REPORT FHWA/NY/SR-90/97

Reinforcement Corrosion Of Mechanically Stabilized Earth Structures

MICHAEL E. DOODY

SPECIAL REPORT 97

ENGINEERING RESEARCH AND DEVELOPMENT BUREAU
NEW YORK STATE DEPARTMENT OF TRANSPORTATION
Mario M. Cuomo, Governor/Franklin E. White, Commissioner

REINFORCEMENT CORROSION OF MECHANICALLY STABILIZED EARTH STRUCTURES

Michael E. Doody, Civil Engineer I

Final Report on Research Project 191-01
Conducted in Cooperation With
The U. S. Department of Transportation
Federal Highway Administration

Special Report 97
July 1990

ENGINEERING RESEARCH AND DEVELOPMENT BUREAU
New York State Department of Transportation
State Campus, Albany, New York 12232

ABSTRACT

This report outlines electrochemical and biological properties of soils that determine the rate and type of corrosion of buried metals. Mechanisms of corrosion are briefly discussed and specifications that consider interaction of the various properties are suggested. The Appendix presents a consultant's opinion, from which the specifications are drawn. A method of ranking corrosivity of materials to be used as backfill is suggested. Although particular reference is made to reinforced earth structures, this information is important to any system where metals are buried in soil.

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I. INTRODUCTION

New York currently has about 160 mechanically stabilized (reinforced) earth structures in place. Reinforced earth (RE) design is a cost-effective construction technique used on fill projects, where right-of-way costs are a significant consideration, or for structures built on compressible soils. One such structure was a reinforced earth wall on the SUNY-Buffalo ramp of the Lockport Expressway in Amherst, New York, constructed with a lightweight cinder backfill material in 1981. Due to severe corrosion of the reinforcing straps and the piles supporting the adjacent abutment, the structure had to be torn down and rebuilt in 1988. On discovery of the extent of the corrosion, a decision was made to hire a corrosion expert to assess the corrosivity of backfill in the Lockport Expressway structure, as well as to prevent potential problems at future sites. His assessment is included here as an appendix. The purpose of this report is to document the consultant's suggested testing methods for the identification of potential corrosion problems with existing structures, and to suggest modifications to incorporate these test methods into the current construction specifications, in order to minimize this type of problem in the future.

In November 1981, the Department's Soil Mechanics Bureau requested that corrosive potential of the backfill material in a reinforced earth wall on the Lockport Expressway be evaluated, due to concerns that the lightweight cinder backfill would promote corrosion of the reinforcing straps. As a result, 2-ft long test reinforcing straps were installed in the cinder embankment near the structure in September 1982. Four test straps were removed at the end of both 1983 and 1984. The corrosion rate was moderately high, but not high enough to cause alarm. In July 1985, the structure was visually inspected and had no apparent problems. In 1985, it was decided to expand the reinforcing strap corrosion monitoring to additional structures. The goal of Research Project 191-1 was to monitor corrosion in mechanically stabilized earth structures to determine a corrosion rate for use in predicting RE wall design life. Reinforcing life would be estimated using weight loss data obtained after 1, 2, 5, 10, and 20 years and relationships between corrosion rates and backfill parameters. Test sites were established at 14 structures.

In April 1987, in conjunction with an FHWA contract study titled "Durability/ Corrosion of Reinforced Soil Structures," the Amherst site was chosen for the installation of a prototype corrosion meter. During the installation of the corrosion meter in June 1987, it was discovered that the structure's reinforcing straps exhibited a corrosion rate greatly exceeding those determined from the test straps. It was decided to remove the next series of test straps (originally scheduled for removal in September 1987) to determine their condition. These test straps also did not show the extensive damage found on the structure's straps. In view of these findings, the Department

Table 1. Comparison of NYS Sites With NYS Specifications (Post-Construction)

		Resistivity ($\Omega \cdot$cm)	pH	Chlorides (ppm)	Sulphates (ppm)	Sulphides (ppm)
1985 NYS Specification		> 3000	5-10	< 100	< 500	< 300
Installation Site	Contract					
Amherst	D96681	65-303	3.6-4.4	0	2100-2800	160-290
Buffalo (mesh)	D251163	686-720	8.1	460-530	500-800	2400-3900
Syracuse	D250918	2093-3300	8.0-8.3	100-130	340-840	200-900
Corning	D250848	6374-7354	8.2-8.4	0-30	800	40-240
Utica	D251207	13,334	7.9	0	200	200
Utica	D500273	13,334	8.3-8.6	0-140	0-300	100-2300
Albany	D500065	6834-7440	8.5	0	300-600	500-900
Ilion	D500291	6080-10,260	8.4-8.7	0	200-300	500
Painted Post	D500354	7487-10,100	8.6	0	200-300	200-300
Binghamton	D500314	965-1045	8.5-8.6	250	0-100	200-300

of Transportation, at the recommendation of the Soil Mechanics Bureau, let an emergency contract to excavate five levels of straps in one vertical section of this structure. Twelve straps were removed and a visual examination of the straps confirmed extensive corrosion.

In 1985, the Department specifications, in accord with then current FHWA guidelines for construction of mechanically stabilized earth structures, required testing of the backfill material only for mechanical properties. Backfill samples from the Amherst and several additional RE structure sites taken during construction were tested, post-construction, for corrosive potential according to then current Departmental guidelines as part of the research project. The results of these tests are given in Table 1. A similar table in the appendix (Table V) includes these data, but also includes additional data taken at times after installation when test straps were removed. Table 1 shows that many sites did not conform to the guidelines in one or more categories. The Amherst data from this table has been analyzed using an assessment technique for classifying the corrosive potential of soils (Table 2), modeled after Jones (1) and the American National Standard AWWA C105 (2), and tailored to Department applications and proposed specifications. This analysis shows that the corrosion potential of the Amherst site backfill material is in the strongly aggressive range (Table 3), indicating a very corrosive soil. The analysis is borne out by the corroded condition of the recovered straps recpvered there.

Of the 14 structures that have test straps installed, four structures have had eight test straps extracted showing negligible corrosion. Because these straps were not in the actual structure environment, they would not necessarily reflect the moisture and wet/dry cycles to which actual reinforcing straps would be subjected. In addition, they were not of sufficient length to provide a realistic means of assessing any possible corrosion cell development as a result of varying conditions along a typical reinforcing strap. Therefore, the test strap monitoring program has been discontinued.

Table 2. Estimation of Soil Aggressiveness (after Jones[1]).

Parameter	Ranking
Kind of Backfill:	
Chalk, chalk marl, sand marl, sand	-2
Loam, loam marl, loamy or clayey sand	0
Clay, clay marl, humus	2
Peat, mud, bog soil	4
Drainage (water table and native soil):	
Good drainage, generally dry	0
Fair drainage, generally moist	1
Poor drainage, continuously wet	2
Coal, coke, or cinders:	
Not Present	0
Present	4
Soil resistivity (Ω·cm):	
Above 10,000	0
5,000 to 10,000	1
2,300 to 5,000	2
1,000 to 2,300	3
Below 1,000	4
pH value:	
Above 10.5	1
4.0 to 10.5	0
Below 4.0	1
Redox potential (mV, SHE, pH=7):	
Above 400 (430 for clay)	-2
200 to 400	0
0 to 200	2
Below 0	4
Sulfate-reducing bacteria:	
Not present	0
Trace	2
Present	4
Chloride (ppm):	
Below 100	0
Above 100	1
Sulfate (ppm):	
Below 500	0
Above 500	1

Sum of rank numbers:

Negative	Practically non-aggressive
0 to 4	Weakly aggressive
5 to 10	Aggressive
Above 10	Strongly aggressive

Table 3. Corrosion Potential of Soil in Lockport (Contract D96681).

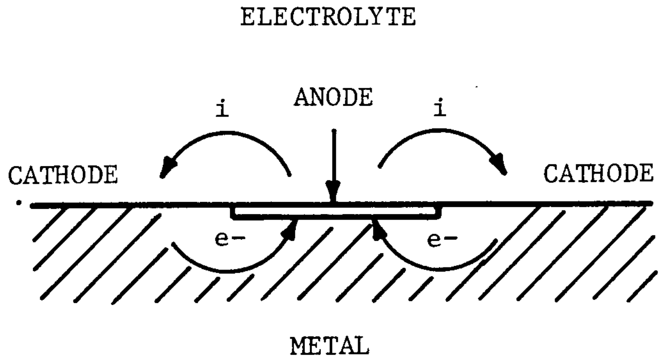
Parameter	Measure	Ranking
Kind of backfill	N/A	0
Drainage	Poor drainage	2
Coal, Coke, Cinders	Present	4
Resistivity	Below 1000	4
pH	Below 4.0	1
Redox potential	N/A	0
SRB	N/A	0
Chlorides	Below 100	0
Sulfate	Above 500	1
Sum of rank numbers		12
Soil ranking		Strongly Aggressive

II. CORROSION PROCESS

Corrosion of metals buried in soil is accomplished by both electrochemical and biochemical processes. Several soil properties have been identified as significantly affecting the rate at which corrosion occurs. These properties include the amount of soil moisture, the electrical conductivity of the soil, the hydrogen ion activity (pH), the oxygen concentration (aeration), and the activity of organisms capable of causing oxidation-reduction reactions. The importance given these properties is based on available research data, particularly from National Bureau of Standards Circular 579 (3).

The electrochemical process is characterized by the development of a galvanic cell. In a galvanic cell, ions are transported through an electrolyte from a positive electrode (anode) to a negative electrode (cathode) with a conventional current passing in the opposite direction through a conductor to complete the cell (Fig. 1). The rate at which corrosion occurs depends on the soluble salt content in the soil and variations in electrical potential either along the conductor or in the electrolyte. Holidays (pinholes) in any strap coating (galvanizing or epoxy) are natural points for corrosion to occur because a difference in electrical potential exists there.

Figure 1. Idealized Galvanic Cell



With respect to corrosion of galvanized steel buried in soil, the electrolyte consists of moisture in the soil containing oxygen and dissolved salts (chlorides and sulfates), the transported ions are iron or zinc from the anode, the cathode is the site where the metal ions are incorporated into the corrosion product, and the conductor is the galvanized steel. Thus, in the case of RE Structures, galvanized steel reinforcement straps and connections may be subject to corrosion in the form of iron ion loss in the reaction at the anode. Because of the electrolytic action of the moisture in the soil,

Table 4. Comparison of Suggested NYS Specifications With Current Guidelines.

	Resistivity ($\Omega \cdot$cm)	pH	Chlorides (ppm)	Sulphates (ppm)	Sulphides (ppm)
FHWA Guideline	> 3000	5-10	< 50	< 500	N/A
FHWA Test Method	Caltrans Test 643	Caltrans Test 643	Caltrans Test 422	Caltrans Test 417	
AASHTO Specification (1987 draft)	> 3000	5-10	< 50	< 500	N/A
AASHTO Test Method	Caltrans Test 643	Caltrans Test 643	Caltrans Test 422	Caltrans Test 417	
1985 NYS Specification	> 3000	5-10	< 100	< 500	< 300
Test Method	Departmental Laboratory Procedures	Departmental Laboratory Procedures	Chemical Analysis	Chemical Analysis	Chemical Analysis
Reinforced Earth Co Spec	> 3000	5-10	< 200	< 1000	N/A
RE Co Test Method	Caltrans Test 643	Caltrans Test 643	Caltrans Test 422	Caltrans Test 417	
VSL Corp Spec	> 3000	5-10	< 200	< 1000	N/A
VSL Test Method	Caltrans Test 643	Caltrans Test 643	Caltrans Test 422	Caltrans Test 417	
Suggested NYS Specification*	> 5000	6-9.5	< 50	< 200	N/A
Suggested Test Method	ASTM Std G 57-78	ASTM Std G 51-77	Caltrans Test 422	Caltrans Test 417	
1990 NYS Specification	> 3000	5-10	< 100	< 200	< 300
Test Method	Caltrans Test 643	NYSDOT Method STM 15	Caltrans Test 422	Caltrans Test 417	ASTM Std D-2492

*Consultant's Suggestions - August 1988 - Redox potential < 400 mV against a standard hydrogen electrode at pH 7. Sulfate-reducing bacteria not present according to test kit.

the controlling factor for the rate at which corrosion occurs is the presence of this moisture.

In soils, the most common form of biochemical corrosion is caused by sulfate reducing bacteria (SRB). SRB occur everywhere, thriving under anaerobic conditions, and becoming dormant in the presence of oxygen. These bacteria convert sulfates in the soil to sulfides, which drives the anodic reaction. A by-product of the reaction may also be organic acids which produce pitting corrosion.

Standardized test methods for corrosivity assessment of soil environments are currently being worked on for AASHTO. It is expected that standard tests will be recommended to them in August 1990. At present, there are no consistent parameters for corrosivity assessment nor have test methods been standardized. The best current approach is to control the material properties of the backfill material to slow the onset of corrosion. Thus, it is recommended that backfill specifications be made as conservative as practical (Table 4).

III. SPECIFICATIONS AND TESTING

A. Suggested Material Requirements

Soil moisture content has the most significant influence on electrochemical corrosion. Unfortunately, there is no standard test method to determine "in-situ" saturation levels. Until such a test becomes available, particular care should be given to provide for positive drainage through the structure.

The corrosive potential with respect to RE walls can be significantly reduced by requiring that backfill used around the reinforcing straps is benign. The 1985 NYS Specifications and Test Methods in Table 4 were in effect when Research Project 191-1 was initiated. These test methods were used to develop Table 1. The more conservative specification suggested in Table 4 include tightening the resistivity requirement from >3000 to >5000 Ω•cm, pH from 5-10 to 6-9.5, chlorides from <100 to <50 ppm, and sulfates from <500 to <200 ppm. Also, it is suggested that tests for redox potential and the presence of SRB be performed as a part of the soil corrosivity assessment. The following paragraphs describe the soil properties to be tested in greater detail.

Resistivity is the most practical parameter that can be measured for use in assessing soil corrosivity. It is a measure of the ability of soil moisture to act as an electrolyte. Various soil characteristics that affect the magnitude of resistivity include water content of the soil (porosity and saturation), water chemistry (pH and dissolved salts), degree of compaction, and temperature. Resistivity decreases as water content increases, so testing should be done at the soil's saturation point for a worst case scenario. The suggested test method for determining resistivity is ASTM Standard G/57-78.

In general, more corrosive soils are characterized by large concentrations of water soluble salts. Resistivity of a soil is inversely proportional to its salt content. Chemical analysis for salts is usually restricted to chloride and sulfate concentrations, because these are the most important salts from a corrosion standpoint. The generally accepted test methods for sulfate and chloride content are California Department of Transportation (Caltrans) Specifications 417 and 422, respectively.

Another widely used indicator of corrosive potential is soil pH. Low pH soils cause high corrosion rates in galvanized steel straps by attacking both iron and zinc, while high pH soils cause rapid consumption of the zinc in the galvanizing coat. The suggested test method for determining pH is ASTM Standard G 51-77.

The amount of oxygen present in soils affects both biochemical and electrochemical corrosion and is referred to as "aeration." This is dependent upon soil properties such as particle size and particle size distribution, wet/dry cycles, and compaction of the soil during construction. The amount of soil moisture and oxygen present decreases as compaction (density) increases. Biochemical corrosion can only take place in deaerated (highly compacted) soils because the bacteria are anaerobic. Electrochemical corrosion occurs when oxygen in soil moisture combines with metal ions to form corrosion products, with soil moisture acting as the electrolyte in forming a galvanic cell.

The best measure of aeration is redox potential, which indicates the soil's ability to sustain oxidation/reduction reactions. Redox potential is not currently in the New York State Standard Specification for Backfill Material for Mechanically Stabilized Earth Systems (Section 554). It is measured by a platinum probe, as described by Jones (1). If positive results (<400 mV, measured against a standard hydrogen electrode) are obtained, the source should be rejected.

The presence of anaerobic SRB in the soil environment is the best indicator of potential biochemical corrosion. Such corrosion is critical because it is highly localized and can lead to catastrophic failure. Soil conditions conducive to bacterial action include deaerated soil, pH between 6.2 and 7.8, and the presence of organic material. Sulfate content of the soil is important because it fuels the biochemical corrosion process, in addition to increasing electrochemical corrosion rates. Sulfates are present wherever organic sulfur compounds are a soil component. Concentrations of sulfates are tested for as noted previously. Kits are available for the detection of SRB which is tested by placing a soil sample in an environment where bacteria will grow, and observing a series of dilutions for the presence of bacterial growth. If results are positive (presence of bacteria indicated by the test kit) the source be rejected.

B. Suggested Backfill Standards and Testing Procedures

The consultant's suggestions for test methods and acceptable test results are included in Table 4 under "Suggested NYS Specification." The Amherst experience illustrates the need for testing of the corrosivity of backfill material before installation. Backfill material used in mechanically stabilized earth walls should be tested and approved by the Department before use. Once a source has been approved, no blending of backfill material from other sources should be allowed. Sampling for chemical and bacterial testing should be carried out at the borrow pit to ensure sufficient time for testing before RE wall construction. Because the material's oxidation state has a direct bearing on the value of resistivity, pH, and redox potential measurements, and oxidation states are subject to changes of uncertain magnitude and direction when stored for analysis at a later date, testing for these parameters should also be carried out at the borrow pit for the most accurate representation of *in situ* characteristics. In addition, the design of RE walls should provide for positive drainage at the base of the structure to ensure that water does not remain standing behind the wall. Further, the analysis technique modeled after Jones (1) and AWWA C105 (2) is presented as a secondary means for assessing the corrosivity of backfill sources. It is recommended for use only if a particular backfill source is of borderline quality as judged by the recommended specifications. If analysis using Jones's technique results in a rank sum greater than 5, the source should not be used. This analysis can also be used on soil samples taken from existing sites to assess the extent of possible corrosion problems.

Maximum life of RE structures can be attained if backfill material is uniform and well drained. Construction specifications and test procedures similar to those suggested in this report have been implemented by the Soil Mechanics Bureau under NYSDOT Engineering Instruction 86-11 (4) to minimize chances that corrosive backfill material is used in these structures, as indicated in Table 4 under "Suggested New York State Specification."

ACKNOWLEDGEMENTS

This investigation was performed under administrative direction of Dr. Robert J. Perry, Director, and J. G. Fred Hiss, Jr., Assistant Director, and technical supervision of David B. Beal, Civil Engineer III, Engineering Research and Development Bureau, New York State Department of Transportation. Planning and implementation of the experimental portion of the original project was conducted by Tina M. Bohl, Civil Engineer I. Laboratory analyses were performed by the Materials Bureau and the Soil Mechanics Bureau. Regional personnel were most cooperative during selection of the test sites and the installation of the test straps.

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2. "Notes on Procedures for Soil Survey Tests and Observations and Their Interpretation to Determine Whether Polyethylene Encasement Should Be Used." Appendix A to ANSI/AWWA Standard C105/A21.5-82 ("Polyethylene Encasement for Ductile-Iron Piping for Water and Other Liquids"). Cleveland: American Waterworks Association, 1982.

3. Romanoff, M. Underground Corrosion. Circular 579, National Bureau of Standards, April 1957.

4. "Standard Specifications: Section 554 - Mechanically Stabilized Earth System." Engineering Instruction 86-11, Structures Design and Construction Division, New York State Department of Transportation, February 27, 1986.

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APPENDIX

AN ASSESSMENT OF CORROSION PROBLEMS ASSOCIATED WITH REINFORCED EARTH STRUCTURES

Prepared For The New York State
Department of Transportation

David J. Duquette, Ph.D.

August 1988

EXECUTIVE SUMMARY

A comprehensive review of the technical literature related to corrosion of metals in reinforced earth structures has been performed. This literature indicates that, as with most buried metals, the most important parameters which affect corrosion resistance are the soil properties. These include soil resistivity, pH, chloride and sulfate concentrations as well as the possibility of corrosion due to microbial species. In contrast to many other buried structures, however, the metals used in reinforced earth structures are not readily amenable to externally applied protection systems and the rates of corrosion, after emplacement, are not easily determined.

Accordingly, a recommended set of specifications for the important properties of soil backfill are here-in presented. These specifications include the following:

Resistivity	> 5000 Ω·cm
pH	6-9.5
Chloride	< 50 ppm
Sulfates	< 200 ppm
Redox potential	> 400 mv vs. SHE at pH7

In addition the specification also suggests that uniform chemistries and compaction be required and that good drainage of the site is critical.

These recommended specifications are based on past practice, as well as experience in other states and countries.

I. INTRODUCTION

A significant amount of research and development has been performed relative to the corrosion of structural steels in soils or soil type environments. The earliest complete study of the problem was prepared and published by Romanoff in 1957,(1) and the latest review of the field was published by Moore in 1985,(2) as a literature survey for a Ph.D. thesis entitled "Soil Properties Affecting Corrosion and Cathodic Protection of Steel in Texas Soils." Thus, it is obvious that, although the problem is quite old and well developed, there are still problems to be resolved. Nevertheless, a great deal is known concerning the corrosion of buried metals, virtually all of it relevant to reinforced earth structures.

The purpose of this document is several fold:

(1) To summarize the current state of knowledge related to buried structural steels, both galvanized and ungalvanized. This summary will be related to a "library" of important published works which is included in this document as Appendix A.*

(2) To briefly discuss test methods for soil corrosivity both <u>in-situ</u>, for already buried structures as well as <u>ex-situ</u>, for soils to be used for future installations.

(3) To briefly discuss protection methods, in particular cathodic protection, for possible use in the field.

(4) Finally, to suggest the critical elements of a specification for future reinforced earth applications, related to the corrosion resistance of structural steels in soils of particular corrosivity.

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*Appendices A and B to Dr. Duquette's "Assessment of Corrosion Problems . . ." are not included here, but are available on request from the Engineering Research and Development Bureau.

II. CURRENT STATE-OF-THE-ART

There have been several recent surveys of the literature associated with buried metals (see, for example, Reference 1 and 2). All of them have concluded that the original concepts of Romanoff (1) are still extant. Among these important variables are:

(a) Soluble Salts

Criteria based on the general chemistry of soils are not expected to be very useful because of the large variation in specific chemistries of different soils. However, of the chemicals generally found in soils, chlorides and sulfates have been specifically identified as particularly important. Chloride, in particular, causes various forms of pitting corrosion, which increase the rates of perforation and accordingly may either sever a length of reinforcing steel, or may lead to sufficient weakening of the steel that the reinforcing members may become overloaded, and may fracture. Sulfates, in addition to increasing the conductivity of the soil, may act as nutrients for sulfate reducing bacteria which exist in many kinds of soils and which are known to cause rapid corrosion of steels.

(b) Hydrogen Ion Concentration (pH)

In natural waters the corrosion rates of structural steels are virtually constant between pH´s of 4 and 10, are reduced at pH´s of more than 10 and are accelerated at pH´s of less than 4. Since pH measurements are actually measurements of hydrogen ion concentrations in water solutions, it is difficult to obtain accurate measurements of pH in soils unless the pH measurements are made in-situ from water extracted from saturated soils at the time of saturation. However, within the limits of accuracy, it is known that at pH´s less than 5, the protective film which covers steels is porous and cracked, and an increase in corrosion rates may be observed. At pH´s of greater than 10 corrosion of steels is considerably reduced because of the production of a "passive" film on the surface which stifles corrosion kinetics. However, zinc, which is used as a protective coating for virtually all steels used in reinforced earth constructions, is an amphoteric metal. That is, it reacts as readily in basic solutions as it does in acidic solutions. Thus, the corrosion rate of zinc occurs at approximately the same rate in solutions of pH 4 and of pH 10, the corrosion rate increasing as pH is further either increased or decreased. Accordingly, the USFHWA has published guidelines that indicate that galvanized steel should not be used outside the pH range of 5-10.(3)

(c) Soil Resistivity

The most commonly used criterion for determining the corrosivity of soils is the electrical resistivity of the soil. The water soluble salt content, and the pH of the soil are the most important parameters which control the resistivity (or inversely, the conductivity). The importance of soil resistivity is in allowing the establishment of so called "macro-cells." Since corrosion is electrochemical, both anodes, where electrons are generated, and cathodes, where electrons are consumed, are required. If the anodes and cathodes are in immediate proximity, the "micro-cells" may become stifled and corrosion will either be highly localized or may proceed at very low rates. On the other hand, if the soil resistivity is low, anodes and cathodes may be quite far apart. Even more importantly, large cathodic areas may be coupled to small anodic areas, and very severe corrosion of these anodic areas may occur. (The rate of the total cathodic reactions must equal the rate of all of the anodic reactions). This is especially important if the soil chemistry (and aeration, see following section) is not uniform, thus coupling two or more different types of chemistries in what is essentially a large battery.

One of the major problems with using soil resistivity as a sole criterion for soil corrosivity is the wide range of "acceptable" resistivities which have been promulgated, and the relationship between resistivity and other chemistry requirements. Additionally, there are circumstances where minimum resistivity (maximum conductivity) may be desirable. For example, if cathodic protection of buried steels is desired, maximum "throwing power" (the ease at which electrons can travel between the cathodically protected steel and the anode) is desirable.

(d) Soil Aeration

Oxygen, which is present as 20% of air, is by far the most potent oxidizer for most natural water or soil corrosion. For example, if oxygen can be effectively eliminated from even sea water, corrosion rates are reduced to the point where no visible corrosion product can be discerned in 50 or more years. It is generally oxygen which combines with water and is reduced at the cathodic sites, to produce hydroxyl according to the following reaction:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

This reaction consumes the electrons which are produced at the anodes either as:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

or

$$Zn \rightarrow Zn^{2+} + 2e^- \text{ (if the steel is galvanized)}$$

The resultant reaction products, Fe^{2+} and OH^- or Zn^{2+} and OH^- or Zn^{2+} and OH^- produce iron hydroxides (rust) or zinc hydroxide (a white powdery corrosion product).

In many instances sections of metallic structures will be oxygen starved, while other sections will have good exposure to air, e.g. in the case of soils, good compaction vs. poor compaction. In this case a "differential aeration" cell is established, particularly if there is good electrical conductivity between anodic and cathodic sites and severe corrosion of those areas which are low in oxygen may occur. It is apparent, then, that backfills for reinforced earth structures should be of uniform composition and of uniform compaction.

(e) Sulfate Reducing Bacteria

One often overlooked aspect of soil corrosion is the presence of sulfate reducing bacteria, which are present in many natural, non-sterilized soils. In general, these bacteria require anaerobic conditions and, though a specific mechanism is still to be definitively established, replace reduction of oxygen with a different cathodic or electron acceptor reaction which drives the anodic, or electron donor, reaction. Requirements for their continued existence are sulfate salts (commonly found in soils) and conditions of low to negligible oxygen. One measure of their ability to survive in a given soil is the reduction-oxidation (redox) potential of the soil. At least one assessment of the possible damage due to biological corrosion suggests that the redox potential should be more positive than 0.40 volts to inhibit bacterial corrosion.(4) On the other hand, the higher (more positive, or noble) is the redox potential, the more oxygen will be present in the soil, which may result in differential aeration corrosion as well as in enhancement of general corrosion.

(f) Time of Wetness

In view of the fact that liquid phase water is required for electrochemical corrosion processes, it is surprising that, except for qualitative statements, the degree and time of wetness of soils are generally not specifically cited in any state specifications, or even in recommended measures of relevant parameters. It is obvious that the less water retention a particular soil has, the less corrosion that will occur, since time of wetness and extent of corrosion are directly related. In fact, King and Nabizedeh(5) have unequivocally stated that drainage and water content are the most important factors in the corrosion process. They have also indicated that mild corrosion begins at 5% water content and the corrosion increases as water content increases to about 30-60% water content. It is conceivable, then, that a "percolation" test, similar to that used for septic systems might be included in a rigid, conservative specification for reinforced earth sites. However, considerable research would have to be performed to develop an appropriate test methodology.

III. CRITERIA FOR CORROSIVITY OF SOIL

Several states have established criteria for acceptance of backfill from the point of view of corrosivity. The data which are available are indicated in Table I. It is obvious that there is a wide range of specifications, with Georgia being the most stringent and, of the specifications available, Colorado being the least demanding. In addition to these criteria, several other methods for classifying the corrosivity of soils have been published. These include, for instance, the tables of Jones, which are reproduced here as Tables II and III.(4) In Table II the sum of all of the parameters determines an estimation of soil aggressiveness.

TABLE I

STATE SPECIFICATIONS FOR REINFORCED EARTH STRUCTURES

	STEEL		SOIL				
	Reinforcement	Galvanizing	Resistivity (ohms•cm)	pH	(ppm)	Chlorides (ppm)	Sulfates Other
California	N.A.	Cal Spec 75-1.05	> 1,000	N.S.	< 500	< 2000	
Colorado	ASTM 572-65	ASTM A-123	N.S.	N.S.	N.S.	N.S.	
Georgia*	ASTM A-36-C	ASTM A-123	> 10,000	6.0-9.5	< 20	< 15	Acidity < 15 ppm $CaCO_3$
Louisiana	ASTM A-572-65	ASTM A-123	> 3,000	5.5-9.5	< 200	< 1000	
Nevada**	ASTM A-572-65	ASTM A-123	> 3,000	5.0-10.0	< 200	< 1000	
Tennessee	ASTM A-570-36	ASTM A-123	> 1,000	5.5-9.5	N.S.	N.S.	
Texas	ASTM A-572-65	ASTM A-123	> 1,500	5.5-9.0	N.S.	N.S.	
Federal Guidelines	N.S.	N.S.	> 3,000	5-10	< 50	< 500	Service life 75-100 years, specific corrosion allowance of 0.030-0.050 mils and/or "corrosion resistant coatings"
New York State	ASTM A446 or ASTM A36 or ASTM A572-65	NYS Specification	> 3,000	5-10	< 100	< 500	< 300 ppm sulfides

*Specification reads > 10,000 ohm/cm rather than ohms-cm.
**Nevada specifies a service life of 75 years, and indicates that soils need not meet chemistry requirements if the steel is epoxy coated.
N.A. = Not Available
N.S. = Not Specified

TABLE II

ESTIMATION OF SOIL AGGRESSIVENESS (AFTER JONES)(4)

Parameter	Ranking
Kind of soil:	-2
Chalk, chalk marl, sand marl or sand	-2
Loam, loam marl, loamy sand or clayey sand	0
Clay, clay marl or humus	2
Peat, mud or bog soil	4
Soil conditions:	
Water present at structure level	1
Disturbed soil	2
Dissimilar soil around structure	3
Water not present	0
Undisturbed soil	0
Homogeneous soil around structure	0
Soil resistivity (ohm-cm):	
Above 10,000	0
5,000 to 10,000	1
2,300 to 5,000	2
1,000 to 2,300	3
Below 1,000	4
Water content:	
Above 20%	1
Below 20%	0
pH value:	
Above 6	0
Below 6	1
Total acidity (meq/kg):	
Below 2.5	0
2.5 to 5.0	1
Above 5.0	2
Redox potential (mV, SHE, pH-7):	
Above 400 (430 for clay)	-2
200 to 400	0
0 to 200	2
Below 0	4

Parameter	Ranking
Hydrogen sulfite/ sulfate-reducing bacteria:	
Not present	0
Trace (below 5 ppm sulphide)	2
Present (above 5 ppm sulphide)	4
Coal, Coke or cinders:	
Present	4
Not present	0
Chloride (ppm):	
Above 100	1
Below 100	0
Sulfate (ppm):	
Above 1,000	3
500 to 1,000	2
200 to 500	1
Below 200	0

Sum of rank numbers

Negative	Practically non-aggressive
0 to 4	Weakly aggressive
5 to 10	Aggressive
Above 10	Strongly aggressive

TABLE III

ASSESSMENT OF SOIL AGGRESSIVENESS TOWARDS BURIED METALS (AFTER JONES)$^{(4)}$

Classification/ Soil Property	Aggressive	Selected Aggressive Soil (average values)	Non-Aggressive	Selected Non-Aggressive (average values)
Resistivity (ohm-cm)	< 2000	1156	> 2000	30,400
Redox potential at pH=7	< 0.400		> 0.440	
Normal hydrogen electrode		0.263		0.520
(volts)	< 0.430 if clay		> 0.430 if clay	
Borderline cases resolved by moisture content (percent)	> 20	28.5	< 20	12.1

Note: The classification involves a measure of soil resistivity which indicates the possibility of oxidation (electrochemical corrosion). The determination of Redox potential provides a means of assessing whether a particular soil is condusive to the activity of sulfate-reducing bacteria (biological corrosion).

This table has the advantage of being a kind of "menu," where compromises may be struck between important parameters in order to select soil conditions which may be acceptable for reinforced earth buried metals.

Tables III attempts to assess some of the specific parameters which have already been discussed, and sets the resistivity of an aggressive soil as < 2000 Ω. cm, based on field experience. Thus, if this criteria alone is used, California, Texas, and Tennessee allow "aggressive" soils for reinforced earth structures.

Other criteria for soil aggressiveness to corrosion of metals have also been suggested. These include the semi-quantitative descriptions of the USDA-SCS (assembled from the NBS-Romanoff study)$^{(6)}$ and reproduced below.

Low Corrosion Hazard

Drainage and Texture - Excessively drained, coarse-textured soils; or, well drained, coarse - to medium-textured soils; or moderately well drained coarse-textured soils; or, somewhat poorly drained coarse-textured soils.

Total Acidity* - < 8 meq/100 g. (milliequivalents per 100 grams of soil)
Resistivity - > 5000 ohm.cm.
Conductivity of Saturated Paste Extract - <0.3 mmho/cm.

Medium Corrosion Hazard

Drainage and Texture - Well drained, moderately fine-textured soils; or moderately well drained, moderately-coarse and medium-textured soils; or somewhat poorly drained, moderately coarse-textured soils; or very poorly drained soils with stable high water tables.

Total Acidity - 8-12 meq/100 g.

Resistivity - 2000-5000 ohm.cm.

Conductivity of Saturated Paste Extract - 0.3-0.8 mmho/cm.

High Corrosion Hazard

Drainage and Texture - Well-drained; fine-textured or stratified soils; or, moderately well drained, fine and moderately fine-textured or stratified soils; or, somewhat poorly drained medium, fine-textured or stratified soils; or poorly drained soil with fluctuating watertables.

Total Acidity - > 12 meq/100 g.

Resistivity - < 2000 ohm.cm.

Conductivity of Saturated Paste Extract - > 0.8 mmho/cm.

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*Note: Total acidity refers to the number of equivalents (or milliequivalents) of a base which, when titrated with an unknown solution, renders a solution neutral. Thus, it measures the buffering ability of a soil, or reserve ability of the soil to release hydrogen, whereas pH measures the existing free hydrogen ion concentration. Total acidity is thus a more rigorous criterion for soil corrosivity, but it is a difficult field measurement. The measurement of pH is usually sufficient to determine the corrosivity of a given soil.

These criteria were assembled from the NBS study (Romanoff, 1957).(1) The primary use of this system is in an interpretation of soil corrosivity from soil surveys provided by the USDA-SCS. They have been recently slightly redefined (albeit still qualitatively) by Moore based on statistical correlations of actual corrosion measurements with soil conditions from at least sixteen separate sites in Texas.(2)

Hazard Class	Criteria
Low	- Electrical Conductivity < mmho/cm - Acidity < 10 meq/100 g
Medium	- Electrical Conductivity = 1-4 mmho/cm - Acidity = 10-25 meq/100 g
High	- Electrical Conductivity 4-10* mmho/cm - Electrical Conductivity > 10 mmho/cm - Acidity > 25 meq/100 g

*Soils of this conductivity which are saturated for extended periods are demoted 1 hazard class.

IV. TEST METHODS FOR SOIL CORROSIVITY

A. Soil Chemistry

The various important tests to determine the corrosivity of soils have already been briefly discussed. They include resistivity (or conductivity), pH, sulfate and chloride ion content, etc.

There are a number of commercial systems available to measure resistivity, the most common perhaps being the Wenner probe. The use of this probe has been extensively discussed and the specific methods of its employ will not be discussed here. However, it is important to note that the best results are always obtained *in-situ,* rather than after removing soils to a laboratory, since soil compaction, oxidation processes, soil mixing, etc. will all affect the resistivity measurements.

pH measurements are also very important, and should be made at the site. Romanoff has shown that, if soil samples are removed to a laboratory, the measurements can be inaccurate by several pH units.(1) It should also be noted that pH measurements measure the hydrogen ion concentration of water in the soil. Because of the large range of chemistries normally found in soils, weak acids may be present, and there may be a larger acid reservoir than a simple pH measurement may indicate. (Accordingly total acidity is sometimes measured, although is seldom specified).

Chloride and sulfate concentrations are generally determined by standard laboratory procedures, and need not be determined at the site.

A measurement of the reduction-oxidation (redox) potential of the backfill, if it is not sterilized, is also important, and may be measured as a function of depth using a conventional redox probe. The redox potential measurements will indicate either the presence of widely differing soils (if the measurements from location to location are quite different) or the presence of highly reducing soils which may indicate the presence of sulfate reducing bacteria.(4)

The presence or absence of sulfate reducing bacteria can be determined by the use of "test kits" recently made available by CONOCO Specialty Products of Houston, Texas, and by Bioindustrial Technologies, Inc. of Grafton, New York.

All of these techniques are reasonably detailed in the chapter authored by C.J.F.P. Jones (see bibliography).(4)

B. Electrochemical Test Methods

There are at least two electrochemical test methods which can be used to assess the corrosion rates of metals buried in soils. These are the linear polarization resistance technique (LPR) or an AC impedance technique. The former method has been available for approximately 30 years, while the latter is a relatively new and unproven technique for corrosion in soils. Unfortunately, both techniques give only instantaneous corrosion rates, require relatively expensive equipment, trained technical personnel, and periodic monitoring. It is unlikely that it will be practical to use either technique for reinforced earth structures. Details of each technique are included in the bibliography with particular reference to the report prepared by Earth Engineering and Sciences.(7)

V. CORROSION PROTECTION SYSTEMS

The most common corrosion protection system for buried structures is cathodic protection. This technique uses auxiliary anodes, either sacrificial or impressed current, to require that all of the surface of a buried metal is, in fact, cathodic. Since only anodic reactions of metals produce corrosion (the conversion of a metal atom to a metal ion), cathodic protection is a very potent method for suppressing corrosion. Galvanizing of steel surfaces is one very common form of cathodic protection since the zinc-steel couple causes the zinc to be preferentially attacked ("sacrificed"), protecting the underlying steel. As long as there is sufficient electrical conductivity between any part of the zinc and the steel, the steel will be protected. An alternate method to induce protection is to place sacrificial anodes such as zinc or magnesium, at some distance from the steel, and to couple the sacrificial anode to the steel by means of a wire. Again, as long as there is sufficient electrical conductivity in the soil so that the zinc is effectively coupled to the steel through the soil, the steel will be completely protected from corrosion. An alternative method for cathodic protection involves the use of impressed currents from a non-sacrifical anode, such as graphite, utilizing an external power supply. It is unlikely, however, that either system is practical for reinforced earth structures, since both require periodic maintenance and trained personnel. Both systems also are most efficient in soils of high conductivity, rather than the usually recommended low conductivity soils for reinforced earths, suggesting that if the cathodic protection system malfunctions, corrosion of the metal will be enhanced by the low resistivity soil.

Thus, galvanic coatings directly applied to the steel are usually more advantageous. In addition to galvanic coatings such as zinc, another effective method of inhibiting corrosion of steel for reinforced earth structures is the use of organic coatings. Of the state specifications which are currently available, only Georgia requires the use of such coatings, specifying a two component coal tar epoxy system "when required on the plans." However, without reference to specific cases, Georgia sometimes requires the coatings to be applied over galvanized coatings, while in other cases only epoxy coatings are required (see Appendix B).

Nevada does not require epoxy coatings. However, if they are used, the contractor is relieved from the soil chemistry requirements.

It is apparent that at least two states have assessed the friction qualities of coatings relative to the soil and have found them to be satisfactory.

VI. NEW YORK STATE RESULTS

Based on the literature which has been surveyed (Appendices A and B), there are several possible routes which can be followed relative to a reasonable specification for backfill for mechanically stabilized earth structures for New York State. Before beginning that discussion, however, it may be beneficial to examine the results obtained by NYSDOT for several sites, and to compare them to both the current State specification and the

TABLE IV

COMPARISON OF NYS SPECIFICATIONS AND FEDERAL GUIDELINES
WITH CURRENT NYS INSTALLATIONS

	Resistivity (Ω-cm)	pH	Chlorides (ppm)	Sulfates (ppm)	Sulfides (ppm)
Current NYS Specification	> 3000	5-10	< 100	< 500	< 300
Federal Guideline	> 3000	5-10	< 50	< 500	N/A
Lockport	65-303	3.6-4.4	0	2100-2800	160-190
Buffalo	686-2834*	8.1-8.4	420-550	400-500	3100-3300
Syracuse	1580-4220	8.0-8.6	100-130	340-840	20-1400
Corning	6374-7454	8.2-8.4	0-30	800	40-240
Utica	13,334	7.9	0	200	200
Albany	6834-7440	8.5	0	300-600	500-900
Illion	6080-10,100	8.4-8.7	0	200-300	500
Painted Post	7487-10,260	8.6	0	200-300	200-300
Proposed Specifications	> 5000	6-9.5	< 50	< 200	None

*686-720 Ω•cm at four locations upon installation, 2833 Ω•cm at one location one year later electrode at pH 7.

TABLE V

NYS DATA

Location	Interval	Level	pH	Resistivity (ohm-cm)	Total Sulfides (ppm)	Sulfates (ppm)	Chlorides (ppm)
Lockport	Install	Low	3.6	303	1800	2600	0
	Install	High	3.6	272	1600	2100	0
	Install	Low	4.4	64	2900	2600	0
	Install	High	3.9	222	1900	2700	0
Buffalo (Mesh reinforcement)	1 year	Low	8.4	2833	3300	400	420
	1 year	High	8.4		3100	500	520
	Install	Unknown	8.1	686			
	Install	Unknwon	8.1	693			
	Install	Unknown	8.1	720			
	Install	Unknown	8.1	698			
Syracuse	Install	Unknown	8.0	2093	900	340	130
	Install	Unknown	8.3	Unavailable	700	450	100
	Install	Unknown	8.3	3300	200	840	100
	1 year	Low	8.6	4220	1100	500	100
	1 year	High	8.4	1580	1400	500	100
Corning	Install	Low	8.2	6373	< 100	800	0
	Install	High	8.4	7353	200	800	30
Utica	Install	Low	7.9	13334	200	200	0
Albany	Install	Low	8.5	7174	500	300	0
	Install	High	8.5	6833	500	400	0
	Install	Low	8.5	7293	500	500	0
	Install	High	8.5	7440	900	600	0
Illion	Install	Low	8.4	6080	500	300	0
	Install	High	8.7	10100	500	200	0
Painted Post	Install	Low	8.6	7487	300	300	0
	Install	High	8.6	10260	200	200	0

Federal guideline (see Table IV). This comparison indicates that only Utica meets or exceeds the Federal guidelines, and even it does not meet the State specification for sulfate. It is also the only site which meets the most stringent state specification, that of Georgia, except for the sulfate levels.

Lockport, where severe corrosion damage has already been observed, violates virtually every specification which has been published, including every recommended range of resistivity, pH, and chemistry, with the exception of chloride content.

The results obtained for Buffalo are somewhat confusing, since very low resistivity measurements were obtained on installation, while a single resistivity measurement made a year later indicates a marked increase in resistivity. It is likely that the later single reading is conservative, and that the backfill does, in fact, have a low resistivity. The average level of chloride is only nominally within the State specification, and the sulfate levels as well as the sulfide levels are clearly outside of the State specifications. An examination of buried test strips (see Table V) indicates that corrosion appears to be most severe at Buffalo and at Syracuse, with corrosion being most severe at deeper levels, consistent with a "time of wetness" hypothesis. Virtually no corrosion has been observed at Painted Post or at Corning. However, the retrieval of two foot lengths of buried steel is, at best, fraught with inaccuracies. As has been indicated, many of the corrosion problems associated with buried metals involve macro-cells, and the correlation of low resistivity of a given soil with corrosion rate is precisely because large macro-cells, coupling anodes and cathodes over long distances, may be established. It is unlikely that significant electrochemical potential differences will be established along a two foot length or buried steel, since the conditions of soil chemistry, aeration, degree of wetness, pH, etc. are likely to be relatively constant. The most accurate method to monitor corrosion rates of buried structures may be electrochemical instrumentation, rather than the retrieval of test strips, but it has already been mentioned that this would require trained personnel, as well as relatively sophisticated and periodically maintainable instrumentation. Accordingly, the most conservative recommendation is to require relatively rigid specifications for backfill for future installations, rather than to rely on on-site corrosion information after the structure has been completed.

VII. RECOMMENDATIONS

An examination of the material presented in this document indicates that there are several possible criteria which can be established. Of the relevant parameters which have been discussed, the most important are soil resistivity, pH, soil chemistry (sulfates and chlorides) and the presence of sulfate reducing bacteria. Oxygen levels and water retention are at least as important, although no criteria have been established relative to these considerations and measurement techniques have not been well developed, at least for soils.

Examining each of the important parameters, the most often used is soil resistivity. According to Reference 7, soils with resistivities less then 700-2000 Ω.cm are considered to be very corrosive, resistivities of 700-2000 Ω.cm to be corrosive, 2000-5000 Ω.cm to be moderately corrosive. Soil with resistivities greater than 5000 Ω.cm are considered to be either mildly corrosive or non-corrosive. The majority of states have used 1000-3000 Ω.cm as lower limits for soil resistivity, although Georgia has chosen > 10,000 Ω.cm. Since it should be relatively easy to select specific backfills, and since most inorganic soils have high resistivities, it is suggested that New York State set a lower limit of at least 5000 Ω.cm for the resistivity of soils to be used as backfill for reinforced earth structures. This relatively high value of resistivity will also decrease the possibility of stray current corrosion since the resistivity of the soil will inhibit electron transport through the soil.

While total acidity may be a better criterion for available hydrogen ion in soils, it is recommended that pH be used as a criterion for selecting backfills. The measurement of total acidity is a tedious process, best performed in a laboratory, while pH measurements are relatively simple to perform and to interpret in the field.

It is recommended that the allowable pH range be narrowed from 5-10 (see Table IV) to 6-9.5. This reduction in the allowable pH range will mitigate against excessive corrosion of the steel (and of the zinc) due to weak acids in the soil which might increase to total acidity without appreciably changing the pH. Also this narrower pH range will allow for a "margin of error" in sampling from point to point in a given structure, due to the relatively small samples that are usually utilized for pH measurements.

Based on the literature available, and experience already available in New York State, the following specifications are recommended for future backfill for reinforced earth structures:

Resistivity	> 5000 Ω.cm
pH	6-9.5
Chloride	< 50 ppm (at installation)
Sulfate	< 200 ppm
Redox Potential	> 0.400 V vs. Standard Hydrogen Electrode at Ph 7

It is recommended that the resistivity measurements for new installations be made at the site in accordance with ASTM Standard G57-78. It is further recommended that, whenever possible, the backfill soil be saturated with water to provide a "worst case" situation in order to assess the great possible extent of corrosion. For existing sites, the soil box method of ASTM Standard G57-78 should be followed, since the Wenner probe pin method will necessarily give poor results due to the high conductivity of buried steel reinforcements. In this case, it is required that large enough cores of earth be removed so that the soil resistivity can be measured as a function of depth.

Obviously if layers of high conductivity soils are in place, the horizontal reinforcing members within those layers will suffer the most corrosion. As in the case for the Wenner probe measurements, it is recommended that soil samples be water saturated prior to measurements to ensure that "worst-case" data are collected.

It is recommended that pH measurements be conducted in accordance with ASTM Standard G51-77. Note that this standard recommends that these measurements be conducted at the soil site and that, if this is not possible, no more than 24 hours should elapse before laboratory measurements are made.

Chloride and sulfate measurements should be performed in accordance with California Department of Transportation specifications 417 (1978) and 422 (1978) respectively.

While there is no available U.S. standard or specification for determining redox potentials in soils, the British Department of Transport (specification BE 3/78) has issued a specification for their measurement. A description of the measurement can be found in Reference 4; the cost of the required equipment is estimated to be in the $300-500 range. The specific purpose of determing the redox potential of the soil is to eliminate the danger of enhanced corrosion due to anaerobic bacteria. It is known that microbes such as sulfate reducing bacteria, which can cause catastrophic corrosion, require active (low) redox potentials (< - 400 mv vs. standard hydrogen electrode at pH 7) and sufficient sulfate to provide metabolic activity. Thus, requiring low sulfate levels and a high redox potential will eliminate this potential cause of corrosion. A specification which requires no bacteria in the original backfill can also be required but will not mitigate against later incursions of the microbes into the soil.

It should perhaps be noted that measurements of sulfide concentrations are not included in this recommended specification. Sulfides at neutral pH´s are relatively insoluble and are not particularly corrosive to iron and steel. If sulfides are found, however, they may indicate that sulfate reducing bacteria have already been active in corroding iron or steel since they are the corrosion products of such microbes. Accordingly, in addition to these semi-quantitative specifications, it is recommended that the backfill soil be tested for sulfate reducing bacteria, and that "good" drainage be required. (Appreciable corrosion will not occur if the water content of the soil is less than 30%). Further, any specifications for backfill should require that all of the backfill be of uniform composition, consistency and drainage ability.

The specifications represent several compromises, but appear to be reasonable in view of the data which have already been collected for various installations.

It might be noted that, if these proposed specifications are followed, the sum of the rank numbers presented in Table II will be either negative or zero, indicating that the soil will be non-aggressive to the metal. These specifications also meet the criteria for non-aggressive soils indicated in Table III.

As far as the chloride levels are concerned, chloride is known to be an accelerator of corrosion in most cases and it is likely that some chloride will be leached from road bed surfaces during de-icing operations. Thus, it would appear to be prudent to specify chloride levels as low as are practicable in new installations. Low sulfate levels, high redox potentials, and the absence of sulfate reducing bacteria are all precautions to inhibit accelerated corrosion due to bacterial activity. While there can be no guarantee that bacteria will not eventually be involved in corrosion processes of buried metals, elimination of the appropriate nutrients and environmental conditions (as measured by the redox potential) will at least delay this complication.

The requirement for uniformity of backfill is intended to eliminate the possibility of "long line" or macro-cell corrosion due to contrasting soil conditions in the horizontal plane.

Finally, while no specification and no recommendations address soil drainage (and accordingly "time-of-wetness") it is obvious that it is an important, if not the determinant factor in the corrosion of metals in soils. While there are no specific guidelines at present, New York State might consider the possibility of pioneering research efforts in this area.

With respect to the presently installed structures, the best that can be expected relative to predicting their useful lives, is to perform a reasonably complete survey of the soils in which they are buried, as a function of depth, perhaps by coring. While this will not alter in any way the extent of corrosion which is presently occurring, it will indicate which presently constructed structures can be expected to have high corrosion rates, and which structures can be expected to perform without problems. (Once the soil data has been collected, a further analysis of specific corrosion rates may be estimated by laboratory techniques. However, recommendations for such a study is outside the scope of the current report).

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