

CORROSION - AN OVERVIEW APPENDIX A

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SYMBOLS USED IN THIS SECTION

pH.....	Acidity or Alkalinity of a Solution	A-7
ASTM.....	American Society for Testing and Materials	A-7
V	Voltage	A-7
I.....	Electrical Current	A-25
R	Resistance or Resistivity	A-8
L.....	Pin spacing	A-8
NBS.....	National Bureau of Standards	A-8
FHWA	Federal Highway Administration	A-9
AASHTO	American Association of State Highway and Transportation Officials	A-9
R_{meter}	Resistivity Indication from Nillson Resistivity Meter	A-13
WSF.....	Wenner Spacing Factor	A-13
CL.....	Corrosion Weight Loss	A-17
GWT	Ground Water Table	A-19
ppm.....	Parts per Million	A-9
ASL	Allowable Steel Loss	A-21
SL.....	Service Life	A-22
G	Amount of Galvanized Coating	A-23
W_s	Weight of Steel Pile	A-24
K_2	Weight Loss by Corrosion	A-24

DISCLAIMER

The information in this manual is provided as a guide to assist you with your design and in writing your own specifications.

Installation conditions, including soil and structure conditions, vary widely from location to location and from point to point on a site.

Independent engineering analysis and consulting state and local building codes and authorities should be conducted prior to any installation to ascertain and verify compliance to relevant rules, regulations and requirements.

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INTRODUCTION

Corrosion is defined as the degradation of a material or its properties due to a reaction with the environment. Corrosion exists in virtually all materials, but is most often associated with metals. Metallic corrosion is a naturally occurring process in which the surface of a metallic structure is oxidized or reduced to a corrosion product such as rust by chemical or electrochemical reaction with the environment. The surface of metallic structures is attacked through the migration of ions away from the surface, resulting in material loss over time. Given enough time, the material loss can result in significant reduction of area, which in turn leads to a reduction in the structural capacity of a given metallic element. When corrosion eventually destroys a sufficient amount of the structure's strength, a failure will occur.

The corrosion mechanisms involved with buried metallic structures are generally understood, but accurate prediction of metal loss rates in soil is not always easily determined. This appendix provides an introduction to the concepts of underground corrosion and the factors that influence this corrosion in disturbed and undisturbed soils. A few design examples are provided to give the reader a better understanding as to whether corrosion is a critical factor in a CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Pier application. This section is not intended to be a rigorous design guide, but rather a "first check" to see if corrosion is a practical concern given the specific project site conditions. A qualified corrosion engineer should be consulted for a site specific recommendation if steel foundation products are to be used in a known corrosive soil.

Experience over the past 50 years has shown the vast majority of square shaft and round shaft helical anchors/piles have a calculated service life well in excess of the design life of the structure (typically 50 to 75 years in the United States). In highly corrosive soils and areas of stray currents (e.g., underground transmission pipelines, DC railroads) additional measures must be taken to protect steel foundation products. In these cases, active protective measures such as sacrificial anodes are employed.

CORROSION THEORY

To understand why metallic corrosion occurs, it is necessary to understand how a metal, such as carbon steel, is formed. During the steel making process, natural low energy iron ore is refined into metal. This process adds a great deal of energy to the metal. When the steel is placed into a corrosive environment, it will, by natural processes, return to its low energy state over time. To make the return trip, the steel must give up the energy gained at the mill. This is the essence of the reduction process that we call corrosion.

Mechanical strength, physical size and shape, and chemical composition of the steel are all properties that must be considered when designing CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Piers. Mechanical and physical properties are well defined and controlled during the manufacturing process. This is also true of the chemical composition, primarily due to the superior process controls used by the steel mills. Of the three properties, chemical composition is the primary factor with respect to corrosion.

Corrosion of steel is an electrochemical process. Romanoff (1957) stated:

"For electrochemical corrosion to occur there must be a potential difference between two points that are electrically connected and immersed in an electrolyte. Whenever these conditions are fulfilled, a small current flows from the anode area through the electrolyte to the cathode area and then through the metal to complete the circuit, and the anode area is the one that has the most negative potential, and is the area that becomes corroded through loss of metal ions to the electrolyte. The cathode area, to which the current flows through the electrolyte, is protected from corrosion because of the deposition of hydrogen or other ions that carry the current.

"The electrochemical theory of corrosion is simple, i.e., corrosion occurs through the loss of metal ions at anode points or areas. However, correlation of this theory with actual or potential corrosion of metals underground is complicated and difficult because of the many factors that singly or in combination affect the course of the electrochemical reaction. These factors not only determine the amount or rate at which corrosion occurs but also the kind of corrosion."

Depending on the many factors that affect the electrochemical reaction, corrosion can affect a metal in several different ways. Some of these types are listed below:

Corrosion Types, Table A-1

TYPE	CHARACTERISTICS
Uniform or Near Uniform	Corrosion takes place at all area of the metal at the same or a similar rate.
Localized	Some areas of the metal corrode at different rates than other areas due to heterogeneities in the metal or environment. This type of attack can approach pitting.
Pitting	Very highly localized attack at specific areas resulting in small pits that may penetrate to perforation.

Considerations need to be applied as to the types and rates of corrosion anticipated. Current theory does not permit accurate prediction of the extent of expected corrosion unless complete information is available regarding all factors. Therefore, uniform corrosion will be the corrosion type discussed herein.

Romanoff states there are several conditions that must be met before the corrosion mechanism takes place. These are:

Electrical Factors

Two points (anode and cathode) on a metallic structure must differ in electrical potential. The anode is defined as the electrode of an electrochemical cell at which oxidation occurs, i.e., the negative terminal of a galvanic cell. The cathode is defined as the electrode of an electrochemical cell at which reduction occurs, i.e., the positive terminal of a galvanic cell. An electrical potential can be caused by differences in grain orientation within the steel structure, i.e., different orientations of the steel grain structure can cause some grains to act as anodes while others act as cathodes, while the rest of the steel material exhibits excellent electrical conductivity. In addition, chemical anisotropy, non-metallic inclusions, strained and unstrained areas, and other imperfections on the surface of a metal can create potential differences that drive the corrosion process.

Metallic Path

The anode and the cathode must be electrically bonded or connected to complete the circuit.

Electrolyte

The principle function of soil moisture is to furnish the electrolyte for carrying current. The ions in the electrolyte may be hydrogen and hydroxyl ions from the water itself and a variety of cations and anions, which depend upon the number and amount of soluble salts dissolved in the water. The presence of these ions determines the electrical conductivity, expressed as resistivity (measured in ohm-cm), of the electrolyte, as well as chemical properties such as acidity or alkalinity, and the development of chemical reactions between the primary products of corrosion and the electrolyte. For example, ferrous material is corroded by electrolytes that contain sulfates or chlorides from the soil because the corrosion products formed at the anode and the cathode are both soluble.

Aeration

Aeration affects the access of oxygen and moisture to the metal. Oxygen, either from atmospheric sources or from oxidizing salts or compounds, stimulates corrosion by combining with metal ions to form oxides, hydroxides, or metal salts. If corrosion products are soluble or are otherwise removed from the anodic areas, corrosion proceeds, but if the products accumulate, they may reduce corrosion by providing a barrier that is more noble (cathodic) than the bare metal. The aeration characteristics of a soil are dependent upon physical characteristics such as the particle size, particle size distribution, and unit weight. In volume change soils such as clay, a reduction in moisture content results in cracks that provide effective channels for the oxygen of the air to reach buried metal. Disturbed soils such as fill result in oxygen being more readily available. In some instances, atmospheric oxygen can become trapped in isolated pockets or cells creating the potential for localized anodic regions.

CORROSION

SOIL ENVIRONMENTS

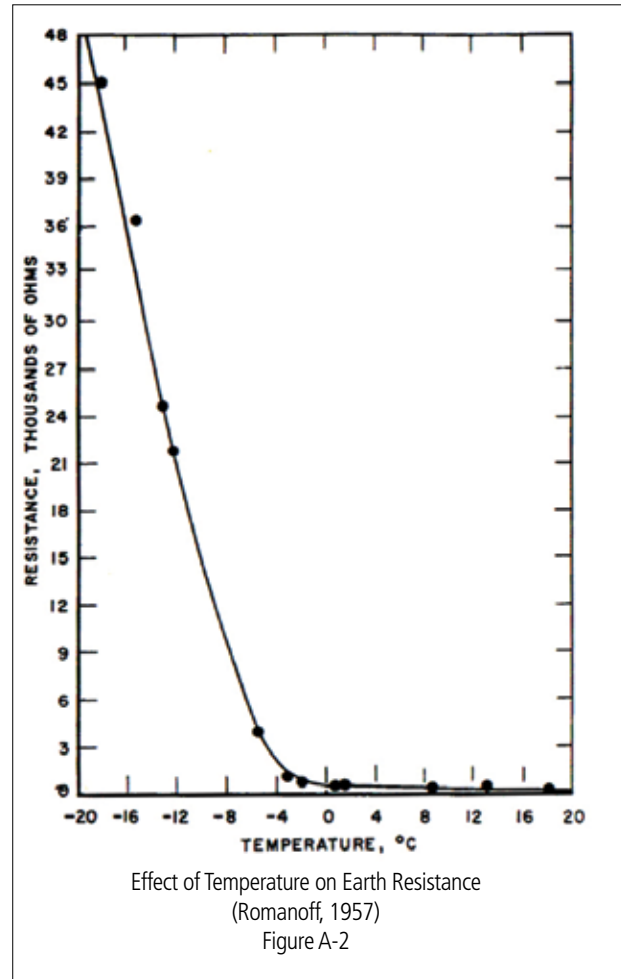
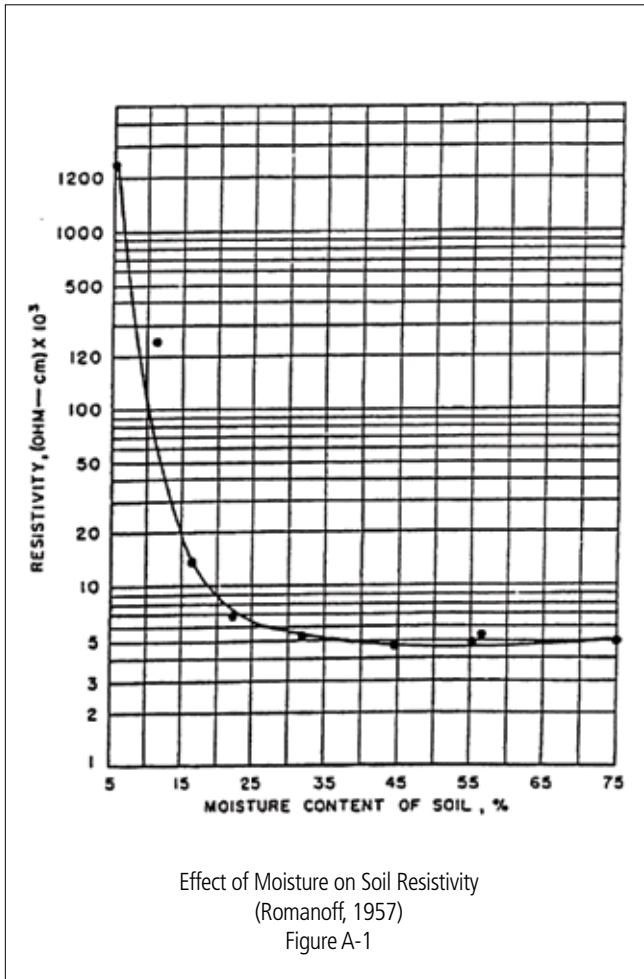
SOIL TYPE

Soils constitute the most complex environment known to metallic corrosion. Corrosion of metals in soil can vary from relatively rapid material loss to negligible effects. Obviously, some soil types are more corrosive than others. The origin of soils, along with climate, geologic location, plant and animal life, and the effects of man all influence the corrosive potential of a given soil. Chemical analysis of soils is usually limited to determinations of the constituents that are soluble in water under standardized conditions. The elements that are usually determined are the base-forming elements, such as sodium, potassium, calcium, and magnesium; and the acid-forming elements, such as carbonate, bicarbonate, chloride, nitrate, and sulfate. The nature and amount of soluble salts, together with the moisture content of the soil, largely determine the ability of the soil to conduct an electric current. Therefore, fine-grained soils such as clays and some silts are considered to have a greater corrosion potential because they typically have lower hydraulic conductivity resulting in the accumulation of acid and base forming materials, which cannot be leached out very quickly. However, granular soils such as sands and gravels are considered to have a reduced corrosion potential because they typically have increased hydraulic conductivity, resulting in the leaching of accumulated salts.

GROUND WATER

Moisture content in soil will probably have the most profound effect when considering corrosion potential than any other variable. No corrosion will occur in environments that are completely dry. The effect of moisture content on the resistivity of a clay soil is shown in Figure A-1. When the soil is nearly dry, its resistivity is very high (i.e., no corrosion potential). However, the resistivity decreases rapidly with increases in moisture content until the saturation point is reached, after which further additions of moisture have little or no effect on the resistivity. Figure A-2 shows the effect of temperature on the resistivity of a soil. As the temperature decreases down to the freezing point (32°F or 0°C), the resistivity increases gradually. At temperatures below the freezing point, the soil resistivity increases very rapidly.

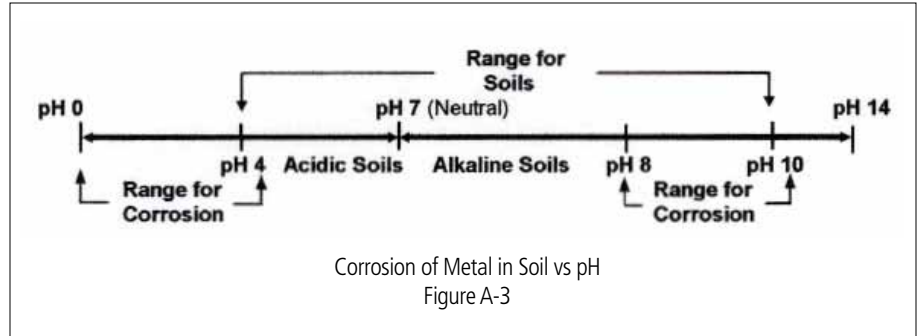
CORROSION



SOIL pH

Soil pH can be used as an indicator of corrosion loss potential for metals in soil. The term “pH” is defined as the acidity or alkalinity of a solution that is assigned a number on a scale from 0 to 14. A value of 7 represents neutrality, lower numbers indicate increasing acidity and higher numbers increasing alkalinity. Each unit of change represents a ten-fold change in acidity or alkalinity which is the negative logarithm of the effective hydrogen-ion concentration or hydrogen-ion activity in gram equivalents per liter of solution. The development of acidity in soils is a result of the natural processes of weathering under humid conditions. Acidic soils are those that have had soluble salts and other materials removed, usually by moderate to high rainfall. In general, the soils of the Midwest and Eastern United States are acid to a considerable depth, whereas the soils whose development has been retarded by poor drainage or other conditions are alkaline. Most soils fall within a pH range that is strongly acid to mildly alkaline.

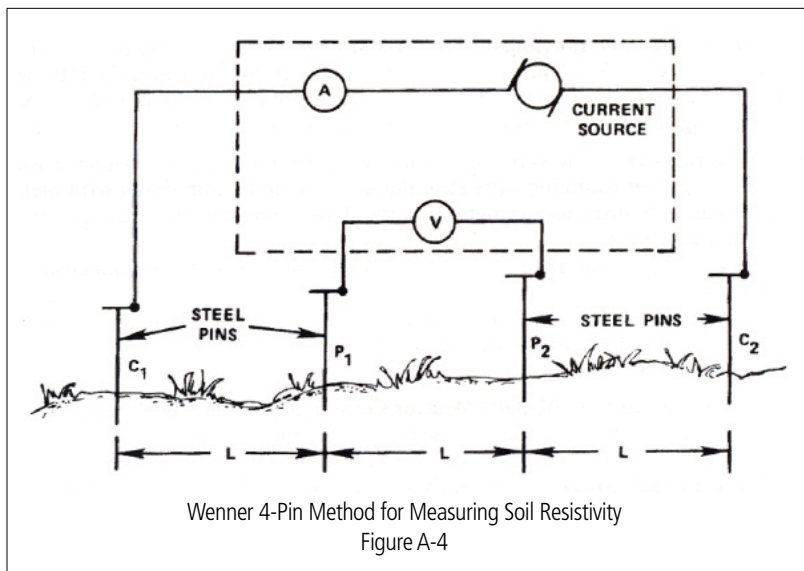
Extremely acid soils (below pH 4.5) and very strongly alkaline soils (above pH 9.1) have significantly high corrosion loss rates when compared to other soils (see Figure A-3). Soil pH is best measured in the field using a pH meter and following the methods defined in ASTM G 51 – 77.



SOIL RESISTIVITY

Soil resistivity (the reciprocal of conductivity) is the one variable that has the greatest influence on corrosion rate. However, other factors such as hydrogen-ion concentration, soluble salts and total acidity are interrelated, and it is difficult to control conditions so that there is only one variable. In general, the lower the resistivity, the higher the corrosion rate. Metals buried in low resistivity soils will generally be anodic, whereas metals buried in adjacent high resistivity soils will generally be cathodic.

As shown in Figure A-1, moisture content has a profound effect on resistivity. Soil that is completely free of water has extremely high resistivity. For example, sandy soils that easily drain water away are typically non-corrosive; clayey soils that hold water have low resistivity and are typically corrosive. Backfill material will generally be more corrosive than native earth because the backfill soil has a higher moisture content. In addition, backfill material typically never reconsolidates back to the same degree as native soil, allowing more penetration and retention of water.



Soil resistivity is typically measured using one or both of two methods: (1) testing onsite with the Wenner four-pin method, and/or (2) taking a soil sample to a laboratory for a soil box resistivity test. The recommended practice is the onsite Wenner four-pin method per ASTM G57-78. The four-pin method is recommended because it measures the average resistivity of a large volume of earth with relative ease. As Figure A-4 shows, this method places four pins at equal distances from each other. A current is then sent through the two outer pins. By measuring the voltage across the two inner pins, the soil resistance can be calculated using Ohm’s Law ($V= IR$). Soil resistivity can be determined using Equation A-1.

$$\text{Resistivity} = 191.5 (R) (L) \text{ (ohm-cm)}$$

Equation A-1

where R = Resistance measured with a soil resistivity meter
 L = Pin spacing (ft)

The soil box resistivity test is not recommended because it requires taking large number of samples for an accurate map of soil resistivities in a given area. The soil box test is also much more time-consuming than the four-pin method. Table A-2 is offered as a guide in predicting the corrosion potential of a soil with respect to resistivity alone.

Soil Resistivity and Potential Corrosion Rate, Table A-2

RESISTANCE CLASSIFICATION	SOIL RESISTIVITY (ohm-cm)	CORROSION POTENTIAL
Low	0 - 2000	Severe
Medium	2000 - 10,000	Moderate
High	10,000 - 30,000	Mild
Very High	Above 30,000	Unlikely

PREDICTING CORROSION LOSS

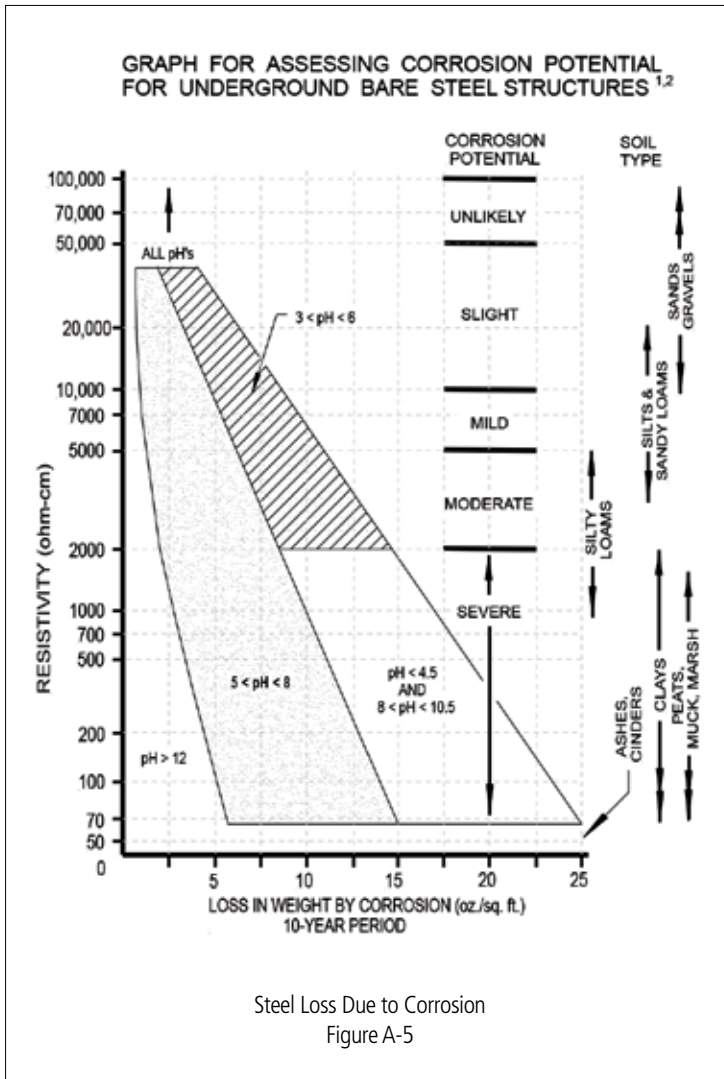
BARE STEEL

The National Bureau of Standards (NBS) performed extensive studies of underground corrosion between 1910 and 1955. More than 36,500 metal samples were exposed at 128 test locations throughout the United States. In 1957, Romanoff presented the results of these investigations in *Underground Corrosion (1957)*. The studies showed that most underground corrosion was a complex electrochemical process dependent on the various properties discussed previously. The NBS studies were primarily concerned with buried pipeline corrosion. Since pipes are installed in backfilled trenches, the NBS work was performed on specimens placed in trenches ranging from 18 in (0.46 m) to 6 ft (1.8 m) deep. The following conclusions can be drawn from these studies:

- The metal loss rates reported were from samples placed in backfilled, i.e., disturbed soils.
- Atmospheric oxygen or oxidizing salts stimulate corrosion by combining with metal ions to form oxides, hydroxides, or metallic salts. This is particularly true in disturbed soils at or near the soil surface.
- The least corrosive soils had resistivities above 3,000 ohm-cm and low soluble salt concentrations.
- Metal loss rates in disturbed soils can be determined by assuming they will be similar to the loss rates found at test sites with similar pH and resistivity levels as provided in NBS Circular 579, Tables 6, 8 and 13.

Hubbell Power System, Inc. bulletin 01-9204, *Anchor Corrosion Reference and Examples*, contains extensive metal loss rate data derived from Romanoff's work. It is recommended that this information be used to determine the service life of non-galvanized steel in disturbed soil. The service life for most structures in the United States is 50 to 75 years. Assuming a corrosion allowance for steel piles/piers, Romanoff's metal loss rate data for specific soil types and locations can be used to determine if the required service life can be achieved.

CORROSION



Romanoff's data can also be arranged in easy-to-use graphs or tables. Figure A-5 provides a preliminary estimate for metal corrosion loss of bare steel if specific information is available on the soil (soil type, pH and resistivity). Figure A-5 provides a technique for quickly assessing those situations for which concern and design consideration for corrosion must be taken into account when metallic structures are placed below ground. For example, a clay soil with resistivity of 2000 ohm-cm and a pH of 6 will have an average metal loss rate of approximately 5 oz/ft²/10yrs, or 0.5 oz/ft²/yr. This figure was developed from the results of the NBS studies in addition to similar field experimentation results as presented in the Proceedings, Eighth International Ash Utilization Symposium, Volume 2, American Coal Ash Association, Washington, DC, 1987.

The Federal Highway Administration (FHWA) has proposed uniform corrosion loss rates based on a simple assessment of the electrochemical index properties. Per FHWA-RD-89-198, the ground is considered aggressive if any one of the critical indicators in Table A-3 shows critical values.

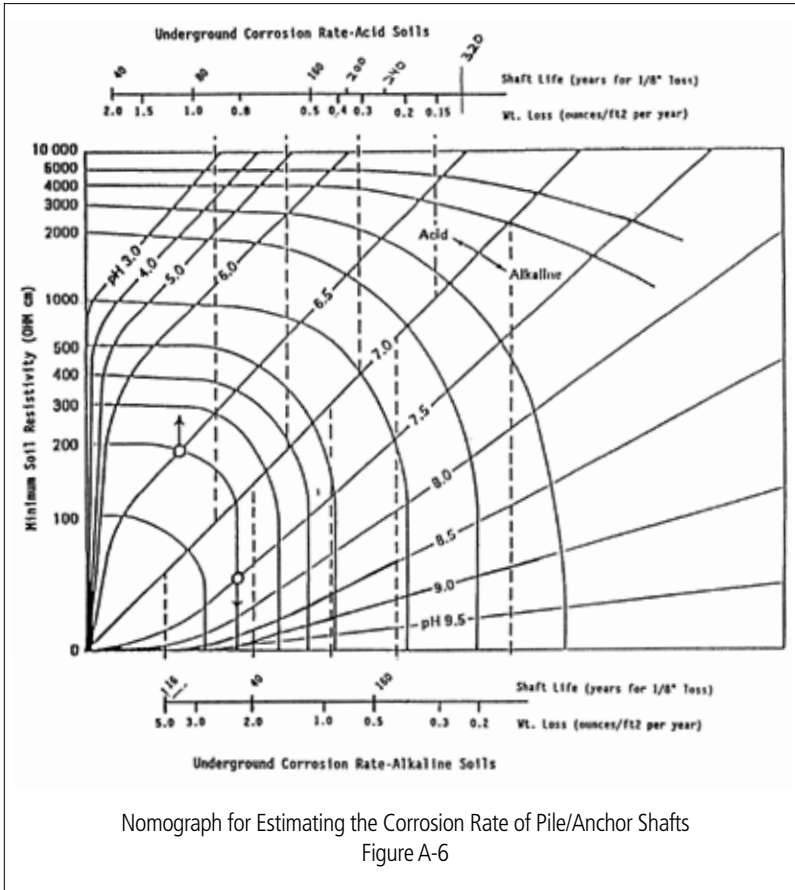
CORROSION

Electromechanical Properties of Mildly Corrosive Soils, Table A-3

PROPERTY	TEST DESIGNATION	CRITERIA
Resistivity	AASHTO T-288-91	> 3000 ohm-cm
pH	AASHTO T-289-91	>5 < 10
Sulfates	AASHTO T-290-91	200 ppm
Chlorides	AASHTO T-291-91	100 ppm
Organic Content	AASHTO T-267-86	1% maximum

The design corrosion rates, per FHWA-SA-96-072, suitable for use in mildly corrosive soils having the electrochemical properties listed in Table A-3 are:

- For zinc: 15 μm/year (0.385oz/ft²/yr) for the first two years
4 μm/year (0.103 oz/ft²/yr) thereafter
- For carbon steel: 12 μm/year (0.308 oz/ft²/yr)



Examples:

- For pH of 6.5 and resistivity of 200 ohm-cm weight loss is approximately 1.3 oz/ft²/yr and expected life (for 1/8" shaft loss) is approximately 65 years.
- For pH of 7.5 and resistivity of 200 ohm-cm weight loss is approximately 2.3 oz/ft²/yr and expected life (for 1/8" shaft loss) is approximately 38 years.

Other methods are available to predict corrosion loss rates. Figure A-6 is a nomograph for estimating the corrosion rate of helical anchor/pile/pier shafts. It is a corrosion nomograph adapted from the British Corrosion Journal (King, 1977). Its appeal is its ease of use. If the resistivity and soil pH are known, an estimate of the service life (defined as 1/8" material loss, for example) of a CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Pier shaft can be obtained for either an acidic or alkaline soil.

CORROSION LOSS RATES

WATER/MARINE ENVIRONMENT

Factors other than resistivity and pH can have a strong influence on corrosion loss rates. It is well known that marine environments can be severely corrosive to unprotected steel, particularly in tidal and splash zones. Corrosion loss rates in these environments can be quite high, averaging 6.9 oz/ft² (Uhlig, Corrosion Handbook, 2000). Salt spray, sea breezes, topography, and proximity all affect corrosion rate. Studies have shown that the corrosion rate for zinc exposed 80 ft (24.4 m) from shore was three times that for zinc exposed 800 ft (244 m) from shore.

Seawater immersion is less corrosive than tidal or splash zones. This is because seawater deposits protective scales on zinc and is less corrosive than soft water. Hard water is usually less corrosive than soft water toward zinc because it also deposits protective scales on the metallic surface. Table A-4 provides corrosion loss rates of zinc in various waters. In most situations, zinc coatings would not be used alone when applied to steel immersed in seawater, but would form the first layer of a more elaborate protective system, such as active protection using sacrificial anodes.

**Corrosion of Zinc in Various Waters (Corrosion Handbook, Volume 13 Corrosion, ASM International),
Table A-4**

WATER TYPE	μ m/yr	mils/yr	oz/ft ²
Seawater			
Global oceans, average	15 - 25	0.6 - 1.0	0.385 - 0.642
North Sea	12	0.5	0.308
Baltic Sea and Gulf of Bothnia	10	0.4	0.257
Freshwater			
Hard	2.5 - 5	0.1 - 0.2	
Soft river water	20	0.8	0.513
Soft tap water	5 - 10	0.2 - 0.4	0.128 - 0.257
Distilled water	50 - 200	2.0 - 8.0	1.284 - 5.130

CORROSION in UNDISTURBED SOIL

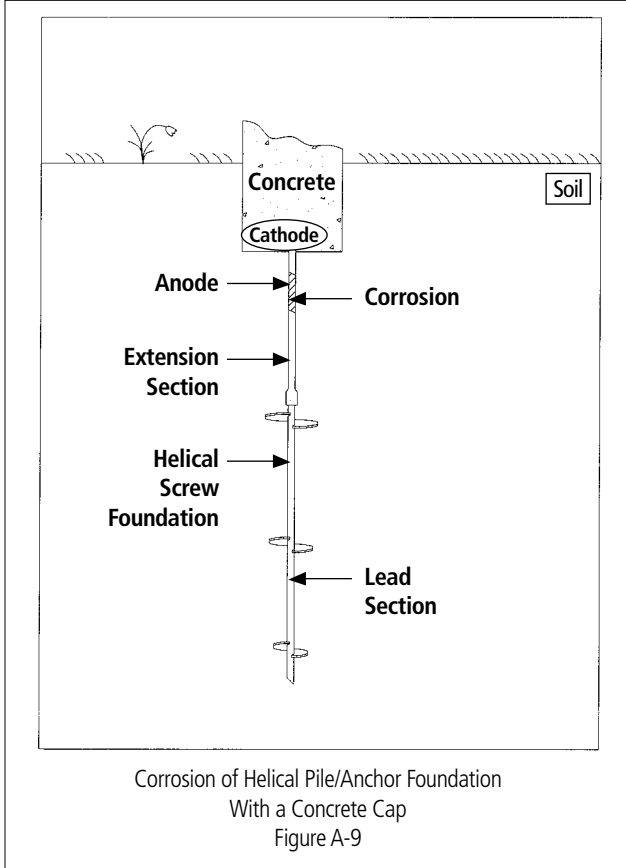
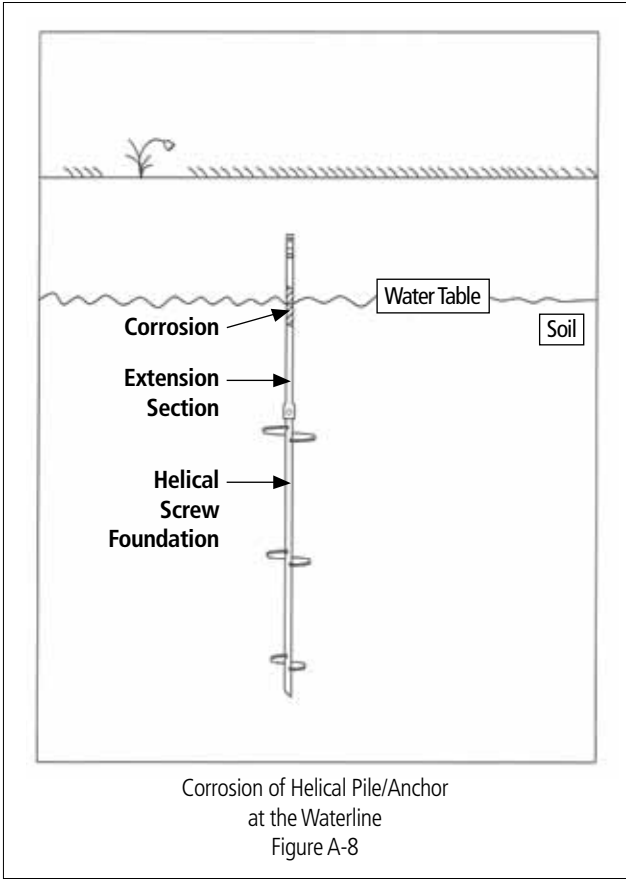
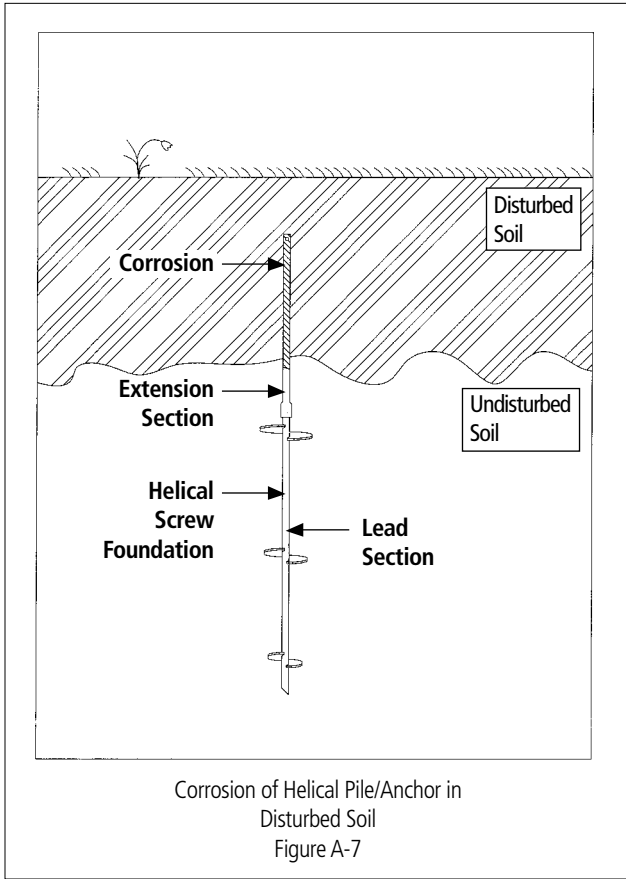
In NBS Monograph 127, (*Underground Corrosion of Steel Pilings*) (Romanoff, 1972), it was reported that driven steel piles did not experience appreciable corrosion when driven into undisturbed soils. These findings were obtained during NBS studies of steel pile corrosion. Romanoff also stated that the NBS corrosion data for steel exposed in disturbed soils was not applicable to steel piles driven in undisturbed soil. He concluded:

“... that soil environments which are severely corrosive to iron and steel buried under disturbed conditions in excavated trenches were not corrosive to steel piling driven in the undisturbed soil. The difference in corrosion is attributed to the differences in oxygen concentration. The data indicates that undisturbed soils are so deficient in oxygen at levels a few feet below the ground line or below the water table zone that steel pilings are not appreciably affected by corrosion, regardless of the soil types or the soil properties. Properties of soils such as type, drainage, resistivity, pH, or chemical composition are of no practical value in determining the corrosiveness of soils toward steel pilings driven underground.”

The following conclusions can be drawn from these studies:

- Oxygen is required at cathodic sites to support underground corrosion of a steel foundation product.
- Disturbed soils (fill) contain an adequate supply of oxygen to support underground corrosion, at least at shallow depths. Thus, the top-most extension(s) of the CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Pier central steel shaft merits corrosion protection, either using passive protection like zinc, epoxy or teflon coatings or active protection like sacrificial anodes.
- The aggressiveness of disturbed soils can be measured, and they can be classified as aggressive and non-aggressive (see Table A-2).
- Undisturbed soils were deficient in oxygen a few feet below the ground surface, or below the water table. It is recommended to install the helical bearing plates of a helical pile/anchor into de-aerated soil.

CORROSION



The role of oxygen in an undisturbed soil overrides the effects of soil resistivity, pH, etc. In those situations where a steel foundation product is installed into a soil profile where a disturbed soil layer overlies undisturbed soil, the section of the central shaft in the disturbed soil is cathodic to the rest of the foundation in the undisturbed region as illustrated in Figure A-7. As a result, the most severe corrosion occurs on the section of the central shaft just below the disturbed layer.

Similarly, a steel foundation product located in undisturbed soil with a high water table can suffer some corrosion attack at the waterline as illustrated in Figure A-8. This combination does not result in serious attack, but it is believed that the situation is aggravated by a continuously changing water table, which would draw in oxygen as the waterline dropped. The section of the central shaft above the waterline acts as a weak cathode to the anode below the waterline.

Helical piles are commonly terminated in concrete cap or grade beams. The area of steel in the concrete forms a passive oxide film generated by the action of the highly alkaline environment, and this area is cathodic to the rest of the helical pile in the soil. However, the high resistivity of the concrete limits the effectiveness of the cathode, thereby limiting the small amount of corrosion attack to the region of the helical pile immediately outside the concrete as illustrated in Figure A-9.

FIELD MEASUREMENT of SOIL RESISTIVITY

Field measurement of soil resistivity is not a difficult or time consuming process and results in the most accurate assessment of corrosion potential for the site. Hubbell Power Systems, Inc. recommends the use of the Nillson Model 400 Soil Resistance Meter System. The depth of the soil resistivity measurement is directly related to the pin spacing on the surface. The most accurate assessment is obtained by performing the test using a pin spacing of 5-20 foot intervals. In addition, the test should be repeated at a right angle to the original test to ensure that stray currents are not influencing the readings.

A. Equipment Set-Up

1. Insert the four sensor pins into the soil in a straight line leading away from the Resistivity Meter at a center-to-center distance of five feet (see Figure A-10).
2. Connect one wire to each pin and to the appropriate terminal on the Nillson meter.

B. Resistivity Measurement

1. Adjust the OHMS resistivity dial and the MULTIPLIER dial to the maximum setting (turned fully to the right) (see Figure A-11).
2. Place the SENSITIVITY switch in the LOW position and rotate the MULTIPLIER dial to the left until the meter needle goes past the NEUTRAL point, then rotate the MULTIPLIER one position to the right. Note the MULTIPLIER (M) amount on the field notes.
3. Move the OHMS dial to the left until the meter needle is at NEUTRAL.
4. Adjust the SENSITIVITY switch to HIGH position and adjust the OHMS dial to refine the reading.
5. Record the reading (R_{meter})
6. Return the OHMS and MULTIPLIER to the maximum settings and repeat the test.
7. Repeat the test with the pins spaced at 10-feet on center, then at 15-feet and 20-feet on center. Record the readings

C. Calculation of Soil Resistivity

$$R = R_{meter} (M) (WSF) \quad \text{Equation A-2}$$

where:

- R_{meter} = Meter resistance reading (ohms)
- M = Meter MULTIPLIER reading
- WSF = Wenner spacing factor = $191.5L$ (ft) = $628L$ (m)
- L = Pin spacing
- R = Soil resistivity (ohm-cm)

D. Additional Resistivity Measurements

1. The soil resistivity (R) is the average value over the depth of soil equal to the spacing of the pins. Therefore, to get a profile of the soil resistivity one must repeat the procedures in paragraph B above with the pins spaced at 10, 15 and 20 feet on center.
2. Repeat the entire test at right angles to the original alignment.



Sensor Pin Installation
Figure A-10



Nillson Resistivity Meter
Figure A-11

E. Documentation

Record the field data and the calculations onto the Soil Resistivity Log. A sample log is presented below (See Figure A-12).

F. Evaluate Results

When the Soil Resistivity (R) has been determined, refer to Figure A-5 to determine an estimate of the loss of weight by corrosion over a 10-year period for underground bare steel structures.

COMBINED WENNER 4-PIN SOIL RESISTIVITY LOG				
Location:		Job No.		
Date:	Weather Conditions:	Orientation of Pins:		
WENNER METHOD OF SOIL RESISTIVITY				
PIN SPACING (Depth in Feet)	METER RESISTANCE (R_{Meter}) (ohms)	METER MULTIPLIER (M)	WENNER SPACING FACTOR (WSF) ($191.5^* \times \text{Pin Spacing}$)	SOIL RESISTIVITY $R = (R_{\text{Meter}}) \times M \times \text{WSF}$

* If pin spacing is measured in meters, use WENNER SPACING FACTOR (WSF) of 628 instead of 191.5

Sample Resistivity Log
Figure A-12

CORROSION CONTROL TECHNIQUES

The amount and type of corrosion control is a function of structure type, service life, and the overall aggressiveness of the project soils. The following requirements are typical. The specifier should review and edit as appropriate for the project.

- **Structure Type:** Temporary structures generally do not require corrosion protection. A temporary structure is defined within a specified time frame (i.e., months rather than years). In general, permanent structures have a service life greater than 24 months.
- **Service Life:** A typical service life of 50 to 75 years should be used unless otherwise specified. If the service life of a temporary CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Pier is likely to be extended due to construction delays, it should be considered permanent. For a service life of less than 20 years in non-aggressive soil, corrosion protection is not recommended.
- **Soil:** Soil can be classified as aggressive or non-aggressive. See Guide to Model Specification - Helical Piles for Structural Support and Model Specification - Helical Tieback Anchors for Earth Retention in Appendix C of this Technical Design Manual for examples of aggressiveness classifications. It is recommended that steel foundation elements installed into soils classified as aggressive be provided with some type of corrosion protection.

Several alternatives are available to protect steel foundation products against corrosion and can be roughly categorized in terms of cost. Because of the added cost, the need for corrosion protection must be carefully determined and specified as necessary. Depending upon the classification as to the corrosion potential for a soil environment, several alternatives are available to deter the corrosion cycle and extend the performance life of the underground steel element. These control measures can be split into categories:

- **Passive Control:** For use in soils classified as mild to moderate corrosion potential. It typically consists of a metal loss allowance (i.e., 1/8") and/or coatings – such as galvanization or epoxy. Passive control is relatively inexpensive.
- **Active Control:** For use in soils classified as moderate to severe corrosion potential. It typically consists of cathodic protection via the use of sacrificial anodes. Active control is relatively expensive and is used in permanent applications.

PASSIVE CONTROL

Allowable Metal Loss Rate

As mentioned previously, Hubbell Power Systems, Inc. bulletin 01-9204, Anchor Corrosion Reference and Examples, contains extensive metal loss rate data derived from Romanoff's work. Other metal loss rate data is presented on pages A-8 through A-12. The design examples at the end of this section demonstrate passive control calculations that estimate the service life of helical pile shafts in soil using these metal loss rates. Design Example 1 uses the metal loss rates from Romanoff (Bulletin 01-9204). The service life is defined as the estimated length of time required for 1/8" of material loss to occur on the helical pile/anchor shaft. Design Example 2 uses the metal loss rates from Figure A-5 in conjunction with Equation A-2. The service life in this example is defined as the estimated length of time required for a 10% material loss to occur on the helical pile shaft. Design Example 3 uses the design corrosion rates per FHWA-SA-96-072 (as quoted here on page A-8) and an assumed service life of 85 years.

The amount of loss in these design examples is strictly arbitrary, but the assumed material loss of 1/8" in Design Example 1 is common for pile evaluation.

Galvanization (Passive Control)

Aggressive soils, and the conditions illustrated in Figures A-7, A-8, and A-9 demonstrate the need to coat the section of the steel foundation product above the waterline in the disturbed soil and, in particular, the area of the central shaft in the concrete cap or grade beam. Thus, by removing the cathode, the anode/cathode system is disrupted resulting in reduced corrosion. If it were possible to apply a coating capable of guaranteed isolation of the steel surface from the electrolyte (soil), all corrosion concerns would be solved. However, a coating capable of 100% guaranteed isolation has yet to be developed. Epoxy coatings provide excellent electrical isolation, but will chip and abrade easily during handling and installation. The same

holds true for porcelain, teflon, and polyurethane coatings. A small chip or crack in the protective coating can cause corrosion activity to be highly localized, possibly leading to severe damage. **The single best coating for steel foundation products is hot dip galvanizing.**

The first step in the galvanizing process is pickling the steel in dilute acid. This removes any rust, scale, oil or other surface contaminants. The clean steel is then dipped in a vat of molten zinc for time periods ranging up to several minutes for the more massive steel foundations. After the hold period, the zinc-coated steel is withdrawn from the vat at a controlled rate, which allows the coating to quickly cool and harden. The result is a tough, combined zinc and zinc-iron coating which metallurgically bonds to the steel. Other galvanization processes, such as mechanical galvanizing and electroplating, do not form a coating that is metallurgically bonded to the steel.

Hubbell Power System, Inc. galvanizes to the latest ASTM standards – either ASTM A153 class B or ASTM A123. ASTM A153 Class B requires an average weight of zinc coating to be 2.0 oz./ft² (3.4 mils) and any individual specimen to be no less than 1.8 oz./ft² (3.1 mils). ASTM A123 can be used to specify thicker zinc coatings – up to 2.3 oz./ft² (3.9 mils) depending on the coating thickness grade used. Regardless of which ASTM galvanizing specification is used, typical zinc coating thickness for hot-dip galvanized CHANCE® Helical Pile/Anchor or ATLAS RESISTANCE® Piers ranges between 4 and 6 mils.

CORROSION

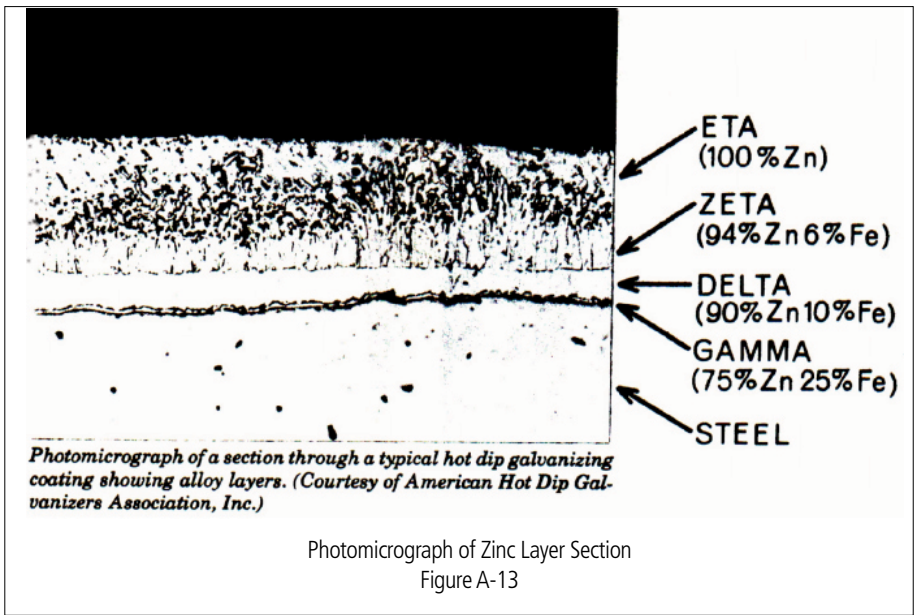


Figure A-13 illustrates how zinc and steel react to form zinc-iron alloy layers. The bottom of the picture shows the base steel, then a series of alloy layers and, on the outside, the relatively pure outer zinc layer. The underlying zinc-iron alloy layers are actually harder than the base steel. Therefore, below the relatively soft pure zinc layer, the zinc-alloy layers provide protection in abrasive conditions such as dense sands and gravels.

Hot dip galvanized coatings protect the carbon steel shaft in two ways. First, the zinc coating provides a protective layer between the foundation’s central shaft and the environment. Second, if the zinc coating is scratched and the steel surface exposed, the zinc, not the steel, will corrode. This is because zinc is a dissimilar metal in electrical contact with the steel, thus the difference in potential between the two metals and their relative chemical performance (anode or cathode) can be judged by examining a galvanic series as shown in Table A-5. The materials at the top of the list are most active (anodic) compared to the noble (cathodic) materials at the bottom of the list. Steel is more noble than zinc, thus the more active zinc coating will act as an anode and corrode while the more noble steel will be the cathode and be protected.

Service Life Increase Through Galvanization

Hubbell Power Systems, Inc. bulletin 01-9204, Anchor Corrosion Reference and Examples, contains extensive metal loss rate data on galvanized steel derived from Romanoff’s work. It is recommended that this information be used to determine the service life of the hot dipped galvanized coating in disturbed soil. When hot-dip galvanized steel is used, the total service life should be increased by the time it takes the zinc coating to be lost due to corrosion. Another method for estimating service life increase is presented in the following paragraphs.

The results of the studies conducted by the National Bureau of Standards and by Porter indicated that a galvanized coating (zinc) was effective in delaying the onset of corrosion in the buried steel structures. Typical conclusions drawn from this study for 5 mil (3 oz/ft²) galvanized coatings include:

- It is adequate for more than 10 years corrosion protection for inorganic oxidizing soils.
- It is adequate for more than 10 years corrosion protection for inorganic reducing soils.
- It is insufficient for corrosion protection in highly reducing organic soils (pH<4), inorganic reducing alkaline soils and cinders, typically offering 3 to 5 years of protection in such cases.

It was also noted, however, that the use of a galvanized coating significantly reduces the rate of corrosion of the underlying steel structure once the zinc coating was destroyed.

The observed rates of corrosion for the galvanized coating were different (less) than that for bare steel in the NBS study. For galvanized coatings (zinc) of 5 mils, Equation A-3 can be used to estimate the corrosion (weight loss) rate.

$$\begin{aligned}
 CL_1 &= 0.25 - 0.12 \log_{10} (R/150) && \text{Equation A-3} \\
 CL_1 &= \text{Weight loss (oz/ft}^2\text{/yr)} \\
 R &= \text{Soil resistivity (ohm-cm)}
 \end{aligned}$$

NOTE: For thinner galvanized coatings, the rate of galvanized coating loss is two to three times the rate determined from Equation A-3.

Manufactured Metallic Coating (Passive Control)

Hubbell Power Systems, Inc. provides triple coat corrosion protection as a standard feature on the 3-1/2" diameter by 0.165" wall (3500.165 series) ATLAS RESISTANCE® Pier pipe and as an optional feature on the 2-7/8" diameter 0.165 wall (2875.165 series) ATLAS RESISTANCE® Pier pipe. The triple coating consists of:

- Hot-dipped uniform zinc galvanizing
- Chromate conversion coating
- Clear organic polymer coating

The triple coating can significantly reduce the corrosion process by mechanically preventing access of oxygen to the steel surface of the pipe. Data from the manufacturer indicates that this corrosion protection is equivalent to 3 mil (1.8 oz/ft²) of hot dip galvanizing. Because of the thinness of this film and possible scratching of the coating, this corrosion protection technique should not be used in soils classified as severe.

Galvanic Series in Seawater, Table A-5

ACTIVE PASSIVE	Magnesium
	Zinc
	Beryllium
	Aluminum Alloys
	Cadmium
	Mild Steel, Cast Iron
	300 Series Stainless Steel (Active)
	Aluminum Bronze
	Naval Brass
	Tin
	Copper
	Lead-Tin Solder (50/50)
	90-10 Copper Nickel
	Lead
	Silver
	300 Series Stainless Steel (Passive)
	Titanium
	Platinum
	Graphite

Bituminous and Other Coatings (Passive Control)

Bituminous as well as other materials have been used as coatings on buried steel elements for years as a corrosion protection technique. The primary requirements of a bituminous coating are good adherence (permanence), continuous coating and resistance to water absorption. The bituminous coating can either be heat baked onto the shaft or field applied just prior to installation. As is the case for the manufactured coatings, this coating technique prevents oxygen and water from contacting the metal surface, thus preventing or retarding the corrosion process.

Bituminous or asphaltic coatings or paints only provide physical protection from the environment. They will wear off quickly due to the abrasive action during installation of CHANCE® Helical Piles/Anchors and ATLAS RESISTANCE® Piers. Extension sections are typically hot-dip galvanized, but other coatings can be specified. Practical application of asphaltic coatings is generally limited to the extension sections located at or near the surface where the coating will provide the greatest benefit. Bituminous and other coatings are best applied in severely corrosive conditions where part of the helical anchor/pile is exposed above grade. Examples are steel foundations used in tidal marshes, coastal regions, and contaminated soils.

A limited amount of available data indicates that bituminous coatings can extend the performance life of underground steel piles and piers by 5 to 15 years, depending on the soil environment and the thickness of the coating. For the vast majority of CHANCE® Helical Piles/Anchors and ATLAS RESISTANCE® Pier applications, the use of coating techniques (galvanized and/or bituminous) will provide a sufficiently long-term solution for corrosion protection.

Cathodic Protection (Active Control)

As indicated previously, corrosion is an electrochemical process that involves a flow of direct electrical current from the corroding (anodic) areas of the underground metallic structure into the electrolyte and back onto the metallic structure at the non-corroding (cathodic) areas. In situations where metallic structures such as Hubbell Power Systems, Inc. foundation products are to be placed in a severe corrosive soil environment, an active corrosion control technique should be used. This active control technique is termed cathodic protection. Cathodic protection is a method of eliminating corrosion damage to buried steel structures by the application of DC current. The effect of the DC current is to force the metallic surface to become cathodic (i.e., collecting current). If the current is of sufficient magnitude, all metallic surfaces will become cathodic to the external anode.

Both sacrificial anode and impressed current (rectifier and ground bed) cathodic protection systems are used to provide the required current. If the current source is derived from a sacrificial metal (magnesium and zinc are the two most common galvanic anodes used in soils), the effectiveness will depend on the soil properties in which it is placed. More available current is generated from a sacrificial anode in low resistance soils than high resistance soils. It is also best to place impressed current anode beds in lower resistant soils. However, since the available driving potential is greater (rectifier control), the soil resistivity is less significant.

Current requirements needed to protect a steel structure from corrosion will vary due to physical and environmental factors. These requirements could range from 0.01 ma/ft² of metal surface for a well-applied, high-dielectric-strength plastic coating to 150 ma/ft² for bare steel immersed in a turbulent, high velocity, salt-water environment. In soil, 1 to 3 ma/ft² is typically used as the required current to protect carbon steel.

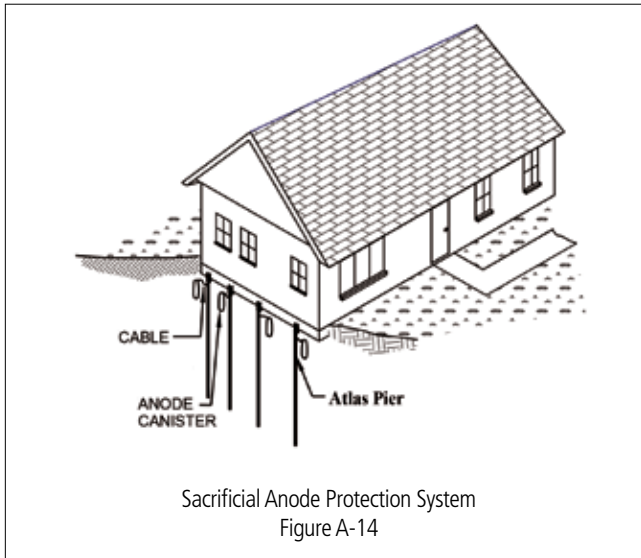
The basic principle in cathodic protection is to apply a direct current of higher electromotive potential than that generated by the corroding metallic structure, thus effectively eliminating the corrosion process.

Sacrificial Anodes (Active Control)

In the case of CHANCE® Helical Piles/Anchors and ATLAS RESISTANCE® Piers, sacrificial anodes are the most common method of cathodic protection used. This is done by electrically connecting the steel to a properly selected anode of a less noble metal such as zinc or magnesium. The dissimilar metals buried in a common electrolyte (soil) form a galvanic cell. The cell works much like the battery in the family car; the less noble anode corrodes or sacrifices itself while the more noble cathode is protected. For steel to be cathodically protected, it is generally recognized that at least one of the following conditions must be met:

- The potential of the steel must be at -0.85 volts or more negative with respect to a saturated copper-copper sulfate half-cell in contact with the electrolyte, or
- A potential shift of -0.3 volts or more negative upon connection of the cathodic protection.

Magnesium, zinc and aluminum are the most commonly used galvanic sacrificial anodes. The sacrificial anode (galvanic) is attached to each underground metallic structure by a metallic conductor (cable) and placed within the common electrolyte (soil medium). The sacrificial anode works best when a small amount of current is needed and/or when the soil resistivities are low. Anodes are installed normally 3 feet below the surface and 3 to 7 feet from the CHANCE® Helical Piles/Anchors and ATLAS RESISTANCE® Pier.



In designing and using sacrificial anode systems, the soil profile conditions as to the type of soil, resistivities, soil pH and location of the ground water table (GWT), if present, must be determined. Among the design considerations for the system:

- Use of wire type or canister type anode
- Selection of the appropriate anode material (magnesium, titanium, etc.)
- Designing the ground bed (location, dimensions, horizontal vs. vertical, depth of placement, type of backfill, etc.)
- Determining the number of piles/piers per anode
- Type, size and connections between pile(s) and the sacrificial anode.

The application of cathodic protection using galvanic sacrificial anode bags to underground metallic structures offers the following advantages:

- No external power supply required
- Low system cost (bags and installation)
- Minimum maintenance costs

CATHODIC PROTECTION PRODUCTS


Hubbell Power Systems, Inc. recommends a selection of magnesium anodes (9, 17, 32, and 48-pound bag sizes) for cathodic protection of foundation support systems. Cathodic protection is generally used to extend the life of a steel product in corrosive soil beyond the added life available by hot dip galvanizing the components. While it is possible to protect mill finish steel, the engineer usually calls for the cathodic protection in addition to zinc galvanizing.

FACTORS INFLUENCING ANODE OUTPUT:

- **Soil Resistivity:** Current output from the magnesium anode increases as the soil resistivity decreases. Therefore, magnesium anodes are usually specified in applications where the soil resistivity is 5,000 ohm-cm or less. The effectiveness of this type of cathodic protection decreases as the resistivity increases above 5,000 ohm-cm. Above 10,000 ohm-cm resistivity, magnesium anodes are not effective.

- **Anode Surface Area:** The amount of current output generated by an anode is directly proportional to the surface area of the anode. Different manufacturers of cathodic protection produce anodes with different surface areas. Just because magnesium anodes from different manufacturers weigh the same is not to be assumed that the current output will be the same. The data presented here is representative for the products identified here.
- **Alloy Potential:** H-1 magnesium alloy has an open circuit potential of -1.53 to -1.55 volts, which works well with vertically installed foundation support systems. High potential anodes are available from other sources. These high cost, high potential anodes are generally used along horizontal pipelines where the higher potential produced by the anode translates to fewer anodes being required. Table A-5 provides estimates of current output from a single, standard potential H-1 magnesium alloy anode as related to soil resistivity.

Magnesium Anodes, Table A-5

	MAGNESIUM ANODES TYPE H-1 STANDARD POTENTIAL MAGNESIUM			
	Item No	Magnesium Weight	Package Size	Unit Weight
	PSA4438	9 lb.	6" Dia. x 17" Tall	27
	PSA4439	17 lb.	6-1/2" Dia. x 24" Tall	45
	PSA5106	32 lb.	8" Dia. x 28" Tall	72
	PSA4440	48 lb.	8" Dia. x 38" Tall	100

MAGNESIUM ANODE CURRENT OUTPUT – mA					
Resistivity – ohm-cm	1,000	2,000	3,000	4,000	5,000
9# Anode	106.5	53.3	35.5	26.6	21.3
17# Anode	150	75	50	37.5	30
32# Anode	159	79.5	53	39.8	31.8
48# Anode	163.5	81.8	54.5	40.9	32.7

Design Example 4 at the end of this section provides a method for estimating the service life of a sacrificial magnesium anode. For additional information on anode selection, refer to Hubbell Power Systems, Inc. bulletin 2-8307, Cathodic Protection of Anchors – A Basic Guide to Anode Selection and Hubbell Power Systems, Inc. bulletin 01-9204, Anchor Corrosion Reference and Examples.

Impressed Current (Active Control)

In areas of the most severe corrosion potential, where a larger current is required and/or in high resistance electrolytes, an impressed current system is generally recommended which requires a power source, rectifier and a ground bed of impressed current anodes. These systems require a continuous external power source.

The majority of applications where Hubbell Power Systems, Inc. foundation products may be specified will not require an active corrosion protection system. In those cases where the combination of soil and electrolyte conditions requires an active system, the sacrificial anode protection system will likely be the most economical approach.

Active cathodic protection systems must be individually designed to the specific application. The major variables are soil moisture content, resistivity of soil and pH. Each of these items influences the final selection of the cathodic protection system. Typical design life for the cathodic protection is 10 to 20 years, depending upon the size and length of the anode canister.

DESIGN EXAMPLES

Design Example 1:

- Project: Santa Rosa, CA Residence

The purpose of the calculations is to estimate the service life of Type SS Helical Pile Shafts on the subject project. Service life is defined as the estimated length of time required for 1/8" of material loss to occur on the helical pile shaft. This amount of loss is strictly arbitrary, but is common for pile evaluation.

- Given:

Helical piles galvanized to ASTM A153 (Minimum Zinc Coating = 1.8 oz/ft²)

Soil resistivity is 760 ohm-cm minimum

Soil pH - 7.70

Water soluble chloride – 11 ppm

Water soluble sulfate – 417 ppm

- Assumptions:

It is assumed that the material loss rates will be similar to the loss rates found at test sites with similar pH and resistivity levels as given in Romanoff's Underground Corrosion, NBS Circular #579 (1957), Tables 6, 8 and 13.

In Circular #579, Site #5 is indicated as having a resistivity of 1,315 ohm-cm and a pH of 7.0. This soil is Dublin Clay Adobe and is located around Oakland, California. In addition, Site #2 is indicated as having a resistivity of 684 ohm-cm and a pH of 7.3. This soil is Bell Clay and is located around Dallas, Texas. The corrosion rates for these two sites will be used to estimate the life of the Type SS helical pile shaft material.

- Allowable Steel Loss:

Based on the loss of 1/8" thickness of the helical pile shaft, calculate the allowable steel loss (ASL) in terms of weight per unit area:

$$\begin{aligned}
 \text{ASL} &= (0.125 \text{ in}) (0.283 \text{ lb/in}^3) (16) \\
 &= (0.566 \text{ oz/in}^2) (144 \text{ in}^2/\text{ft}^2) \\
 &= 81.5 \text{ oz/ft}^2
 \end{aligned}$$

- Average Metal Loss per Year:

From Site #5: (Dublin Clay Adobe)

EXPOSURE DURATION (years)	WEIGHT LOSS (oz/ft ²)	LOSS PER YEAR (oz/ft ²)
1.9	1.4	0.737
4.1	2.2	0.585
6.2	4.8	0.774
8.1	5.2	0.642
12.1	5.4	0.446
17.5	8.3	0.474

The average metal loss per year is 0.61 oz/ft². Note that as the duration of exposure increases, the material loss per year generally decreases.

- **Pile Shaft Life:**

To determine the pile shaft service life (SL), the allowable steel loss is divided by the average loss per year:

$$\begin{aligned} \text{SL} &= (81.5 \text{ oz/ft}^2) / (0.61 \text{ oz/ft}^2) \\ &= 133.6 \text{ years} \end{aligned}$$

- **Total Zinc Coating Loss:**

CHANCE® Helical Piles/Anchors are typically provided already hot dip galvanized per ASTM A153. The coating thickness for ASTM A153 class B = 1.8 oz/ft². From Romanoff, NBS Circular #579, Page 110, Table 65 gives the following average loss rates for Site #5 soils:

EXPOSURE DURATION (years)	WEIGHT LOSS (oz/ft ²)	LOSS PER YEAR (oz/ft ²)
10.17	2.66	0.262

- Estimated Life of Zinc: $1.8 \text{ oz/ft}^2 / 0.262 \text{ oz/ft}^2 = 6.9 \text{ years}$
- Total Estimated Service Life of Helical Pile Shaft: $133.6 + 6.9 = 140.5 \text{ years}$
- From Romanoff Site #2 (Bell Clay):

EXPOSURE DURATION (years)	WEIGHT LOSS (oz/ft ²)	LOSS PER YEAR (oz/ft ²)
2.1	2.4	1.143
4.0	3.0	0.750
5.9	3.4	0.576
7.9	3.6	0.456
12.0	5.9	0.492
17.6	8.1	0.460

The average loss per year is 0.65 oz/ft². Note that as the duration of exposure increases, the material loss per year generally decreases.

- **Helical Pile Shaft Life:**

To determine the helical pile shaft's service life (SL), the allowable steel loss is divided by the average loss per year.

$$\begin{aligned} \text{SL} &= (81.5 \text{ oz/ft}^2) / (0.65 \text{ oz/ft}^2) \\ &= 125.4 \text{ years} \end{aligned}$$

- **Total Zinc Coating Loss:**

CHANCE® Civil Construction helical anchors/piles are already provided hot dip galvanized per ASTM A153. The coating thickness for ASTM A153 class B = 1.8 oz/ft². From Romanoff, NBS Circular #579, Page 110, Table 65 gives the following average loss rates for site #2 soils.

EXPOSURE DURATION (years)	WEIGHT LOSS (oz/ft ²)	LOSS PER YEAR (oz/ft ²)
9.92	0.44	0.044

- Estimated Life of Zinc: $1.8 \text{ oz/ft}^2 / 0.044 \text{ oz/ft}^2 = 40.9 \text{ years}$
- Total Estimated Service Life of Helical Pile Shaft: $125.4 + 40.9 = 166.3 \text{ years}$

CORROSION

- Summary:

Total estimated service life of helical pile shaft in Site #5 soils = 140.5 years

Total estimated service life of helical pile shaft in Site #2 soils = 166.3 years

These calculations are an estimate of the service life only (1/8" material loss from shaft) and are based upon loss rates obtained from Romanoff's disturbed soil sites. It is generally accepted that the majority of any corrosion will occur at or near the surface. Therefore, it is very likely that helical pile shaft metal loss will control the design. In the event the estimated service life does not meet the design requirements, one option is to use a larger sized helical pile shaft.

Design Example 2:

- Project: An access bridge designed to cross a wetland area.

The purpose of the calculations is to estimate the service life of Type RS3500.300 Helical Piles on this project. The service life is defined as the estimated length of time required for a 10% metal loss to occur to the helical pile shaft.

- Given:

1. Helical Piles will receive a hot dipped galvanized coating (G) of 5-mil thick (3-oz/ft²)
2. Soil Resistivity (R) – 1,000 ohm-cm
3. Soil pH – 6.0
4. Soil type – organic silt in top 10' with SPT blow counts of 2 to 4 blows per foot.

- Assumptions:

1. The metal loss rates will be based on the values given in Figure A-5 with a pH of 6.0 and a resistivity of 1,000 ohm-cm. These values place the organic silt in the severe corrosion environment region.
2. The galvanized coating loss rates will be based on Equation A-3 as shown on page A-17.

- Estimated Life of Galvanized Coating:

To estimate average life for galvanized coating in a location with a soil resistivity of 1000 ohm-cm, Equation A-3 is used:

$$\begin{aligned}
 CL_1 &= 0.25 - 0.12 \log_{10} (R/150) \\
 &= 0.25 - 0.12 \log_{10} (1000/150) \\
 &= 0.25 - 0.12 (0.824) \\
 &= 0.15 \text{ oz/ft}^2/\text{yr}
 \end{aligned}$$

where: CL_1 = Weight loss per year

The estimated life of the galvanized coat is:

$$\begin{aligned}
 L_1 &= G/CL_1 && \text{Equation A-4} \\
 &= (3 \text{ oz/ft}^2) / (0.15 \text{ oz/ft}^2) \\
 &= 20 \text{ years}
 \end{aligned}$$

where: G = Amount of galvanized coating = 3.0 oz/ft² for typical hot dipped galvanized coating (5 mil)

L_1 = Life expectancy (yrs)

- Estimated Life of of Steel:

The formula for estimating average life for loss in steel wall thickness is given in Equation A-5 below:

$$L_2 = W_s / K_2 \quad \text{Equation A-5}$$

where:

- L_2 = Life expectancy (yrs)
- W_s = Weight of steel pile (oz/ft²)
- K_2 = Loss in weight by corrosion (oz/ft²/yr) as determined from Figure A-5

Reference to Figure A-5 indicates a corrosion weight loss range for bare steel of approximately 3 to 10 oz/ft² for a 10-year period. In this case (also checking the NBS data) an estimate was used of 8 oz/ft² for 10 years. Therefore $K_2 = 8.0 \text{ oz/ft}^2$ per 10 years or $0.8 \text{ oz/ft}^2/\text{year}$.

A 10% weight loss of the wall thickness of the steel for the RS3500.300 pile results in:

$$W_s = 0.1 (0.300 \text{ in}/12 \text{ in/ft}) (489.6 \text{ lb/ft}^3) (16 \text{ oz/lb}) = 20 \text{ oz/ft}^2$$

The estimated additional life becomes:

$$L_2 = W_s / K_2 = (20 \text{ oz/ft}^2) / (0.8 \text{ oz/ft}^2/\text{yr}) = 25 \text{ yrs}$$

- Life Estimate Summary (Galvanized Steel Round Shaft):

Based upon the assumptions, the results of this analysis indicate that the CHANCE® Type RS3500.300 helical pile as specified for the bridge foundation will experience an average 40 to 45 year estimated life.

Design Example 3:

Extendable helical piles/anchors consist of segmented elements that are coupled together with structural bolts. It is possible for coupling bolts to be located near the surface in disturbed soils. Therefore, it is recommended that the coupling bolt service life be calculated based on corrosion loss rates. This can be accomplished using methods similar to those shown in Design Example 1.

- Determine the diameter reduction of Type SS5/150 coupling bolts using corrosion loss rates per FHWA-SA-96-072. Type SS5/150 Helical Piles/Anchors use 3/4" diameter bolts per ASTM A325. Assume a service life of 85 years.
- Total Zinc Coat Loss:
 Hubbell Power Systems, Inc. provided fasteners are hot dip galvanized per ASTM A153. The coating thickness for ASTM A153 class B = 1.8 oz/ft^2 .
 Zinc loss the first two years: $= 0.385 \text{ oz/ft}^2/\text{year} \times 2 \text{ years} = 0.77 \text{ oz/ft}^2$
 Estimated life of zinc coating = $[1.8 \text{ oz/ft}^2 - 0.77 \text{ oz/ft}^2 = 1.03 \text{ oz/ft}^2 / 0.103 \text{ oz/ft}^2 = 10 \text{ years}] + 2 \text{ years} = 12 \text{ years}$
- Total Steel Loss:
 Coupling bolt steel loss will occur after the zinc coating is lost. The exposure time to corrosion for the bolt steel is: $85 \text{ years} - 12 \text{ years} = 73 \text{ years}$.
 Bolt steel loss over 73 years: $= 0.308 \text{ oz/ft}^2/\text{year} \times 73 \text{ years} = 22.5 \text{ oz/ft}^2$
 $22.5 \text{ oz/ft}^2 / 144 \text{ in}^2/\text{ft}^2 \times 16 \text{ oz/lb} \times 0.283 \text{ lb/in}^3 = 0.035" (0.9 \text{ mm})$
 Diameter reduction after 85 years is $0.75" - 2 \times 0.035" = 0.68" (17.3 \text{ mm})$

- Determine the tensile load capacity reduction of Type SS5/150 Coupling Bolts: The minimum ultimate tensile strength for CHANCE® Type SS5/150 Helical Piles/Anchors is 70 kip. The failure mechanism is double shear of the coupling bolt. Assuming a linear relationship between diameter and shear capacity, the bolt diameter reduction from an 85-year exposure per FHWA-SA-96-072 corrosion loss rates suitable for use in mildly corrosive soils will result in a reduced tension load capacity, i.e., $0.68 \times 70/0.75 = 63.5$ kips.

Design Example 4:

1. Estimated Average Life of Sacrificial Magnesium Type Anode:

The formula for estimating average life for sacrificial magnesium anode life is given in Equation A-6 below:

$$L_3 = [57.08 (K_3) (W_a)] / I \quad \text{Equation A-6}$$

where:

- L_3 = Life expectancy of magnesium or zinc anode (yrs)
- K_3 = Efficiency of anode bag (60%-70%)
- W_a = Weight of anode (lbs)
- I = Current output of anode (mA). Available from Table A-5 for CHANCE® Civil Construction supplied anodes or from the vendor when using other anodes.

NOTE: Equation A-6 is not unit consistent.

Assume that in the previous Design Example 2, the pile performance life is to be further extended (beyond 40 to 45 years) by use of a 48-pound magnesium sacrificial anode for each pile. For this size bar and soil resistivity condition ($R = 1000$ ohm-cm), the vendor indicates $I = 163.5$ mA and $K = 65\%$. Therefore, Equation A-12 becomes:

$$\begin{aligned} L_3 &= [57.08 (0.65) (48)] / 163.5 \\ &= 11 \text{ yrs} \end{aligned}$$



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