick ice layer and an accompanying ice collar from the wall. Four cycles of the EES system were required to completely remove all of the ice from the panel. Figure 3 shows the initial ice accumulation on the panel, and the panel clear of ice after cycling the system the fourth time.

As part of these laboratory tests we also tried to remove the ice from the wall with the EES panel submerged under water. In these tests we found the ice did not separate from the panel, and the water rendered the EES completely ineffective.

Thus, this system would work only when the ice is in air (e.g., EES panels would not work on ice frozen to the upstream skin plate of a dam gate).

The EES panel has been deployed at Lock and Dam 25 on the Mississippi River for field trials and evaluation during the winter of 2001–2002.

Figure 3. Shedding ice using electro-expulsive separation (EES). Initial ice collar on the EES panel (black) is shown at left, the panel clear of ice after four cycles is shown at right. The panel measures 1.2 m wide and 1.0 m tall.

Efficiency of electrical methods

Table 3 gives a comparison of the systems discussed in this report, namely heaters, electrolytic shedding, and electro-expulsive separation. Though heated trash racks were not discussed previously, for comparison we included in Table 3 the performance of trash rack heaters (obtained from the literature).

Table 3. Power and energy requirements for complete removal of ice using various methods applied to different applications.

Method	Power *(kW/m²)*	Energy *(kJ/m²)*	Approximate reponse time *(min)*
Conventional heaters			
Heater panels on riverine structures (in air)[a]	0.6–0.7	540–630	15
Heater panels on riverine structures (immersed)[b]	4.5	3,900	15
Trash rack heaters (immersed)[c]	2–6.7	—	Used in continuous anti-icing mode
Electrolysis			
River water[d]	3–6	300–3,000	3–8
Saline ice[d, e]	0.7–3	40–540	1–3
Pure ice using micro-grid electrodes	0.2–0.8	12–48	1
Electro-expulsive			
Lock wall panel (present work)	0.7	75	18

[a] Haynes et al. 1997, Bockerman and Wagner 1998
[b] Haehnel and Clark 1998
[c] Ruths 1924, Samsioe 1924, Reid 1928, Logan 1974, Billfalk 1987, Daly et al. 1992
[d] Haehnel et al. in review
[e] Petrenko and Qi 1999
[f] Petrenko and Courville 2000

Table 3 shows that, in general, the power requirement is the same for all of these systems, with the systems operating in air requiring 0.2–0.8 kW/m^2. Systems that operate under water (immersed) have power requirements about an order of magnitude higher. Of greater concern to operators, because it affects annual operational costs, is the energy consumed to remove the ice. In this case we see a much broader separation in performance, with EES and electrolytic systems consuming a fraction of the energy needed to operate conventional heaters. Another factor of great concern to operators is how quickly the ice can be removed to restore their facilities to full service (response time). Here again there is little separation in these methods, recognizing that a response time as long as 20 minutes is acceptable in most cases. We note that trash rack heaters must be operated in continuous anti-icing mode to prevent ice from forming at all, otherwise they are ineffective at keeping the trash racks free of ice.

Conclusions

Electrolytic and electro-expulsive (EES) deicing methods show great promise in removing ice quickly while reducing energy consumption by one to two orders of magnitude in comparison to conventional electric heaters. Future work will be needed to engineer these technologies for potential application at navigation and hydroelectric structures. They must be made to fit the areas and components that need protecting, and they must be hardened to withstand rigorous field conditions. CRREL is conducting field tests of an EES prototype panel during the 2001–2002 winter season.

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