Evaluation of Galvanized and Painted Galvanized Steel Piling

Interim Report
September 2022

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16. Abstract

This project investigated the long-term protection of steel piles with galvanized and painted galvanized coatings using a corrosion chamber to accelerate corrosion effects in the laboratory. Further investigation was completed through observation of painted galvanized piles installed in the field at a newly constructed bridge in Buchanan County, Iowa.

The primary objective of this research was to evaluate the effectiveness of galvanized and painted galvanized piles in extending bridge service life in a cost-effective manner. An economic evaluation was conducted comparing the use of a larger H-pile section, a galvanized coating, and a painted galvanized coating to protect the piles against corrosion.

One solution to achieve a 100-yr design life is to increase the section size of the pile to allow for section loss without compromising the required pile capacity While the cost to increase the pile size was determined to be less than the premium for galvanizing or galvanizing and painting the piles for the bridge in this study, a cost-benefit evaluation for each protection measure is suggested knowing that costs can vary widely depending on specific project requirements, location, market prices, etc.

This is an interim report, and the research team plans to continue to collect additional annual data from the Buffalo Creek Bridge in Buchanan County for future analysis.

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EXECUTIVE SUMMARY

Corrosion is important to consider in the design, maintenance, and preservation of steel pile foundation systems. An inevitable phenomenon takes place when steel is exposed to the environment, as metals tend to return to their lower energy state. While the corrosion rate of steel is predictable for atmospheric exposures, it is highly variable and difficult to predict for steel buried underground because of the high variability of soils.

Zinc and other coatings protect steel piles from corrosion by isolating the steel from its surrounding environment and by cathodic protection. The performance of zinc coatings is dependent on the thickness of the coating and factors influencing the environment to which the piles are exposed.

Concrete-encased steel piles are common for Iowa Department of Transportation (DOT) and Iowa county structures and have historically achieved acceptable performance. However, cases of early deterioration and pile corrosion have occurred. As such, interest has grown in using coatings to protect piles from atmospheric deterioration.

This project investigated the long-term protection of steel piles with galvanized and painted galvanized coatings using a corrosion chamber to accelerate corrosion effects in the laboratory. Further investigation was completed through observation of painted galvanized piles installed in the field at a newly constructed bridge in Buchanan County, Iowa.

An economic evaluation was also conducted comparing the use of a larger H-pile section, a galvanized coating, and a painted galvanized coating to protect the piles against corrosion.

One solution to achieve a 100-yr design life is to increase the section size of the pile to allow for section loss without compromising the required pile capacity While the cost to increase the pile size was determined to be less than the premium for galvanizing or galvanizing and painting the piles for the bridge in this study, a cost-benefit evaluation for each protection measure is suggested knowing that costs can vary widely depending on specific project requirements, location, market prices, etc.

This is an interim report, and the research team plans to continue to collect additional annual data from the Buffalo Creek Bridge in Buchanan County for future analysis.

CHAPTER 1. INTRODUCTION

1.1 Background and Problem Statement

Corrosion is important to consider in the design, maintenance, and preservation of steel pile foundation systems. An inevitable phenomenon takes place when steel is exposed to the environment, as metals tend to return to their lower energy state.

Corrosion may result in a reduction of the pile cross-sectional area, leading to a loss of structural capacity and, in the worst case, possible failure. For example, the H-pile of Pier 22 on the I-43 Leo Frigo Memorial Bridge in Wisconsin failed due to corrosion (Becke and Rudat 2015).

The rate at which steel corrodes is dependent on whether it is exposed to the atmosphere, soil, and/or water. While the corrosion rate of steel is predictable for atmospheric exposures, it is highly variable and difficult to predict for steel buried underground because of the high variability of soils.

Zinc and other coatings protect steel piles from corrosion by isolating the steel from its surrounding environment and by cathodic protection. The performance of zinc coatings is dependent on the thickness of the coating and factors influencing the environment to which the piles are exposed. For example, when considering atmospheric exposure, the zinc coating corrodes faster in industrial environments compared to rural and urban environments.

Concrete-encased steel piles are common for Iowa Department of Transportation (DOT) and Iowa county structures and have historically achieved acceptable performance. However, cases of early deterioration and pile corrosion have occurred.

As such, interest in using coatings to protect piles from atmospheric deterioration has grown. Of main interest are galvanized piles and painted galvanized piles, which provide added protection. However, the cost effectiveness and corrosion resistance performance of these coatings is basically unknown.

A unique opportunity emerged with the Buffalo Creek Bridge in Buchanan County to monitor the performance of a galvanized pile system on a local bridge structure in Iowa. The Buffalo Creek Bridge is a 200 ft by 40 ft three-span bridge that was under construction at the initiation of this project and available for in-service data acquisition. The performance of the galvanized pile could be evaluated based on the thickness change of the coatings.

1.2 Objective

The primary objective of this research was to evaluate the effectiveness of galvanized and painted galvanized piles at extending bridge service life in a cost-effective manner.

1.3 Research Plan

The research objective was achieved through a systematic laboratory and field investigation, coupled with a life-cycle cost analysis. This project began with a comprehensive literature search, which supplemented the knowledge and experience of the research team in working with substructure components.

In the laboratory, a series of pile sections was evaluated via an accelerated corrosion testing protocol. During this testing, various types of piles, including traditional bare, steel piles, and coating systems were evaluated. This testing provided side-by-side performance data as well as valuable inputs for the life-cycle cost analysis.

In addition, a unique opportunity existed to evaluate the in-place performance of a bridge constructed using galvanized steel components. The performance of this bridge was evaluated for its long-term corrosion resistance performance.

A service life analysis was then performed to understand the costs and benefits associated with using substructure coatings, which is an important step in making the decision to implement the investigated coatings on a broader scale.

CHAPTER 2. LITERATURE REVIEW

2.1 Steel Pile Corrosion

According to ASTM, Inc., corrosion is the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a degradation of the material and its associated properties. Corrosion is initiated when two different metals or two points on the same metal come into contact with an electrolyte. The electrolyte may be water and/or soil depending on the environment to which the metal is exposed.

As a result of the potential difference existing between the two metals or two surfaces on the same metal, a current is generated between the anodic area and the cathodic area. This potential difference is a function of several factors, such as the nature of the metal, the nature of the electrolyte, a difference in the amount of oxygen present, and/or a difference in temperature.

Corrosion affecting metals, in general, and steel piles, in particular, can be classified as atmospheric corrosion, freshwater corrosion, seawater corrosion (not applicable to Iowa locations and not discussed further), and soil corrosion. The corrosion rate of each type is influenced by various factors.

Steel piles exposed to the atmosphere have access to a large amount of oxygen; thus, the corrosion in this environment is mainly driven by the presence of humidity, which acts as an electrolyte. A relative humidity of 70% to 80% combined with a temperature above 32° F results in the corrosion of carbon steel.

Other factors, such as the air pollutant concentration, the air salinity, temperature, and rainfall can contribute to accelerated corrosion of steel piles. The piles may be subjected to a rural environment, an urban environment, an industrial environment, or a marine-type environment, and this difference in the type of exposure has a significant effect on the corrosion rate. For example, in marine environments, the corrosion rate is remarkably high because of the higher concentration of seawater particles (Alcántara et al. 2017).

The second category of corrosion that affects steel piles is freshwater corrosion. Factors influencing the rate of corrosion in this type of environment includes dissolved salts, gases, and pollutants. Freshwater corrosion also depends on the type of the water (hard or soft); however, since the pH range for natural water is between 4 and 9, pH in this range has little effect on the corrosion rate.

Nonetheless, freshwater varies greatly in how it is addressed in some design codes. For example, EN 1993/Eurocode 3 considers the rate of the corrosion for immersed steel members nearly 0.02 to 0.05 mm per year for one side (Corus 2005).

The last category of corrosion that all steel piles experience is soil corrosion. Piles driven in the ground come into contact with different soil layers having different oxygen concentrations, and

corrosion occurs by the process of differential aeration. Generally, the upper soil layers and the region near the ground water table will have greater oxygen content. Soil layers with low oxygen concentration act as anodes in the corrosion mechanism, while layers rich in oxygen act as cathodes.

Corrosion of steel piles in soil can be divided in two categories: corrosion of piles in undisturbed soils and corrosion of piles in disturbed soils. An extensive investigation by Romanoff (1962) showed that the amount of corrosion experienced by steel piles driven in undisturbed soils is small, and it is not sufficient to affect the load bearing capacity of the piles. Other soil properties, including soil type, drainage, resistivity, and pH were found to have a negligible effect on the corrosion of the piles.

Undisturbed soils have been found to be deficient in oxygen, and this limited amount of oxygen cannot sustain the corrosion process over time. The corrosion of the piles will stop once the small amount of oxygen present in the soil has been completely consumed.

On the other hand, disturbed soils, such as backfills, are rich in oxygen, making them more corrosive than undisturbed soils. In the case of disturbed soils, other properties including soil type, moisture content, pH level, soluble salts, resistivity, chemical composition, and the presence of bacteria have an influence on the corrosion of steel piles.

Figure 1 (left) illustrates the region prone to corrosion for piles immersed in disturbed soil.

Corrosion of piles in disturbed soils   Corrosion of piles in water
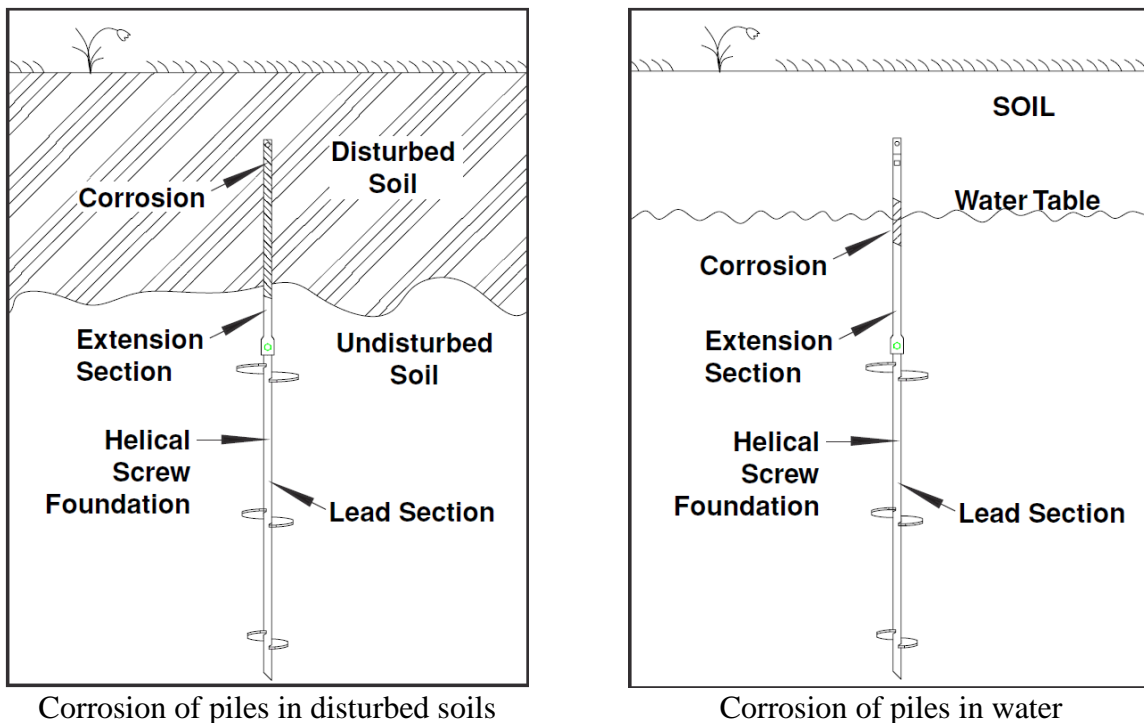
A.B. Chance Company 2003, © 2003 Hubbell, Inc.

Figure 1. Corrosion of piles in disturbed soils and water

The rate of corrosion for steel piles underground is varied and difficult to predict because of the effect of the various factors previously listed. Studies by Romanoff (1962) for the U.S. National Bureau of Standards (NBS) resulted in equation (1) for predicting the uniform corrosion rate of metals in soil:

$$P = Kt^n \tag{1}$$

where, P is thickness loss; t is time in years after burial; and K and n are constants that yield corrosion rates that slow with time as $n < 1$. Equation (1) has been found to be a reasonable predictive model for corrosion of buried metals. The difficulty in its application lies in selecting the appropriate n and K values, especially in the case of galvanized steels, as these values are a function of the site and soil conditions.

If it is determined that corrosion may be a problem at a specific site, measures should be taken to protect the steel piles and prolong their useful service life. This can be done by increasing the pile size to provide an allowance for corrosion loss or by protecting the pile with a coating such as zinc (Corus 2005). The latter method is discussed in more detail in the following sections.

Protective measures such as zinc coatings should be used on piles when corrosion may be a potential problem at a site. In the case of piles driven through disturbed soils, the protection should be applied to the critical region, which extends from the bottom of the pile cap down to about 3.28 ft (1 m) below the water table, as shown in the previous Figure 1 (right).

2.2 Corrosion Protection

The most convenient method in addressing corrosion is utilizing a structural section thicker than the original designed pile. In this method, the required sacrificial layer has the same material as the pile. The extra thickness is selected based on the corrosion rate of the environment for which the pile is designed. Estimating a reliable corrosion rate is a fundamental factor with this method.

Applying a protective sacrificial layer in galvanic coating is another common protection method against corrosion. Active metals, such as zinc, have a great tendency to oxidize when compared to the primary steel member, which is protected by the zinc layer. This method is also commonly used in corrugated steel culverts and members of mechanically stabilized earth structures (Clarke et al. 2014, Elias et al. 2009).

Zinc coatings protect steel piles from corrosion by isolating the steel from its surrounding environment and by cathodic protection. The sacrificial performance of zinc coatings is dependent on the thickness of the coating and factors influencing the environment to which the piles are exposed. For example, when considering atmospheric exposure, the zinc coating corrodes faster in industrial environments compared to rural and urban environments.

Zinc, like other metals, corrodes and makes a corrosion byproduct layer called patina. This white exterior layer of zinc rust protects the zinc underneath. The patina layer is created during a series of chemical reactions.

The initial products of zinc corrosion are zinc oxide and zinc hydroxide created during natural wet and dry cycles. In later reactions of these products with available carbon dioxide in the atmosphere, zinc carbonate is produced, which is a stable layer adhering to the zinc surfaces and does not easily wash off. The corrosion rate of this layer is very low (nearly 1/30th that of the bare steel), and this layer provides long-term corrosion protection of the zinc coating. The formation of zinc carbonate turns the zinc coating to a dull gray color (AGA 2012).

Various methods are available to apply zinc to the surface of steel, including the hot-dip galvanizing method. Hot dip galvanizing is promoted by galvanizers to be one of the most effective ways of protecting steel piles from corrosion (Kumar and Stephenson 2006). This method was introduced by the French chemist P. J. Malouin in 1742, who suggested this method of coating iron by dipping it in molten zinc during a presentation for the French Royal Academy (AGA 2012).

As stated on the American Galvanizers Association (AGA) website, "hot-dip galvanizing is the process of dipping fabricated steel into a kettle or vat containing molten zinc." During the hot dip galvanizing process, the molten zinc reacts with the iron in the steel to form a coating composed of three to four different layers.

2.3 Corrosion Test Approaches

In the earlier studies on pile corrosion, test samples were buried in soil for specific periods of time, or they were taken from old structures. Since the corrosion process is very slow, and the time it takes to prepare samples with the desired corrosion levels is long, later studies utilized automated and accelerated mechanisms that simulate the specific environmental conditions in which corrosion occurs.

In the past, the continuous salt spray corrosion test following ASTM B117 has been widely adopted to study the metal corrosion process. However, for corrosion resistant materials, such as galvanized steel, the test usually takes a very long period to see significant corrosion effects. For example, Till and Davis (1998) conducted a corrosion test on a hot-dipped galvanized W-beam guardrail following ASTM B117, with the results indicating that the salt fog method failed to show significant corrosion on the galvanized specimen after a substantial exposure period of 5,000 hours (208 days).

As an alternative to consider, cyclic corrosion tests (CCTs) in a chamber have been developed in the automotive industry to study the corrosion resistance performance of materials, including those with corrosion-resistant coatings. Using the CCT approach, the specimen is first exposed to high humidity conditions with a relatively low temperature and sprayed with a near-neutral pH, salt-containing-electrolyte water. After a certain period, the specimen is then exposed to a low humidity environment with high temperature to "dry-off" the specimen. The same procedure is repeated for hundreds of cycles.

LeBozec et al. (2008) used this CCT approach to predict the lifetime of steel- and zinc-coated materials. It was concluded that the evaporation of the salty water during the dry-off process increased the concentration of electrolytes, which results in an increase of the localized attack on the surface. Consequently, this procedure leads to an increase in the corrosion rate and a rapid degradation of the material.

In addition, National Cooperative Highway Research Program (NCHRP) 20-07 (Elzly Technology Corporation 2014) summarized that the GMW 14872 (2010) CCT approach was used by the US military to predict the service life of various coatings and materials on vehicles. The researchers found that, for the coated galvanized material, 150 cycles were equivalent to 25 years with an acceleration factor of 60 (GMW 2006).

In the field of civil engineering, Elzly Technology Corporation (2014) used the GMW 14872 CCT approach to test the corrosion rate of a galvanized W-beam guardrail section. The results indicated that visual rusting occurred after 120 cycles.

CHAPTER 3. LABORATORY TESTING

The objective of the laboratory investigation was to estimate how many years the traditional steel pile and galvanized steel pile, with or without painted coating, can satisfactorily perform. It was thus proposed that the test procedure used for this research would generally follow GMW 14872, which is the same procedure used in NCHRP 20-07 (Elzly Technology Corporation 2014).

In this chapter, the details of the laboratory tests are presented in Section 3.1. The specimen design and specimen construction are presented in Section 3.2. The results from each test are presented and discussed in Section 3.3.

3.1 Cyclic Corrosion Tests (CCTs)

Each cycle was a 24-hr period and consisted of three 8-hr stages: ambient stage, humid stage, and dry-off stage. Based on NCHRP 20-07 that indicated 150 cycles were equivalent to 25 years (Elzly Technology Corporation 2014), the research team proposed that the cycles for this project would be repeated for 600 days to simulate a 100-yr pile service life.

Romanoff (1962) indicated that the rate of the corrosion of the embedded piles usually slows after the first year, as the corrosion process consumes the available oxygen in the soil. For the laboratory-tested samples, which would experience continuous exposure to the air, a higher corrosion rate would occur when compared to that of a pile embedded in soil.

As such, the test results were expected to be conservative from this perspective. However, the results would allow for a direct comparison of traditional steel piles, galvanized piles, and painted galvanized piles.

To perform the proposed laboratory testing, a chamber with sufficient internal space was utilized. Figure 2 shows the CCT chamber.

Figure 2. Cyclic corrosion test chamber

To imitate the environmental situation and reflect on available salts in nature that accelerate the corrosion process, a salt-containing electrolyte (simply called salt solution) was uniformly sprayed with a nozzle on the samples. The salt solution was the combination of three main salts, including 9.05 g/liter of sodium chloride (NaCl), 1.01 g/liter of calcium chloride ($CaCl_2$), and 0.75 g/liter of sodium bicarbonate ($NaHCO_3$).

The chamber simulated years of environmental exposure through repetitive cycles. Each cycle was a 24-hr period and consisted of three 8-hr stages: ambient stage, humid stage, and dry-off stage. Two reservoirs in the chamber supplied the salt solution and the deionized (DI) water to produce the required humidity. Figure 3 shows the predefined temperature and humidity variation in each period during one cycle inside the chamber based on the GMW 14872 specification (GMW 2006).
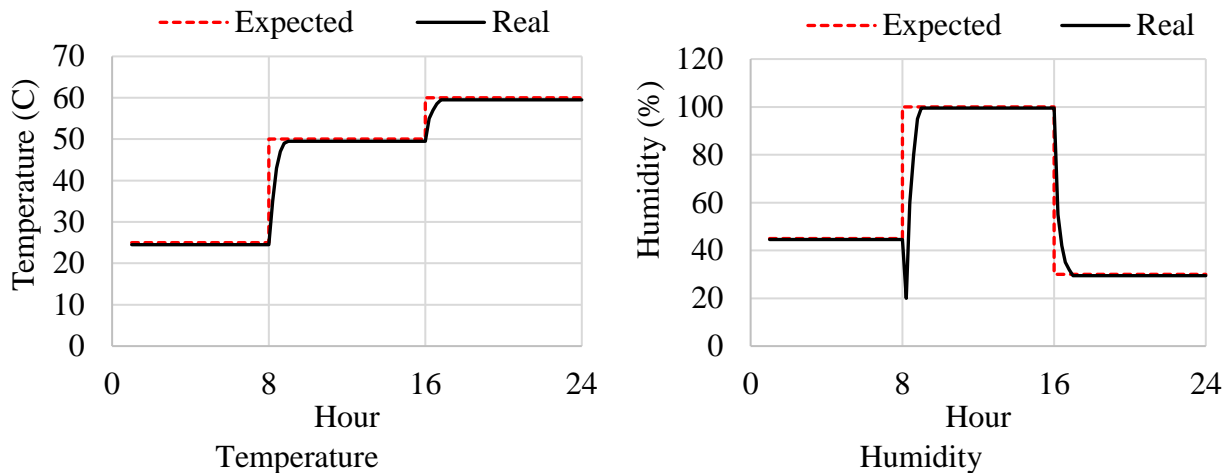
Figure 3. Temperature and humidity variation during each cycle

During the first 8-hr period, called the ambient stage, the temperature was 77°F (25°C), and the relative humidity was about 45%. In the second period, called the humid stage, the temperature rose to 122°F (50°C), and the relative humidity rose to nearly 100%. In this period, a salt solution fog was produced and uniformly enveloped the samples. The last 8-hr period is called the dry-off stage, and the temperature was increased to 140°F (60°C), while the relative humidity dropped to 30%.

As shown in Figure 3, changing the humidity and temperature inside the chamber between the stages took about 30 minutes, after which the measured temperature and relative humidity were maintained.

3.2 Specimen Descriptions

Two types of specimens (coupon and one-foot length of pile) were prepared for the tests including bare steel and others with various protective methods. Table 1 lists the details for all the specimens tested in the CCT chamber.

Table 1. Specimen descriptions

Specimen type	Coating method	No. of specimens
	None, bare steel	3
	Galvanized pile	3
	Painted galvanized	3
Coupon	Painted galvanized, with painting layer damaged	3
	Painted galvanized, with both painting and galvanizing layers damaged	9 Total: 3 with 1/8 in. wide damage 3 with 2/8 in. wide damage 3 with 3/8 in. wide damage

Specimen type	Coating method	No. of specimens
One-foot pile	None, bare steel	3
	Galvanized pile	2
	Painted galvanized	2
	Painted galvanized, with painting layer damaged	2

Five variations of coupon specimens were included: bare steel, galvanized, painted galvanized, painted galvanized with simulated paint layer damage, and galvanized with the galvanizing layer damaged. For the 1-ft pile specimens, four variations were included: bare steel, galvanized, painted galvanized, and painted galvanized with simulated paint layer damage. Figure 4 shows the samples inside the cyclic corrosion chamber.

Figure 4. Samples inside the cyclic corrosion chamber

3.2.1 Coupon Samples

The coupon samples were prepared and tested with their weights easily measurable. All the coupon specimens were cut from the flanges of the same pile section that was used to fabricate the 1-ft pile specimens. The pile size (HP 10×57) was also the size of that used for the Buffalo Creek Bridge. These coupons were about 2×2 in. square-shaped with a thickness of about 0.5 in. The weights of these samples ranged from 269.98g to 300g.

Steel (S) Coupon Samples

Three steel coupon samples were prepared. After they were cut, no protective measure was applied to the coupon surfaces. Appendix A.1.1 shows the condition of the S coupon samples during the CCT process.

Galvanized (G) Coupon Samples

Three steel coupon samples were galvanized based on ASTM A123 guidelines (AGA 2012). These coupons were galvanized utilizing the hot-dip galvanizing method. Given that all pile sections commonly used under a bridge have a web and flange thickness greater than 1/4 in., the coupons were galvanized as grade 100 according to AGA (2012). With this grade, a minimum coating thickness of 3.9 mils (100 µm) was applied, which provides a 2.3 oz/ft^2 zinc layer on each surface. In general, the galvanizing layer increased the sample weight by about 5.43g (0.19 oz). Appendix A.1.2 shows the condition of the G coupon samples during the CCT process.

Painted Galvanized (P) Coupon Samples

Three painted galvanized coupon samples, named P samples, were first galvanized with the same approach as that used for the G samples. After that, the samples were painted with primer and a top paint layer. The primer layer was a cycloaliphatic amine epoxy, which gives a thickness of 4 to 6 mils (102–152 µm), and the top layer was an aliphatic acrylic-polyester polyurethane, which gives a thickness a 3 to 5 mils (76–127 µm). In general, the galvanizing and painting layers increased the sample weight by about 8.09g (0.28 oz). Appendix A.1.3 shows the condition of the P coupon samples during the CCT process.

Painting Layer Damaged (D) Coupon Samples

During field installation of bridge piles, it is common for the paint coating to become damaged when handled or when driven into the ground. To simulate the effect of these damages on the coating layers, additional coupon samples were prepared.

Three coupon samples were made to simulate the damage on the painted layer. To mimic this type of damage, areas of the galvanized samples were covered with adhesive tape before painting. When the painting process was completed, the tape was removed, and the galvanized surfaces beneath the tape were exposed. With these three samples, the galvanized coating was undamaged and intact. Appendix A.1.4 shows the condition of the D coupon samples during the CCT process.

Galvanizing Layer Damaged (SG) Coupon Samples

The last group of coupon samples were SG samples. The purpose of preparing these samples was to investigate the effect of damage to the galvanized layer. The damage on these samples was

made by removing a portion of the galvanized coating with an electric grinder. Note that these samples were only galvanized, not painted.

In total, nine coupon samples were prepared using this approach with damage in three different widths. The first group included three samples with a scratch width of 1/8 in. and were named SG-18. The second group included three samples with a scratch width of 2/8 in. and were named SG-28. Finally, the last group included three samples with a scratch width 3/8 in. and were named SG-38. Appendix A.1.5, A.1.6, and A.1.7 show the conditions for the SG-18, SG-28, and SG-38 samples, respectively, during the CCT process.

3.2.2 One-Foot Pile Samples

To obtain a direct visualization of the corrosion process on the pile structures, nine 1-ft long HP 10×57 sections (three bare steel, two galvanized, two galvanized with painted coating, and two galvanized and painted with painting layer damaged) were prepared and placed into the chamber, as shown in the previous Figure 4. Appendix A.2.1 through A.2.4 show the condition of the S, G, P, and D pile samples, respectively, during the CCT process.

3.3 Laboratory Test Results

The change in surface condition is evaluated by measuring the rate of the coupon mass loss or gain. The weight of the coupon was measured with a precision of 0.01 gram on day 1, 3, 5, 15, 30, and every 30 days from the 30th day to the 600th day. Before each measurement, to be accurate, the accumulated salts on the surface of the S samples and G samples were removed using a fine-metal brush. To avoid damaging the paint layer, the other coupon types were only cleaned by rinsing with water and wiping dry.

In addition to measuring the coupon weight, the changes in surface condition of each coupon sample was captured utilizing a high-resolution camera. Examples of these images for each sample type are included in Appendix A.1.1 through A.1.7.

The nine 1-ft long piles were continuously placed in the cyclic corrosion chamber during the 600 days of testing. Before and after the CCT process, numerous images were captured for each pile specimen, providing a visual comparison of the condition of the piles before and after a simulated 100-yr service life. These images are included in Appendix A.2.1 through A.2.4.

3.3.1 Coupon Sample Test Results

S Sample Results

The S samples were bare steel samples without any coating. Figure 5 shows the weight variations for each of the S samples and their average during the 600 days.
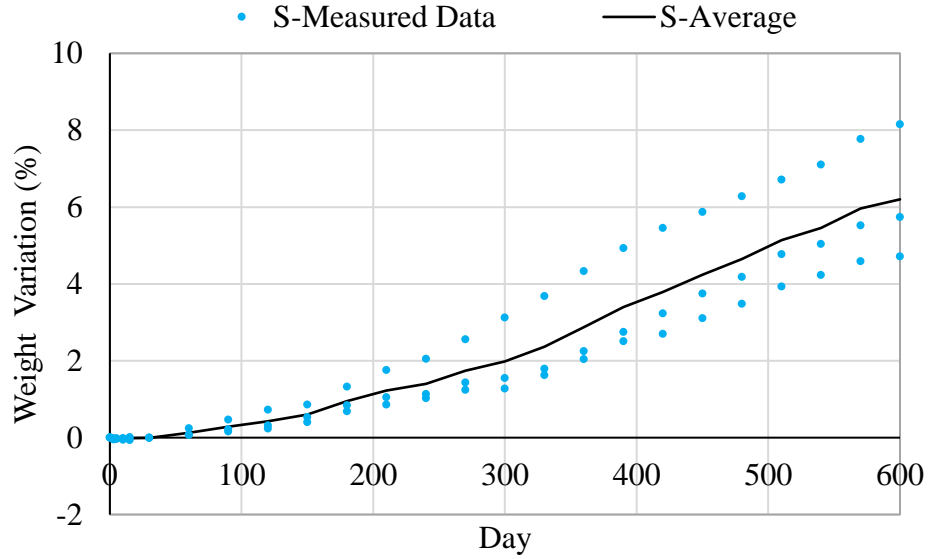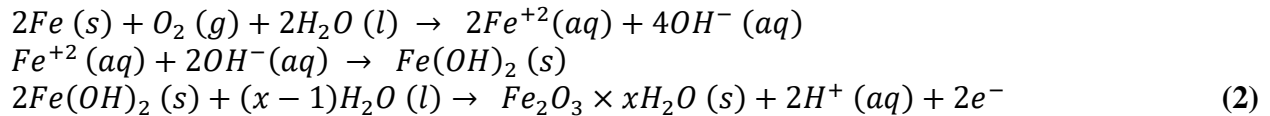
Figure 5. Weight variation (%) of samples without coating

Figure 5 shows that the weight of the samples continually increased through the duration of the CCT process. This weight variation occurred as a result of a series of chemical reactions that take place during the oxidizing process of steel. These chemical reactions can be expressed as equation (2) (McCafferty 2010, Gräfen et al. 2000).

$$2Fe\ (s) + O_2\ (g) + 2H_2O\ (l)\ \rightarrow\ 2Fe^{+2}(aq) + 4OH^-\ (aq)$$
$$Fe^{+2}\ (aq) + 2OH^-(aq)\ \rightarrow\ Fe(OH)_2\ (s)$$
$$2Fe(OH)_2\ (s) + (x-1)H_2O\ (l)\ \rightarrow\ Fe_2O_3 \times xH_2O\ (s) + 2H^+\ (aq) + 2e^- \qquad \textbf{(2)}$$

To validate the obtained data, weight changes of the coupons were converted to the thickness variation that was used in previous research (Baboian and Treseder 2002). To achieve this, a few assumptions were made: thickness loss happens at the same rate for all surfaces of the coupon; only Fe_2O_3 was produced as the result of the chemical reaction; and, although in equation (2), the x amount of water is attached to the iron oxide (Fe_2O_3), in this study, it was assumed that the measured weight variation was completely due to the iron oxide (Fe_2O_3), and the water evaporated during the dry period.

Figure 6 shows a view of the coupon with initial dimensions (a, b, and c) and final dimension (a′, b′, and c′) after a thickness loss of dt of each face in all directions.
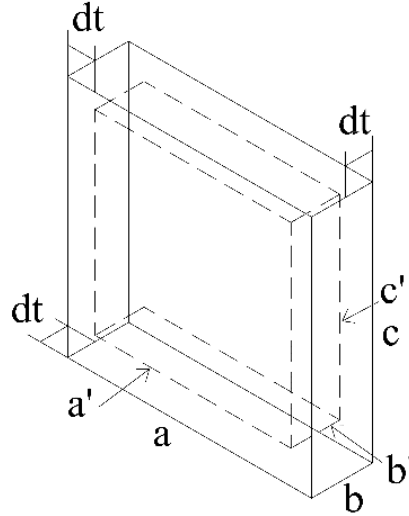
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Figure 6. Coupon sample dimensions before and after corrosion

The volume of the corroded steel, dv, could be calculated based on the initial dimensions and section loss as follows:

$$dv = 2(a \times c \times dt) + 2(b - 2dt) \times a \times dt + 2(c - 2dt)(b - 2dt) \times dt$$
$$= 2(a \times c + a \times b + b \times c)dt - 4(a + b + c)dt^2 + 8dt^3 \tag{3}$$

Given that dt is small, all terms taking dt to the second and third power in equation (3) can be ignored, and this equation can be simplified as follows:

$$dv = 2(a \times c + a \times b + b \times c)dt \tag{4}$$

With equation (4), the thickness variation of the thickness loss, $dt,$ can be calculated utilizing equation (5):

$$dt = \frac{dw}{2\rho(a \times b + a \times c + b \times c)} \tag{5}$$

In the above equation, ρ is the density of steel with the value of 7.87 gr/cm^3 (128.65 gr/in^3), and dw is the weight of the steel that participates in the chemical reaction. The weight of the steel that participates in the chemical reaction, dw, can be obtained based on equation (2) and the molar weights of iron (55.845 gr/mol) and oxygen (15.999 gr/mol) (National Center for Biotechnology Information 2022).

Based on the chemical reaction resultant iron oxide (Fe_2O_3), the oxidizing of every two iron atoms needs three oxygen atoms. Hence, the weight of steel that participates in the chemical reaction, dw, can be calculated based on the weight of oxygen that participates in the reaction, which is the weight gained in each measurement. With that, the weight change in the recorded data needs to be multiplied by a factor $c,$ or 2.312, which can be calculated as follows:

$c = 2 \times 55.485 / 3 \times 15.999 = 2.312$ **(6)**

Figure 7 shows the resulting thickness variation (solid squares) fitted by the linear regression (dashed line).
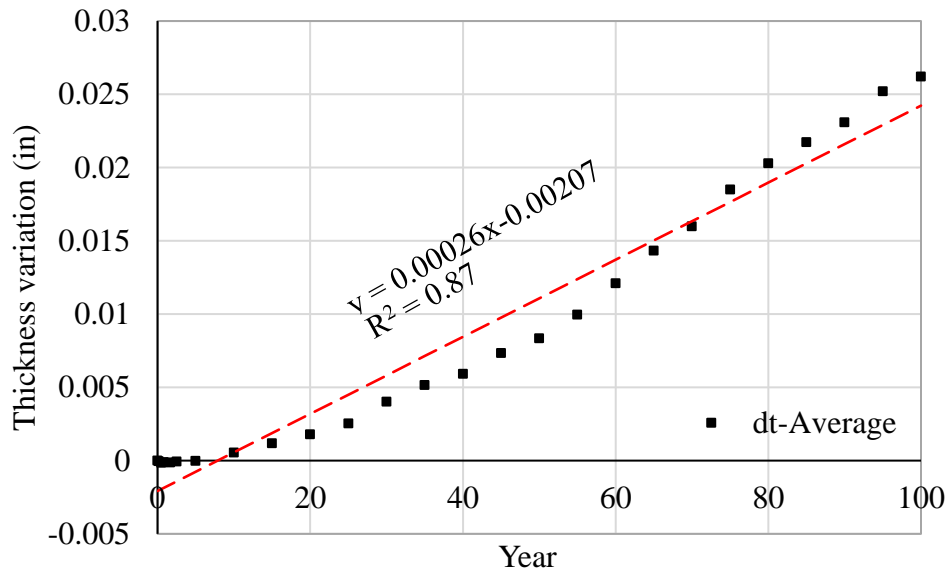
Figure 7. Estimated thickness loss of the bare steel in each year

The slope of the dashed line (0.00026 in/yr) shows the thickness loss per year on one side of the coupon. This value is close to the suggested value of 0.000235 in/yr (0.00047 in/yr for two sides) in various references (EN 1993/Eurocode 3, Gaythwaite 1981, Ohsaki 1982).

Appendix A.1.1 includes images of the corrosion process for one of the S coupon samples. The test results showed that, during the first 30 days, the uncoated steel coupons quickly formed iron-oxide on their surfaces.

G Sample Results

Figure 8 shows the weight variations for the G coupon samples and their average during the 600 days of CCT cycles.

Figure 8. Weight variation (%) of samples with galvanized coating

The plot shows that the weight of the samples decreased significantly during the first 100 days, which could be caused by the loss of the galvanized layer during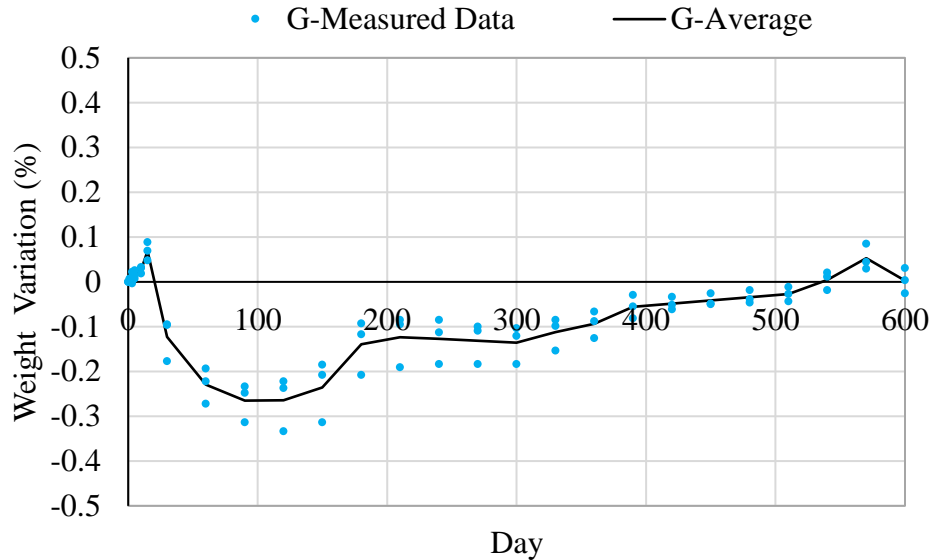 brush cleaning. Although the metal brush was used through 600 days, the weight after nearly 120 days (20 years), started to increase until the end of the period. This is because a patina layer (zinc carbonate) formed on the surface of the coupons after 120 days, which is harder than the fresh galvanizing layer. Hence the hand brush induced less effect on the weight of the coupons. Nevertheless, comparing to the weight change (about 6%) of the S samples in the previous Figure 5 at 600 days, the weight variation of G samples was small (within ±0.3%).

Appendix A.1.2 includes images of the corrosion process for one of the G coupon samples. The images show that the galvanized surfaces continually changed during the first 120 days to form a patina layer (zinc carbonate). After that, the surface changes were less significant.

P Sample Results

Figure 9 shows the weight variations for the P coupon samples and their average during the tests.
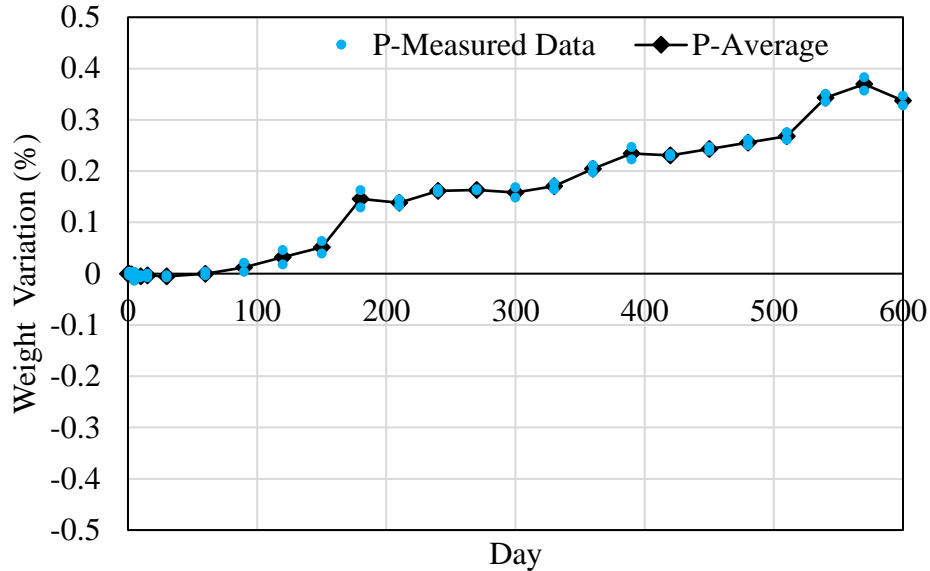

Figure 9, Weight variation (%) of samples with painted galvanized coating

Appendix A.1.3 includes images of the corrosion process for one of the P coupon samples. The data indicate that, in the first 60 days (10 years), the paint is completely intact and the variation in the weight of the samples is not significant. However, after 60 days, the weight of the samples started to increase, which coincides with the observed cracking of the paint layer.

This result indicated that, after 60 days, the paint layer was compromised and was unable to fully prevent oxygen and moisture from reaching the galvanized layer, and the oxidation process of zinc increased the weight of the samples. This result indicated that the paint layer contributes to the overall length of the surface life by delaying the oxidation of the galvanized layer for at least 10 years, in this case.

The data for the P2 samples included two sudden weight drops, which occurred after 210 days and 270 days. These occurred because of the rapid deterioration of the paint layer (peeling and separation) from the sample. (Appendix A.1.3 includes images of a P2 sample.) Because of the significant change in the weight, the data from the P2 samples were not presented or used in the experimental result analysis. The previous Figure 9 includes the weight variations of the P1 and P3 samples and their average values in 600 days.

D Sample Results

Figure 10 shows the weight variations for the D coupon samples and their average during the 600 days of testing.
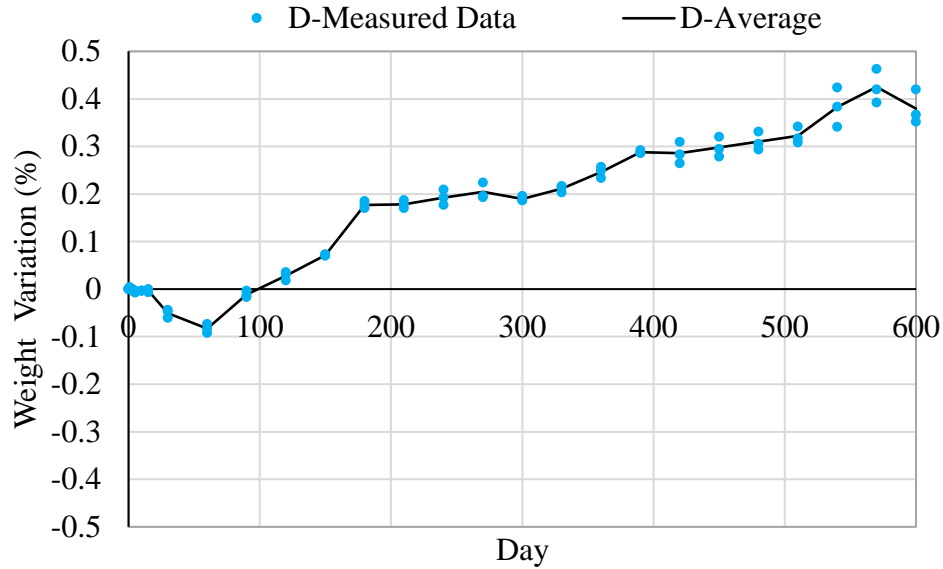
Figure 10. Weight variation (%) of samples with damaged painted galvanized coating

In general, the weight changes of the D samples showed a similar trend and magnitude as that for the P samples. This result indicated that the damage on the paint layer does not impose significant weight change on the samples.

Appendix A.1.4 includes images of the corrosion process for one of the G coupon samples. The images show similarities to the G and P samples where a patina layer (zinc carbonate) formed on the exposed galvanized layers.

SG Sample Results

Figure 11, Figure 12, and Figure 13 show the weight variations for the SG-18, SG-28, and SG-38 samples, respectively, and their averages.
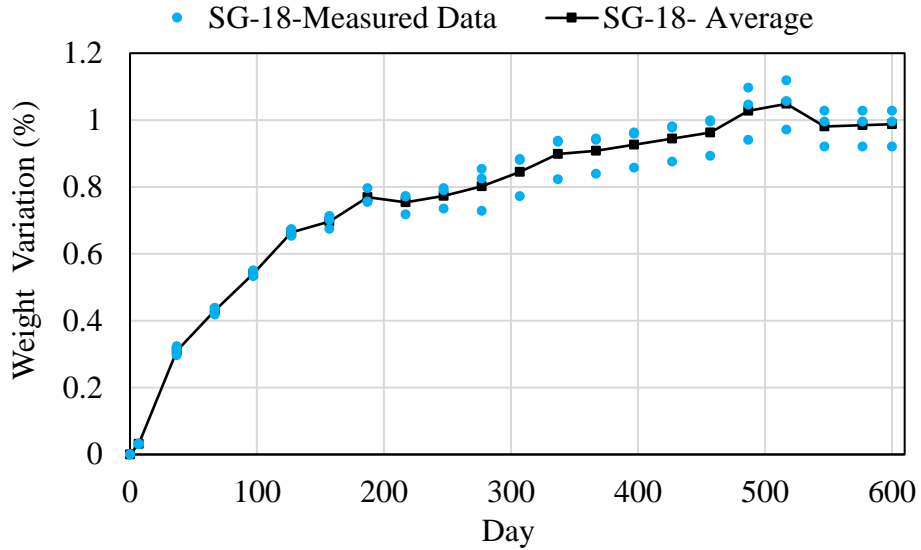
Figure 11. Weight variation (%) of SG-18 samples
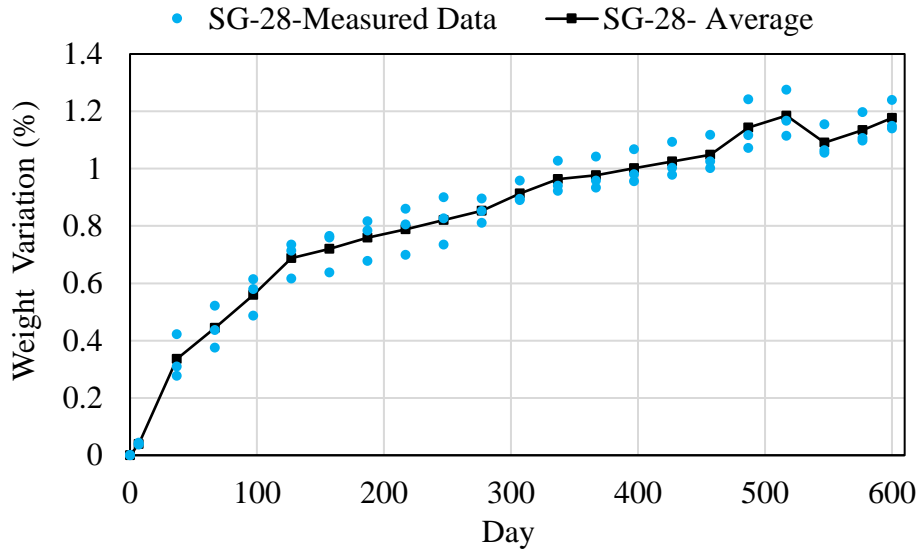
Figure 12. Weight variation (%) of SG-28 samples
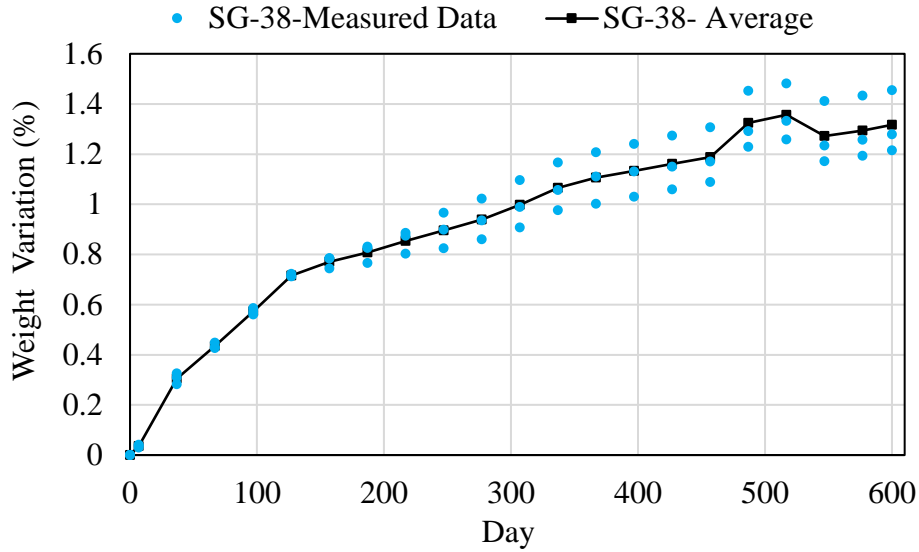
Figure 13. Weight variation (%) of SG-38 samples

The data indicated that, on all of these samples, the weight significantly increased during the first 120 days (20 years), regardless of the width of the scratches. These weight variations are induced by the steel oxidation process where the galvanizing layers are damaged, and the bare steel is exposed. After this period, the rates of the weight changes are reduced. In general, the samples with wider scratches resulted in higher weight variations.

Appendix A.1.5, A.1.6, and A.1.7 include images for the corrosion process of the SG-18, SG-28, and SG-38 samples, respectively. The results showed that a damaged galvanized layer offers better protection to smaller scratches, and galvanized coatings have an ability to restore protection to exposed areas where the scratch width is relatively minor.

3.3.2 One-Foot Pile Test Results

The weights of the 1-ft pile sections were only measured on the first and last (600th) days of testing. These samples included three bare steel samples (S1, S2, and S3), two samples with galvanized coating (G1and G2), two samples with painted galvanized coating (P1 and P2), and two samples with damaged painted galvanized coating (D1 and D2).

Figure 14 compares the weight measurements before and after the 600 days of testing for all the pile samples.
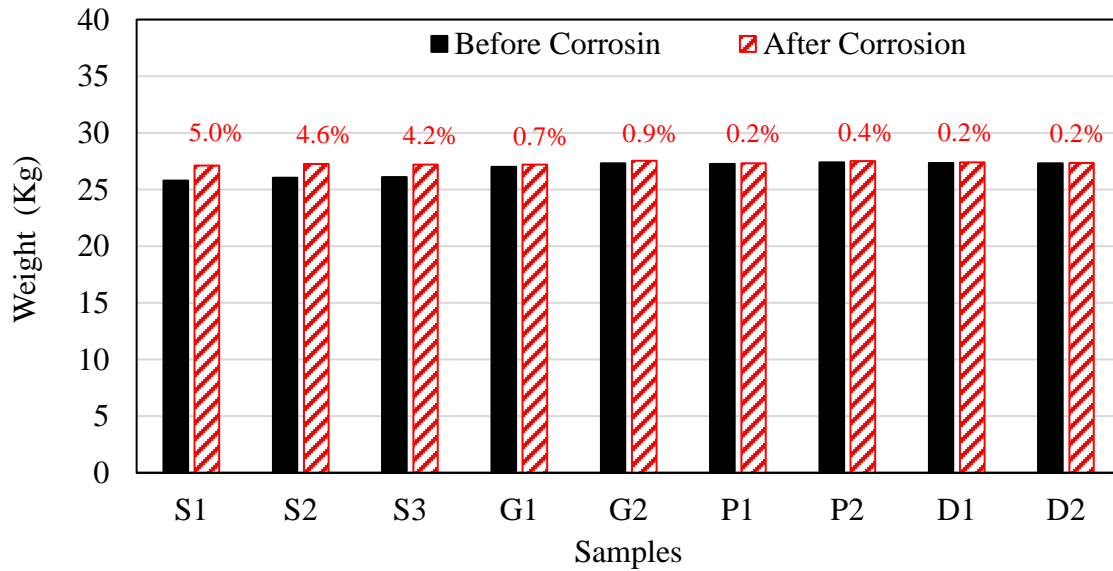
Figure 14. Weight variation in one-foot pile sections

The results indicated that, for the S samples, the weight of each pile increased by 4.2% to 5.0%. For the three types of coating samples, the weight of each increased by 0.2% to 0.9%.

Appendix A.2.1 through A.2.4 include representative images for the S, G, P, and D pile samples, respectively. Similar to the findings from the coupon samples, the bare steel piles experienced significant rusting, the G piles formed a patina layer (zinc carbonate) on the surface, the P piles experienced the peeling and separation of the paint layer, and the D piles formed a patina layer (zinc carbonate) where the galvanized layer was exposed and cracking and delamination of the paint layer also exposed the galvanized layer below.

3.3.3 Test Results Analysis and Discussion

Figure 15 shows the average weight variations for the S, G, and P coupon samples.

Figure 15. Comparison of average weight variation (%) for S, G, and P samples

The results indicate that the S samples, without any protective measures, gain weight (and lose cross-sections) at a higher rate compared to the G and P samples with galvanized and/or paint layers. This figure also shows that the weight variation magnitude for the P and G samples are very similar.

Figure 16 compares the average of the weight variations for the G, P, D, and SG samples.
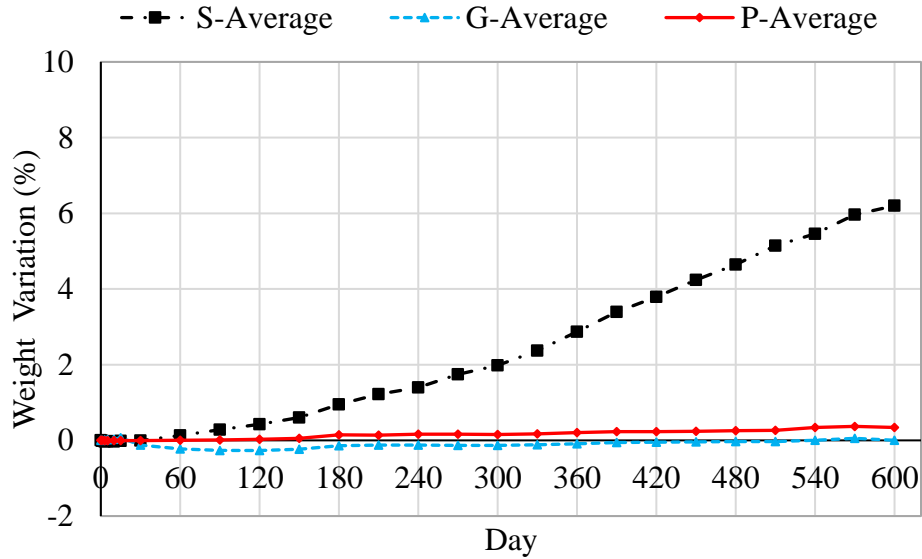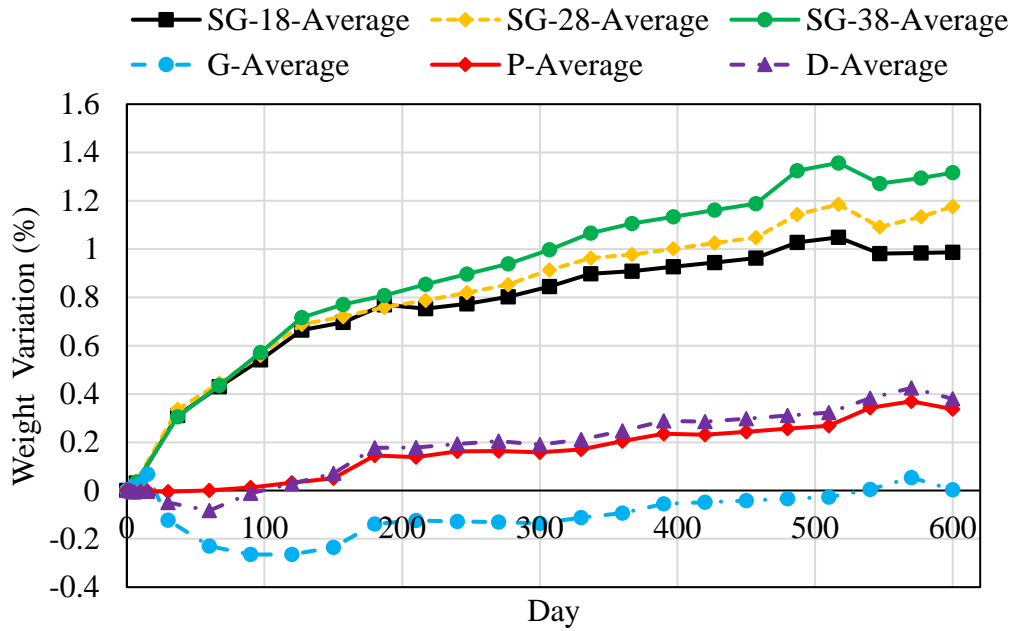

Figure 16. Comparison of average weight variation (%) for G, P, D, and SG samples

The results indicate that, with a portion of steel exposed to the air, the SG samples experienced a much higher weight increase than the other three sample types. This is induced by the oxidation process of the bare steel. The results indicate that the oxidation process of the steel is the main source of the weight increase. This also demonstrates that damage of the galvanized surface can result in greater weight increases when compared to the damage of only the paint on painted galvanized samples.

Comparing between the SG-18, SG-28, and SG-38 samples, the results showed that the samples with higher scratch width eventually resulted in a higher weight variation. Comparing the results from the P and D samples, the weight increase for the D samples was slightly higher than that for the P samples. This was induced by the oxidation process of the large portion of unpainted galvanized surface on the D samples.

CHAPTER 4. FIELD INVESTIGATION OF PILE CORROSION

This study took advantage of a unique opportunity to monitor the performance of a painted galvanized pile system on a bridge structure in Iowa. In this chapter, a bridge constructed with painted and galvanized piles was selected for the evaluation of the on-site performance of the coated piles. In order to do this, yearly monitoring via in situ ultrasonic tests (UTs) on the thickness of the pile flanges was conducted accompanying visual inspections to quantify any section loss.

The in situ UTs were performed utilizing the Krautkramer DM4 ultrasonic thickness. The DM4E, DM4, and DM4 DL gauges are hand-held, microprocessor-controlled instruments designed for general thickness measurements on a variety of elements that have access to them on only one side gauge (GE 2022). This capability is especially important in the measurement of remaining wall thicknesses for tubes, pipes, pressure vessels, and other elements subject to wall thickness loss due to corrosion or erosion.

With this device, the sound waves reflect from the first interior surface encountered. Because of part geometry and overlapped flaws or overlapped surfaces, thickness gauges may measure the distance to an internal flaw rather than to the back wall of the material. Operators must take steps to ensure that the entire thickness of the test material is being examined (GE 2022). Hence, during the field work, this gauge was used in conjunction with visual observation, which, to this point, showed no significant change in pile conditions.

4.1 Bridge Description

The bridge is located on Buchanan County Road (CR) D-22 over Buffalo Creek. The bridge has three spans totaling 200 ft in length, and the bridge is 40 ft wide. The bridge superstructure consists of steel girders and a concrete deck. The superstructure bears on concrete abutments supported by painted galvanized piles at each end and two piers comprised of painted galvanized piles and concrete pile caps. The pile size used in each location is HP 10×57. Figure 17 shows the bridge side view with specific focus on the pier structures.

a) Bridge side view (with water level low)

b) Bridge side view (with water level high)

c) Galvanized and painted piles

Figure 17. Field evaluated bridge

The bridge construction extended from August 2018 through January 2019 with the piles driven in September 2018. The bridge plans contain the following note regarding the HP 10×57 piling:

All pilings shall be galvanized in accordance to ASTM 123 as well as coated with a protective spray that shall comply with regulations set forth in SSPC Guide 19.

Buffalo Creek is especially sensitive to high-total rain events. A significant amount of rain can quickly raise the water levels; thus, the piles are differently exposed to air, water, and river debris throughout its service life. Generally, the water level remains low as shown in Figure 17-a. However, it is not unusual to see increased water levels like that shown in Figure 17-b. When precipitation ceases, the water levels drop relatively quickly.

4.2 Coating Thickness Measurement

The bridge is oriented in the east-west direction. Piles on the west pier were selected for the thickness measurements as shown in the previous Figure 17-b. Figure 18 compares the images of 10 measurement locations over three years from March 28, 2019 through May 3, 2021.

| a) Measurement location 1 and 2 | b) Measurement location 1 and 2 |
| March 28, 2019 | May 3, 2021 |

c) Measurement location 3 and 4
March 28, 2019

d) Measurement location 3 and
May 3, 2021

e) Measurement location 5 and 6
March 28, 2019

f) Measurement location 5 and 6
May 3, 2021

g) Measurement location 7 and 8
March 28, 2019

h) Measurement location 7 and
May 3, 2021

| i) Measurement location 9 and 10 | j) Measurement location 9 and 10 |
| March 28, 2019 | May 3, 2021 |

Figure 18. Measurement locations on March 28, 2019 and May 3, 2021

In total, 10 unique locations close to the edge of the pile flanges near the ground surface were selected. Note that, as the water level changes, some of these measurement locations were inaccessible at the time of measurement. All of the measurements were taken after the water level receded and the locations were exposed.

4.3 Results and Discussion

Table 2 presents the thickness data from the 10 measurement locations taken during the four trips from 2019 through 2021.

Table 2. Thickness measurement results

Date	Pile Location/Thickness (in.)									
	1	2	3	4	5	6	7	8	9	10
3/27/2019	0.611	0.617	0.594	0.604	0.605	0.619	0.604	0.586	0.601	0.619
10/18/2019	0.604	0.611	0.596	0.607	0.611	0.624	0.603	0.590	0.606	0.604
6/10/2020	Water level was high.									
5/3/2021	0.587	0.572	0.552	0.557	0.583	0.607	0.591	0.572	0.619	0.565

For the 2020 site visit, the water level was high (as shown in Figure 17), and no thickness data were collected.

It can be concluded that, within the first three years, the painting and galvanizing coating performed well, and no damage or corrosion was observed near the measurement locations.

Given the amount of data was not sufficient to make any reliable conclusion on the thickness change, the data were not further analyzed at this point. The research team will continue to collect more annual data for future analysis.

CHAPTER 5. ECONOMIC EVALUATION

The available approaches to prevent bridge piles from the detrimental structural effects of corrosion include adding a galvanized coating, using a duplex system of galvanized and painted coating, and/or increasing the sizes of the cross-sections to allow for section loss.

The results from the experimental tests to date revealed that both galvanized and galvanized and painted coating methods show remarkable performance in preventing corrosion, and both methods can protect piles from corrosion for more than 100 yrs, which is the U.S. highway bridge design life. In addition, the paint layer delays the oxidation of the galvanized layer for at least a simulated 10-yr period.

This chapter presents the economical comparison that was conducted between the use of a larger H-pile section, a galvanized coating, and a painted galvanized coating to protect the piles against corrosion.

This analysis was conducted using the HP 10×57 pile section given this section was used for both the CCT process and the Buffalo Creek Bridge. Based on the information obtained from the Buchanan County engineer, the total finished cost (including the material and installation costs) of bare steel HP 10×57 piles for the Buffalo Creek Bridge would have been $36.00/LF. For painted galvanized piles, this cost increased to $85.00/LF. The cost for just galvanizing the piles was not available; however, this value should be in the range between the cost of bare steel and the cost of painted galvanized piles. Hence, it was assumed for this example that 60% of the total cost of painting and galvanizing is for galvanizing and 40% of it is for painting. This assumption brings the estimated value for the galvanized pile cost to $65.40/LF.

An HP 10×57 section has a web and flange thickness of 9/16 in. The closest section with an increased web and flange thickness is an HP 12×74 with a web and flange thickness of 10/16 in. Assuming that pile cost increases proportionally to the increase of the pile weight, the expected cost for the bare HP 12×74 pile is about $47.00/LF. The web and flange thickness of this section is 10/16 in. The results from the coupon test in Section 3.3.1 indicated that the thickness loss on each surface of the bare steel is about 0.00026 in/yr. Based on this, the expected service life of an HP 12×74 section is about 119 years before the flanges decrease to the same thickness as the HP 10×57.

Table 3 compares the unit costs between different protection methods.

Table 3. Comparison of the costs between different protection methods

	HP 10×57 Bare Steel	HP 10×57 Galvanized	HP 10×57 Painted Galvanized	HP 12×74 Bare Steel
Cost ($/LF)	36	65.4	85	47
Cost over the cost of HP 10×57 Bare steel	100%	182%	236%	130%

In this table, the cost of each method was compared with the cost of HP 10×57 bare steel.

The results indicated that, the most economical solution to ensure the pile can provide the required capacity throughout the intended service life is to use a larger pile section. When an HP 10×57 pile is required for the design capacity, an HP 12×74 could be used with an extra cost of about 30%. However, in the same situation, if the galvanizing method or painting (and galvanizing) methods are used, these methods induce a cost increment of 82% to 136%.

It should be noted that this example was conducted using an HP 10×57 with an HP 12×74 as an alternative, and the costs are based on the market prices of steel at the time of bridge construction. The result may change when a larger pile section is required for the design capacity.

Furthermore, the price of the galvanized and paint coatings used in this example reflect the prices for one project using uncommon methods. It is possible that increased use of duplex methods on H-piles could reduce the overall costs borne by other projects due to the economy of scale. Hence, it is recommended that a cost-benefit calculation be performed prior to the selection of pile protection measures.

CHAPTER 6. SUMMARY AND CONCLUSIONS

Interest has grown in using coatings to protect bridge piles from in situ environmental conditions. Of main interest are galvanized piles and painted galvanized piles, which provide added protection. However, the information available to support the use of these coatings is limited. Thus, additional research was warranted. The primary objective of this research was to evaluate the effectiveness of galvanized and painted galvanized piles in extending bridge service life in a cost-effective manner.

To achieve the objective, a systematic laboratory and field investigation, coupled with a life-cycle cost analysis was conducted. This project began with a comprehensive literature search, which supplemented the knowledge and experience of the research team in working with substructure components.

In the laboratory, a series of coupon samples and pile sections coated using corrosion protection methods were tested through an accelerated corrosion testing protocol. The in-place performance of a bridge constructed using painted galvanized steel components was evaluated for its long-term corrosion resistance performance. A service life analysis was then performed to understand the costs and benefits associated with using substructure coatings, which is an important step in making the decision to implement the investigated coatings on a broader scale.

Based on the results from the laboratory tests, the following conclusions can be drawn:

- Without protection, bare steel sees the most significant change in surface condition through the formation of iron-oxide. The thickness loss on each surface of the bare steel is about 0.00026 in/yr.

- Both galvanized and galvanized and painted coating methods perform well in protecting bare steel and in preventing corrosion. Both methods have the potential to protect piles from corrosion for more than 100 years, which is the U.S. highway bridge design life.

- Paint coatings initially offer additional protection, but eventual degradation of paint leaves the galvanized layer to provide the protection alone. The paint layer delayed the oxidation of the galvanized layer for at least a simulated 10-yr period. The painted galvanized coupons showed no appreciable change on the surface condition except for where the paint had been penetrated.

- Damaged galvanized layers offer better protection to smaller scratches (self-healing).

- The initial three-year period of service life of the Buffalo Creek Bridge in Buchanan County shows the paint and galvanized coating of the piles to perform well with no damage or corrosion observed.

- With a 100-yr bridge design life, the most economical solution to maintain the required design capacity of steel bridge piles is to increase the section size of the pile to allow for section loss without compromising the required pile capacity. The cost to increase the pile size is less than the premium for galvanizing or galvanizing and painting the piles. However, a cost-benefit evaluation for each protection measure is suggested knowing that costs can vary widely depending on specific project requirements, location, market prices, etc.

REFERENCES

A.B. Chance Company. 2003. Step 7 – Corrosion Guide. *Helical Screw Foundation System Design Manual for New Construction*. A.B. Chance Company, Centralia, MO.

Alcántara, J., D. de la Fuente, B. Chico, J. Simancas, I. Díaz, and M. Morcillo. 2017. Marine Atmospheric Corrosion of Carbon Steel: A Review. *Materials*, Vol. 10, No. 406, pp. 1–67.

AGA. 2012. *Hot-Dip Galvanizing for Corrosion Protection - A Specifier's Guide*. American Galvanizers Association, Centennial, CO.

ASTM B117-19 Standard Practice for Operating Salt Spray (Fog) Apparatus. ASTM International, West Conshohocken, PA.

Baboian, R. and R. S. Treseder. 2002. *NACE Corrosion Engineer's Reference*. Third edition. National Association of Corrosion Engineers (NACE) International, Houston, TX.

Becker, S. and K. Rudat. 2015. *I-43 Leo Frigo Memorial Bridge Investigation Report*. Wisconsin Department of Transportation, Madison, WI.

Clarke, W. M., P. D. Krauss, and J. S. Lawler. 2014. *Maintenance and Design of Steel Abutment Piles in Iowa Bridges*. Iowa Highway Research Board and Iowa Department of Transportation, Ames, IA.

Corus. 2005. *A Corrosion Protection Guide for Steel Bearing Piles in Temperate Climates*. Corus Construction and Industrial, Scunthorpe, UK.

Elias, V., K. L. Fishman, B. R. Christopher, and R. R. Berg. 2009. *Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes*. FHWA-NHI-09-087. National Highway Institute, Federal Highway Administration, Washington, DC.

Elzly Technology Corporation. 2014. *Comparing the Corrosion Protection of Hot Dip Batch versus Hot Dip Continuously Galvanized W-Beam Guardrail Sections*. NCHRP Project 20-07/Task 333 Task 16 Deliverable. National Cooperative Highway Research Program, Washington, DC.

EN 1993/Eurocode 3. 1993. *EN 1993-5: Eurocode 3: Design of Steel Structures - Part 5: Piling*. The European Union.

Gaythwaite, J. W. 1981. *The Marine Environment and Structural Design*. Van Nostrand and Reinhold Co., New York, NY.

GE. 2022. *Krautkramer DM4 Series Operating Manual*. General Electric. http://intechnd.nextmp.net/downloads/Manuals/DMS%204%20Series%20Manual.pdf.

GMW. 2006. *14872 Cyclic Corrosion Laboratory Test*. GM Worldwide Engineering Standards, pp. 1–21.

Gräfen, H., E.-M. Horn, H, Schlecker, and H. Schindler. 2000. Corrosion. *Ullmann's Encyclopedia of Industrial Chemistry.* Wiley-VCH.

Kumar, A. and L. D. Stephenson. 2006. *Thirty-Three Year Study of Steel Pilings in Seawater*. Corrosion 2006, 61st Annual Conference & Exposition, March 12–16, San Diego, CA, pp. 1–11.

Lebozec, N., N. Blandin, and D. Thierry. 2008. Accelerated Corrosion Tests in the Automotive Industry: A Comparison of the Performance towards Cosmetic Corrosion. *Materials and Corrosion*, Vol. 59, No. 11, pp. 889–894.

McCafferty, E. 2010. *Introduction to Corrosion Science.* Springer New York, NY.

National Center for Biotechnology Information. 2022. Compound Summary: Iron and Compound Summary: Oxygen. *PubChem*. National Library of Medicine, National Institutes of Health, Bethesda, MD.

Ohsaki, Y. 1982. Corrosion of Steel Piles Driven in Soil Deposits. *Soils and Foundations*, Vol. 22, No. 3, pp. 57–76.

Romanoff, M. 1962. *Corrosion of Steel Pilings in Soils*. Research of the National Bureau of Standards -C Engineering and Instrumentation.

Till, R. and C. Davis. 1998. *Comparison of Methods Used to Produce Hot-Dipped Galvanized W-Beam Guardrail*. Michigan Department of Transportation, Construction and Technology Division, Lansing, MI.

APPENDIX: VISUAL COMPARISONS

For each coating type of the coupon samples, one (of three) was selected as a representative. Only the images at day 0, 30, 60, 90, 120, 180, 240, 300, 450, and 600 for each sample are presented in this appendix.

For each coating type for the 1-ft pile samples, one (of three) was selected as a representative. The images at day 0 and 600 for each sample are presented in this appendix.

A.1 Coupon Samples

A.1.1 S Coupon Sample Images

Day 0	Day 30	Day 60	Day 90	Day 120

Day 180	Day 240	Day 300	Day 450	Day 600

| Day 0 | Day 30 | Day 60 | Day 90 | Day 120 |

| Day 180 | Day 240 | Day 300 | Day 450 | Day 600 |

| Day 0 | Day 30 | Day 60 | Day 90 | Day 120 |

| Day 180 | Day 240 | Day 300 | Day 450 | Day 600 |

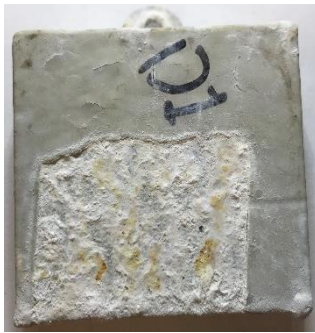Day 0   Day 30   Day 60   Day 90   Day 120

Day 180   Day 240   Day 300   Day 450   Day 600

A.1.5 SG-18 Coupon Sample Images
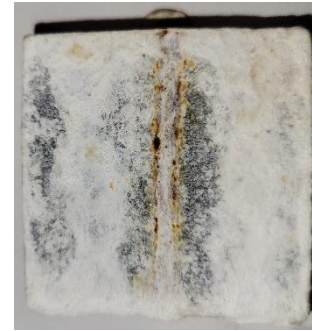

| Day 7 | Day 37 | Day 67 | Day 97 | Day 127 |

| Day 187 | Day 247 | Day 307 | Day 457 | Day 600 |

| Day 7 | Day 37 | Day 67 | Day 97 | Day 127 |

| Day 187 | Day 247 | Day 307 | Day 457 | Day 600 |

| Day 7 | Day 37 | Day 67 | Day 97 | Day 127 |

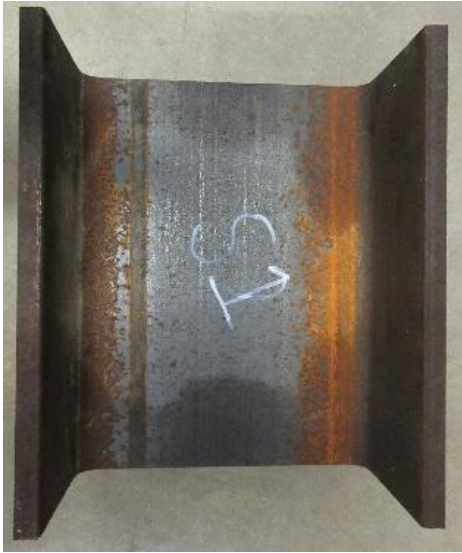| Day 187 | Day 247 | Day 307 | Day 457 | Day 600 |

A.2 Pile Samples

A.2.1 S Pile Sample Images

Day 0

Day 600

A.2.2 G Pile Sample Images

Day 0

Day 600

A.2.3 P Pile Sample Images

Day 0

Day 600

A.2.4 D Pile Sample Images

Day 0

Day 600

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