Accelerated Fresh Water Corrosion Study & Remediation of Steel Structures

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Abstract

Sheet pile and other steel structures installed in the Duluth, Minnesota and Superior, Wisconsin shared harbor are corroding at an accelerated rate compared to other Great Lakes harbors and ports. The harbor is located on Lake Superior and fed fresh water by the St. Louis River. Originally discovered in 1998, the cause and potential solutions to the phenomenon have been investigated through a series of studies that carry on through today. An expert panel convened in 2004 to make an initial assessment of the extent and cause of the accelerated corrosion as well as make recommendations for future testing necessary to identify and resolve the problem. Subsequent studies based on panel's recommendations have 1) determined the extent and rate of corrosion on steel structures in the Duluth / Superior Harbor (DSH) and established a long term corrosion rate monitoring program, 2) determined one possible cause directly influencing the accelerated corrosion through extensive biological testing, 3) established long term testing of coating and cathodic protection systems including the study of different coating's abilities to resist ice impact and abrasion experienced in cold region waters, 4) initiated long term full scale testing of alternative pile protective systems designed for cold regions, and 5) have shown that the accelerated corrosion is not only isolated to the DSH and has been found in other ports, harbors and small marinas within the confines of Lake Superior. Results from protection systems testing to date have identified several attractive coating and alternative protection systems that have showed to be resistant to ice impact and abrasion while preventing further corrosion of the steel structures. Future plans include the continued monitoring of existing long term tests as well as the initiation of further coating and alternative technology trials. Results of all trials will be published for utilization in the DSH and other cold region harbors.

Background

In 1998, it was discovered that many marine structures in the DSH were experiencing significant corrosion and pitting levels higher than typically experienced in fresh water harbors. The problem was especially pronounced in areas around 0.5 to 3 meters (1 to 10 ft) below the surface. In 2003 the Accelerated Freshwater Corrosion Study Team was formed to make recommendations how to further investigate the findings of preliminary observations, and to ultimately determine the cause and potential solutions for the control of the accelerated corrosion problem.

In fall of 2004, a panel of corrosion experts was brought to the DSH by the study team with the financial support of numerous federal, state, local, and private agencies to view the accelerated corrosion and recommend further action items. The panel made recommendations on both short and long term testing necessary to:

1. Investigate the extent of harbor steel corrosion, especially on critical structures.
2. Determine corrosion rates and establish a corrosion rate monitoring program.
3. Identify the cause of the accelerated corrosion.
4. Develop standard replacement designs using coatings and cathodic protection.
5. Test or develop alternative protective or repair systems for existing or new structures.
6. Initiate a corrosion characterization survey of other Great Lakes port facilities.

The panel's analysis and recommendations were published by the Army Corps of Engineers which can be found in their publication ERDC/CERL SR-05-3 (2005). The following sections are a summary of the recommended testing completed and compiled results to date, as well as testing planned in the future.

Corrosion Extent and Rate Monitoring

As part of the recommended testing, a study was initiated in 2006 to perform an underwater survey to visually document and measure corrosion found on harbor structures, as well as to initiate a long term corrosion rate monitoring program.

At 22 sites located around the DSH, divers made visual inspections and took pile thickness readings. Similar corrosion rates and pitting were found throughout the sites on structures of similar age. In general, corrosion and pitting was greatest in the areas 0.3 to 3 meters (0.5 to 10 ft) below the DSH Mean Low Water (MLW) level, with the most severe around the 1.2 meter (4 ft) depth. On piling older than 35 years, pitting was significant and perforations through structural members were found. Figure 1 shows an example of pitting and penetrations found at the 1.2 meter (4 ft) depth. Table 1 shows a qualitative summary of the corrosion and pitting levels.

Figure 1. Typical Sheet Pile Pitting and Penetrations
Table 1. Corrosion Rate and Pitting Summary

Distance Below MLW	Base Metal Corrosion	Pitting
0.0 to 0.2 Meters (0.0 to 0.5 Feet)	Minor 0.01 - 0.04 mm/y (0.4 – 1.6 mils /y)	Low Concentration Small Uniform Pits
0.2 to 1.2 Meters (0.5 to 4 Feet)	Significant 0.04 – 0.10 mm/y (1.6 – 3.9 mils /y)	High Concentration, Large Diameter Deep Pitting and Penetrations
1.2 to 3 Meters (4 to 10 Feet)	Less Severe 0.02 – 0.07 mm/y (0.8 – 2.8 mils /y)	High Concentration, Medium to Small Pitting
>3 Meters (> 10 Feet)	Minor 0.01 - 0.04 mm/year (0.4 – 1.6 mils /y)	Small Concentrated Pitting Resembling Etching

To assist in confirming average corrosion rates through the harbor, Linear Polarization Resistance (LPR) measurements were taken and a series of steel coupon test samples were installed in various sites around the harbor. LPR testing monitors the current flowing between electrically charged electrodes to calculate instantaneous corrosion rates. LPR measurements were taken at 8 sites in the harbor on two different dates in the fall of 2006.

A series of test samples were installed in 2006 at seven different sites around the harbor as part of the same study. At each site, eight 10mm (3/8 in) thick uncoated ASTM A328 coupons with measured weights and dimensions were installed at a depth of 1.2 meters (4 feet). Mill scale was left on the coupons to simulate standard uncoated steel structure installation. A coupon is removed from each site every 6 months, cleaned, and measured to determine its physical corrosion loss. Examples of sample appearance before (left image) and after (right image) cleaning are shown in Figure 2.

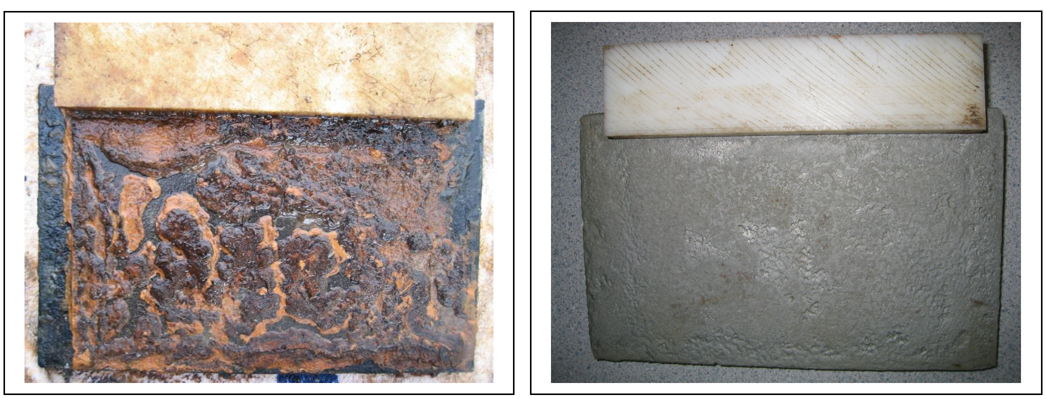

Figure 2. Uncoated Test Coupon Before and After Cleaning

Results of the testing to date show uniform corrosion rates between 0.043 mm to 0.095 mm (1.7 to 3.7 mils) loss per year which is consistent with both the long term degradation rates and the measurements recorded in the 2006 LPR study. It is important to note that *average* thickness of unprotected steel structures will deteriorate at these values, but *pitting rates* will be approximately 7.5 times higher. These higher pitting rates need to be taken into consideration when estimating the expected useful life of unprotected steel.

Cause of Accelerated Corrosion

While the exact cause of the accelerated corrosion has not yet been positively identified, most potential sources have been ruled out through the team's investigations. Analysis from the 2006 to 2008 studies show that a probable principle corrosion acceleration mechanism is microbiologically influenced corrosion (MIC), which is unusual for a fresh water harbor.

Coupons continue to be removed periodically from the test sample sites described in the previous and following sections to undergo biological testing and DNA analysis. Further testing is being carried out by the University of Minnesota Duluth and the Naval Research Laboratory to confirm which forms of MIC may be causing or at least directly influencing the accelerated corrosion and potentially develop solutions to inhibit the sources.

Coating and Cathodic Protection Test Summary

As part of the 2004 panel's recommendation, the corrosion study team was to develop a strategy for repair and replacement management and to develop a standard replacement design using coatings and cathodic protection (CP) for steel structures. Through funding and guidance from industry sources, the Army Corps of Engineers, Wisconsin Sea Grant, Wisconsin Coastal Management, NOAA, the Wisconsin DNR, Bushman & Associates, CURA, and AMI Consulting Engineers; a number of different coating and alternative repair studies were initiated that continue through 2009.

The first of the studies began in 2003 where applied coatings were applied to H piles on a local wharf structure and monitored over a 5 year period. Although the testing and study was not performed and documented as thoroughly as would be desired due to a lack of funding, the visual inspections performed by a NACE certified coatings inspector provided great initial insight into the ability of certain types of coatings to resist the impact and abrasion from ice on coated steel structures, and provided a basis for further testing plans.

In 2007, eight additional test coupon test sites similar to those from the corrosion rate study described in the previous section were installed in the harbor, each containing 8 sample steel coupons: 4 of which were uncoated steel without mill scale and 4 that were sandblasted and coated. These steel plates were cut from 13mm (0.5 in) thick ASTM A328 sheet piling then weighed and measured.

The uncoated samples were installed as an extension of the already initiated corrosion rate test as they provided data from additional sites through the harbor. On the coated samples, 6 different coating types from various manufacturers were used, and each will be evaluated for its long term corrosion resistance and durability in the DSH. Scribes to bare metal were made on each coated sample to allow the assessment of each coating's ability to remain adhered near areas with damage due to ice impact or abrasion, contact from ships, etc.

In the fall of 2008, representative coupons were removed from all of the test sites installed in 2006 and 2007 and inspected. Visual observations were documented on all samples, and some coupons were analyzed for corrosion loss and biological growth testing. Coated samples were inspected and all showed no signs of loss of adhesion anywhere including near the etched areas. A typical coated test sample removed for inspection is shown in Figure 3.

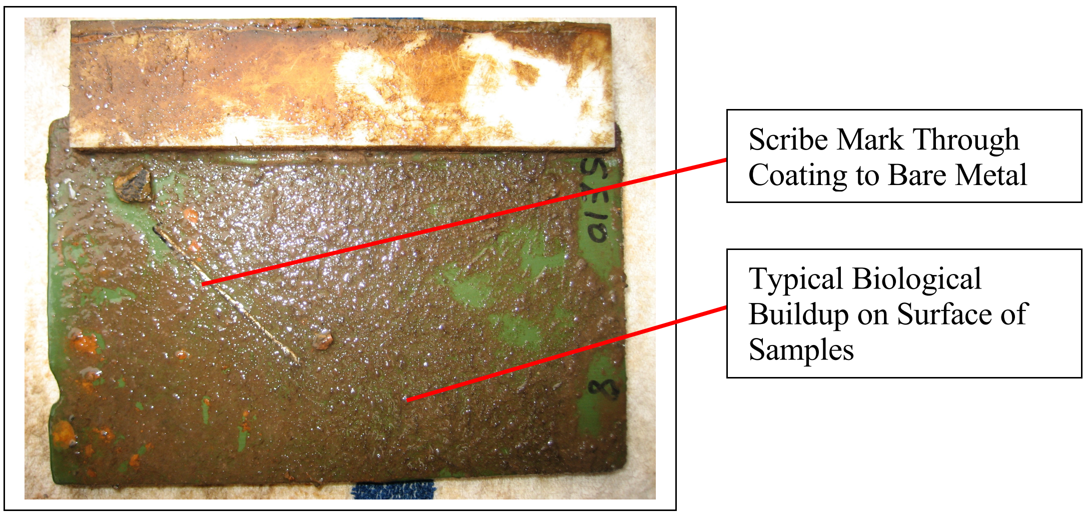

Figure 3. Coated Test Coupon

Also in the fall of 2008, a test was begun to evaluate different coatings' abilities to hold up to actual ice abrasion and impact. Freeze ice thicknesses in the DSH range from 0.5 to 1.2 meters (1.5 to 4.0 ft), with an additional 0.5 to 1.5 meters (1.5 to 5.0 ft) of stack and pack ice typically found along harbor walls. The abrasion effects on coatings from ice expansion and contraction are significant, but even greater damage can be caused from ice impact – especially in the fall, early winter, and spring when shipping is active in the ice covered waters.

The long term cold region abrasion and impact test installed a total of 18 total samples, each coated with one of 9 different coatings. The 1 meter (3 ft) long samples were fabricated from C6x8.2 ASTM A36 steel channel, sandblasted, coated, and mounted on a pier along a high shipping traffic channel in the harbor to promote impact and abrasion from moving ice formations.

The samples were installed in the heaviest ice impact and corrosion zones, with their top edges just above MLW level as shown in the right image of Figure 4. The abrasion test samples will be inspected yearly and each sample's coating thicknesses, adhesion, and overall condition will be recorded.

Figure 4. Ice Abrasion Samples Before and After Installation

In addition, six sites in the DSH already with full scale coating systems in place are being monitored yearly beginning in 2008 to monitor permanently installed coatings' resistance to wear and impact from ice. Two specific positions at each site in the zone of heavy ice impact and corrosion have been marked so that measurements and testing of coating thicknesses are in the same exact physical locations each year.

The average of 10 coating thickness readings, adhesion, and overall conditions at each site will be recorded. Results of the test sample and full scale abrasion and impact monitoring will be published for use in the DSH and other cold water regions.

In the fall of 2008, the team's first cathodic protection system (CPS) testing began. The goal of the year long test is to evaluate the effectiveness of these systems in the harbor as compared to other fresh water installations, and to assist in calculations and recommendations for future full scale CPSs.

Sacrificial anodes were installed on two steel pipe samples with known measurements and weights; one uncoated and one coated. A scribe was made to bare metal on the coated sample to simulate damage from ice impact or abrasion.

The electric potential between the anodes and pipes were adjusted to levels that would be typically be used on full scale systems to assure that test results will be representative of future CPSs installed on harbor steel structures, most likely in conjunction with protective coating systems.

Once per week, the electrical current flow between the pipe samples and the magnesium anodes, as well as voltage potential between the samples and harbor water are measured. Periodically the samples are raised from the water, and corrosion is compared to identical pipe samples without cathodic protection that are installed adjacently as part of the test. A schematic of the test samples with sacrificial cathodic protection applied is shown in Figure 5.

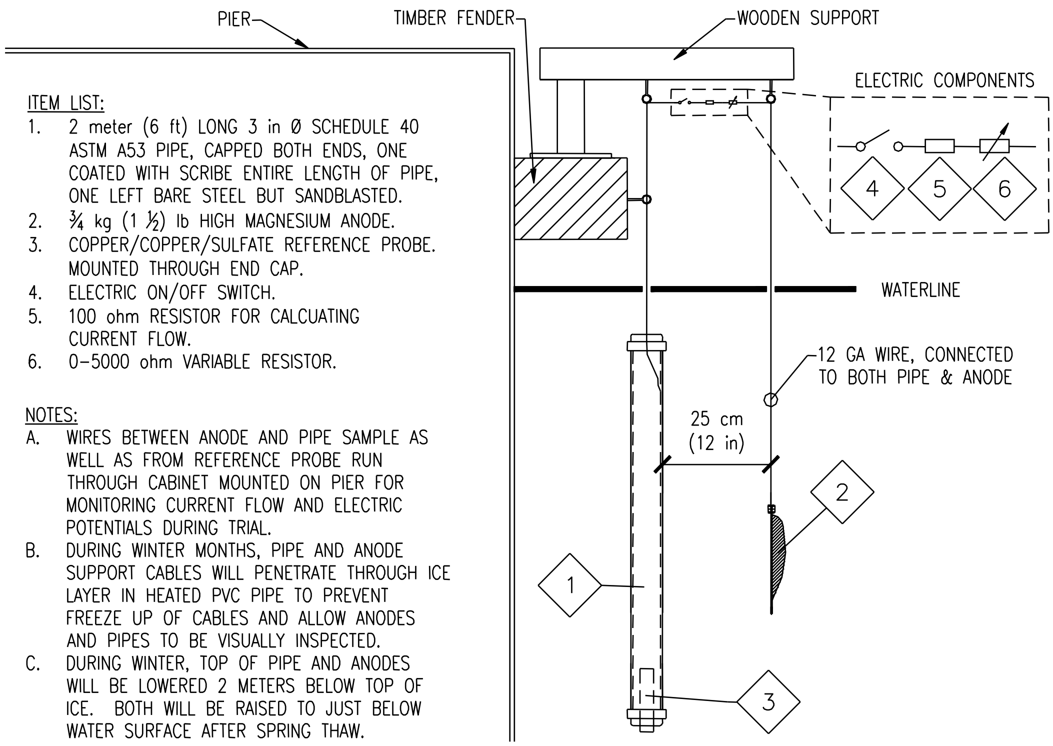

Figure 5. Cathodic Protection Test Schematic

The data collected and final analysis, in conjunction with experiences at other fresh water sites, will be used at the conclusion of the trial to assist in the determination of degree of cathodic protection levels required in the DSH, and for the design of full scale protection systems. Preliminary results show cathodic protective systems could be effective in the DSH, especially when used on small localized areas and in conjunction with protective coatings.

Alternative Repair Technologies

Another 2004 panel recommendation to the corrosion study team was to test or develop alternative protective or repair systems for steel structures in lieu of stand alone coating systems. As mentioned in previous sections, traditional protective coating systems can be susceptible to damage and/or removal from the ice.

Between 2005 and 2008, three different full scale alternative corrosion protective systems were installed and are being monitored. Existing steel pile members adjacent to a main channel in the harbor were chosen for the tests as the high ship traffic will expose each system to the highest level of ice impact found in the harbor. All systems were installed to protect an area from 1 meter (3 ft) above to 3 meters (9 ft) below MLW, protecting the heaviest ice impact and corrosion zone.

The systems installed were chosen for their low installation costs, proven abilities to protect against corrosion in less rugged environments, low coefficients of friction, ease of installation, and durability against ice impact and abrasion.

The first system is comprised of an H shaped fiberglass jacket installed around an existing steel H-Pile after removing marine growth and corrosion. The jacket is fabricated in two halves which are held together by tongue and groove closures. Dimensions of the fiberglass jacket were customized to create a 25 mm (1 in) void between it and the steel. The bottom of this void is sealed, and an epoxy grout is pumped into the space, forming bonds with the steel and fiberglass and preventing further corrosion. A depiction of H shape fiberglass system is shown in Figure 6.

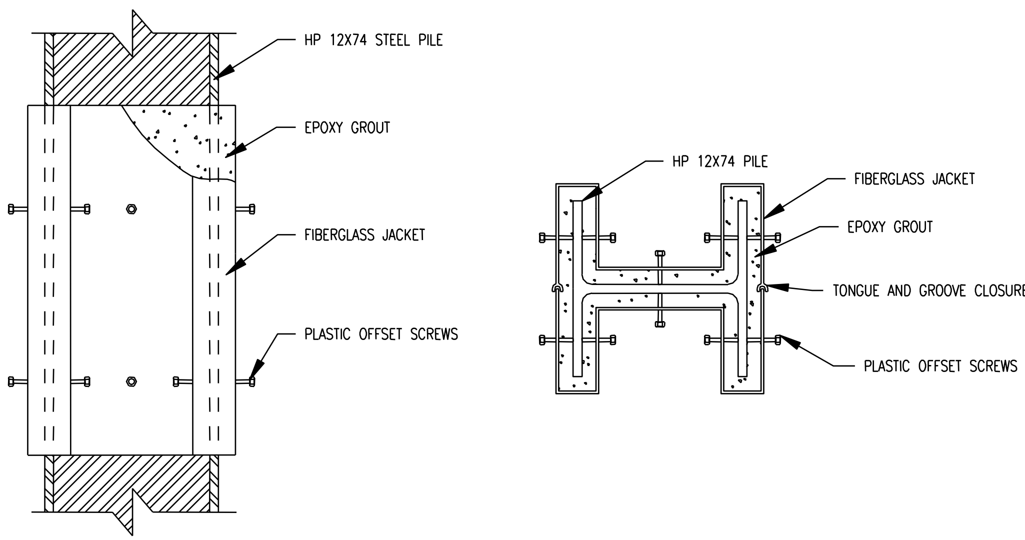

Figure 6. H-Shaped Fiberglass Protective System

This system also has an added advantage as it provides some structural benefits in addition to corrosion protection. Cost for installation materials for this system is approximately $615 per meter ($190 per ft); installation labor will vary by site.

A second fiberglass jacket system similar to that described above was installed on an adjacent H-Pile, with the difference being that the outer cover is rectangular shaped rather than in the shape of the pile. While this system is more flexible as its dimensions do not been to be as tailored to the specific H shape being protected, installation costs become less attractive as about 40% more epoxy grout is needed to fill the void between the fiberglass and steel. Material costs for this system are approximately $1,180 per meter ($360 per ft).

The final system installed to date is designed to protect cylindrical steel pipe pile. The outer jacket cover of this system is fabricated from high density polyethylene (HDPE). After cleaning the pile, petrolatum paste is used to fill any large pits on the steel surface. The paste is water displacing and contains corrosion inhibiting and biocide additives and creates a seal to prevent direct contact between water and steel and resulting corrosion.

An HPDE and synthetic fabric tape is then wrapped around the paste, providing an additional barrier to water penetration. Finally the HPDE jacket is installed around the other components and joined together with 316 stainless steel bolts which are tightened to force out any water and air and protect the inner corrosion inhibiting components from damage by external forces. Installation materials for this system are approximately $265 per meter ($80 per ft). A depiction of the HPDE pipe pile system is shown in Figure 7.

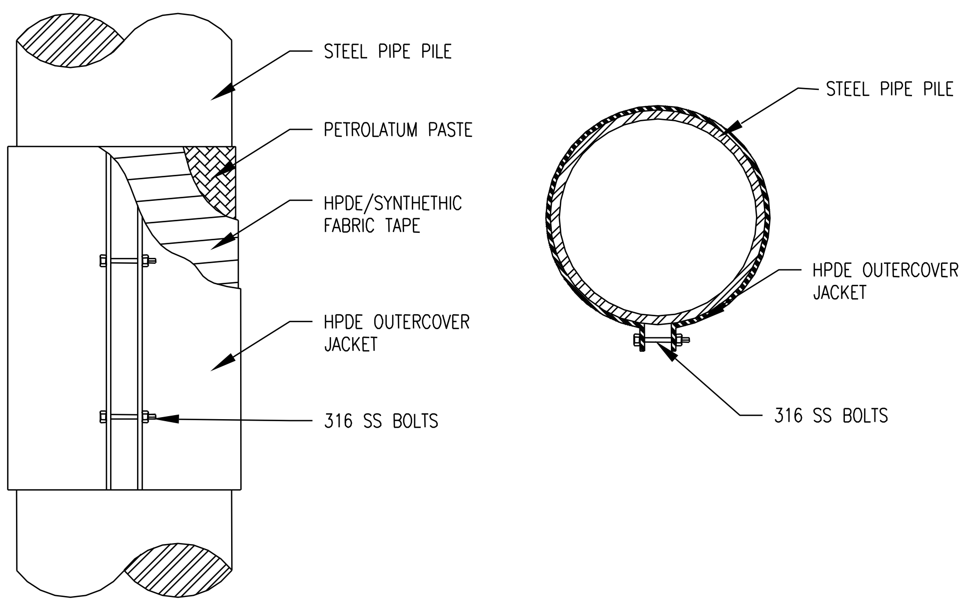

Figure 7. HPDE Pipe Pile Protective System

The project study team will continue with systematic yearly observations of each system's ability to withstand ice impact and abrasion forces and publish results for use by harbor and other cold region port facility owners and managers. A photo of each alternative repair installation is shown in Figure 7.

Figure 8. H-Shaped, Rectangular, and Pipe Pile Protective Systems

Corrosion at Other Port Facilities

Another of the team's tasks was to initiate a corrosion characterization survey of other Great Lakes port facilities to determine if similar accelerated corrosion is occurring. To date, similar accelerated corrosion has only been found during inspections at ports and harbors located on Lake Superior. The steel structures in these locations do show accelerated corrosion similar to the DSH (but often to a lesser extent), thus emphasizing the importance in determining the cause and potential solutions for the control of the problem. Further investigations at other Great Lake facilities will continue in the future, and those findings will also be incorporated into and coordinated with the ongoing studies.

Future Studies

In addition to monitoring the already initiated long term coating and alternative protection trials and investigating for accelerated corrosion at other ports; further biological testing will continue in order to determine the exact cause and origin of the MIC, as well as potentially develop a means to inhibit their influence on harbor structures. Additional full scale coating and alternative technology protective systems will also be installed and monitored for effectiveness for corrosion protection and ability to withstand cold region ice forces.

Conclusion

Results from our studies to date surrounding the cause and possible solutions to the accelerated corrosion problem have established average steel corrosion rates in the DSH, initiated a long term corrosion rate monitoring program to alert of any changes, shown that a source of the corrosion acceleration is likely related to or influenced by MIC, and that the accelerated corrosion problem is not isolated to this harbor alone. Long term testing already initiated, in conjunction with trials that will soon begin, will determine the best coating and alternative protection technologies that will prevent corrosion as well as endure the ice impact and abrasion forces found in cold regions.

We wish to thank all industry, municipal, state, and federal agencies that have given their financial and academic support, as well as the numerous harbor facility owners and operators that have granted access to their facilities in order to conduct the testing. Additional evaluations will continue in order to isolate the precise source of the problem and identify the best solutions, the results of which will be reported for use in all fresh water cold region harbors experiencing accelerated freshwater corrosion.

References

US Army Corps of Engineers ERDC/CERL SR-05-03 (2005), *Freshwater Corrosion in the Duluth – Superior Harbor,* March