Corrosion Risk Mitigation Strategies for the Foundations of Transmission and Distribution Structures—Part 2

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This two-part article covers corrosion risk assessment of electric power transmission and distribution structures. It spans the materials issues, program development, technology alternatives, and assessment strategies. At each stage, there is a risk of corrosion that must be considered. Part 1 (published in the March 2014 issue of MP) covered the metallurgy of steel and galvanizing. Part 2 addresses corrosion of buried galvanized steel, soil testing, and a corrosion risk assessment strategy.

A substantial portion of metallic structures for electric transmission and distribution (T & D) lines in North America consist of galvanized steel and weathering steel lattice towers and poles. Millions of these structures have been in service for over 30 years. So, it is critical that asset owners understand corrosion and anticipate and manage its effects.

Key factors in conducting a quantitative assessment of corrosion risk are:

- Electrochemical field considerations
- Oxidizing and reducing soil environment considerations
- Whether unique soil layers, resistivity and corrosion activity can be determined
- Whether current(s) circulating in a soil and outside interference can be measured and controlled

Corrosion of Galvanized Steel Foundations

Under most soil environments, galvanized steel exhibits a low corrosion rate and performs well because it readily forms a protective film on the surface. Accelerated corrosion of the embedded portion of galvanized steel structures can occur, however, if exposed to highly corrosive or reducing soil environments, even when no oxygen is present. The presence of a reducing environment (i.e., acidic chlorides or microbiologically influenced corrosion [MIC]) is a necessary condition for accelerated corrosion to occur. Outside electrical interference and stray currents can also accelerate corrosion of galvanized steel structures.

In near neutral environments, corrosion is retarded by compact, adherent, insoluble corrosion products. Conversely, in highly acidic or alkaline environments, soluble corrosion products are formed, which destroy protective films and permit corrosion to proceed. If basic carbonate forms, the increase in pH does not take place, preventing the formation of corrosion products or oxides.

The corrosion resistance of galvanized coating increases because the formation of protective basic carbonate zinc extends the region of passivation toward neutral pH values.

Corrosion Characteristics of Galvanized Steel

Zinc is a highly reactive metal. It exhibits a low corrosion rate only if a continuous passive film forms on the surface. A key requirement of corrosion control with galvanized steel is that the surface needs to remain in a soil environment that does not reduce or damage the protective surface film. Galvanized steel T&D structures are exposed to different environments and grounding that can also accelerate corrosion activity depending on soil chemistry, soil resistivity, and the nature and surface area of the grounding materials (Figure 1).

Soil Corrosion

Soils vary widely in their composition and behavior, even over short distances, which can make it difficult to obtain consistent data for designing a risk mitigation solution. While galvanized steel has considerable resistance to corrosion when buried, the greatest attack is caused by soils that are reducing, acidic, or contain large amounts of corrosive water-soluble salts (Figures 2 through 5).

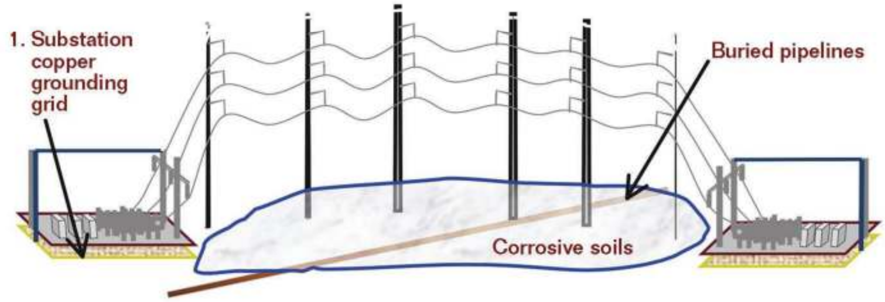

FIGURE 1 Transmission lines, corrosive soils, and substations form an integrated electrochemical system that accelerates corrosion.

Determination of Soil Corrosiveness

To fully understand the corrosion risk to the buried portion of T&D structures, a basis for estimating the probability of corrosion for external surfaces in contact with soil must be established. The probability of corrosion of these items is not only governed by the corrosiveness of the soil and the properties of the galvanized steel, but also by a structure's design and dimensions, and by external electrochemical effects (stray currents, etc.). Since these parameters cannot always be described with adequate accuracy, the likely corrosion behavior can only be estimated.

In determining the corrosiveness of a soil, the different constituent soil characteristics and relevant attributes of the physical environment should be considered. A ranking of the various factors is assigned in order of relevance to corrosion. The sum of those rating factors is a measure for the overall soil corrosiveness. Table 1 presents the key characteristics usually considered.

It is important to have an understanding of the key factors that are measured or assessed to accurately and adequately interpret the results. For example, soil resistivity, which is an approximate measure of the concentration of reactant ions that leads to corrosion, typically decreases as the moisture and ionic concentration increases. Generally, terrains with lower resistivity and reducing properties experi-

FIGURE 2 Transmission and distribution structures are exposed to all types of corrosion-inducing environments, including MIC, that require risk assessment.

FIGURE 3 T&D towers are located in very corrosive and waterlogged soils with active bacteria present.

FIGURE 4 Heavy and corrosive backfills lead to accelerated corrosion of T&D towers.

FIGURE 5 T&D towers on farmland are subjected to accelerated corrosion from corrosive ions.

TABLE 1. CORROSION PARAMETERS

Soil Characteristics
Factors/Attributes: Soil type, homogeneity, moisture content, pH, resistivity, chemical properties, buffer capacity, level of oxidation, organic content, presence of excessive sulfates, and chlorides could lead to microbiologically influenced corrosion (MIC).
Physical Environment Characteristics
Factors/Attributes: Time of wetness, ground water, and land use can indicate possible chemicals and salts, interference from electrical and impressed current cathodic protection (ICCP from gas lines), stray currents, and galvanic action due to grounding and contamination.

TABLE 2. ZINC CORROSION RATES FOR CORRESPONDING SOIL TYPES

Soil Type	Zinc Corrosion Rate (mpy)
Oxidizing clay	0.05-0.20
Reducing acidic soil	0.1-2.0
Salty marsh	0.5-2.5
Moist natural clay	0.1-0.50

ence higher corrosion rates. All tests for the defined corrosion factors are typically performed using standard ASTM, CSA, NACE International, or ASSHTO methods (or modified methods) developed from experience and testing.

One method of measuring soil resistivity is described in AASHTO T 288.[1] The AASHTO method was developed from a California Department of Transportation procedure sanctioned by the Federal Highway Administration (FHWA) for evaluating mechanically stabilized earth (MSE) backfill. ASTM has a different procedure, as described in ASTM G57.[2] This will be replaced by a two-part standard: Part A will cover the four-electrode method for in situ field measurements, and Part B will cover the use of a soil box for laboratory and field test measurements. Corrosion tests on galvanized steel poles buried at different sites are performed by measuring soil resistivity at different depths, pH, total dissolved solids (TDS), chlorides and sulfates, redox potentials (where applicable), resistance polarization, and corrosion rate. It has been found that galvanized steel resists corrosion far better than bare steel at most sites. Table 2 shows the zinc corrosion rate in mils per year for 60 sites.

The corrosion rate for oxidizing soils decreases with the formation of protective layers on galvanized steel. In reducing soil, this layer does not form so the corrosion may increase over time. In this case, the structure should be adequately protected when located in reducing soils. For galvanized steel poles, protection should be applied both outside and inside the pole if the water table is high or is expected to be a concern. Agricultural soils are typically more corrosive because of the high concentration of corrosive ions in fertilizers. Likewise, structures exposed to excess amounts of road or seawater salts (sodium chloride [NaCl]) experience higher corrosion rates from more exposure to chlorides. Magnesium chloride ($MgCl_2$), an alternative to traditional deicing salt, has also been shown to increase the corrosion rate.[3]

Inspection Techniques and Confidence Level

The methods for determining corrosion risk of galvanized steel foundations include knowledge-based assessments that bring together materials science, metallurgy. electrochemical, and corrosion science with the understanding of how a structure is designed, built, and assembled. The key techniques involved are geared toward quantitatively determining the soil and physical characteristics of the service environment in order to carry out a multi-factor risk-based assessment of corrosion. The authors have successfully initiated and carried out work of a similar nature and recommend the following activities:

- Physical assessment of the soil service environment to rate corrosiveness
- Electrochemical testing of soil condition and steel interaction (potential values and soil resistivities to predict corrosion profile at lower depths)
- Focused visual, physical, and electrochemical assessment and testing of buried components at a shallow depth

In risk assessment, these test results should be taken into consideration along with structure age, size, design, function, and importance. Each structure is then assigned a below-grade corrosion risk rating or condition assessment value. This rating is used to recommend appropriate remediation and mitigation procedures. Special attention should be given to structure designs that lead to accumulation of moisture and corrosive salts regardless of whether the foundation is buried in soil or encased in concrete.

Depending on the method of evaluation, a level of confidence can be assigned to indicate the ability of that procedure to produce reliable corrosion risk data on their own without combining it with another form of assessment.

TABLE 3. SOIL CORROSIVENESS PARAMETERS

	Corrosiveness	
Soil Condition	**Corrosive**	**Progressively Noncorrosive**
Texture	Fine	Coarse
Color	Dark (black or grey)	Light (red or brown)
Acidity	High	Low
Aeration	Poorly aerated	Well aerated
Resistivity	Low	High
Organic content	Present	Absent
Moisture content	High	Low
Redox potential	Low or negative	High or positive
Sulfides/sulfates	Sulfides present	Sulfates present
Chlorides	Chlorides present or high	Low or absent

TABLE 4. KEY CONSIDERATIONS FOR A CORROSION PROGRAM

Consideration	Recommendations/Key Learning
You have steel structures	They will corrode so a program approach is required
Visual inspections are not adequate to determine risk	Corrosion is not limited to ground line or the top 600 mm below grade
Selected tests can increase confidence in corrosion assessment	Knowledge-based inspections will quantify the risk
Replace structures at end-of-life	Life expectancy can be extended "significantly"

Desk Study (Least Confidence)

A desk study can be carried out using geographic information system (GIS) data with geological records giving soil parameters and survey results for assets. Data collected should include any available soil classifications, resistivities, corrosiveness, pH, and other relevant information. The accuracy and reliability of desk studies are based on the data used and the ability of the user to categorize, integrate, and determine the importance of all the relevant aspects in order to determine risk. This method does not account for shifts in terrain or the coarseness of map and geological data.

Soil Testing and Soil Sampling (Moderate Confidence)

Soil testing and sampling can be conducted by testing resistivity and electrochemical potential of the soil around footings and anchors. These parameters are the two key factors in the soil corrosiveness equations.

The resistivity measurements will express the capacity of the soil to act as an electrolyte. The electrochemical potential measurements will express the soil's corrosion activity or how active it is toward an oxidative/reductive corrosion reaction. Corrosion rate measurements can provide maximum thickness loss and life expectancy estimates or remaining life under the worst possible condition. This is a quantitative assessment that depends on the skill of the inspector, the condition and calibration of the instruments, and the sample size of the tests.

Knowledge-Based Inspection (High Confidence)

The target structure foundation is usually inspected to a depth of 36 in (914 mm) below grade. Soil samples are collected in areas of concern based on soil resistivities <2,000 to 5,000 Ω·cm and where structure-to-soil potentials exhibit accelerated corrosion activity. If corrosion on the excavated structure component shows signs of significant material loss, a more detailed coating and steel substrate condition inspection should be considered and performed. Inspection of the protective coating consists of adhesion measurement, thickness measurement, and defect characterization. Measurement of corrosion rate (loss in thickness/unit time) is performed based on the electrochemical polarization techniques, which determine the loss in thickness under worst wet conditions. The loss in thickness can be related to load bearing capacity and uplift resistance of the structure with a relationship established between member size reduction and uplift resistance. This is a quantitative assessment that focuses on each structure and allows engineers to determine the amount of galvanized steel thickness reduction (based on corrosion rate) a grillage foundation can sustain. Concrete inspection and, if required, petrographic analysis are performed for damaged or degraded concrete base structures. Soils with high sulfate content may also react unfavorably with concrete footing and foundations.

This detailed quantitative assessment focuses on each structure and depends on the skill and training of the inspector. Because all the relevant corrosion and structural parameters are assessed in addition to a visual inspection during the detailed assessment, the level of confidence in the results from such knowledge-based inspections is high.

Assigning Soil Corrosiveness Value

The soil around a selected structure can be assigned a soil corrosivity rating based on a number of parameters including soil resistivity, pH, chlorides, sulfates, and electrochemical polarization parameters (Table 3).

Data Collection, Sorting, and Analysis

Data collection, sorting, and analysis should be given special attention as these activities directly impact the quality of the assessment and subsequent analysis. A computerized platform with data capture, storage, and analysis should be used.

In general, the computer platform should be designed with the following attributes:

- GIS capability
- Mobile device compatible
- Multi-platform and multi-format capability
- Ease of data entry (user interface is key) and retrieval
- Data validation and quality management
- Real-time risk analysis based on risk algorithms
- Data management strategy and administration

Corrosion Mitigation for Aging Structures

To carry out or develop a corrosion mitigation strategy for steel structures, the corrosion risk must be well defined through knowledge-based inspections that are focused on the relevant criteria. The key steps to properly managing galvanized steel assets and assessing conditions are:

Plan Ahead

- Store galvanized steel components properly and rotate stock.
- Ensure galvanizing and coating specifications allow for aging and future management.
- Require suppliers to provide performance and test results for recommended coatings.
- Develop corrosion management and risk assessment programs for aged assets.

Assess

- Perform desk studies, corrosion risk assessment, and knowledge-based inspections.
- Utilize modern computer platforms for data collection, sorting, and analysis.
- Utilize certified corrosion specialists for any specifications, assessment, or design.

Prioritize

From a technical and business perspective, the assessment needs to answer the following questions to optimize risk management and prioritize any work:

- Where and when should resources be applied?
- Should only the worst T&D line assets be addressed first?
- Should resources be diverted from less risky assets in order to better mitigate risks in higher-risk areas?
- How much urgency should be attached to any specific risk mitigation proposal?

Manage Risk

- Collect data on asset condition and evaluate the structure's remaining life and capacity based on condition.
- Develop risk management programs to monitor, protect (coat, recoat, repair, apply cathodic protection [CP]), or replace assets.
- Consider suitable protective coatings in corrosive environments and consider using corrosion-resistant or passivating backfills. Consider a CP system (wide or isolated) in conductive and/or corrosive soils, taking into account electrical continuity and grounding.
- Employ best practices and qualified engineers and technicians to perform any recoating or CP installation.

Conclusions

Corrosion risk assessment is an evolving field and should be looked at as such. Significant interrelationships exist among the wide variety of possible parameters that contribute, lead to, or accelerate or reduce the corrosion risk to steel structure foundations. Because it is difficult to develop a "one-size-fits-all" application or solution for mitigating corrosion risk, knowledge-based assessments should consider the service environment, corrosion science, business risk, and financial objectives. Table 4 shows the key considerations that asset owners and engineers should factor into evaluations for determining whether it is necessary to develop a corrosion program.

As asset owners and engineers gain experience in considering as many of the corrosion-related parameters as practicable, and as appropriate testing and expertise are deployed, the confidence level in condition assessments and proposed solutions will increase.

Factors external to the assets operation should also be considered, such as outside mechanical and chemical interference, as well as electrical impacts like stray currents. It is vital that competent NACE-certified Corrosion Specialists and engineers participate in the efforts of asset owners to deal with this issue to avoid preventable risks.

Acknowledgments

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