

Electrochemical Testing for Soil Corrosivity Determination – The Impact of Test Methods on Corrosion Modelling

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ABSTRACT

Soil resistivity measurements are an important parameter when designing earth installations such as steel-driven piles, soil nails, power supply facilities, electrical conduits, or instrumentation systems. Corrosion modelling considers many factors such as soil stratification and mineralogy, soils resistivity, moisture, chemical content and concentration of the soil, and potential for contamination.

Selection of an accurate resistivity model for the soil is critical when designing the system that is expected to meet safety and reliability criteria. A wide range of soil resistivity test methods include in situ testing and testing of soils samples removed from the ground for use in the assessment and control of corrosion of buried structures. Other parameters to determine soil corrosivity include testing for sulphate and chloride concentrations, pH, and organic content determination.

Evaluation of soil corrosion potential relies on specific standardized methods and on the limits for electrochemical parameters. When non-standardized analysis is conducted but the same limits for the electrochemical parameters are applied, the classification of soil corrosivity maybe skewed, and the risk of inadequate or conservative corrosion protection methods is increased.

This paper is focused on evaluating test methods for resistivity and electrochemical parameters and the validity of the results. The sensitivity analysis test results and the potential impact on design of corrosion protection systems is discussed.

RÉSUMÉ

1 INTRODUCTION

The electrochemical corrosion of metal has a significant impact on the performance and life cycle of civil engineering structures exposed to corrosive soils and other aggressive elements. Foundation investigations should include corrosion investigations and evaluations for bridges, tunnels, retaining walls, mechanically stabilized earth (MSE) walls, sound walls, tie-back walls, and many other structures. The corrosion evaluation reports should include all available corrosion data for the site and a detailed discussion of the data and conclusive information regarding site corrosivity. The guidelines and the test methods should be referenced in the evaluation.

There are no studies available on how the different test methods affect soil corrosivity determination. The criteria and limits for the determination of corrosion potential of soils was developed based on specific standards. The challenge in reviewing non-standard results for soil corrosivity assessments lies in the testing methodology to which the current criteria do not apply.

An internal testing program was developed to compare and analyze the electrochemical testing results of sets of samples when different test methods were applied.

1.1 Mechanism of Steel Corrosion

The corrosion of steel is electrochemical in nature (i.e., chemical reactions and flow of electrical current are coupled in the process). The mechanism is well known, reported in many standard textbooks, and thus is described in this letter report only in summary form. The corrosion process involves anodic and cathodic reactions. The two reactions are as follows.

Anodic reaction:



Cathodic reaction:



The anodic reaction results in a loss of metal at the anodic site. The iron ions are dissolved in the water solution around the steel and the electrons are deposited on the steel surface thus raising its electrical potential. The electrons flow along the steel to a lower potential (cathodic site). The cathodic reaction at this site combines electrons with dissolved oxygen ions and water to form hydroxide ions. A critical factor that determines whether corrosion occurs and influences the rate of corrosion is the availability of dissolved oxygen since the metal removal process will continue only if oxygen and water are present at the cathodic sites.

Experimental results show that diffusion coefficient of oxygen is strongly influenced by the degree of saturation

and by porosity. In soils, the effective diffusion coefficient diminishes as the water content increases and it reaches its minimum value at full saturation.

The underground corrosion is irregular in nature; sections of steel may be penetrated only at one or more points while no corrosion is found elsewhere on the section. The major cause of the irregular or localized corrosion is the non-uniform distribution of oxygen and moisture.

2 CORROSION ASSESSMENT CRITERIA

There are several guidelines for assessing ground corrosion. Federal Highway Administration (FHAWA-NHI-14-007) criteria are presented in Table 1. Similar limits are specified by many other agencies in North America.

Table 1. Criteria for Assessing Ground Corrosion

Test (Units)	Threshold for Non-Aggressive	Test Method
pH (-)	5.0 < pH < 10	AASHTO T-289
Resistivity (Ohm-cm)	> 3,000	AASHTO T-288
Sulphates (ppm)	< 200	AASHTO T-290
Chlorides (ppm)	< 100	AASHTO T-291
Organics (%/mass)	< 1%	AASHTO T-267

For some of the properties listed in Table 1, more than one type of test can be used, occasionally deviating from American Society for Testing and Materials (ASTM) or American Association of State Highway and Transportation Officials (AASHTO). The difference in results might be small in most cases with some methods being more accurate and reproducible than others. Equivalent tests methods to AASHTO methods are listed in Table 2.

Table 2. Equivalent Test Methods

Test	AASHTO Test Methods	Alternative Test Methods
pH	AASHTO T-289	ASTM D2976
Resistivity	AASHTO T-288	ASTM G187
Sulphates	AASHTO T-290	CSA A23.2-4B
Chlorides	AASHTO T-291	CSA A23.2-3B
Organics	AASHTO T-267	All other methods are acceptable

2.1 In Situ Resistivity Testing vs. Laboratory Testing

The methods listed above are for testing of soil samples in the laboratory. In situ resistivity testing on site is conducted in accordance with ASTM G57 and other methods but a direct comparison of the results of in situ and laboratory results is not possible. The discrepancies are due to differing testing conditions. Laboratory resistivities are

measured over a small distance and cross-sectional area and, therefore, are very specific to the soil sample and saturation conditions that are reconstituted. The samples are prepared under standardized conditions that are used in corrosivity of soils determinations. In situ resistivity values are bulk measurements over distances of tens or even hundreds of metres and, therefore, will represent a bulk, averaged resistivity value that will reflect variations of soil moisture, soil type, and gradation over that distance. They reflect the site conditions at the time of the test and are influenced by the seasonal variations of the moisture and groundwater conditions.

Sampling of the soils may influence the results as laboratory resistivities are measured on discrete samples targeting individual soil layers in a manner that seeks to be consistent to obtain the minimum soil resistivity. In situ measurements are bulk measurements in an undisturbed resistive state of the soil at the time of measurement. This may include conductive pore fluids, partial saturation of the soil, and variations in soil type and gradation over the bulk measurement distance.

The resistivities tested in the laboratory are accompanied by other electrochemical testing that takes into consideration the chemistry, either natural or from site contamination, and their contribution to corrosion of steel.

In situ testing is conducted using four-electrode methods. The laboratory procedures can be conducted using four-electrode or two-electrode methods. The differences between the resistivity tested by four- and two-electrode procedures are small and are within a 10% range for saturated soils.

Considering these distinct differences, which are an intrinsic result of the different testing methodologies, the normal expectation would be that the laboratory testing resistivity results would provide a gauge of the potential resistivity extremes, while the in situ resistivity results would provide values that are more reflective of the typical site conditions. The appropriate selection of resistivity values will be dictated by the design objectives and approach.

2.2 Evaluation of Soil Corrosion Potential

The level of corrosion protection is selected based on the soil corrosion potential, which takes into consideration conditions promoting corrosion. These include pH level of the ground, electric resistivity of the ground, high concentration of chlorides and sulphates in the ground and groundwater, degree of soil saturation, organic content of soil, and availability of oxygen.

Corrosivity ratings based on soil resistivity are presented in Table 3 (Handbook of Corrosion Engineering, Roberge, 1999).

Table 3. Effect of Resistivity on Corrosion Potential

Soil Resistivity (ohm-cm)	Corrosion Potential
>20,000	Essentially non-corrosive
10,000 - 20,000	Mildly corrosive
5,000 – 10,000	Moderately corrosive
3,000 – 5,000	Corrosive
1,000 – 3,000	Highly corrosive
<1,000	Extremely corrosive

There are small differences in the corrosion potential classification of soils based on resistivity provided in other guidelines, but, in general, all electrochemical criteria in Table 1 must be satisfied.

3 NON-STANDARD ELECTROCHEMICAL TESTING

The electrochemical testing is conducted by materials and chemical laboratories in accordance with the methods used for assessing ground corrosion criteria. When non-standard test methods are used, the results are variable depending on the methodology used. The implications associated with using these test methods are not always understood and, when used to classify the soils' corrosivity, may misrepresent the actual soil properties.

In the absence of literature on the impact of different test methods on the determination and classification of soil corrosivity, an internal research program was developed and conducted by Tetra Tech to compare different test methods and to explain the origin of results variability.

3.1 Resistivity Testing

Samples tested in accordance with the Standard Methods for the Examination of Water & Wastewater provide the results that are significantly different when tested in accordance with the specified AASHTO and ASTM methods for resistivity. The testing based on the book of Standard Methods for the Examination of Water & Wastewater follows the procedure 2510 Conductivity, and the laboratory method is 2510B. The soil sample is saturated in water and the extracted liquid from the soil is tested for conductivity. The resistivity is calculated as the inverse of conductivity. This method does not directly measure resistivity of the soil samples. A comparison of the resistivity calculated from conductivity of extracted water and the resistivity tested in accordance with AASHTO T-288 on the same granular material samples is presented in Figure 1.

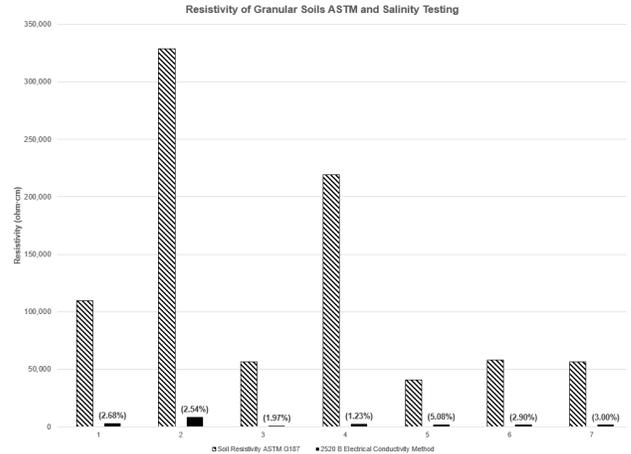


Figure 1. Comparison of resistivity by AASHTO T-288 and salinity by 2510B

The results indicate that resistivity, when calculated from conductivity of water, represents 2% to 5% of the value obtained by testing soil resistivity. The actual values on the bar chart in brackets show the percentage for individual samples. When these results are used in the corrosion evaluation, the soils are classified as extremely corrosive, and either a costly corrosion protection system is designed, or the type of foundation system has to be altered.

The fundamental reason for such low resistivity values is in the test itself. When a soil sample is directly tested for resistivity, it is impacted by the mineralogy of rock and soil formation. When the extracted liquid from the soil is tested, the impact of mineralogy of the soil grains is not considered.

The distribution of resistivity for rock and soil formations is presented in Figure 2.

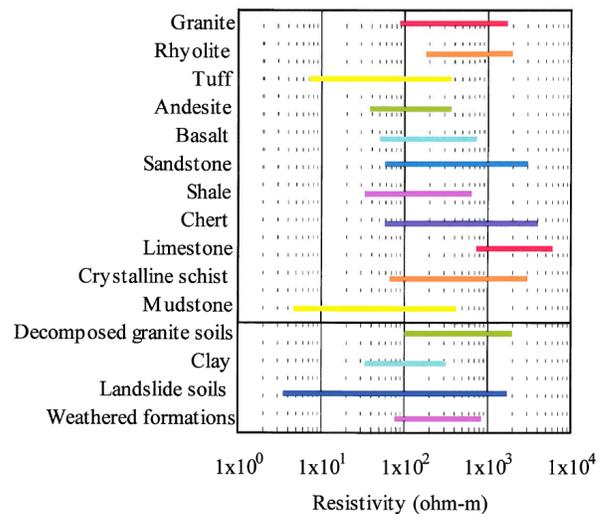


Figure 2. Distribution of resistivity for rock and soil formations

The resistivity of rocks is dependent on their mineralogy and is in the range of 10,000 to 1,000,000 ohm-cm for the most common rocks found in granular materials.

The porosity of rocks has an impact on the resistivity values and is presented in Figure 3 (Matsui, T. et al. 1999).

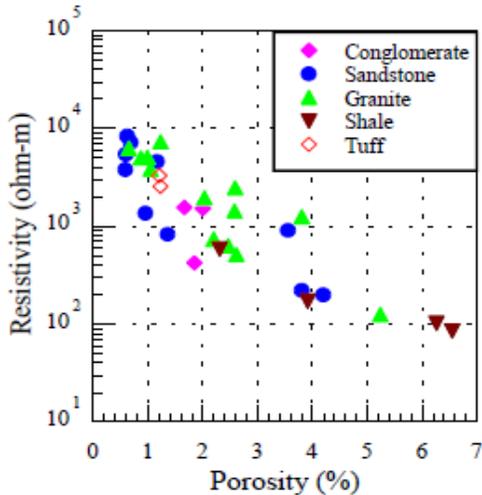


Figure 3. Relationship between resistivity and porosity of rocks

In general, an increase in porosity causes a reduction of resistivity but the correlation is influenced by the mineralogy and pore geometry.

As expected, the degree of water saturation has an impact on the resistivity of rock (Figure 4).

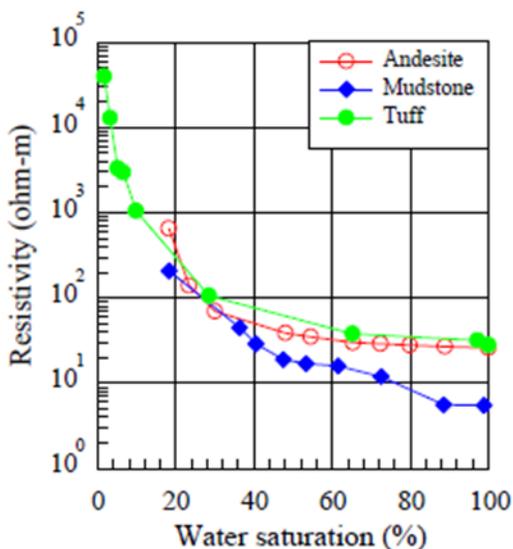


Figure 4. Relationship between resistivity and degree of saturation

Increasing the degree of saturation results in a decreased resistivity for the same type of rock.

The test method 2510B for water and wastewater conductivity testing does not recognize the impact of mineralogy, porosity, and degree of saturation on the resistivity of granular soils. The comparative testing of the granular materials using both methods confirms that when the properties of rocks present are ignored, the conductivity method greatly underestimated the material's resistivity. When non-compliant test methods are used, the potential for low resistivity and the risk of unnecessary corrosion protection methods or a rejection of either granular material of the steel foundation design is high.

3.2 Sulfate Testing

Sample preparation for sulphate content determination in soils using AASHTO T290 test method includes collecting material finer than a 2 mm sieve to be tested. A known mass of sample is mixed with a known volume of distilled water and is filtered to obtain a clear sample. This clear sample can be tested for sulphate using gravimetric method or turbidimetric method. The sulphate content result is expressed in parts per million (ppm) or mg/kg. Since the initial mass of sample is known, the conversion to percentage of total sulphate content is possible to check against the limits expressed as percent.

Canadian Standards Association (CSA) A23.2-3B is also accepted for testing of soils. A soil sample that is finer than 315 um is collected for testing. For evaluation of total sulphate content, a 1 gram sample is weighed with 25 mL of distilled water, mixed, and 5 mL of hydrochloric acid is added. The solution is diluted and digested (just short of boiling) for 15 minutes and filtered afterwards to obtain a clear filtrate. The clear filtrate is then tested for gravimetric method. The total sulphate content result is expressed in percentage, %. If the total sulphate ion content is more than 0.2%, the test method for evaluating water-soluble sulphate content is to be done. Since the initial mass of sample is known, the conversion to ppm in the total sulphate content is possible, when needed. The sulphate content is expressed to the nearest 0.01%.

The CSA method specifies acid digestion method and the AASHTO preparation does not include acid digestion.

The sulphate ion testing conducted for the examination of water and wastewater (4500 Sulphate) does not follow AASHTO or CSA procedures. While some laboratories state that the soil extract is produced by saturated paste extraction procedure and tested in accordance with 6010B – gas chromatography, no comparison with the CSA or AASHTO methods is possible.

The detection limit of the 4500 Sulphate procedure is 0.05%, which is five times lower than the specified CSA A23.2-3B precision of 0.01%.

Without a direct comparison of the test methods to develop a correlation, the risk of false positive or false negative results failing the limits is high.

3.3 Chloride Testing

In accordance with the AASHTO T291 test method, a sample that is finer than a 2 mm sieve is collected and used

for the test. A known weight of sample is mixed with a known volume of deionized water and is filtered. The filtrate with its known volume will be tested for chloride using several methods such as Mohr titration method and pH/mV meter with ion selective electrode method. The chloride content result is expressed in ppm or mg/kg.

Another test method being used for determination of chloride in soils is CSA A23.2-4B, the test method for sampling and determination of water-soluble chloride ion content in hardened grout or concrete. This procedure specifies that a material that is finer than a 315 um sieve is collected for testing. Since the material is either a grout or concrete, hot deionized water is added to the sample to make a slurry and is ground until all lumps are eliminated. The slurry sample, after another addition of hot deionized water, is boiled for 5 minutes and is left to stand for 24 hours. The sample is then filtered and tested for chloride using pH/mV meter with ion selective electrode method. The chloride content result is expressed to the nearest percentage (%).

CSA requires boiling of the sample prior to testing and AASHTO requires testing of the sample that is only mixed with deionized water.

The chloride ion content result is expressed as either ppm (mg/kg) or percentage. Since the initial mass of sample is known, the conversion of units defining total chloride content is possible for the AASHTO and CSA methods.

The chloride ion testing conducted for the examination of water and wastewater (4500 Chloride E, Automated Ferricyanide Method) does not follow AASHTO or CSA procedures. The details of the procedure to extract liquid from the saturated paste are not included, and since the initial mass of the sample is not reported, a conversion from ppm to percentage to confirm conformance with limits for the soil corrosivity criteria is not possible.

In the absence of correlations between the 4500 Chloride E method and the accepted AASHTO and CSA methods, the risk of relying on the non-standard method for corrosion evaluation is high.

4 CONCLUSIONS

Only a selection of the most used non-standard electrochemical testing procedures are discussed in the context of accepted testing protocol for soil corrosion determinations. There are other laboratory procedures that are developed for water and wastewater analyses and utilized in the electrochemical testing for soils. While these methods are valid for conformance with the environmental guidelines, they are not designed to be used in corrosion evaluation of soils and granular materials.

It has been demonstrated that the criteria for corrosion potential determination do not apply when non-standard test methods are used and that such results produce false positives and false negatives, and possible rejection of materials or extensive corrosion protection systems that may not be necessary.

Since the sample preparation for these methods is much different than the sample preparation requirements for soils, and the testing methods are different, it is

expected that the results are variable, and correlations would need to be developed to better understand the differences.

A common mistake is to calculate percentage from ppm, or ppm to percentage of the units of non-standard chemical analyses when the initial mass of the sample tested is not reported.

In the absence of understanding of the results obtained by non-standard methods, the reliability of the corrosion evaluation may be low and the risk of false positive or false negative results is increased.

The highest sensitivity of the non-standard testing is confirmed when the conductivity of water extracted from soils is tested and converted to resistivity. This method does not take into consideration resistivity of rocks and minerals in the soils and granular materials. Since the results are on average 95% lower when compared with standard test for soil resistivity, the probability of classifying soils as highly corrosive is high.

The use of non-standard electrochemical testing should not be accepted or as it may result in significant costs of the unnecessary corrosion protection requirements, changes to the foundation designs, and the unjustified prediction of reduced life cycle of the structures.

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