by R. Brett Holland, Kimberly E. Kurtis, Robert D. Moser, Lawrence F. Kahn, Fred Aguayo, and Preet M. Singh

Built in 1977, the I-95 Turtle River bridge sits about 10 miles (16 km) inland from the Atlantic Ocean in coastal Georgia. After decades in service, inspection reports described visual signs of degradation. Reports of longitudinal cracking, spalling, and exposed reinforcement, in particular, suggested chloride-induced corrosion of the reinforcement as primary source of damage. Observations of “softening” below the waterline to the mudline suggested the possibility of some chemical and/or biological attack, although these have not been well-documented in the region. As a result, after 36 years in service, the bridge substructure was replaced.

Four of the original prestressed concrete piles were subject to a forensic evaluation to identify through mechanical and analytical testing as well as microscopy— the deterioration mechanisms producing the damage observed in the field. The goal of the forensic investigation of the recovered piles was twofold: to gain a better understanding of the causes and severity of degradation in a marine environment and to allow for the identification of appropriate methods to increase the durability and service lives of coastal bridges and other structures exposed to marine environments. Results from this forensic evaluation are presented herein.

Service History

Materials and pile design

The piles were 30 in. (762 mm) square in cross section, with a central 15 in. (381 mm) diameter hollow core. They were constructed with 1/2 in. (13 mm) prestressing strands arranged in a square pattern and W3.8 wire square spirals, with a nominal 3 in. (76 mm) cover. A 0.50 water-cement ratio (w/c) concrete was specified, using ASTM C150 Type I cement. Natural quartz sand was used for the fine aggregate, and 1 in. (25 mm) maximum size aggregate (MSA) Pleistocene limestone or “limerock” was used for the coarse aggregate.

Inspection reports

The most recent inspection reports prior to pile removal indicated that in the splash and tidal zones, the piles showed heavy marine growth, moderate scaling and abrasion, vertical cracking, spalling, exposed prestressing steel, rust staining, and delaminations (refer to Fig. 1). The reported vertical cracks varied in width from hairline to 1/4 in. (6.4 mm). For the submerged region of the piles, it was noted by divers that the concrete piles were “soft” and
that the concrete could be easily chiseled off. Also, several piles had vertical cracks in the corners of the submerged zone that ran from the mudline up 6 to 12 ft (1.8 to 3.7 m) and stopped below the tidal zone, with widths varying from hairline to 1/32 in. (0.8 mm).

*Exposure conditions in service*

Tests from the brackish waters surrounding the bridge showed that the concrete piles were exposed to sulfates up to 2000 ppm and low pH of 4 to 5, along with chlorides. These results suggest that the prestressed piles were subjected to multiple modes of deterioration which could have contributed to their damage during service.

![Image of bridge and piles](https://www.giatecscientific.com)

**Fig. 1: Typical corrosion-induced spalling**

in splash zone along with marine growth in tidal and submerged zones of marine piling for the I-95 Turtle River Bridge

**Corrosion of Prestressing Steel**

Portland cement concrete’s highly alkaline environment passivates embedded reinforcement by the formation of a thin oxide layer on the surface of the steel, protecting it from corrosion. The passive film can be broken down by decreasing the pH of the surrounding environment, local attack from aggressive ions (for example, chlorides), or a concurrence of both, leading to active corrosion. Corrosion of the reinforcing steels causes loss of steel area; additionally, the formation of iron oxide corrosion products, which occupy more volume than the steel, can lead to cracking and delamination of the cover concrete, as well as rust staining on the concrete surface.
The causes and extent of damage produced by corrosion in the piles were investigated by performing a visual assessment of the damage, assessment of carbonation depth, mapping the corrosion potentials, and determination of chloride profiles.

**Visual assessment of damage**

As previously noted, visual inspection of the splash and tidal zones of the piles showed vertical cracks along the corners of the piles, as shown in Fig. 2(a). The average crack widths were approximately 0.01 in. (0.25 mm), but were as large as 0.05 in. (1.27 mm). Additionally, delamination of the cover concrete had occurred over the corner strand on one pile. The exposed surface showed extensive corrosion damage to the strand and staining of the surrounding concrete (Fig. 2(b)). The pH of the concrete cover was studied by using a phenolphthalein indicator solution on freshly cut surfaces of the piles. At pH greater than about 9.2, the indicator solution turns pink, representing uncarbonated concrete.

As shown in Fig. 3, the carbonation front was found to be approximately 1 in. (25 mm) beneath the exposed surface of a pile, both in the submerged and tidal regions. This limited depth suggests that it is unlikely that corrosion of the reinforcement resulted solely from carbonation.
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Fig. 2: Visual inspection of the splash and tidal zones of piles: (a) corrosion-induced longitudinal cracking; and (b) corrosion of prestressing strands and transverse reinforcement
Fig. 3: Determination of pH of concrete cover: (a) (right) phenolphthalein indicator solution on sawn surface of pile; and (b) (left) measurement of carbonation front

_Half-cell corrosion potentials_

The half-cell potential of the embedded steel strands was used in accordance with ASTM C876-09, “Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete,” to identify regions where corrosion was occurring. Figure 4 shows the half-cell corrosion potentials from all four sides of a pile. As stated in Section 5.3.2 of ACI 222.2-01,2 according to ASTM C876, a half-cell potential more negative than $-350$ mV indicates a 90% or greater probability of corrosion occurring. A half-cell potential less negative than $-200$ mV indicates a 10% or less probability of corrosion occurring. The results suggest that from 2 ft (0.6 m) above high tide and below, there is a high probability that corrosion is occurring. However, these potential measurements are only indicative of the propensity for corrosion to occur but provide no information regarding the potential rate of corrosion. The lack of oxygen
in the submerged zones of piles explains why no corrosion-induced damage was seen, even though the half-cell potential suggests that corrosion is occurring. The tidal and splash zones of piles have adequate access to moisture and oxygen due to the wetting and drying cycles present.

Fig. 4: Half-cell potential map of the four faces of a typical precast prestressed concrete pile. Elevations are given with respect to high tide

Cl\text{\textsuperscript{-}} profiles

The concentration of chlorides near the reinforcement surface is critical in causing the onset of corrosion; as a result, it is important to understand the migration of chlorides through the concrete and the interactions between those ions and the cementitious system. While other transport mechanisms, such as capillary action, can affect the transport of chlorides through the cement paste, Fick’s second law of diffusion is most commonly used to model the transport of chlorides (Cl\text{\textsuperscript{-}}) through the concrete. The apparent diffusion coefficient of a concrete mixture exposed to chlorides can be determined experimentally and used for
service life estimation in a given environment.¹

When the concentration of chlorides reaches a threshold value at the surface of the reinforcing steel, corrosion will initiate when the passive film is broken down. In practice, the total chloride content is used more frequently for threshold values, even though it is generally believed that the free chlorides are responsible for the initiation of corrosion.³ The chloride threshold level (CTL) is typically assumed to be between 0.4% to 1% mass of binder, or approximately 0.05% to 0.2% by mass of concrete, for total chloride content.¹ Research by Moser et al.⁴ has also shown that crevice effects and surface imperfections on prestressing strand have an influence on the CTL for use with service life modeling.

For the purpose of investigating the chloride diffusion characteristics of concrete in the present study, total and free chloride concentrations were determined at various heights along the pile. The total chloride concentration was measured using the ASTM C1152/C1152M-04, “Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete,” procedure. Samples were obtained by taking 3 in. (76 mm) diameter cores through the depth of the cross section, and drilling at 1/2 in. (13 mm) increments using a 3/8 in. (10 mm) masonry bit to collect powder.

As seen in Fig. 5, the concentration of total chlorides at the level of the reinforcement was significantly higher than the typical CTL values given in the literature, with particularly high levels noted at the high tide level and below. The chloride profiles for high tide, -5 ft (1.5 m), and -12 ft (3.7 m) elevations were very similar, with the exception of the surface chloride content which varied widely between the elevations. The variation in surface chloride content may be due to the effects of leaching and capillary suction during wetting and drying cycles in the tidal zone compared to the fully saturated condition in the submerged region. At just 2 ft (0.6 m) above high tide, the chloride content was significantly less than in the submerged regions. Overall, the concentrations were in agreement with the measured half-cell corrosion potentials, suggesting that active corrosion was occurring due to chloride-induced depassivation of the steel.

The experimental data were fit by nonlinear regression analysis to Fick’s second law to determine the apparent diffusion coefficient and surface chloride concentration, and these were used for service life modeling. Additionally, the Life 365 Service Life Prediction Model, also based on Fick’s second law,⁵ was used to estimate the diffusion coefficient and expected service life of the piles. The Life 365 estimates were based on selection of a marine tidal zone exposure in Savannah, GA, for a 0.50 w/c concrete containing only portland cement. The experimentally determined data were compared to the Life 365 data for the estimated time to corrosion initiation based on a CTL of 0.05% by mass of concrete, which is the default
value used by Life 365. Table 1 shows this comparison.

Overall, Life 365 gave reasonable predictions of diffusion coefficient, surface chloride concentration, and time to corrosion (Table 1). It should be noted that the predicted time to corrosion initiation represents only a portion of the usable service life of the structure, and the period of time for corrosion to propagate to a critical point can take years to occur after corrosion initiates. Life 365 underestimated the diffusion coefficient determined from curve fitting. However, the diffusion coefficient observed could be influenced by other damage mechanisms that were occurring in the piles. For example, the identified biological attack, sulfate attack, and potential cracking from construction practices could all lead to an increased permeability and diffusion coefficient which would not have been accounted for in the Life 365 estimate.
Fig. 5: Total measured chloride content of concrete piles at various depths. In the legend, a positive value indicates depth below high tide, and a negative value represents height above high tide.
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Table 1: Comparison of Life 365 estimates to experimental data

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<th>Experimental</th>
<th>Life 365</th>
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<td>2.14</td>
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<tr>
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<td>Surface chloride</td>
<td>0.797</td>
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<td>Time to corrosion</td>
<td>3.1</td>
<td>3.7</td>
<td>19.35</td>
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| Sulfate Attack |

In addition to chlorides, the concrete piles were exposed to sulfate (SO₄²⁻) concentrations of up to 2000 ppm. Sulfate attack can damage concrete through the reaction with hydration products to form sulfate-containing phases, such as ettringite and gypsum (and in some cases brucite), which can contribute to expansion, cracking, softening, and/or loss of strength and stiffness.⁷ Visually, a whitish appearance of the cement paste in damaged areas, as well as greater incidence of cracking and spalling at corners and edges, are indications of potential sulfate attack. The potential for sulfate attack to contribute to the damage found in the bridge piles was assessed by visual inspection and surface hardness measurements. Additional techniques not discussed herein, including X-ray diffraction (XRD) and thermal analysis, were also employed; details on these findings are provided by Holland.⁸

Visual assessment of damage

In addition to the cracking in splash and tidal zones previously described, below the low tide line cracking was particularly noted near the corners of the piles, extending from the mudline up to the low tide elevation. The width of these cracks varied widely, with a maximum of 0.05 in. (1.3 mm), but most were approximately 0.025 in. (0.6 mm) wide; marine life was found

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growing along the cracks. Surface spalling and abrasion were also apparent in this region. Additionally, the paste fraction nearer to the surface had a whitish appearance (Fig. 6).

Fig. 6: Typical cross section showing whitish discoloration, nearer to the marine-exposed surface, on top portion of sample (length of sample is about 3 in. [76 mm])

*Hardness measurements*

To assess if the changes in paste color observed through the concrete depth could be
correlated with a change in properties, hardness of the concrete was measured on cross sections of the cover concrete. Vickers indentations were performed in accordance with ASTM C1327-08, “Standard Test Method for Vickers Indentation Hardness of Advanced Ceramics,” using 2.2 lb (1 kg) mass applied for 15 seconds. A minimum of five indentations were made at 1/4 in. (6.4 mm) increments into the section on sections polished with 1 micron alumina. Figure 7 shows the results of the measurements for 2 ft (0.6 m) above high tide and 12 ft (3.7 m) below in the submerged region. The reduced hardness in the outer 2 in. (51 mm) of the submerged region was low when compared to the same region at greater depth. The consistency of these values with those made at 2 ft (0.6 m) above high tide suggests that at depths of 2 in. (51 mm) or greater, the concrete is relatively unaffected by marine exposure. The depth associated with the lower hardness coincided with the location of the whitish color change in the matrix as well as compositional changes detected by XRD. These suggest sulfate attack as well as carbonation, leaching, or both, have contributed to softening in the near-surface paste.

Fig. 7: Vickers hardness measurements of polished concrete cross sections

Biodeterioration

Heavy marine growth was noted on the surface and within cracks in the splash and tidal zones. Visual inspection and microscopy were used to better understand the nature of the apparent biodeterioration.
Fig. 8: Visible damage on submerged portion of a concrete pile: (a) large pits on pile surface; (b) larger concentration of pits along pile corner; and (c) depth of penetration in concrete core caused by biodeterioration.

**Visual inspection of damage**

After the marine growth was cleaned from the surface of the submerged region of the piles, large amounts of surface damage were made visible. The damage, as seen in Fig. 8, consisted of large pits on the pile surfaces, with the damage more pronounced along the corners. There, increased porosity (or perhaps “boreholes”) and some spalling were evident.
Cores taken in the submerged region showed extensive damage to aggregate within 1 in. (25 mm) of the surface of the piles to depths over 1 in. (25 mm), as shown in Fig. 8(c). Interestingly, the damage was largely concentrated where Pleistocene limestone coarse aggregates had been present on or near the surface of the piles, with this pattern of damaged near-surface aggregate observed in over 70% of cores taken.

This damage pattern observed visually was consistent with reported descriptions of damage to limestone and coral by *Cliona* or boring sponges in brackish or seawater exposures. There have been reports of *Cliona* sponges at Gardiner’s Island, New York\(^9\); along the coast of Virginia\(^10\); Corpus Christi in Texas\(^11\); and off the coast of Jamaica\(^12\). Studies on the erosion rate of the sponge show that the rate may exceed 0.04 in. (1 mm) per year of ingress in solid limestone.\(^13\) While the factors affecting rate of marine attack on concrete are largely unknown, the rate of biological degradation of the limestone aggregate in these piles, greater than 1 in. (25 mm) in 35 years, is consistent with the rate of attack measured by Neumann\(^13\) for *Cliona* on solid limestone.

It is believed the sponge’s acidic secretions penetrate calcium carbonate, forming boreholes.\(^9,14\) The genus *Cliona* sponges leave silica-rich spicules near the surface of their borings. The length of the spicules varies by species but is typically between 200 to 400 μm.\(^15\) Micrographs (Fig. 9) of damaged aggregate in these piles show rod-like structures with one pointed and one rounded end, morphologically consistent with spicules, with energy-dispersive X-ray spectroscopy (EDS) spectra showing the structures are predominantly silica. Clearly, the loss of aggregate by boring sponge attrition will have a significant negative effect on concrete performance. In a marine environment, in particular, the localized reductions in cover depth are especially important, as corrosion initiation likely occurs at earlier than anticipated ages.
Fig. 9: Micrographs of damaged aggregates: (a) silicate-rich rod-like structures (boring sponge spicules) observed within voids in coarse aggregate; and (b) close-up of spicules (Note: 1 mm = 0.04 in.)
Conclusions

The forensic investigation of precast prestressed concrete piles taken from a coastal environment revealed extensive damage derived from multiple deterioration mechanisms. Chloride-induced corrosion of the prestressing strands in the splash and tidal zones of the piles led to cracking and delamination of the cover concrete as well as a loss of steel cross section. Measured patterns of chloride ingress suggested that the concrete quality was not adequate to provide a 100+ year service life in the marine environment. Additionally, severe deterioration of the concrete due to sulfate attack occurred in the submerged regions of the piles, with carbonation also evident there and in the tidal regions. Also, extensive damage to the Pleistocene limestone coarse aggregate in the submerged region was linked to biodegradation by Cliona boring sponges. It is worth noting that inspections of other bridges along the coast suggest that the causes of damage observed during the forensic investigation of piling from the Turtle River Bridge are generally representative of other regional coastal bridges.

The piles exhibited extensive damage that led to the discovery of unexpected threats to bridge substructures in marine environments, and the need for adequate protection from known environmental hazards. Furthermore, the results of the study emphasize the need to consider the presence of multiple modes of deterioration in concrete structures and their potential synergistic interaction. For example, deterioration of the cover concrete caused by sulfate attack along with the formation of boreholes in coarse aggregates very likely resulted in accelerated ingress of chlorides and subsequent chloride-induced corrosion of embedded reinforcing steel. As required service lives become longer for critical infrastructure, consideration of all potential modes of concrete deterioration becomes more and more important to ensure that adequate serviceability can be maintained.

Acknowledgments

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