

COPY NO. _____

CORROSION IN THE SOIL ENVIRONMENT: SOIL RESISTIVITY
AND PH MEASUREMENTS

FINAL REPORT

Prepared For

National Cooperative Highway Research Program
Transportation Research Board
National Research Council

TRANSPORTATION RESEARCH BOARD

NAS-NRC
PRIVILEGED DOCUMENT

This report, not released for publication, is furnished only for review to members of or participants in the work of the National Cooperative Highway Research Program. It is to be regarded as fully privileged, and dissemination of the information included herein must be approved by the NCHRP.

William S. Vilda III
Corpro Companies, Inc.
Ocean City Research Group
Ocean City, NJ

January 2009

Acknowledgement

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program which is administered by the Transportation Board of the National Research Council.

Disclaimer

This copy is an uncorrected draft as submitted by the research agency. A decision concerning acceptance by the Transportation Research Board, and publication in the regular NCHRP series will not be made until a complete technical review has been made and discussed with the researchers. The opinions and conclusion expressed or implied in the report are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation officials, or of the individual states participating in the National Cooperative Highway Research Program.

COPY NO. _____

CORROSION IN THE SOIL ENVIRONMENT: SOIL RESISTIVITY
AND PH MEASUREMENTS

FINAL REPORT

Prepared For

National Cooperative Highway Research Program
Transportation Research Board
National Research Council

TRANSPORTATION RESEARCH BOARD

NAS-NRC
PRIVILEGED DOCUMENT

This report, not released for publication, is furnished only for review to members of or participants in the work of the National Cooperative Highway Research Program. It is to be regarded as fully privileged, and dissemination of the information included herein must be approved by the NCHRP.

William S. Vilda III
Corrpro Companies, Inc.
Ocean City Research Group
Ocean City, NJ

January 2009

TABLE OF CONTENTS

	Page
List of Figures	v
List of Tables.....	vi
Acknowledgement.....	vii
Abstract.....	viii
Summary	ix
Chapter 1 INTRODUCTION AND RESEARCH APPROACH	1
Chapter 2 FINDINGS	8
Task 1 – Conduct Survey	8
Task 2 – Evaluate Existing Methods	9
Task 3 – Phase I Interim Report	33
Task 4 – Development of Laboratory Corrosion Rate Proc~.....	33
Task 5 – Development of Field Corrosion Rate Procedures~	35
Task 6 – Installation and Initial Testing of Long Term Exp~.....	41
Task 7 – Evaluation of pH Measurement Techniques and R~.....	42
Task 8 – Further Evaluations of Other Issues from Phase I.....	43
Task 9 – Phase II Interim Report.....	44
Task 10 – Evaluation of Long Term Exposure Materials	44
Task 11 – Phase III Interim Report.....	48
Task 12 – Round Robin Testing / Field Trials	48
Chapter 3 CONCLUSIONS AND SUGGESTED RESEARCH.....	49
References	51
Appendix A Laboratory Methods for Resistivity and Corrosion Rate	
Appendix B pH Measurement Comparison and Method	
Appendix C Soil Analysis	
Appendix D FHWA and German Soil Corrosivity Ratings	
Appendix E Phase II Figures and Tables	
Appendix F Task 10 Figures and Tables	
Appendix G Field Method for Corrosion Rate Measurement	
Appendix H Survey Information	

LIST OF FIGURES

Figure	Page
1. Four pin soil box for resistivity measurements	10
2. The Nilsson 400.....	11
3. The LEM Unilap.....	11
4. The Vibroground	11
5. The Megger model DET/4R.....	12
6. The Gamry Model 750.....	12
7. Geonics EM31-MK2 in field use.....	15
8. Collins Rod.....	17
9. Nova Probe.....	18
10. Four pin resistivity data from Site A	20
11. Four pin resistivity data from Site B, location 1	21
12. Four pin resistivity data from Site B, location 2	21
13. Four pin resistivity data from Site C, location 1	22
14. Four pin resistivity data from Site C, location 2	22
15. Resistivity data obtained with Geonics EM31-MK2 from Site A.....	23
16. Resistivity data obtained with Geonics EM31-MK2 from Site B~.....	23
17. Resistivity data obtained with Geonics EM31-MK2 from Site B~.....	24
18. Resistivity data obtained with Geonics EM31-MK2 from Site C~.....	24
19. Resistivity data obtained with Geonics EM31-MK2 from Site C~.....	25
20. Resistivity data obtained with Geonics EM31-MK2 from Site B~.....	26
21. Superimposed four pin and Geonics data from Site A	27
22. Superimposed four pin and Geonics data from Site B, location 1	27
23. Superimposed four pin and Geonics data from Site B, location 2	28
24. Superimposed four pin and Geonics data from Site C, location 1	28
25. Superimposed four pin and Geonics data from Site C, location 2	29
26. Resistivity vs corrosion rate data from Site B.....	30
27. Cylinder probe B	35
28. Cylinder Probe B with Tip Removed	35
29. Comparison of Resistivity Measurements	36
30. Original Disposable Probe	38
31. Original Disposable Probe	38
32. pH Versus Potential	40
33. Four Electrode versus Two Electrode Soil Resistivity	43

LIST OF TABLES

Table		Page
1	Different devices for lab and field resistivity measurement	11
2	List of test media and instruments used in laboratory tests	11
3	Soil box resistivity data in various media using different~	14
4	Resistivity data obtained with EM31-MK2 at Site B	27
5	Collins rod data.....	31
6	Nova probe data.....	32
7	Equipment prices	33

ACKNOWLEDGEMENT

Corrpro Companies, Inc performed this research under NCHRP Project 21-06. The work was performed at Corrpro Companies, Inc. facilities in West Chester, Pennsylvania and Ocean City, New Jersey. Mr. Dale Lindemuth, P.E. and James A. Ellor, P.E. were the principal investigators for the project. Dr. Moavin Islam, P.E., Mr. J. Peter Ault, P.E., Mr. Emer C. Flounders Jr., P.E., and Mr. John Repp, P.E. were associate investigators.

ABSTRACT

The ultimate goal of this program was to develop a correlation between standard, and possibly improved, soil resistivity and pH measurements and soil corrosivity over a range of soil types. To achieve this goal, the three key objectives were addressed, summarized below:

- (1) Develop accurate, precise, and practical field and laboratory measurements of soil resistivity and pH. These methods may be modifications of existing tests or new methods developed from theoretical approaches.
- (2) Develop correlation factors between these new methods and previous measurement techniques.
- (3) Using the recommended test methods, develop correlations between the soil resistivity and pH measurements and metallic corrosion rates. Develop guidelines to assist transportation practitioners to predict the corrosion rate of buried structures.

These objectives were accomplished through a four phase program consisting of 13 individual tasks. Preliminary tasks included a survey of State Departments of Transportation to assess their current use and understanding of resistivity and pH measurements, as well as an evaluation of methods currently available. Using this information, laboratory and field measurement techniques were developed and field testing was conducted at various sites around the US in order to validate the new instrumentation and methods.

SUMMARY OF FINDINGS

Accurate tools and methods to predict soil corrosivity would greatly benefit our nation's infrastructure in helping to clearly define the extent of preventive measures necessary to protect buried structures. For many years a definitive relationship has been sought between soil resistivity, pH, and corrosivity. This study aims to develop reliable techniques and instruments to predict the corrosivity of soil using resistivity and pH through a set of defined tasks:

Task 1 – Conduct Survey: A questionnaire was distributed to numerous transportation professionals in order to gauge the current methods in use for measuring resistivity and pH, the equipment used, and how the collected data is used. Among the respondents, all measured 4 pin resistance, most commonly with a Nilsson 400. More variability was seen in pH techniques. The most common usage of the data was for material selection and corrosion assessment.

Task 2 – Evaluate Existing Methods: Various common methods and equipment were compared in measuring primarily resistivity in order to gauge differences in performance. The common soil box based laboratory methods were shown to be comparable across the board. Some field trials were conducted and the 4 pin method was chosen as the most representative of actual conditions.

Task 3 – Phase I Interim Report: Summarized results of tasks 1 and 2 and suggested work plan for Phase II.

Task 4 – Development of Laboratory Corrosion Rate Procedures/Instruments: Tests were conducted in the lab to identify methods and equipment for measuring soil resistivity and corrosion rate directly using a soil box. The Aquamate Corratrater instrument was chosen because of cost and ease of use. It measures corrosion rate via LPR measurements as well as conductivity (reciprocal of resistivity).

Task 5 – Development of Field Corrosion Rate Procedures/Instrumentation: Probes were developed for measuring soil corrosion rate in the field. After preliminary lab and field trials, two types of probe were settled upon: a cheap disposable block LPR probe with pH and resistivity measurement capability, and a more robust reusable steel spike probe with LPR, resistivity, pH, and mass loss rings for long term study.

Task 6 – Installation of Initial Testing of Long Term Exposure Materials: Sets of disposable block probes, reusable spike probes, and mass loss coupons of different materials were installed in 5 locations around the US. Block probes and mass loss coupons were buried in trenches 4 and 8 feet deep, while spike probes with attached block probes were embedded at a depth of 25 to 30 feet. Initial measurements were made of pH, resistivity, and LPR corrosion rate. Samples of soil were tested to procedures from task 4.

Task 7 – Evaluation of pH Measurements Techniques and Recommendations: Standard soil pH measurement methods were evaluated against each other. The Corrpro in house method was found to strike a balance between standard AASHTO and ASTM methods. Antimony –

Sintered Silver Chloride pH measurement junctions were identified for use in field probes in conjunction with task 5.

Task 8 – Further Evaluation of Other Issues from Phase I: 2 pin vs 4 pin resistivity was investigated and found to have good correlation. Evaluation of Chaker compactor concept was suspended after ASTM working group was heard to be moving away from inclusion of the compactor in the G57. Investigation of the effect of underground structures and overhead power lines on 4 pin resistivity readings was abandoned after the focus of the field trials turned to 30-foot deep wells where such influences are unlikely to be felt.

Task 9 – Phase II Interim Report: Summarized results of tasks 4 through 8.

Task 10 – Evaluation of Long Term Exposure Materials: Portions of the buried probes and coupons were retrieved for study approximately 1.5 yrs after initial installation. An attempt was made to correlate LPR, resistivity, and pH readings taken initially and before retrieval to mass loss as measured on the coupons. Correlation was found to be generally weak, and tended to overestimate the actual corrosion rate.

Task 11 – Phase III Interim Report: Report on task 10. Rolled into final report.

Task 12 – Round Robin Tests / Field Trials: Techniques developed by this program for lab and field measurements were to be conducted by independent labs to verify the methods' validity. Very little response was received from participation inquiries. Due to this and the general lack of improved methodology over existing techniques, round robin testing was not conducted.

Task 13 – Final Report

Status of main objectives

The lab and field test methods generated by this study are of comparable utility to existing methods. Correlation factors between project methods and existing methods are of little consequence given the lack of significant divergence. Correlation between measured resistivities, LPR data, and pH data and soil corrosivity was tenuous though not outright dismissible. Some established methods of predicting corrosivity based upon factors such as soil moisture and various soluble salts showed promise in correlating with mass loss coupon data.

Recommended Work

Installations are still intact around the country, providing opportunities for three more extractions. Monitoring should continue with extractions at extended periods (5, 10, 20 years) to evaluate long term functionality. Alternate measurement techniques should be used to verify the accuracy of the Aquamate probe.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

Introduction

The ultimate goal of the program was to develop a correlation between standard, and possibly improved, soil resistivity and pH measurements and soil corrosivity. To achieve this goal, the solicitation provides three key objectives, summarized below:

- (4) Develop accurate, precise, and practical field and laboratory measurements of soil resistivity and pH. Include guidelines for the frequency, location, and implementation of these tests. These methods may be modifications of existing tests or new methods developed from theoretical approaches.*
- (5) Develop correlation factors between these new methods and previous measurement techniques.
- (6) Using the recommended test methods, develop correlations between the soil resistivity and pH measurements and metallic corrosion rates. Develop guidelines to assist transportation practitioners to predict the corrosion rate of buried structures.

As recognized by the Research Problem Statement, there is a “major debate” about the application of such measurements to determine soil corrosivity. Over the past 50 years, there have been several attempts to develop correlation models between measured soil resistivity, pH and corrosivity—often with varying degrees of success (1). Corrosion is important to transportation systems where structures such as drainage culverts, retaining wall anchors, tensioning rods, and steel piles are subject to corrosion. Considerable effort has been expended to predict corrosion of these and other buried structures. These methods primarily have relied on soil resistivity and pH (2,3,4). Some success has been obtained with practices developed for local areas, thereby areas with similar soil characteristics. Examples include well-characterized pipeline right-of-ways. However, it has been difficult to expand these models to encompass a wide range of variable soil chemistries. Over the past several years, there has been considerably more success in predicting the corrosivity of soils surrounding buried underground steel storage tanks (UST) (5). These techniques, developed in conjunction with UST corrosion control regulations, require the acquisition of substantially more soil characterization data than resistivity and pH. Similar efforts have been made to correlate corrosivity and local chemistry for concrete, aqueous, and atmospheric environments (6,7,8).

Soil resistivity and pH are two of several factors that determine the corrosivity of a soil. Soil resistivity is a measure of a soil’s ability to support electrochemical corrosion by migration of charged species necessary to balance corrosion reactions, and soil pH is a measure of soil acidity. Both influence the corrosion of metals underground (9). However, resistivity and pH are not the only factors affecting corrosion. Total acidity, aeration, moisture content, soil type, soil permeability, soil composition, and heterogeneity in all of these factors play a role in determining the corrosivity of a given soil (10,11). Because of the natural heterogeneity of soil, there is also no single value of resistivity or pH that represents a particular site. Instead, for a given site, a range of values can be measured. In some cases soil resistivity values follow a normal statistical distribution. In such cases the probabilities of resistivity outside the measurement range can be predicted (12, 13, 14). The use of extreme value statistical methods can also be applied to predict the probability of maximum and minimum values of resistivity based on a relatively small measurement population. The variability of soil resistivity and pH must be taken into account in any analysis of the corrosivity of a given soil.

In other environments, such as aqueous environments, researchers have shown conclusively that corrosivity can be determined accurately with electrochemical polarization resistance measurements (15). Such parameters were initially determined using direct current techniques, but are now also determined using AC impedance spectroscopy and electrochemical noise analysis (16,17). Interestingly, some of the earliest documented

use of polarization measurements to determine corrosivity were not associated with aqueous environments but rather natural soils. In the often-referenced classical work of Romanoff, various types of electrochemical polarization measurements were shown to correlate best with soil corrosivity as opposed to the soil chemistry characterizations. However, the underground corrosion-control industry was not able to take full advantage of these findings, because instrumentation and field applicable practices were not readily available. Furthermore, many parts of this industry tended to focus on cathodic protection applications as a standard practice. Soil (ohmic) resistivity measurements became a key piece of cathodic protection design data while soil polarization resistance values were not needed for cathodic protection design. Rules-of-thumb began to appear relating soil (ohmic) resistivity and pH to corrosivity as opposed to using polarization measurements.

As soil resistivity measurements were developed, the focus on ohmic resistivity fostered techniques using different electrical waveforms and test frequencies principally to avoid electrochemical polarization effects in the measurements. Thus, data that might shed light on corrosivity were eliminated from the measurement. With today's advanced instrumentation and computational abilities, one is able to observe both ohmic and electrochemical resistivity offering an excellent chance to significantly improve the predictive capabilities of resistivity and pH measurements with respect to soil corrosivity. Such measurements can be implemented as modified procedures of current standard practices using available equipment.

Engineers in one of our offices found that commercially available corrosion probes designed for use in aqueous systems work quite well for collecting design information during the construction of the Santos pipeline, a large Australian pipeline (18). They used a corrosion probe that consists of two 1.25 inch long steel elements which are wired to an instrument that calculates polarization resistance using an extremely low frequency signal (<0.01Hz) and calculates soil resistance using a high frequency (864Hz) signal. Engineers found that the corrosion rate correlated well with known local corrosivity.

Various means of measuring resistivity exist. These include the Wenner 4-pin method as described in ASTM Test Method G57, the Shepard Cane, Collins Rod, and electromagnetic induction methods. The original 4-pin resistivity method developed by Wenner, involves the use of 4 pins driven into the ground (19). A current is applied to the outer pins, and the voltage between the inner pins is measured. The resistivity is a function of the current, voltage, and spacing of the electrodes (which is equal to the depth of the test). The resulting equation is: $\rho = 2\pi \times a \times (\Delta\phi/I)$, where ρ is the resistivity, "a" is the spacing between the electrodes, $\Delta\phi$ is the voltage, and I is the applied current (20). The current is usually applied using an instrument that supplies alternating current, otherwise polarization effects occur at the electrodes that can alter the reading. Stray earth currents and inducted AC can also affect the readings if these effects are not separated from the data. Instruments can use current generated from batteries by a vibrator (e.g., Vibroground or Nilsson), or current generated by hand cranking (e.g., Meggar). The Nilsson uses a voltage of 12 volts at 97 Hz and the Vibroground use a voltage of 100 volts at a frequency of 97 Hz. The LEM is an automated microprocessor controlled instrument and uses a range of frequencies (50-128 Hz) and 48/20 volts. Neither the original paper by Wenner, nor subsequent discussions reviewed in the preparation of this proposal define appropriate testing parameters (voltage, current, frequency). Wenner's original work was done with alternating current, but the frequency was not reported.

The Shepard Cane uses two electrodes mounted on rods. This instrument measures the current between the two electrodes that are a set distance apart. Another similar instrument mounts the electrodes on a single rod. An alternating current is supplied, and the resistivity is measured using a galvanometer (e.g., Collins Rod) (21). A relatively new method, the Nova Probe mounts four probes onto a rod that is inserted into the area being measured (22). Resistivity is measured using standard instrumentation (pH, potential, and redox potential can be measured as well). These techniques measure local volumes of soil, and can be useful for that very reason. They fit into confined spaces, such as next to tanks and between pipes, where the standard, more global, techniques are inappropriate.

Another method of measuring resistivity does not rely on contact with the ground at all. The Geonics instruments are manufactured by Geonics, Ltd., 1745 Merry side Dr., Unit #8, Mississauga, Ontario, Canada. The

instruments use electromagnetic induction (“time-domain electromagnetic systems”) consisting of a transmitter and receiver to measure soil resistivity. It can be used from aircraft as well as ground-based crews. The instrument has an effective depth of about 6 to 60 meters. The inductance between adjacent coils placed on the ground is a function of the conductivity of the soil medium. A primary coil induces current in the ground with a sinusoidally varying magnetic field. The second coil determines the magnitude of the current via the induced magnetic field. The magnitude of the current is related to the ground conductivity. One of the most significant benefits of this technology is that it is not dependent on contact quality with the ground, thus it has the ability to be used in very high resistivity soils. These techniques have also been used to locate ground waters.

Corrpro uses two types of Geonics units, primarily in the Middle East – the EM-31 that measures up to 6m deep, and the EM-34 that measures up to 60 m deep. This is the only type of soil resistivity device that Aramco in Saudi Arabia allows because of problems with pins in very dry surface layers.

Laboratory measurement of resistivity involves placing a soil sample in a container having electrodes. These electrodes are then connected to a power supply and voltage measuring device and the resistance of the soil between two potential electrodes measured. The differences are primarily in the method of preparing the soil for testing. ASTM G51 provides a method for testing the soil in the as-received state and saturated with ground water, distilled water, or tap water (23). AASHTO T288 calls for drying the sample, sieving it, and then adding water. The measurement is made in a specially designed box having two electrodes (24). California Test 643 for estimating steel culvert service life uses a method similar to AASHTO, except that the sample is sieved, but not necessarily dried (25). Corrpro uses still another method in determining the life expectancy of underground tanks. This method is similar to the AASHTO method, except that the moisture content of the soil is measured, then demineralized water is added in an amount dependent on the original moisture content. Soil conductivity of a soil-water slurry is then measured. All of these methods measure a “minimum” resistivity. All of these methods measure the resistivity of a relatively small soil sample that does not represent the in-situ soil in terms of compaction, pressure, temperature, permeability, or moisture content. These test methods should not, therefore, be expected to replicate field measurements.

Soil pH is measured either on-site or, more commonly, in the laboratory. ASTM G51 measures the pH of the soil directly, while AASHTO T289, California Method 643, and the Corrpro method for underground storage tank service life prediction measure the pH of a soil-water slurry. It might be expected that these different techniques would produce inconsistent results. For example, Round Robin testing by ASTM G10 in 1993 revealed that one of the variables in testing was the buffer used to standardize the pH meters. Soil collection, transport, storage, soil preparation methods, and testing techniques should also be evaluated.

Research Approach

The entire project as planned consisted of 13 tasks, grouped into 4 phases:

Phase I

- Task 1 – Conduct Survey
- Task 2 – Evaluate Existing Methods
- Task 3 – Phase I Interim Report

Phase II

- Task 4 – Development of Laboratory Corrosion Rate Procedures/Instrumentation
- Task 5 – Development of Field Corrosion Rate Procedures/Instrumentation
- Task 6 – Installation and Initial Testing of Long Term Exposure Materials
- Task 7 – Evaluation of pH Measurement Techniques and Recommendations
- Task 8 – Further Evaluation of Other Issues from Phase I
- Task 9 – Phase II Interim Report

Phase III

- Task 10 – Evaluation of Long Term Exposure Materials
- Task 11 – Phase III Interim Report

Phase IV

Task 12 – Round Robin Tests / Field Trials

Task 13 – Final Report

Task 1 – Conduct Survey

The main activity under Task 1 has been to develop a survey questionnaire and disseminate it primarily to the state DOTs. The purpose is to determine what experience the DOTs have in the determination of soil resistivity and pH, what use they make of these parameters, what unique experiences they may have in the application of these parameters, and what instruments they deploy in determining these parameters. A 3-page user-friendly questionnaire was developed in spreadsheet format and is included in Appendix H. Dissemination of the questionnaire and receipt of responses were primarily handled electronically via email. The NCHRP panel members were included in the distribution of the questionnaire.

The survey questionnaire was submitted to all fifty State Departments of Transportation (DOT), the Highway Administration of Puerto Rico and two consultants affiliated with two of the State DOTs. Thirty-seven responses (thirty six DOTs and one consultant) were received. All responses to the questionnaire have been tabulated by major area and are included in Appendix H for reference.

Task 2 – Evaluate Existing Methods

The purpose of Task 2 was to preliminarily evaluate existing as well as any new or untried resistivity and pH measurement instruments and methods based on the Task 1 findings and our in-house expertise in this area. This was followed by generating some supporting laboratory and field data as appropriate. The purpose was to determine whether the different instruments show any differences in measured values and if possible to identify the cause(s) of the observed differences. In our assessment between resistivity and pH measurements, the former is of greater complexity, particularly for field application. Thus the main effort in Task 2 has been directed towards resistivity measurement issues. Evaluation of pH data collection techniques was conducted further on in the project.

Task 3 – Phase III Interim Report

An interim report detailing the results of Tasks 1 and 2 as well as proposing a work plan for tasks 4 and 12 was submitted to the board in May 2001.

Task 4 – Development of Laboratory Corrosion Rate Procedures/Instrumentation

This task was related to evaluating modifications to standard laboratory soil box resistivity measurements to directly measure a metallic corrosion rate for the soil sample under investigation. The intent of this research was based on the goal of measuring a reliable corrosion rate directly that would be representative of in-situ conditions, rather than determining the inferred soil corrosivity from laboratory measurement of collected soil samples' resistivity and pH. The procedures proposed could also be used in the field for evaluation of soil samples after they are collected.

The main focus of this laboratory task dealt with using the electrodes in a soil box for measuring soil resistivity, as well as, for estimating the actual electrode corrosion rate using linear polarization resistance (LPR) techniques. We felt that this was a novel use of the of the soil box. The goal of the research under this task was to develop a means to measure an actual corrosion rate under the same conditions used for the accepted laboratory soil box resistivity measurements that is representative of in-situ values. In order to be viewed as successful, the new measurement technique could not add significant additional time, complexity, or cost to the established laboratory procedures.

Task 5 – Development of Field Corrosion Rate Procedures/Instrumentation

Our initial concept of a “combination probe” was discarded when it was learned that the Review Panel had a different concept in mind. We perceived a probe to collect soil resistivity and LPR corrosion rate data at shallow depths of 3 to 5 feet. The Review Panel envisioned a probe for deeper soil explorations (30 feet) where conventional geotechnical drill rigs are used.

The key to successful completion of this task was the fabrication of a probe recognizing that, in commercial production, it must be able to withstand the rigors of repeated use, be field-friendly, be reasonably priced, and yield reliable and repeatable data that correlates with in-situ conditions. The probe development must be compatible with different drilling procedures and equipment with little if any modification. Also, possible field maintenance of the probe must be kept to a bare minimum because of the specialized fabrication of the probe elements and cabling to assure reliable data collection. To be successful, the inclusion of the combination probe into existing field data collection procedures must also not introduce appreciable additional time or complexity to the established processes.

Task 6 – Installation and Initial Testing of Long Term Exposure Materials

The ultimate purpose of this task coupled with Task 10 was to validate and refine, as necessary, test procedures/instrumentation derived from other aspects of the research and their correlation with actual underground corrosion deterioration using buried metal coupons. Corrosion rate, soil resistivity and pH data from the test procedures/instrumentation was compared with those from the coupons after an extended exposure time.

The original work plan and the Phase I interim report presented an approach to this task whereby two relatively shallow depths of study were planned – nominally 2 feet and 10-15 feet. Feedback from the panel at the Phase I review meeting indicates that information from deeper depths (to 25-30 feet) would be of greater value given the particular structures of interest, including driven pilings. The course of action decided upon was to install disposable probes and coupons in shallow trenches of 4 feet and 8 feet in depth, as well as install disposable and reusable probes at 25 feet and 30 feet.

Five sites were chosen for installation:

- Sea Isle City, NJ – Corrpro's Marine Atmospheric Exposure Site
- Medina, OH – Corrpro's Headquarters
- Voorheesville, NY – New York State DOT Yard
- Elk Grove Village, IL – Illinois DOT Yard
- Emeryville, CA – CALTRANS Site

Note: Due to high water table, 8-foot deep trenches could not be dug in Sea Isle City, NJ.

Task 7 – Evaluation of pH Measurement Techniques and Recommendations

The primary purpose of this task was to evaluate different procedures and instrumentation for measuring soil pH and provide recommendations for improved methodologies for obtaining reliable pH data.

In addition to the inclusion of a pH sensor into the Task 5 Multipurpose Soil Probe and the Disposable Multipurpose Soil Probe, we evaluated soil samples removed from the different test sites under Task 6 and Task 10. Further, we continued to review data provided by our laboratory.

Task 8 – Further Evaluation of Other Issues from Phase I

Follow up investigations in the areas of resistivity measurement techniques, soil compaction, and the influence of underground structures on 4-pin resistivity measurements were conducted in response to comments from the panel on the Phase I Interim Report.

Task 9 – Phase II Interim Report

An Interim Report addressing progress on tasks 4 through 8 was submitted to the board in November 2004.

Task 10 – Evaluation of Long Term Exposure Materials

Within one and a half (1 ½) years after installation removals from the test sites at a depth of four (4) feet and eight (8) feet were made. This allows for three (3) additional removals at future intervals at these depths as well

as a future removal at the 25-foot and 30-foot (nominal) depths. Since removals were only made at the 4-foot and 8-foot depths the analysis concentrates on these data sets.

Task 11 – Phase III Interim Report

Due to work plan changes over the course of this multi-year effort, the Phase III results to date are combined with the final report.

Task 12 – Round Robin Testing / Field Trials

Round-robin testing and field trials were to be completed following the demonstration of a viable test methodology for determining corrosivity of the soil environments with improved accuracy.

Task 13 – Final Report

CHAPTER 2

FINDINGS

Task 1 – Conduct Survey

The survey confirmed that both soil resistivity and pH are important parameters that the DOTs use in decision making processes in a number of applications such as structure/component life prediction, corrosion assessment, materials selection, use of coatings, and cathodic protection design.

The survey revealed that all DOTs that responded rely on the traditional 4-pin method for field resistivity measurements with the Nilsson-400 being the most commonly used instrument. For laboratory measurement of soil resistivity, the 4-pin soil box was the most prevalent. There was no indication that use of other non-traditional techniques were attempted or considered. Instrumentation for pH measurement showed more variability.

Most of the DOTs use or specify the standard ASTM (1), AASHTO (2) or the California Method 643 (3) procedures for resistivity and pH testing. Some of the DOTs have developed their own in-house methods (based on or modified versions of ASTM, AASHTO, or California procedures) for determining both these parameters. These are claimed to be more reliable than the standard procedures.

General Information from Questionnaire Responses

Of the thirty-seven respondents to the questionnaire,

- Twenty eight (76%) conduct resistivity testing and thirty two (86%) conduct pH tests.
- Twenty eight (76%) conduct these tests in-house.
- To conduct one or both of the tests, eight (22%) respondents hire consultants, nine (24%) contract outside labs, and five (14%) hire contractors in addition to conducting these tests in-house.

Whether or not resistivity tests are conducted,

- Seventeen (45%) of the respondents use resistivity measurements in their decision making process for structure/component life prediction.
- Twenty three (62%) for corrosion assessment.
- Thirty (70%) for material selection.
- Thirteen (35%) in the use of coatings.
- Three (8%) for design of cathodic protection.

In the case of pH measurements,

- Twenty (54%) of the respondents utilize these values for predicting structure/component life.
- Twenty three (62%) for corrosion assessment.
- Twenty eight (76%) for material selection.
- Sixteen (41%) in the use of coatings.
- Two (5%) in their cathodic protection design.

Instrumentation for Field and Laboratory

Usage/selection of resistivity and pH testing instruments was assessed in the questionnaire. Twenty seven of the thirty seven respondents provided information. However, all twenty seven do not conduct both field and laboratory measurements.

Measurement of Resistivity:

For the purpose of field soil resistivity testing,

- A multiple pin resistance instrument was most highly used, with the Nilsson 400 being the most prevalent.
- The use of the Vibroground by Associated Research, the Soil Moisture Bridge and R2-2A Conductivity Meter by Beckman, and the Strata Scout by Soiltest were also reported.

For soil resistivity testing in the laboratory,

- Seven of the twenty seven respondents who provided information use the MC Miller 4-pin soil box.
- One DOT uses the AGRA MK-II soil box.
- Three respondents reported using single probe resistivity instruments. The manufacturers of these are Cole-Parmer, Orion, and Fisher Scientific.
- Three respondents use in-house fabricated devices that use ASTM/AASHTO standards as a basis.

Measurement of pH:

Twenty one of the thirty seven respondents provided information on pH measurements. There seemed to be a wide variety of instruments used by the DOTs for determining pH of soils and all of these are used in the laboratory.

- Five of the respondents use Orion instruments.
- Three use Corning products.
- Three use Cole-Parmer's pH instruments.
- Two use Mettler products.
- Two use Hanna Instrument products.
- One each use Controls International, Beckman, Fisher Scientific, Sentron, and VWR products.
- One DOT uses an in-house method
- There is no indication from the DOTs that pH measurements are employed for field data acquisition.

Task 2 – Evaluate Existing Methods

Resistivity Measurements (Laboratory)

Resistivity measurements in the laboratory are most frequently made with a “soil-box” in the corrosion-engineering field and often by analytical chemistry methods in the geo-technological field. The soil-box methodology is described in ASTM G-57, AASHTO T-288, and California method 643. ASTM G-57 describes a 4-pin soil box (see Figure 1) for resistivity

measurements. California method 643, which deals with the estimation of service life of steel culverts, and AASHTO T-288, both deal with determination of the minimum soil resistivity, and utilize a 2-electrode soil-box for measurements.



Figure 1 - Four pin soil box for resistivity measurements (MC Miller Company).

During the course of this project, a modified laboratory procedure being proposed for soil resistivity using the MC Miller soil compaction box was evaluated. The compaction box is being developed by MC Miller and incorporates the typical soil box resistivity measuring circuit in conjunction with a means to compact the soil sample being tested.

For typical laboratory soil box type resistivity measurements, the soil sample from the field is first processed as stipulated in the above standards and then packed by hand into the soil-box. The resistance measurement in all the above three test methods (ASTM G-57, AASHTO T-288, and California method 643) can be made either with an AC impedance meter where resistance is read directly from the meter display, or through the use of a DC supply in conjunction with a DC voltmeter and ammeter where the resistance is calculated using Ohm's Law. Soil resistivity is calculated as a multiple of the measured resistance with the correction factor determined by characteristic box geometry and is typically a factor of 1 for most 4-pin soil boxes.

In the 4-pin soil box, an electrical current is injected on the two outer pins of the soil-box and the resultant voltage drop across the two inner pins is measured. For most soil-boxes with a constant of 1, the meter reading gives the direct resistivity value of the sample. An external battery (direct DC source) along with a voltmeter and ammeter can also be used in which case the resistivity is calculated as the ratio of ΔV (change in potential between pins) / I (applied test current). An AC current source is typically used since the use of DC can cause polarization of most metal electrodes unless a current-interrupt technique is used for the potential measurement, which complicates the testing procedure somewhat. In the 2-electrode soil-box, current is applied to the two electrodes and the resistance is directly read on the meter. The typical correction factor for a 2-electrode soil box is 6.67 cm.

The analytical chemistry method (4) consists of extracting an aqueous solution from the soil and reading the electrical conductivity (EC) of the liquid with a special conductivity probe and meter. The reciprocal of conductivity is the resistivity of the medium.

A number of different commercial AC instruments are available for making resistivity measurements with soil-boxes. These include the Nilsson-400, the Vibroground, the Megger,

and the LEM. A suitable DC voltage source (such as a 12V battery) with provisions for measuring current and voltage in the circuit can also be used for determining resistivity. More sophisticated but less commonly used instruments such as the Gamry potentiostat can also be utilized for soil resistivity measurements in the laboratory. The Gamry is a versatile multifunctional instrument capable of performing resistivity measurements as well as a variety of other electrochemical experiments. Essential details about the different instruments investigated to date under this research are provided in Table 1. Of the above instruments, the Nilsson is perhaps the most commonly used today, based on information gathered from the questionnaire in Task 1 and our in-house experience.

Table 1. Different devices for lab and field resistivity measurement

No.	Device	Voltage	Frequency	Remarks
1.	DC source	12V*	-	For lab use but can be used in the field; max resistance measured depends on voltage source
2.	Nilsson	12V	97 Hz	For lab and field use; analog meter; maximum resistance value 100 K Ω
3.	Vibroground	100V	97 Hz	For lab and field use; analog meter; maximum resistance value 10 K Ω
4.	Megger	50V	128 Hz	For lab and field use; digital meter; maximum resistance 20 K Ω ; different models available
5.	LEM	48V	90-128 Hz	For lab and field use; digital meter; maximum resistance 100 K Ω ; different models available
6.	Gamry	100V	0.01-100KHz	For lab use; may possibly be used in the field; computerized; maximum resistance 1000 K Ω

*Higher voltage source may be used depending on resistance to be measured.

Table 2. List of test media and instruments used in laboratory tests

Test Media	Test Instruments Used
<ul style="list-style-type: none"> • Distilled water • Tap water (nothing added) • Tap water (with 1 gm salt) • Tap water (with 2 gm salt) • Tap water (with 3 gm salt) • Soil (as received) • Soil (saturated with tap water) • Sand (as received) • Sand (saturated with tap water) 	<ul style="list-style-type: none"> • 12V DC source • Nilsson-400 • LEM • Vibroground • Megger • Gamry

For the NCHRP project, laboratory testing was conducted in an MC Miller 4-pin soil-box as shown in Figure 1. Nine different test media (with a wide resistivity range from about 20 ohm-cm to over 100, 000 ohm-cm) and six different instruments were used in the laboratory testing as shown in Tables 1 and 2. Figures 2 through 6 show the different instruments. The purpose of this effort was to determine whether different instruments gave comparable resistivity values in a soil-box set-up for the different types of media and whether the resistivity value was impacted by the magnitude of the measurement frequency and applied test voltage. The Gamry with its wide frequency range was a valuable instrument. Prior to testing, all instruments were calibrated with known resistors.



Figure 2 - The Nilsson 400



Figure 3 – The LEM Unilap



Figure 4 – The Vibroground



Figure 5 – The Megger Model DET5/4R



Figure 6 – The Gamry Model 750

The laboratory test results are shown in Table 3. It can be seen that except in the case of distilled water (high resistivity), all instruments gave generally similar resistivity values for the different media, which would be expected given the homogeneity of the media and simple geometry of the soil box. Two of the devices (Vibroground and Megger) were unable to read the resistivity value of distilled water, which was expected because of the resistance measuring capability of these instruments. Additionally, there was a significant difference in the resistivity readings for distilled water obtained with the other devices. The cause of these conditions is may be due to instrument measurement limitations relative to applied test voltage and or measurement sensitivity, and or possibly the test frequency, recognizing that the measured “resistance” is

actually an impedance with resistive, inductive and capacitive components. The data obtained with the Gamry instrument at five different frequencies (10 Hz to 100,000 Hz) indicate that at least in a soil-box environment, the impact of variable frequency on resistivity is insignificant except in the case of distilled water. The resistivity values for distilled water showed a moderate variance with the change in frequency (from 132,000 ohm-cm at 10 Hz to 97,000 ohm-cm at 100 kHz). This variance was most likely due to capacitive and or inductive effects.

Table 3. Soil Box resistivity data in various media using different instruments.

Test Media	Resistivity (ohm-cm) Determined by										
	12V DC		Nilsson	LEM	VG	Megger	Gamry				
	On	Inst Off	97 Hz	111 Hz	97 Hz	128 Hz	10 Hz	100 Hz	1K Hz	10 K Hz	100K Hz
Distilled water	64,900	65,050	87,000	84,900	NR	NR	132,000	120,000	114,000	108,000	97,600
Tap water (nothing added)	2,533	2,620	2,300	2,385	2,400	2,420	2,310	2,310	2,320	2,320	2,310
Tap water (+ 1 gm of salt)	168	171	152	154	160	154	152	152	152	152	152
Tap water (+ 2 gm of salt)	46	45	44	45	44	45	45	45	45	45	45
Tap water (+ 3 gm of salt)	20	20	19	20	21	20	20	19	19	19	19
Soil (as received)	1,055	1,092	945	939	915	951	947	939	933	925	907
Soil (saturated with tap water)	289	292	272	278	280	279	279	276	274	272	270
Sand (as received)	6,490	6,647	6,475	6,500	6,400	6,660	6,350	6,390	6,400	6,380	6,320
Sand (saturated with tap water)	532	536	510	521	525	522	531	526	524	521	517

Key:

On = on potential; Inst Off = instant off potential; VG = Vibroground; NR = no reading

Our overall general conclusion from the obtained laboratory data is that typical instruments used for soil-box type resistivity testing yield comparable results for many situations. The variation that does occur is not considered particularly significant relative to the use of these data in corrosion assessments and corrosion control applications. The user must recognize the limitations in specific equipment for relatively high resistivity media, and this will be delineated in our formalized test procedure under Task 5. In such instances, our experience and the results of this lab testing indicate that the applied DC test current/DC voltage measurement technique is most suitable and provides for the most accurate information, provided sufficient applied test current and meter sensitivity/resistance considerations are accounted for. The impact of test frequency on measured resistance and calculated resistivity will be further evaluated later in this research.

Resistivity (Field)

Various means exist for measuring soil resistivity in the field. These include the Wenner 4-pin method as described in ASTM Test Method G57, single probe method (e.g. the Shepard's Cane, or Collins Rod) as described in California Method 643, and electromagnetic induction methods. The 4-pin method and the Collins Rod have been used in the corrosion engineering field for well over 30 years. To our knowledge, the electromagnetic induction methods have been in use for less than 10 to 15 years and are notably less common than the 4-pin and single

probe techniques. A single probe device, the Nova Probe developed in the early 1990s (5), which can measure several in-situ soil parameters, including resistivity, is also available but not commonly used.

Four-pin Method

The 4-pin resistivity method was originally developed by Frank Wenner (6) and involves the use of 4 metal pins (or electrodes) driven into the ground. The pins are typically placed with equal separation in a straight line in the surface of the soil to a depth not exceeding 5% of the minimum separation of the pins. The pin separation is selected with consideration of the soil strata of interest. A current is applied to the outer pins, and the voltage between the inner pins is measured using a sensitive voltmeter. More commonly, the resistance is measured directly with appropriate resistance bridge type instrumentation. Resistivity (expressed in units of ohm-cm) is a function of the current, voltage, and spacing of the pins (which is considered equal to the depth of the test). The resistivity is calculated by equations from references 6 and 7, and is well accepted in the corrosion engineering field. The resulting resistivity values are considered to represent the average (bulk) resistivity of a hemisphere of soil of a radius equal to the pin separation. Stray earth currents and induced AC can affect the readings if these effects are not separated from the data.

AC meters, which are used for laboratory resistivity measurements (discussed previously), are also used for field resistivity measurements. During the present field-testing, three of the meters (the Nilsson-400, LEM and Vibroground) shown in Figures 2 through 4 were used. In addition, the applied direct test current technique was used.

The raw resistance data was manipulated by the Barnes Layer Analysis method (8) to obtain layer resistivity at different depths.

Electromagnetic Induction Method

Unlike the preceding methods, the electromagnetic induction (EMI) technique for determining soil resistivity does not rely on direct contact of test electrodes with the ground. Instead a primary magnetic field is established within the ground through the use of a suitable transmitter held above the ground. This primary magnetic field induces circular eddy current loops in the soil, which in turn generates a secondary magnetic field that is then detected with a receiver. The theory used by the manufacturer is the ratio of the secondary to the primary magnetic field is directly proportional to the soil conductivity or inversely proportional to the soil resistivity. With this inductive method, it is reported by the manufacturers that extensive surveys can be carried out relatively fast (compared to traditional 4-pin data collection procedures) under many geological conditions including those of high surface resistivity such as sand and gravel. Descriptions of this technique and its development are available in the literature (10-12). The EMI method is widely used in geophysical exploration in a variety of patented systems. Some of these include Geonics, Geometrix, and Crone Pulse, Phoenix Geophysics.

Geonics Ltd., of Canada is one of the more well known suppliers of equipment using EMI technology and has produced several types of instruments relating to soil resistivity and

other geo-physical surveys. The Geonics Ltd. EM31-MK2, which was used during the present fieldwork (Figure 7), is reportedly designed for determining resistivities to an effective depth of 6m (~20 ft.) when it is used in a vertical configuration (in the vertical configuration, the instrument faces upwards). Information from the manufacturer indicates about 75% of the reflected electromagnetic signal comes from a layer of about 1 to 3m (~3 to 10 ft.) in thickness from the 6-m soil strata (12). There is hardly any contribution from the near surface layer. Hence the conductivity (or resistivity) data obtained is considered an average value for a soil layer of about 1-3m (~3-10 ft.) thick.



Figure 7 - Geonics EM31-MK2 in field use.

In the horizontal position (with the instrument rotated 90° about its horizontal axis), the effective measuring depth of the EM31-MK2 is 3 m (~10 ft.). In this case, the measured data is from a layer of about 0.5 to 1.5 m (~1 to 4.5 ft.). The inter-coil spacing of the instrument (i.e. distance between the transmitter and receiver mounted on a pole) is fixed at 3.66 m (~12 ft.). A single operator can manipulate the device.

Another Geonics device, the EM34-3, with three variable inter-coil spacings can be used to survey depths of up to 60 m (~200 ft.) in the vertical mode and up to 30 m (~100 ft.) in the horizontal mode. Two operators are required for data collection with this device. This unit was not used during the present fieldwork as most highway substructures and other facilities of interest during the present research are typically less than ~20 to 30 feet below grade. During normal operation, the EM31-MK2 (with its transmitter/receiver pole) is carried parallel to the ground at about 1 m (~3 ft.) height pointing in the direction of travel. The device is equipped with a data logger on the control console so that data can be recorded on a continuous basis over a large area in a short amount of time. The raw data is retrieved and manipulated with special software on a personal computer to obtain final plots of conductivity (or resistivity) versus distance. It is possible to determine layer resistivity by collecting data with the transmitter/receiver pole at different heights from the ground surface. However, the raw data has to be analyzed with more sophisticated software, which is available commercially. The basic data generated as part of this initial research using the Geonics EM31-MK2 instrument is such that use and evaluation of the more sophisticated layer resistivity software was not deemed appropriate at this time.

Single Probe Method

The single probe devices include the Shepard Cane, the Collins Rod, and the Nova Probe. These devices determine the local soil resistivity in the immediate vicinity of the tip of a probe pushed into the earth to a desired depth.

The Shepard Cane (which is no longer commercially available in the USA) uses two electrodes mounted on rods. The instrument measures the current flow between the two electrodes that are a set distance apart and then computes the soil resistivity.

The Collins Rod consists of a hollow steel rod typically 4 to 6 feet long by 0.5 inch in diameter with a steel tip that is separated from the main rod by an insulating spacer approximately 0.25 inch thick. A wire is connected to the tip of the rod through the hollow shaft. A second wire is connected to the main part of the rod. An AC bridge measures the resistance between the tip and body of the probe. The resistance measured is a function of the soil resistivity and can be read with a direct-reading meter. The meter uses an earphone and the nulling of an audible tone to determine the measured resistivity value. Figure 8a shows a Collins Rod in field use. Figures 8b and 8c show closer views of the device.

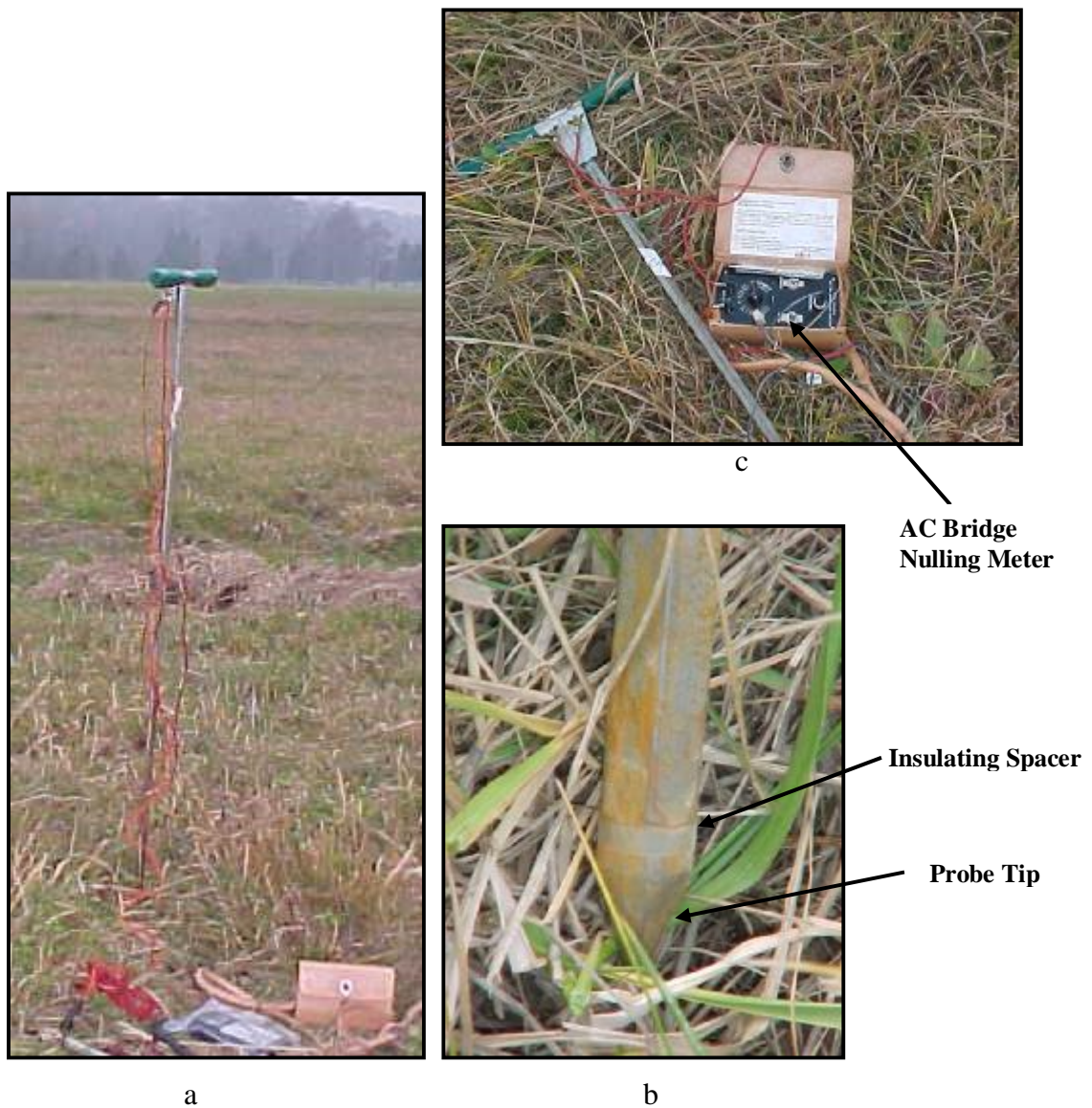
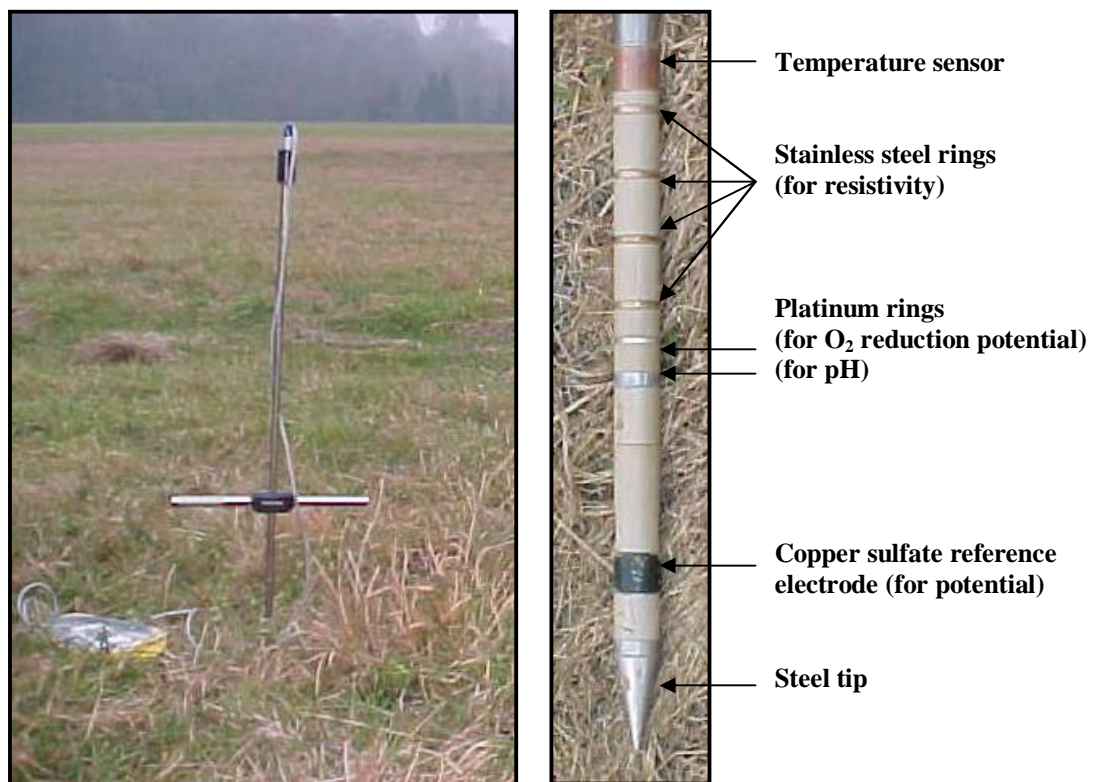


Figure 8 – a) Collins Rod in field use, b) Closer view of Collins Rod and meter, c) Close up of probe tip

The Nova Probe (developed in Canada in the early 1990s) is a rod-type device designed to acquire local information related to soil properties that help in understanding corrosion scenarios at a particular site. The probe has multiple sensors mounted on the shaft. A battery-operated digital meter is used to acquire and display data. The probe is intended to measure soil resistivity, soil redox potential, soil temperature, pipe to soil potential, and soil pH. Figure 9 (a through c) shows the Nova Probe in field use, a closer view of the probe and meter, and a close up of the probe tip with sensors. The Nova Probe is manufactured by Harris Scientific Products of Edmonton, Canada.



a

c



b

Figure 9 – a) Nova Probe in field use, b) Closer view of Nova Probe and meter, c) Close up view of probe tip showing different sensors.

To obtain data with either the Collins Rod or the Nova Probe one often has to first establish a pilot hole in the ground particularly if the soil is hard. The tip of the probe is then pushed into the ground firmly to make sure the probe body makes proper contact with the soil. The manufacturers of the Nova Probe advise not to use excessive force. The soil conditions will dictate how much effort is required to make the pilot hole and then push the probe into the ground.

The Nova Probe is supplied with a rod and slide-hammer to facilitate making the pilot hole. The slide hammer weighs 40+ pounds and it is cumbersome to manipulate the device in making the pilot hole. The instrumented section of the Nova Probe for measurement is about 10 inches in length (Figure 9) and is located at the bottom of the rod. One has to make certain the probe is pushed at least 2 feet or deeper into the ground to collect even near-surface data. If the soil is hard it is very difficult to push the probe to the required depth.

The measuring tip of the Collins Rod is about an inch in and hence less effort is required to collect accurate data at typical utility depths of 3 to 4 feet below grade when compared to the Nova Probe. The Collins Rod is a well established field instrument and has been used by Corpro and others in the corrosion engineering field for well over 40 years.

The design of the Collins Rod presents the high probability of adapting this basic concept for corrosion rate measurements using 2-electrode LPR (linear polarization resistance) technology, which is a standard and generally accepted method of determining corrosion rates of metals in electrolytic environments (9). The basic concept of using a Collins Rod for LPR data acquisition was preliminarily evaluated during the subject field tests. Suitable instrumentation to perform these preliminary LPR measurements are readily available in-house within Corpro. The instrument we used, a Corratr Aquamate, is popular for corrosion monitoring in the water treatment and refining industry sector. It is a versatile, compact, battery operated device, which can perform corrosion rate as well as conductivity measurements. It is to be noted that the Corratr has its own calibrated 2-electrode probe for making measurements based on electrode element surface area of 5 cm. Hence, given the difference in geometry and electrode surface area, it was realized that using the Aquamate with the Collins Rod would not be directly accurate for a real corrosion rate read directly from the meter. Some correction factors for the Collins Rod/Aquamate combination are necessary. Further development of a portable field resistivity/corrosion rate probe based on this concept is part of Task 5.

Test Sites – Field Resistivity Measurements

Three field sites with different characteristics were selected to conduct initial resistivity testing. All three sites are in close proximity of the Corpro office in Dulles, Virginia (western suburb of Washington DC). The sites included (A) an open sports playing field with no apparent buried utilities in the test area, (B) an open agricultural field with two underground coated and cathodically protected steel natural gas pipelines set about 300 ft. apart, and (C) a field with a buried 42-inch diameter un-coated and electrically bonded ductile iron water pipeline traversing through it. The main purpose of selecting Sites B and C was to preliminarily assess the effect of underground metallic pipelines on the field resistivity measurements.

Four-pin resistivity data was collected at the three sites primarily with the Nilsson and Vibroground devices. Some data was collected with the LEM and the straight DC technique at Test Sites A and B. Geonics data was collected at all three sites. Data was collected with the single probe devices at Test Site B.

Four-pin Data

Raw resistance data collected at the different sites were converted to layer resistivity by the Barnes Layer Analysis method with results shown in Figures 10 through 14. At Test Site A, four devices (Nilsson, Vibroground, LEM, and direct DC) were used. The resistivity data is plotted in Figure 10 and as can be seen all four measurement systems showed similar trends up to about a 12 ft. pin spacing. The LEM reached its limit at 12 ft spacing and the Nilsson showed somewhat erratic behavior and showed a limit at 25 ft. The Vibroground and the direct DC technique showed more stable behavior. Additional test sites to further evaluate the 4-pin resistance field measurement technique are addressed under Task 5.

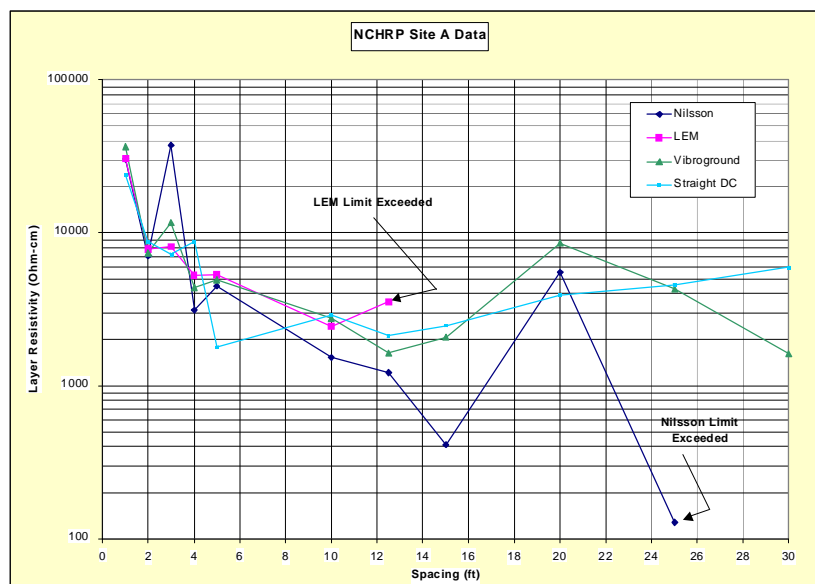


Figure 10 – Four pin resistivity data from Site A

At Site B, resistivity scans were performed at two locations across (perpendicular to) the buried natural gas pipelines using pin spacings of 2.5, 5, 10, and 12.5 ft. At location 1, the LEM and Nilsson devices were used while the Nilsson and Vibroground devices were used at location 2. Calculated layer resistivity data (as a function of distance) from these locations are shown in Figures 11 and 12. For the most part, the devices gave comparable results but there was some variance at 12.5 ft. spacing. While there appears to some effect caused by the presence of the coated natural gas transmission lines, it is not extreme or consistent. The lack of a strong influence because of the pipelines may be related to a high-grade dielectric type external coating on the pipelines, which would not be uncommon.

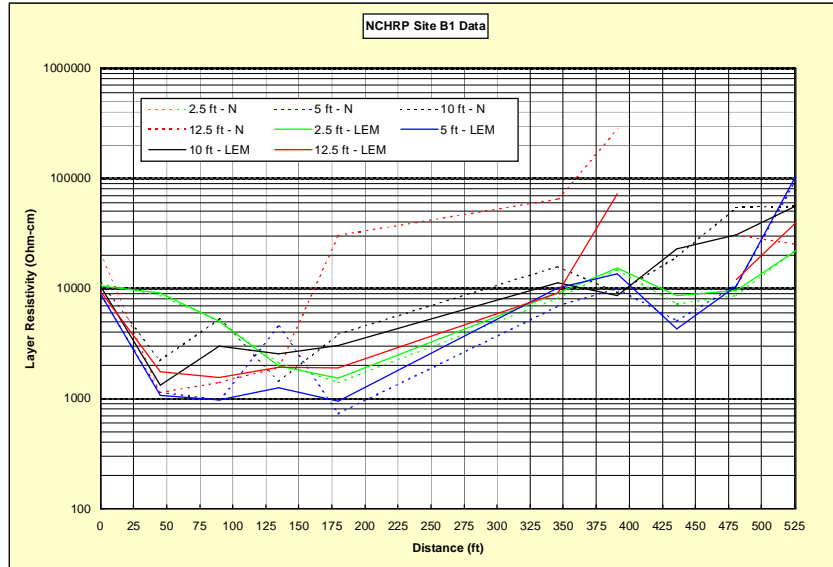


Figure 11 – Four pin resistivity data from Site B, location 1.

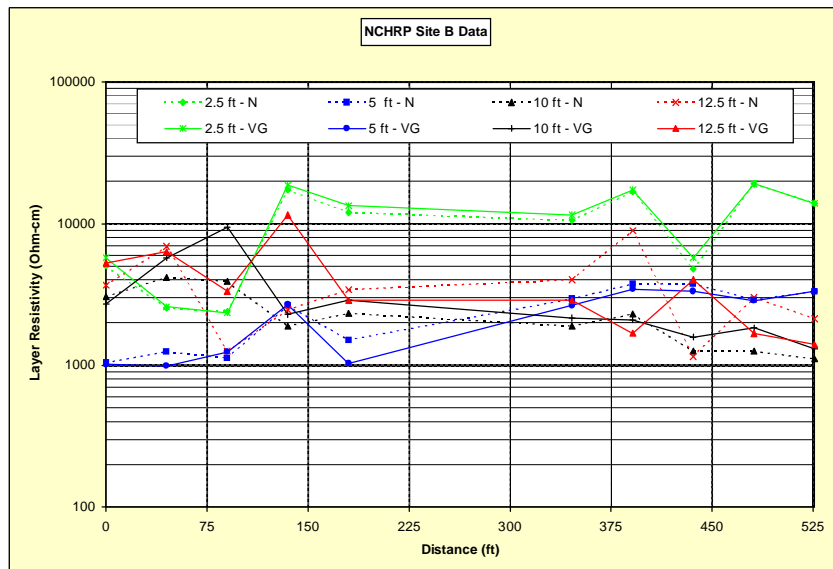


Figure 12 – Four pin resistivity data from Site B, location 2

Four-pin data from Site C, obtained with Nilsson and Vibroground devices at two locations on the site, are shown in Figures 13 and 14. At both locations, resistivity scans were conducted perpendicular to the water pipe at pin spacings of 2.5, 5, 10, and 12.5 ft. Again as observed in the previous case, some discrepancy was noted between the two devices at the 12.5 ft. pin spacing. At the lower spacings, the two sets of data showed fairly good agreement.

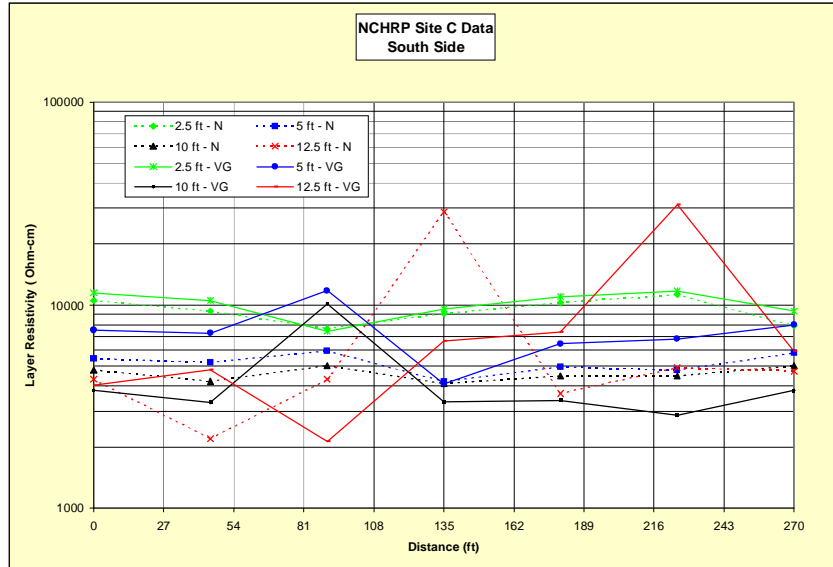


Figure 13 – Four pin data from Site C, location 1

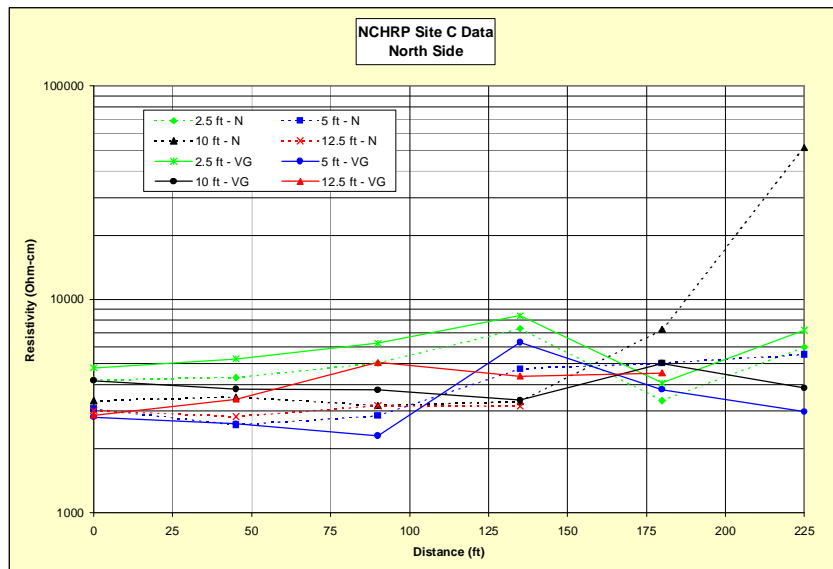


Figure 14 – Four pin resistivity data from Site C, location 2

No consistent, readily apparent pattern was observed in the change of resistivity values due to the presence of the buried pipelines. However, in some cases a general increase in the resistivity value was noticed in the vicinity of the pipeline particularly at a pin spacing of 12.5 ft. Further investigations were originally planned under Task 5 to determine the impact buried structures have an impact on resistivity measurements. This plan was dismissed as unnecessary after the work plan was altered to include 30-foot deep test wells (see Task 8).

Electromagnetic Induction (Geonics) Data

Data obtained with the Geonics EM31-MK2 unit at the 3 test sites are shown in Figures 15 through 19. Data was collected in a continuous mode by walking with the instrument

between two points spaced 90 to 550 feet apart. Scans were typically conducted at three heights: (a) ~6 inches above the ground surface, (b) ~30 inches from the surface (waist height), and (c) ~60 inches from the surface (shoulder height). A characteristic feature of EMI resistivity data when plotted as a function of distance is that metal objects buried in the ground (e.g. a pipeline, or underground storage tank) in the path of the survey show up as strong peaks. This feature can be noted in Figures 16 through 19 where pipelines were present in the ground.

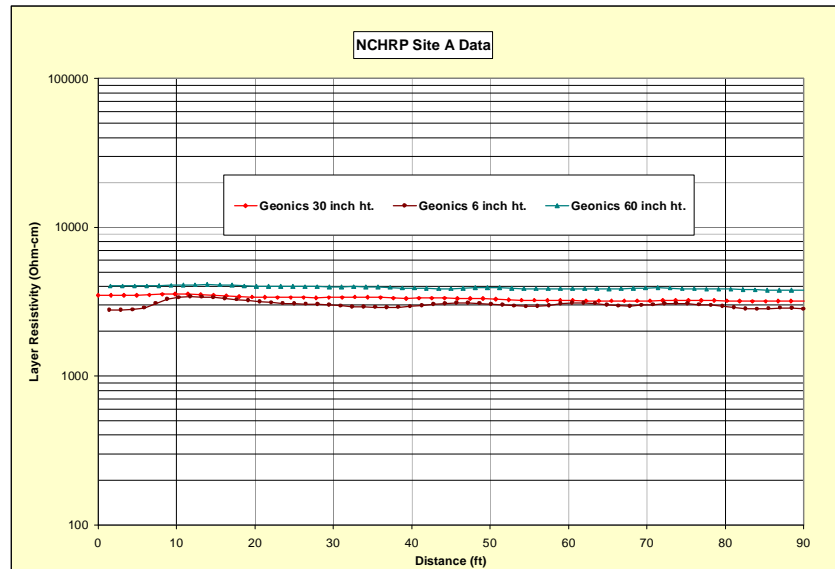


Figure 15 – Resistivity data obtained with Geonics EM31-MK2 from Site A

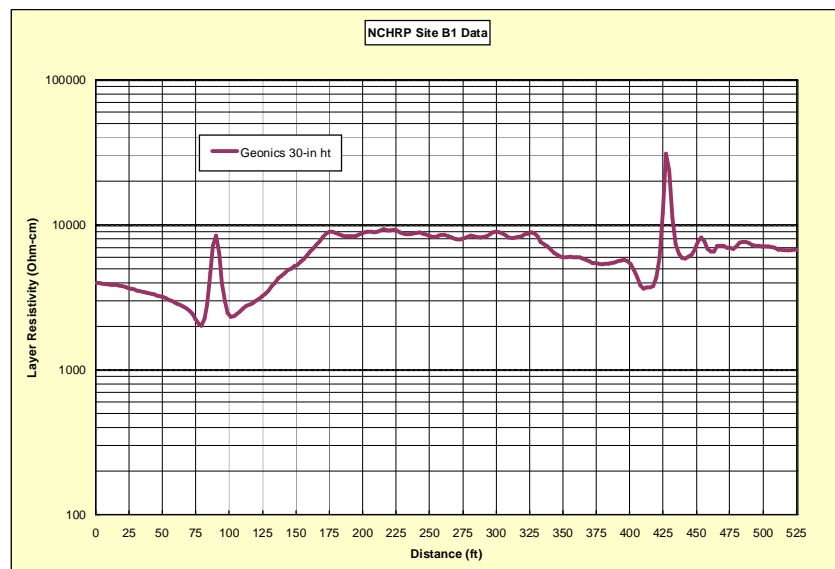


Figure 16 – Resistivity data obtained with Geonics EM31-MK2 from Site B, location 1

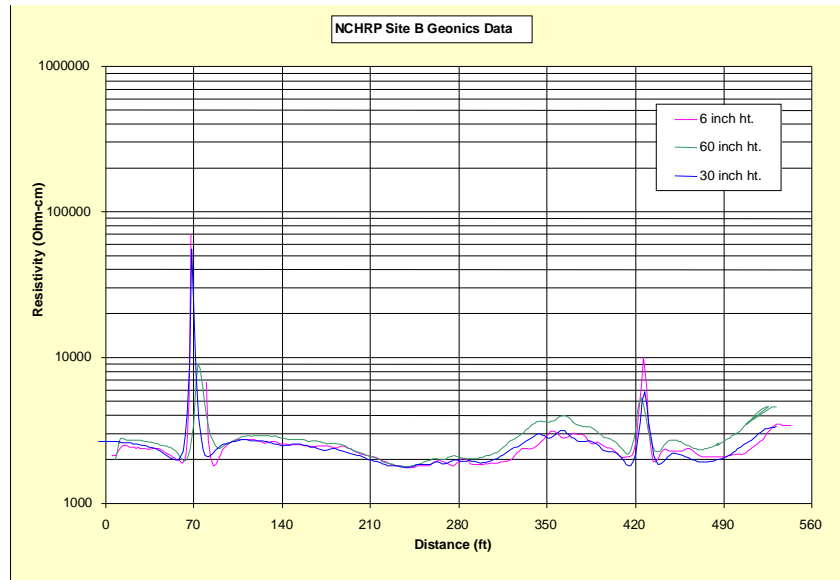


Figure 17 - Resistivity data obtained with Geonics EM31-MK2 from Site B, location 2

It is noticed that peaks in the resistivity plots are more pronounced in the case of the coated and cathodically protected pipeline (Figures 16 and 17) as compared to the bare pipeline (Figures 18 and 19). It is not clear at this time based on information from the manufacturer of the EMI equipment whether the peak readings near the pipelines approximate an apparent resistivity value (similar to the 4-pin technique) or whether this is simply a limitation in instrumentation with no reasonable correlation to apparent resistivity.

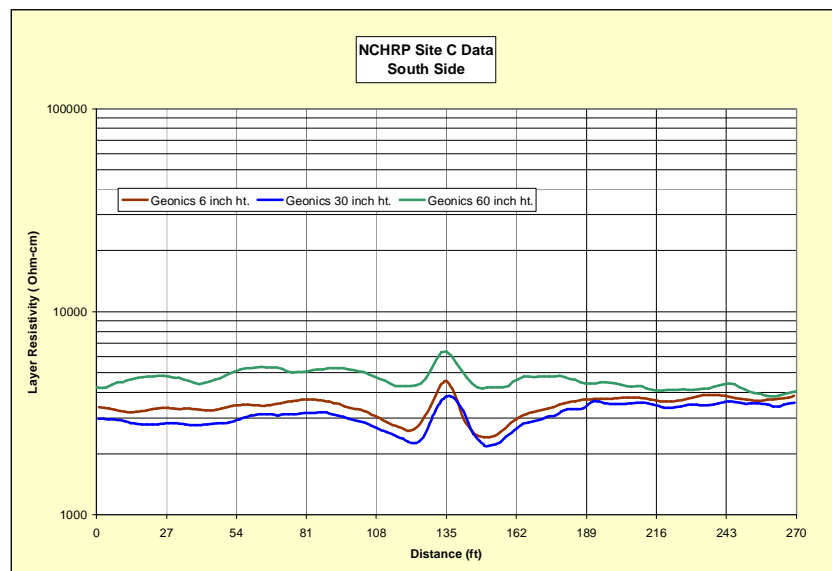


Figure 18 - Resistivity data obtained with Geonics EM31-MK2 from Site C, location 1

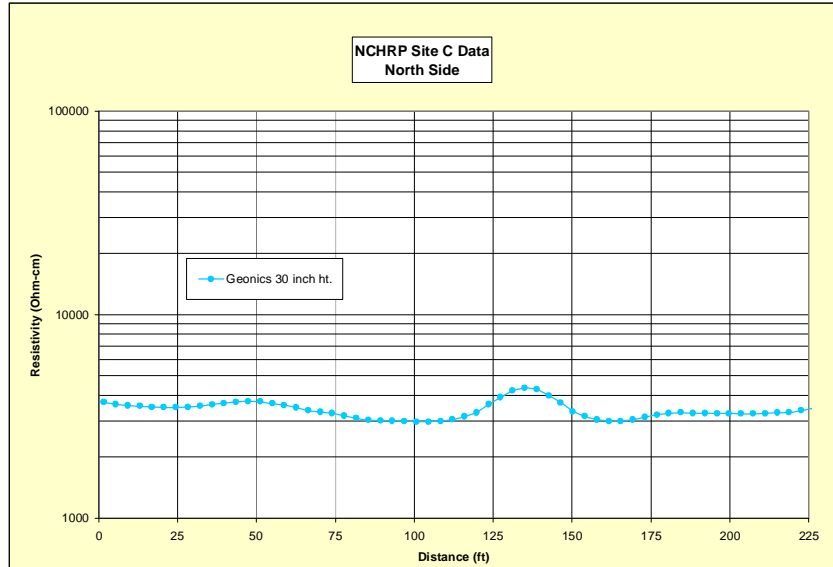


Figure 19 - Resistivity data obtained with Geonics EM31-MK2 from Site C, location 2

At Site B, data was also collected from various discreet locations at different heights from the surface at 1-foot intervals. Both vertical and horizontal orientations of the instrument were used. This data is shown in Table 4 and Figure 20. With the proprietary software available through Geonics, we believe the data in Table 4 would have given a quantitative estimation of layer resistivity with depth, but as mentioned earlier such type of software was not at our disposal at the time of our evaluation. Nonetheless, Figure 20 gives a fair idea about the variation of Geonics-measured resistivity with depth. The impact of the coated natural gas line at the center of the test area appears to be of no noteworthy significance relative to the overall range in resistivities.

Table 4. Resistivity data obtained with EM31-MK2 at Site-B

Height From ground Ft.	Distance from center of pipe									
	90 ft. south		45 ft. south		0		45 ft. north		90 ft. north	
	Instrument orientation									
	H	V	H	V	H	V	H	V	H	V
	Resistivity (ohm-cm)									
0	3960	10471	4805	4887	5171	7240	5083	7240	5818	10471
1	4969	10013	6015	4884	6304	6785	6047	6785	7030	10013
2	5935	9804	6969	5047	7111	7162	6861	7162	8502	9804
3	7018	9756	7569	5362	8304	7715	8264	7715	10063	9756
4	7805	9732	8032	5926	9259	7976	9227	7976	11396	9732
5	9238	10512	9259	6415	10204	8222	10270	8222	13072	10512

H = horizontal; V = vertical

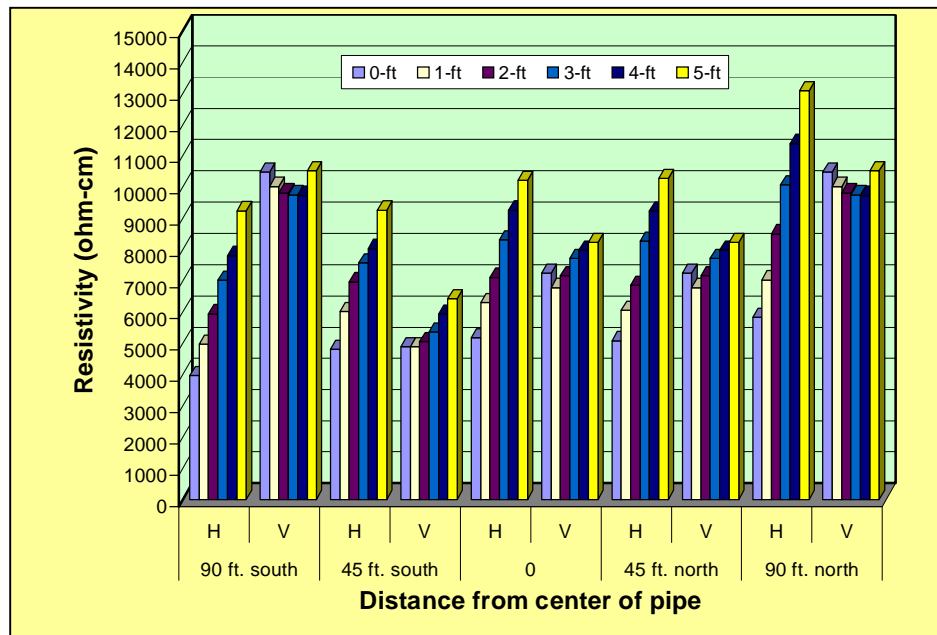


Figure 20 – Resistivity data obtained with Geonics EM31-MK2 from Site B discrete locations.

Comparison of 4-pin and Geonics Data

Composite plots of 4-pin and Geonics data were created to see how the two compared. These are represented in Figures 21 through 25. In general terms the Geonics data collected

from a height of about 30 inches from the surface appear to agree reasonably well with 4-pin data obtained at a depth of 5-12.5 ft. It may be recalled that at this height 75% of the signals sampled by the Geonics EM31-MK2 in the vertical mode comes from a soil layer of about 3-10 ft in depth.

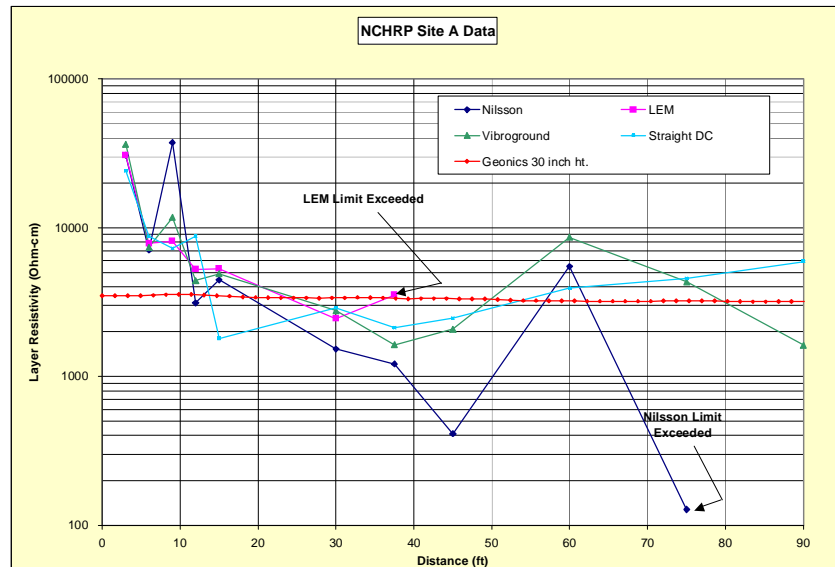


Figure 21 – Superimposed four pin and Geonics data from Site A

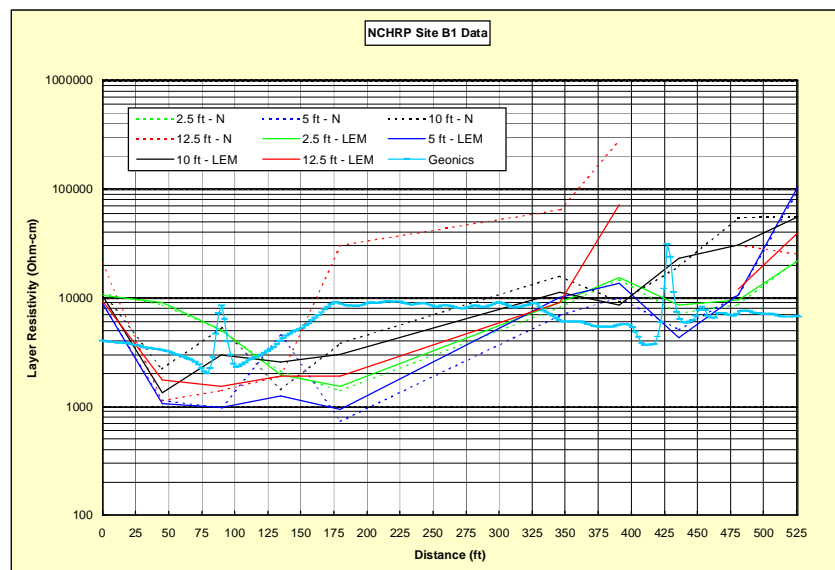


Figure 22 - Superimposed four pin and Geonics data from Site B location 1

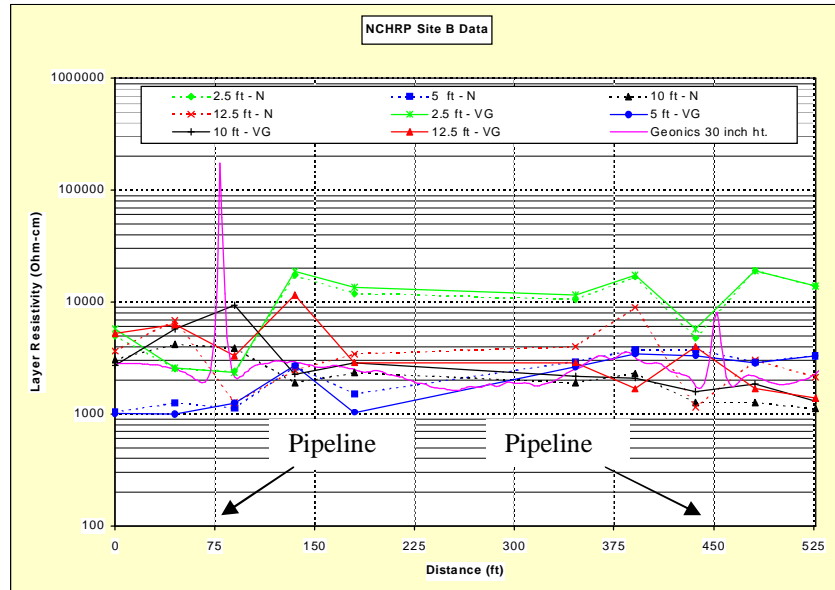


Figure 23 - Superimposed four pin and Geonics data from Site B location 2

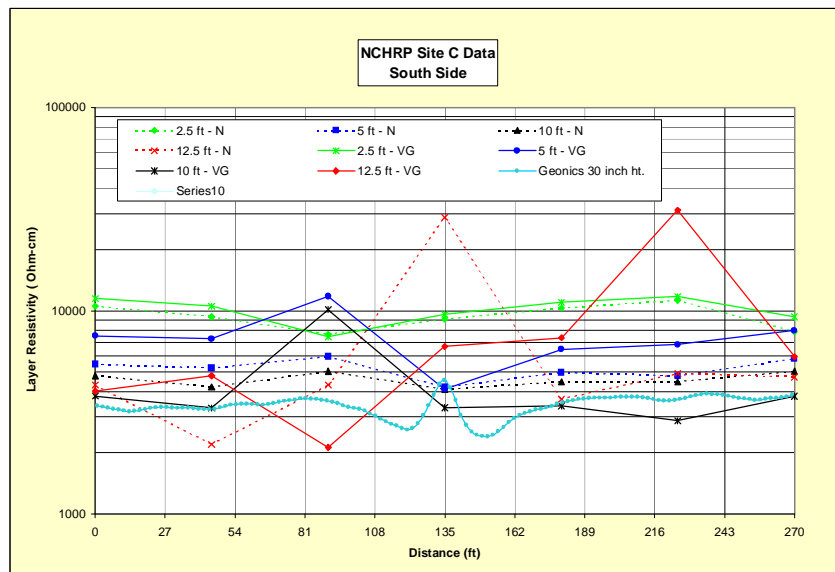


Figure 24 - Superimposed four pin and Geonics data from Site C location 1

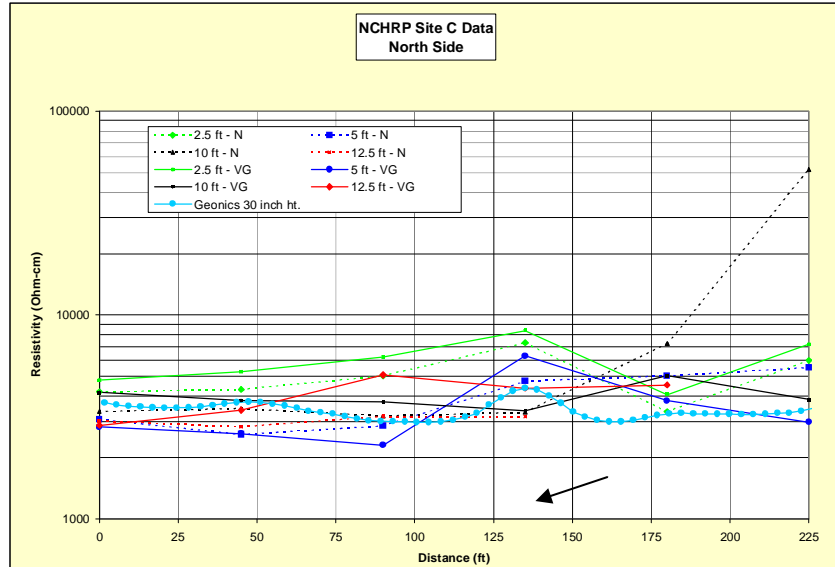


Figure 25 - Superimposed four pin and Geonics data from Site C location 2

It may be noted from Figure 21 that the 4-pin data from Site-A shows notable variability while the Geonics data show steady behavior. This same general observation is also noted from the other data, where any changes in Geonics resistivity are very subtle. Our general experience suggests that the 4-pin data more closely resembles the heterogeneity of common soils, however, the general consistency of the Geonics data requires further evaluation.

Single Probe Data

Collins Rod:

Limited field data was collected with the Collins Rod from Site B. As mentioned earlier, initial efforts have been made to utilize the Collins Rod to obtain corrosion rate data with the help of a Corrat, which also gives a conductivity value at the measurement location that has been converted to a resistivity value. In addition, a resistivity value was obtained from the Collins Rod itself using the mating resistivity meter. The results are shown in Table 5. The resistivity values from the Collins Rod and those obtained with the Corrat-Collins Rod combination show some general correlation. The corrosion rates obtained with the Corrat-Collins Rod combination are of course not accurate since no correction factor was applied. More extensive work is required to come up with such a factor. Nonetheless, closer examination of the data shows that in general terms, there is an inverse relationship between the corrosion rate and resistivity values (Figure 26), which is consistent with general experience. The important thing to note is that the concept is workable and it would be feasible to obtain simultaneously a resistivity value and a true corrosion rate value with a single measurement once the instrument is correctly configured. Based on these preliminary findings, a modified probe was designed and built as part of Task 5.

Table 5. Collins Rod data

No.	Location	Media	Depth	Collins Rod	Corrater	
				Resistivity	Resistivity	Corrosion Rate
1	Lab	Tap water	-	2800	2151	15.1
2	Lab	Water + salt	-	150	103	21.3
3	Field	Soil	18	20000	13889	7.8
4	Field	Soil	12	40000	40816	6.7
5	Field	Soil	12	17500	22472	5.1
6	Field	Soil	18	14000	8439	8.3
7	Field	Soil	12	10000	8511	9.6
8	Field	Soil	12	12000	8475	7.5
9	Field	Soil	24	1750	882	14.6

Key:

Depth: inch; Resistivity: ohm-cm; Corrosion rate: mpy

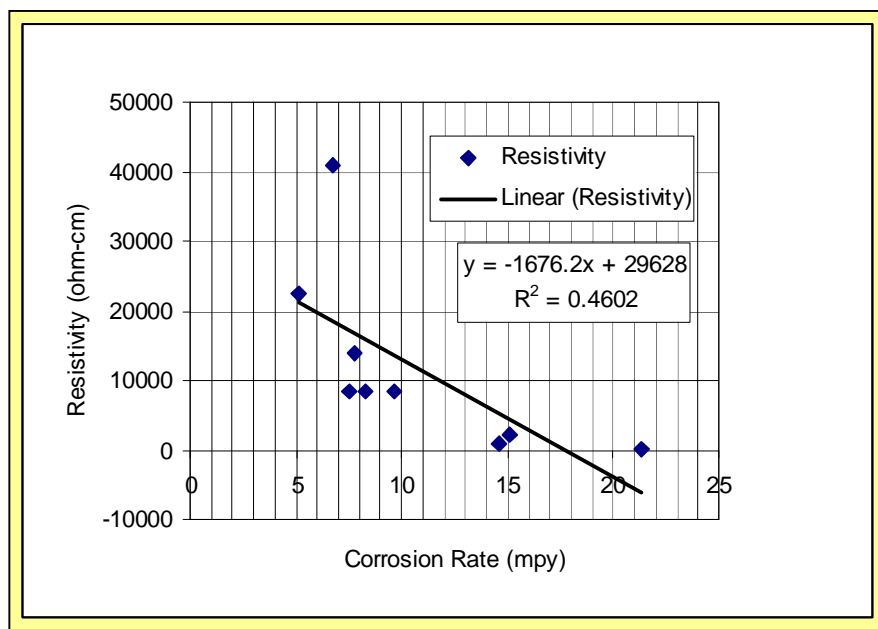


Figure 26 – Resistivity vs corrosion rate data from Site B

Nova Probe:

Data obtained with the Nova Probe is shown in Table 6. Most of the test locations were close to where the Collins Rod data were obtained. Conceptually, the device is very versatile since it reportedly can yield information on a number of useful soil parameters (temperature, pH,

oxygen reduction potential, and resistivity). However, obtaining reliable data needs careful manipulation. The large contact area of the probe surface incorporating the various sensors means that the probe has to be pushed at least a few feet into the soil. Additionally, proper contact of the probe surface with the soil is essential. When the soil is hard, this becomes a practical issue. In the present case, the soil at Site B was not very hard but still it was difficult to push the probe beyond about 18 inches (attempts to use the device at Site A proved futile since the ground was quite dry and hard). The resistivity data obtained with the Nova Probe (Table 6) and Collins Rod (Table 5) taken in close proximity to each other does not show good correspondence and is most likely due to poor contact.

Table 6. Nova Probe Data

No.	Depth	Temp	PH	Resistivity	ORP	Potential
1	12	15	3.2	20347	70	
2	12	12	4.7	29000	256	
3	12	10	2.9	26355	254	
4	18	11	4.2	14296	279	
5	18	11	4.0	41313	183	-229
6	12	10	3.8	47221	265	-231
7	12	11	4.8	35421	197	-212
8	18	10	5.0	13423	277	-174
9	12	9	5.6	33939	256	-22

Key:

Depth: inches; **Temp:** °C; **Resistivity:** ohm-cm;

ORP (oxygen reduction potential): mV;

Potential (of embedded metal): mV

It should be mentioned that prior to taking data in the field, the Nova Probe was calibrated in the laboratory in a bucket of water (as per manufacturers recommendations). Except for pH, which was off by about 1 unit (probably due to a dirty pH sensor), values of the other parameters (ORP, resistivity, temperature, and potential) were reasonably accurate. Hence, data collected in the field is expected to be reliable provided the testing is done properly and there is good contact of the element array with the soil.

Equipment Cost

The prices of different equipment used so far in the project are listed in Table 7 and range from about \$800 (for the Collins Rod) to about \$18,000 (for the Geonics EM31-MK2). The price range is understandably huge because of the varying degrees of sophistication and complexity. We believe that for effective implementation of any new or modified field test instrumentation on a large-scale basis, the cost must not be more than \$2000 to \$3000.

Table 7. Equipment Prices

No.	Equipment Name	Approx. Price
1	Nilsson-400	\$800
	Vibroground	\$1500
	Megger DET5/4R	\$1300
	LEM-Unilap	\$1700
	Gamry-750	\$15,000
	Geonics EM31-MK2	\$18,000
	Collins Rod + meter	\$700
	Nova Probe	\$8,000

Task 3 – Phase I Interim Report

Submitted to the board May 2001.

Task 4 – Development of Laboratory Corrosion Rate Procedures/Instrumentation

LPR-type electrochemical test procedures have been in use for many years for estimating corrosion rates in numerous applications, including aqueous media, steel-in-concrete, and underground structures. This proven technique is appropriate for measuring instantaneous corrosion rates when the metallic specimen under test is exposed to an electrolyte, e.g. soil and water, which will be part of its normal service conditions.

A limitation of LPR measurements is that they are indicative of the corrosion rate only at the time of measurement. A single LPR measurement may not adequately reflect the time-weighted average corrosion rate or cumulative corrosion damage. This is particularly true in situations where environmental or service conditions are subject to change. In such instances, the instantaneous corrosion rates would probably fluctuate widely over time. Another limitation is that LPR measures the uniform corrosion rate and may not adequately reflect pitting corrosion of the test sample. This would only be considered a problem for structures that transport or store product like pipelines or tanks.

Illustrations of many Phase II concepts can be found in Appendix E. Figure E1 (Appendix E) illustrates the basic laboratory set-up where a standard 4-electrode soil resistivity box is used for traditional resistivity measurements. Then, without making any change, the same soil box and soil sample are used to measure the LPR corrosion rate. This allows factors such as moisture distribution and compaction (density) within the soil box to remain the same during both the resistivity and corrosion rate measurements. Any other procedure where different set-

ups are used would alter the soil sample or use different samples altogether would not allow for this consistency.

The 4-electrode version of the soil box with a resistance-to-resistivity conversion factor of unity has been used for most the testing to date. This decision was based on the results of the Task 1 questionnaire which indicated that the use of the 4-electrode soil box appears to be the most prevalent among the state DOTs. We recognize there are various versions of 4-electrode and 2-electrode soil boxes in industry. We would expect the general findings of the corrosion rate measurement research under this task to be applicable to the other soil boxes as well. Further evaluation of 2-electrode soil boxes and the use of different materials for the electrodes were conducted under Task 8.

A Nilsson Model 400 resistance meter (97 Hz) was used to conduct the standard 4-electrode soil box resistivity measurements. The results of the Phase I research showed there is little practical difference between the Nilsson meter and the other most commonly used resistance meters using a similar measurement process. The soil samples that have been evaluated were prepared following ASTM G57 under both as-received and saturated moisture conditions.

The Aquamate, manufactured by Rohrback Cosasco Systems (RCS), was used to measure the LPR corrosion rate. This unit was initially evaluated as part of our Phase I research. It uses the patented 2-electrode “Corrater” technique for measuring LPR. The Aquamate was selected because of its low cost (about \$1,400) and its ease of operation. We believe such an instrument would be readily acceptable.

The Aquamate instrument directly outputs corrosion rate, solution conductivity (reciprocal of resistivity), and “corrosion pitting index”. A single set of readings takes approximately 5 minutes. According to RCS, the corrosion pitting index was derived empirically as part of the Corrater/Aquamate development. It is a general indication of whether the direct-read corrosion rate would be more indicative of pitting corrosion or uniform corrosion and addresses one of the concerns mentioned earlier.

Appendix A provides the modified procedure for determination of soil resistivity and corrosion rate developed under this task.

One important aspect of test procedures using LPR is that, because of the applied direct current to determine corrosion rate, the electrodes will experience accelerated corrosion beyond that which would occur naturally just by being exposed to the soil. Extensive repeated use of the same electrodes for different soil samples, without consistent pre-conditioning, would not be appropriate. This is because the corrosion deterioration coupled with the formation of oxides and other films on the sample surface would mask corrosion rates caused solely by the particular soil under test. Recognizing this, our soil box testing has used 1”x1-1/2”x1/4” thick carbon steel electrodes in lieu of the manufacturer’s standard flat stainless steel electrodes at both ends of the 4-electrode soil box. Before each LPR test, the exposed surface of the carbon steel electrodes has been blasted with a glass bead abrasive, rinsed with deionized water and acetone, and then air-dried, which is an acceptable procedure for the controlled laboratory tests. For wide-scale

testing by others if this procedure is adopted, our current thinking is that minor modifications to the soil box and low-cost disposable and standardized electrodes would be the most appropriate. Preconditioning or polishing before each test with emery cloth would be reasonable. These electrodes would be considered a consumable item and replaced when the surface appears to be pitted or could not be adequately reconditioned.

We reported in March 2002 that considerable efforts regarding consistency in soil compaction for soil box resistivity testing has been undertaken over the last few years by ASTM Subcommittee G.01.10.01.02, *Soil Resistivity*. The ASTM work group was revising ASTM Standard No. G57 to include the use of a new 4-electrode resistivity box called the “Chaker compactor” (Victor Chaker was very instrumental in the early phases of this endeavor) that uses a variable load piston and cylinder to reportedly apply a uniform 40 pounds of force throughout the cross-sectional area of the compactor and the soil sample. Similar to some other standard soil boxes, the resistance-to-resistivity conversion factor for the Chaker compactor is unity.

We were able to obtain a pre-production version of the Chaker compactor for use as part of the NCHRP research. We performed some comparative resistivity tests using the standard soil box and the Chaker compactor and we found only subtle differences in measured resistivity between the two devices.

While the planned revision to ASTM Standard G57 initially included the Chaker compactor as an alternate to the standard 4-electrode soil box that has been part of this standard for several years, that no longer appears to be the case. The working group meeting held in Florida in November 2003 revealed that the members were in the process of moving toward a 2-electrode soil box.

Task 5 – Development of Field Corrosion Rate Procedures/Instrumentation

Two prototype cylinder probes were completed during the third quarter of 2003 (See Figures 27 and 28). Initial tests were performed to verify that silicone sealant would prevent moisture entry at each ring joint or into the center of the probe. All corrosion activity must be constrained to the external surface of the rings rather than any corrosion across the rings’ cross sectional area. The probes showed no water or moisture entry after immersion testing over a 10 day period. This effort resulted in some minor improvements in the upcoming fabrication of additional probes.

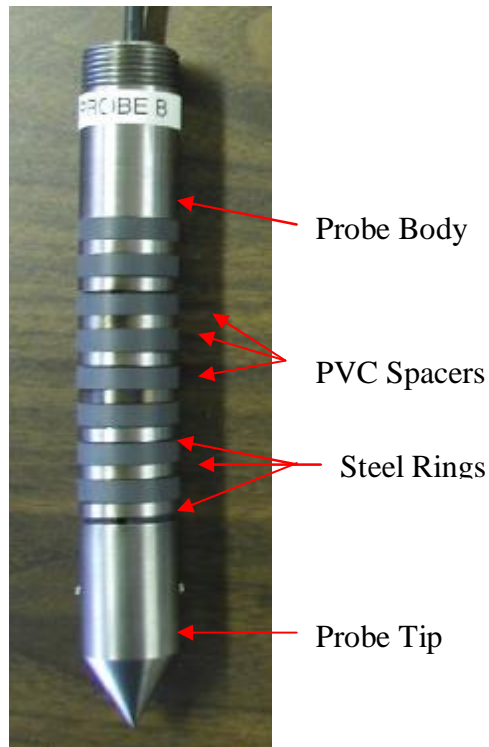


Figure 27 – Cylinder Probe B



Figure 28 – Cylinder Probe B with Tip Removed

The cylinder probes were tested in various solutions with different resistivities to determine what geometric factor or multiplier is required to accurately measure resistivity. After using a 4-electrode soil box and the Nilsson Model 400 resistance meter to measure the resistivity of a solution, the probe was then placed into the same solution so that it could be used to make a “four-pin” measurement of the resistivity with the Nilsson meter. This was done for each probe to determine the similarity of their factors. The soil box measured resistivity was

divided by the probe measured resistivity to establish this factor. The resultant plot yielded the factor for the cylinder probes and the disposable probe which are discussed in detail below (See Figure 29).

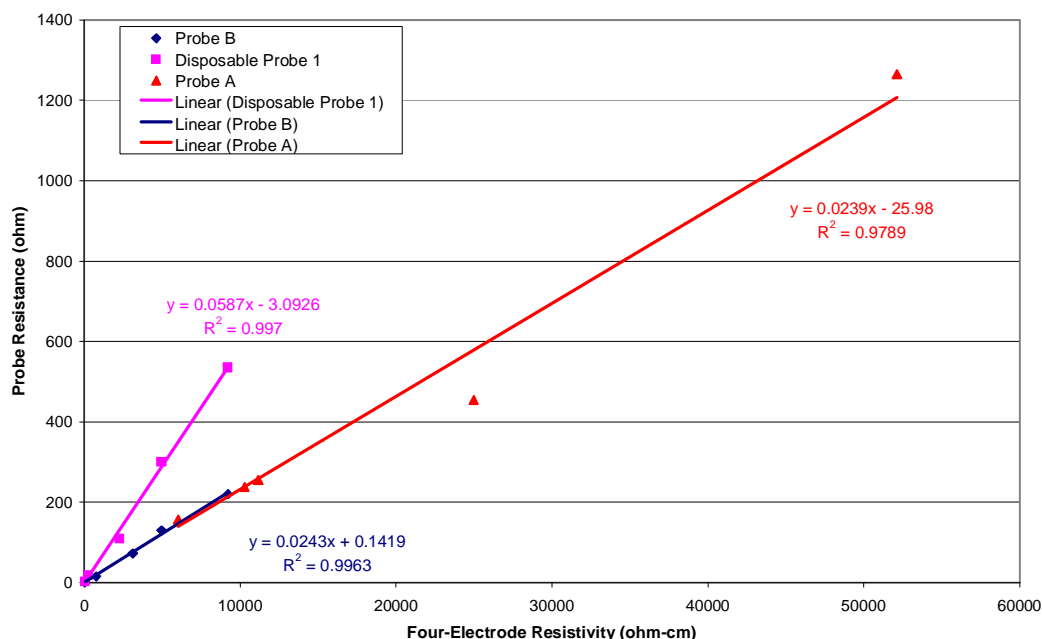


Figure 29 – Comparison of Resistivity Measurements

Laboratory testing was conducted into the comparison of linear polarization resistance (LPR) data obtained using the cylinder probes in various solutions measured with the Gamry instrument and the Aquamate unit. During the initial testing and debugging phase, the corrosion rate of the cylinder probe (Probe B) was found to be in good agreement when measured with the Gamry or Aquamate. Representative of the data, the corrosion rate of the Probe B in tapwater was measured at 14.8 mils per year (mpy) with the Gamry and 17.9 mpy with the Aquamate, which is good order of magnitude agreement. Similarly with the prototype disposable probe, the measured corrosion rate in tapwater of 1.77 mpy with the Gamry and 1.68 mpy with the Aquamate is good order of magnitude agreement. The order of magnitude difference between disposable probe and cylinder probe is likely due to repeated testing performed on the disposable probe without reconditioning the heavily oxidized surface.

In the September 2003 quarterly report, a modification was made to our long-term exposure test plan. A concern arose about the realistic ability of extracting the vertical columns without losing the weight loss coupons. We decided to install weight loss coupons at 2 depths, 4 feet and 8 feet, in direct burial trenches with various extraction times. In order to develop a proper statistical analysis of the weight loss data, 7 coupons of each material will be placed into each time period quadrant at each depth. We will install 56 coupons of each material or a total of 224 samples at each burial site.

So that the weight-loss data can be correlated to the corrosion rate measurements, we have designed and fabricated low-cost, disposable probes that will also be placed in the direct burial trenches for each time period quadrant at each depth. In addition, as the program evolved, we also became concerned about the ability of the cylinder probe to provide longer-term approximation of corrosion rate based on a one-time measurement. We felt there might be more value in discerning corrosion rate by a DOT crew if they could leave a probe buried for a long(er) duration. As discussed with respect to the soil box, the readings that one obtains immediately upon burial may not be the same as longer-term data. Over a longer-term corrosion films may build up which may drastically alter the corrosion rate. While the price of the cylinder probe (about \$1,500) seemed reasonable as a repeated-use DOT test instrument, it would probably be too expensive to warrant longer term burial in the soil to accumulate more meaningful corrosion rate data. Thus we designed a low-cost (<\$150) probe that could be installed in the same hole made upon removal of the test probe that may be left for long term burial. We envisioned that a DOT crew could periodically re-visit the site and make a measurement using a standard test instrument (i.e., an Aquamate) and get much better data on site corrosivity.

Our original disposable probe is presented in Figures 30 and 31 while the burial site layout is presented in Figures E3 and E4. The test sites had the cylinder probes driven into undisturbed soil at the bottom of drilled wells (25 and 30 feet) and left in place over the entire duration. LPR and resistivity data at this depth were gathered over a period of time. On the driven cylinder probes we are using four of the steel rings to measure LPR and resistivity. We will use the remaining steel rings per probe to measure weight loss at depth after extraction. We have also added 2 disposable probes to be installed down-hole with each cylinder probe so that LPR and resistivity data can be obtained using a similar probe as that used in the direct burial trenches. This low-cost scope enhancement is presented in Figure E5.

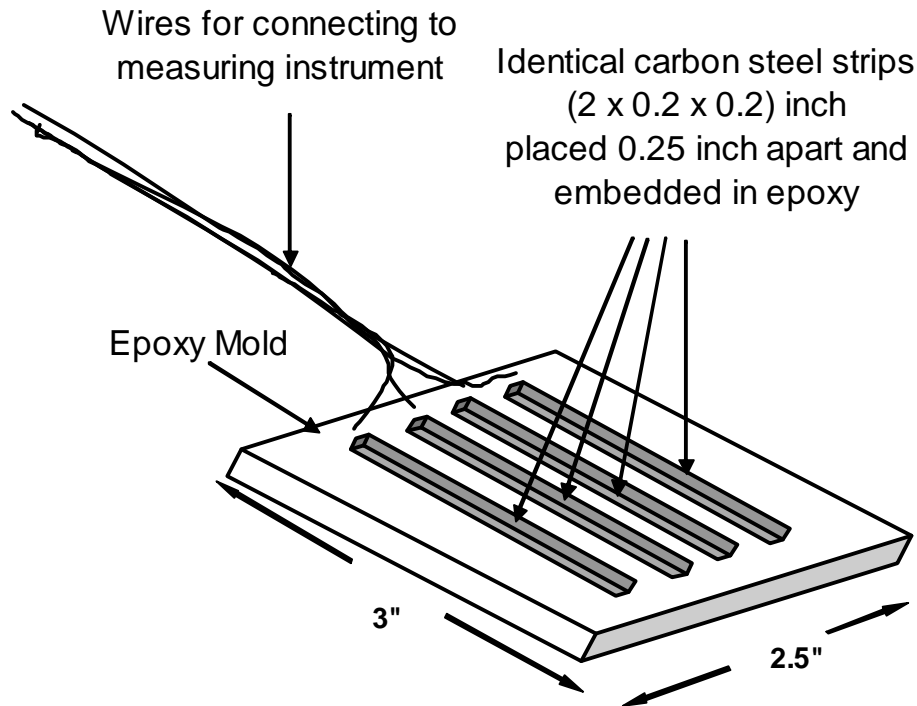


Figure 30 – Original Disposable Probe

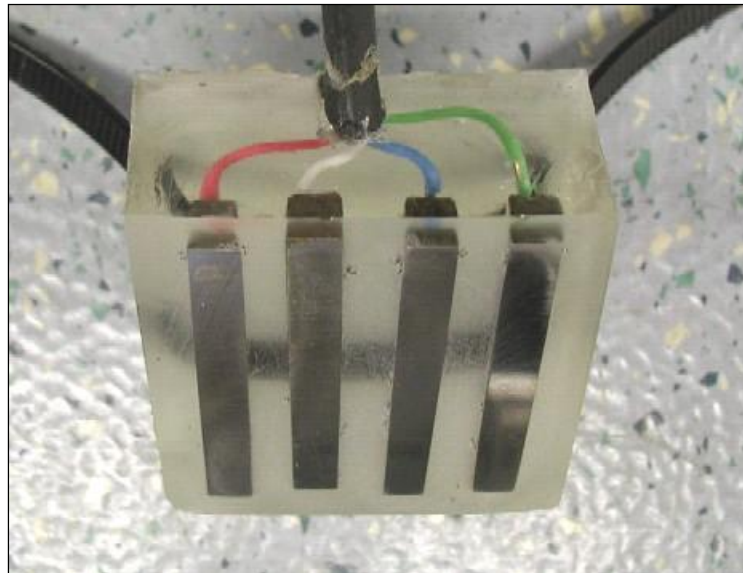


Figure 31 – Original Disposable Probe

The disposable probes were used to obtain both LPR data and soil resistivity data at different depths over an extended period of time. This information was then compared to the adjacent weight-loss coupons. In the long run this entire data set will allow us to correlate instantaneous LPR data (corrosion rate) at depth (25 and 30 feet) to extrapolated LPR data based on actual weight-loss samples. An instantaneous measurement of resistivity and corrosion rate can be used to project the actual long-term corrosion rate.

In December 2003, one of the prototype cylinder probes, Probe A, was installed at our test site in Sea Isle City, New Jersey, at a depth of 5 feet to evaluate the probe's ruggedness and durability. The site is typified by a shallow saltwater line (approximately 3 feet) and low resistivity sandy soil. During December 2003 and January 2004, we monitored Probe A on a regular basis to obtain soil resistivity and LPR data. LPR data was obtained using the Aquamate unit and checked with the Gamry electrochemical instrument. Soil resistivity data was obtained using the Aquamate and the Nilsson meter.

The combination probe initially introduced under Phase I included LPR corrosion rate and soil resistivity as the primary measurements. As part of our ongoing probe development for use with the drilling operations, we have made modifications to allow the addition of a pH sensor.

A commonly used field practice to determine the approximate pH of soil involves measuring the potential between an antimony electrode and copper sulfate electrode while both are in contact with the soil being tested. The antimony electrode is a commercially available item. Based on this technique, we modified the cylinder probe to accommodate a pH sensor made from a piece of antimony rod and a sintered silver chloride reference electrode. The modified cylinder probe or the Multipurpose Soil Probe (MSP) is shown in Figures E6 and E11 of Appendix E while the modified disposable probe or the Disposable Multipurpose Soil Probe (DMSP) is shown in Figures E7 and E11.

In order to verify this technique, we plotted the pH versus potential for numerous electrode combinations. We started with the commercially available Agra Antimony electrode coupled to a copper sulfate electrode and measured the potential between them in three standard buffer solutions. Our electrode combinations included:

Agra antimony to standard copper sulfate;
Agra antimony to standard silver chloride;
Agra antimony to sintered silver chloride;
OCRC antimony rod to standard copper sulfate;
OCRC antimony rod to standard silver chloride; and finally
OCRC antimony rod to sintered silver chloride.

We prepared a plot of two of the data sets. The first data set was the Agra antimony to standard copper sulfate which acted as the control. The second data set was the OCRC antimony rod to sintered silver chloride which is used in the Multipurpose Soil Probes. This information was compared to the scale inscribed on the side of the Agra Antimony electrode and seems to have good correlation (See Figure 32).

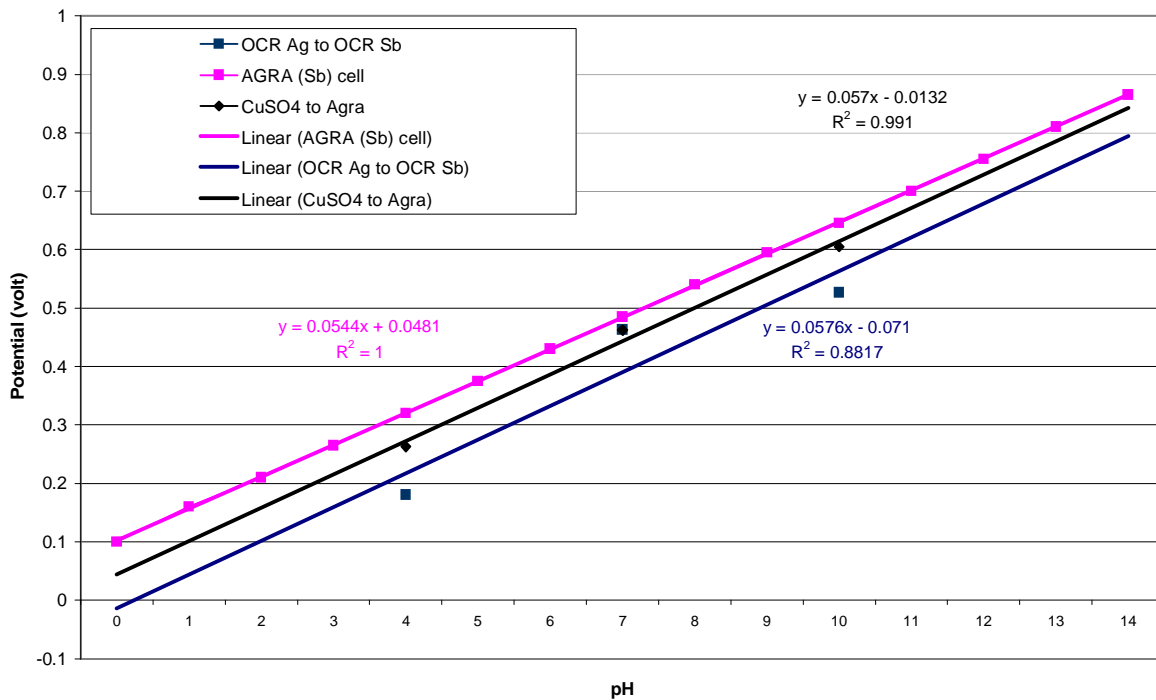


Figure 32 – pH Versus Potential

To summarize, the MSP and the DMSP are for in-situ measurement of resistivity, corrosion rate and pH. The resistivity measurement is made using the four-electrode method with the Nilsson meter. The corrosion rate is determined through measurement of LPR on two electrodes using the Aquamate meter. The pH is determined by measuring the potential between the silver chloride electrode and the antimony electrode and plotting on the pH versus potential diagram.

The remaining three steel rings on the MSP probe will be used to measure weight loss at depth after extraction. This will serve as direct confirmation of the measured corrosion rate at each site. Once confidence is established in this procedure, future probes will not remain in place for extended periods of time. The probes will be used to obtain instantaneous measurements that can be extrapolated to provide the long term corrosion rate for a specific site.

Task 6 – Installation and Initial Testing of Long Term Exposure Materials

Our original cylinder probe, Probe A was removed from the Sea Isle City test site in January 2004 and along with Probe B installed at our preliminary long-term exposure test site in Medina, Ohio (approximately 25 miles south of Cleveland, OH) at a depth of 30 feet. This installation work was performed during the week of January 26, 2004.

A well drilling rig with a standard auger (a hollow-stem auger was not required) was used to reach a depth of 28 - 29 feet. Since the cylinder probes will remain in place for an extended period, they were attached to drill pipe and then pushed the final 18 inches into undisturbed soil. We also attached two of our disposable probes just above each cylinder probe so that linear polarization resistance (LPR) and soil resistivity data could be obtained using a probe similar to that used in the direct burial trenches. All wires from the wells were brought up into NEMA 4X Terminal Boxes. See Figures E17. After drilling, the hole was partially backfilled with soil obtained during the drilling operations. At the three month inspection, it was observed that the hole had naturally collapsed.

A modification was made to our long-term exposure test plan after a concern arose about the realistic ability of extracting the vertical columns without losing the weight-loss coupons. We decided to install weight-loss coupons at 2 depths, 4 feet and 8 feet, in direct burial trenches with various extraction times. In order to develop a proper statistical analysis of the weight-loss data, 7 coupons of each material are being placed into each time period quadrant at each depth. We are installing 56 coupons of each material or a total of 224 samples (4 Materials X 7 Coupons X 2 Depths X 4 Removals) at each burial site. The planned duration of the coupon exposure program is approximately 36 months.

In addition to the weight-loss coupons, disposable probes were also installed in the direct burial trenches. The locations were noted to facilitate the various extraction times. All weight-loss coupons were cleaned, weighed and stored in a moisture-free environment prior to arriving on site. Coupons were obtained for the following materials: 1010 cold rolled steel, galvanized steel, copper and ductile iron. The coupons were covered first with soil and then with a geotextile material prior to complete backfill. The geotextile material will allow water to penetrate to the coupons but will alert the backhoe operator of their close proximity during the scheduled retrieval operations. The test leads for the disposable probes (2 in each trench) were brought up into Terminal Boxes and mounted to facilitate future measurements of LPR and soil resistivity.

Once all probes and coupons were installed, initial LPR and soil resistivity data were collected.

The remaining four installations were accomplished in a similar manner to Medina, OH with the exception of Sea Isle City, NJ where a high water table prevented digging trenches to a depth of 8 feet.

Task 7 – Evaluation of pH Measurement Techniques and Recommendations

We have performed a review of the four methods presented below.

AASHTO Method T-289 – Determining pH of Soil for Use in Corrosion Testing.

ASTM G51 – Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing.

ASTM D4972 – Test Method for pH of Soils.

Corrpro in-house procedures, which are a derivative of ASTM D4972.

We have summarized our review in Table 8 (Appendix B). For the purposes of Task 7 of the NCHRP-2 Work Plan, the existing Corrpro Companies, Inc. Soil Tests Laboratory Procedures Manual, pH Measurement, is recommended for use (Presented in Appendix B). The Corrpro method strikes a balance among the two ASTM standards and the AASHTO method. For example, ASTM D4972 and AASHTO 289 specify that the soil sample should be dried, and then rehydrated to a 1:1 soil-water ratio by mass. The ASTM G51 standard states that samples should be measured “as-is”. Corrpro’s method entails measuring the moisture content of the sample, then adding water to bring the water/soil mass ratio to 1:1, thereby minimizing alteration of the sample as well as erroneous readings due to soil particle-probe surface contact. Other main point comparisons can be found in Table 8. For the majority of issues, the Corrpro method merges the other 3 standards for a more accurate and user friendly approach to pH measurement. Analysis of the pH data is discussed under Task 10 as it relates to the in-situ corrosion measurements made during the visits.

Task 8 – Further Evaluation of Other Issued from Phase I

The Phase I research and feedback from the panel identified specific issues that require further exploration. A few of these issues have been investigated and are presented below.

Laboratory Investigations

- 2-electrode (AASHTO) vs. 4-electrode (ASTM) laboratory soil resistivity measurements, mainly using standard “open top” soil boxes. Controlled tests using known resistivity solutions to confirm soil box resistivity conversion factors, mainly for the AASHTO 2-electrode and the ASTM 4-electrode open-top soil boxes, as well as the ASTM Chaker compactor.

This task has been completed based on the data provided by our Houston laboratory. The soil resistivity was measured using both a 2-electrode and a 4-electrode soil box. The data presented in Appendix C was analyzed and is presented in Figure 33. This chart shows that there is a good correlation between the data.

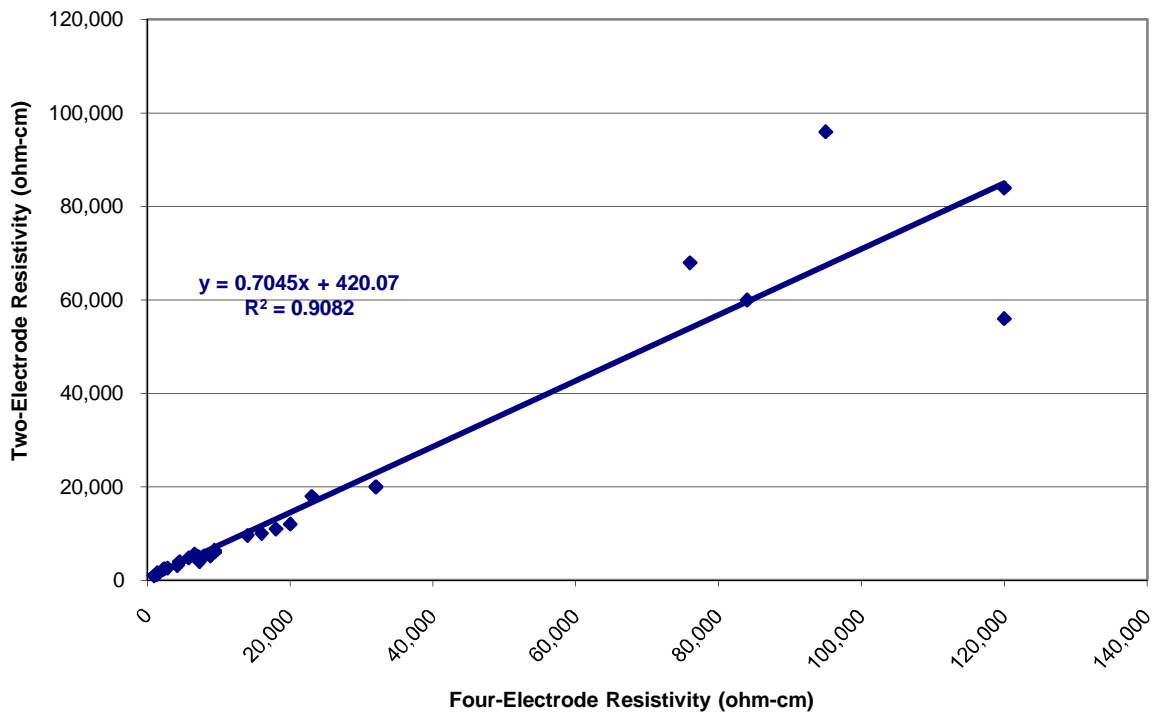


Figure 33 – Four Electrode versus Two Electrode Soil Resistivity

- Further evaluation of issues relating to compaction for the soil box resistivity measurements. This will include further exploration of the Chaker compactor concept. It will also include the possible use of a 3-inch diameter by 7.9-inch (20-centimeter) long test cylinder with the capability to compress the soil sample under test, as has been recommended by one of the panel members.

Testing with the Chaker compactor was suspended after attending the ASTM Standard G57 meeting that was held in Florida in November 2003. It appears that the working group was moving away from considering the Chaker compactor in favor of a 2-electrode soil box.

Task 9 – Phase II Interim Report

Submitted to the board November 2004.

Task 10 – Evaluation of Long Term Exposure Materials

Within 1.5 years after installation, mass loss coupons and disposable probes were recovered from one 4-foot deep trench and one 8-foot deep trench at each exposure site. Resistivity, LPR, and pH measurements were taken prior to extraction using the method detailed in Appendix G. Three trenches at each depth were left undisturbed. The samples in these undisturbed trenches can be recovered at later dates as deemed appropriate in order to supplement the relatively short term data collected already. The 25-foot and 30-foot deep wells

were also left undisturbed. The following analysis focuses on data taken from the 4-foot and 8-foot trenches, as there are mass loss measurements with which to compare LPR, resistivity and pH readings.

Mass Loss Analysis

Following removal of test samples, metal coupons were cleaned of all corrosion products and weighed to determine mass loss as a result of corrosion. Utilizing the surface area of the samples, the density of the base metal and the duration of exposure a corrosion penetration rate (corrosion rate) were determined by Equation 1. Please see Appendix F for charts and tables regarding Task 10. Table F1 presents the average corrosion rate (MPY) and the standard deviation for all test sites and metal alloys.

$$\text{Equation 1: } MPY = \frac{394 \times \text{massloss}(\text{grams})}{\text{density}(\frac{\text{g}}{\text{cm}^3}) \times \text{area}(\text{cm}^2) \times \text{time}(\text{years})}$$

This data demonstrates the variability of corrosion of metal samples exposed to a natural environment. These results are for laboratory specimens prepared to close tolerances and weighed to 0.1-mg accuracy. The high variability of these samples indicates that results obtained on buried structures would be expected to experience similar (if not greater) variability. This further suggests that any test used to predict long-term corrosion rates would provide a general indication of severity of the environment, but due to the variability of the mass loss and LPR data precise prediction is likely not possible.

Casual observation of the data presented in Table F1 suggests that overall the Cold Rolled Steel samples have the least variation. To determine which material(s) have the most repeatable results the ratio of standard deviation and average corrosion rate was determined and presented as a percentage in Table F2. Those having the lowest percentage have the least variation. This confirmed that the Cold Rolled Steel samples had the lowest variation between measurements at both 4-foot and 8-foot depths. Despite having the lowest overall variation at 21% of its mean, at a 95% confidence interval (assuming a normal distribution) the expected variation is 41%, demonstrating the variability of the measurement. Having the lowest variation and being the same metal of manufacture as the electrochemical probes, the steel samples will be compared to these test results.

Electrochemical Probe Analysis

pH and Resistivity

Soil pH and resistivity were collected upon installation and just prior to extraction at each test site using the DSMP probes as well as using laboratory (installation only) methods. These measurements were collected as they are those most commonly used in determining corrosivity of soil. Using linear programming techniques, an attempt was made to determine if there was a linear relationship between the pH and resistivity measurements with the mass loss corrosion rates. Tables F3 and F4 show these results using the DSMP and laboratory data, respectively.

These tables show that while for some locations corrosion rates could be readily predicted or reasonably approximated, most locations corrosion rates could not be predicted. Further, the predicted corrosion rates did not have a similar trend as the actual corrosion rates. The development of a linear relationship model to predict corrosion from pH and resistivity is not possible with the current data set. The limiting factor(s) are indeterminate with this data set as they may be due to the variability of the corrosion rate data, the soil chemistry data or a combination thereof.

LPR Corrosion Rate

Using the DSMP and cylinder probes linear polarization resistance (LPR) measurements were made to electrochemically determine the corrosion rate of the in-situ soil environments. Using an Aquamate, the corrosion rate measurement of the steel probes was readily made upon installation and just prior to removal. These rates were compared to mass loss corrosion rates to determine their correlation. Figures F3 through F12 show these comparisons for each site and depth. Figure F13 shows a comparison of average mass loss and Aquamate corrosion rate data.

Figures F3 through F12 demonstrated that at most of the sites and depths, the Aquamate measurements were more variable than the mass loss data. Figure F13 shows that there is a similar trend in the average mass loss and Aquamate measurements. However, their variability as already demonstrated and low r-square value (goodness of fit) suggest that this is not a significant relationship.

This increased variability is of concern, in that a finalized field technique would likely rely on a few (less than 5) measurements possibly during a one-time availability of access to the site to determine corrosion rates in the soil environment. With a measurement that is naturally variable and technique that introduces additional variation, it is highly improbable to predict a long-term corrosion rate with any accuracy or repeatability.

Casual observation of Figures F3 through F12 did demonstrate that with a few exceptions most of the Aquamate derived data was close to or above the range of corrosion rates by mass loss. This led to the hypothesis that perhaps Aquamate data can be used as a conservative estimate of corrosion rate in soil. To investigate this, the Aquamate data was analyzed as a normally distributed data set. The distribution of this data set was compared to the minimum and maximum mass loss corrosion rate values to determine the probability that the data set contained values above and below the minimum and maximum values as well as between the minimum and maximum values. Tables F5 and F6 show the analysis for the initial Aquamate and removal Aquamate measurements, respectively.

The tables show that with the exception of the California 4-foot site, the Illinois 4-foot site, the Illinois 8-foot site (removal only) and the Medina 8-foot site (removal only) the measurements have a 64% or higher probability of being above the minimum mass loss corrosion rate value and a 60% or higher probability of being above the maximum mass loss corrosion rate value. Therefore, 60% of the time the measurement made will provide a corrosion rate higher than the actual corrosion rate (for nominally one year of burial). While not practical as a design tool (as several of the individual Aquamate measurements exceed 100-MPY), for a

sensitive application this corrosion rate measurement could be used as an initial screening tool. For example, if a critical installation required the corrosion rate not to exceed 3-MPY and measurements were 2.5-MPY or less you would be 60% confident that your rate would be within your threshold. Conversely, if measurements were made above 3-MPY, you would be uncertain if the soil corrosivity was within tolerances.

The mass loss corrosion rates were also compared to laboratory measurements of corrosion rates using the Task 4 procedure. Figure F14 shows the relationship between average mass loss and LPR corrosion rate measurements made in a soil box using the Aquamate. This chart shows an inverse relationship between the average mass loss and soil box corrosion rate measurements. However, the r-square value of this relationship is also low, suggesting that it is not significant. Removal of the outlier data point (namely 0.42-MPY soil box corrosion rate), has only a minimal effect on the r-square as seen in Figure F15. This lack of correlation indicates that laboratory measurements would not be able to reliably predict field corrosion rates.

The use of a direct measurement technique for determining corrosivity of a soil may not be a viable stand-alone method to evaluate long-term performance. However, review of available literature on soil corrosivity identified past work and currently used methods to provide a corrosion rating based on measured parameters (resistivity, pH, redox potential, etc.). A total of seven (7) techniques were reviewed, with four (4) found to use parameters currently being measured as part of this study. Table F7 provides a summary of the methods reviewed, their key parameters used to determine corrosivity and whether or not it was found to be applicable to the current project.

As these methods use descriptive terms (i.e., non-corrosive, severely corrosive, etc.) they could not be conveniently plotted or compared to the mass loss corrosion data. Arbitrarily the descriptive terms were assigned values 0 to 7 as shown in Table F8. Table F9 shows the rankings obtained by test method based on the soil chemistry data available. The severity ratings (Table F7) and the corrosion rate data obtained (mass loss and Aquamate) are plotted in Figure F16. This was limited to the 4-foot and 8-foot depths so that comparisons could be made between corrosivity (as determined by the various methods), Aquamate and mass loss corrosion rates.

Figure F16 compares soil corrosivity amongst the various rating methods and compares those with the corrosion rate measurements made (overall averages by depth). Of the methods shown, the Federal Highway Administration (FHWA) and German Gas and Water Works (German) appear to agree most closely with the mass loss average corrosion rate (see Appendix D). Both of these are subjective ratings, with a 6- or 4-tiered (respectively) qualitative ranking provided. The FHWA method predicts solely on resistivity, whereas the German method uses most of the soil parameters measured/available as well as:

- Water Level,
- Carbonate,
- Chloride,
- Sulfate and
- Cinder/Coke.

This plot also shows that the average Aquamate initial corrosion rate (AQ Initial) data is similar to the mass loss data. However, as previously discussed this data is highly variable and without repeatability between measurements it cannot be determined if the LPR method would provide consistently low, high or as-observed corrosion rates (even within the variations observed of the steel mass loss data).

Perhaps a statistically large (>30) set of measurements may allow for the use of an average value to predict corrosion rates. An analysis of the SIC data set (approximately 95 measurements made over two years) showed that if all data points are used large average corrosion rates were observed (Figure F17). Eliminating unusually high corrosion rates (found to be >10MPY) reduced the average corrosion rate. However, in a field application a tester would be uncertain which values were erroneous. These measurements are instantaneous corrosion rates over a large period of time, therefore, they may represent fluctuations in the local environment not representative of long-term conditions. To determine if a statistically significant data set would allow for improved prediction of corrosion rates, a minimum of 30 measurements per site per location and depth should be made prior to extractions or as site visits are available.

Task 11 – Phase III Interim Report

Incorporated into Final Report.

Task 12 – Round Robin Testing / Field Trials

Round-robin testing and field trials were to be completed following the demonstration of a viable test methodology for determining corrosivity of the soil environments with improved accuracy. Minimal responses were received from state DOTs and others willing to participate in this phase. Based on the results of this program the methods employed did not result in an improved methodology for determining soil corrosivity.

The methods employed demonstrated that the environments can be variable as evaluated using laboratory prepared test samples and test methods. The field techniques employed demonstrated that general trends in corrosivity and corrosion rates can be observed, but that the data is highly variable and a large sample set is needed. Finally, the program evaluated the mass loss corrosion rate data and compared that to current industry techniques. This identified two techniques which used laboratory soil data and achieved corrosivity rankings similar to that of the corrosion rates. However, as these are industry used techniques independent round-robin testing should not be required, as it is assumed the governing bodies of these methods have already conducted such evaluations. If through follow-on efforts an improved technique requiring round-robin testing is identified/developed, Corrpro would be willing to participate in this testing.

CHAPTER 3

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

Objective: Development of recommended test methods for practical laboratory and field measurements of soil resistivity and pH.

Conclusion:

1. The probe design and measurement techniques investigated did demonstrate an ability to make resistivity, pH and corrosion measurements in soil, although, the correlation of these measurements to mass-loss determine corrosion rates was minimal.
2. There exists two (2) ratings that provide qualitative ratings that trended closely with the quantitative mass loss measurements for steel at four (4) and eight (8) foot depths.
 - a. Federal Highway Administration (FHWA)
 - b. German Gas and Water Works (German)
3. Laboratory testing of the soils using the modified Corrpro method did provide data that when used with the FHWA and German test methods reasonably approximated corrosivity of the soil environments investigated.

Objective: Development of correlation factors to compare the recommended methods with previously existing methods.

Conclusion: Correlation of data taken from field measurements had minimal correlation with actual corrosion as measured from mass loss coupons. Correlating the project methods as-is to existing methods would be of limited utility.

Objective: Correlation of soil resistivity and pH measurements with soil corrosivity, including the development of practical guidelines to assist in the prediction of the rate of corrosion in buried structures.

Conclusion: Further measurements and investigation would be required to determine if a direct-measurement of corrosion rate can be made to reliably predict corrosivity.

- a. Primarily these measurements over-stated the corrosion rate of the soil environment.
- b. Use of these estimations would provide an overly-conservative estimation of corrosion rate approximately 60% of the time.

SUGGESTED RESEARCH

1. Continuation of data collection

- 1.1. Continue monitoring exposures and plan future removals. The NCHRP should consider continuing the monitoring of the exposures and plan future removals through minimally 10 years of total exposure. This is expected to allow for fully developed corrosion of the metal alloys buried at all depths. Furthermore, by performing corrosion monitoring at regular intervals (not less than yearly) a statistically large dataset can be developed for each site and depth, allowing detailed analysis. A total of 30 measurements per location (site and depth) and visit should be made for statistical analysis.
- 1.2. Monitor samples using alternative electrochemical techniques. The Aquamate meter was selected as it is a ruggedized field instrument for performing LPR measurements. To verify the results obtained over longer exposures laboratory electrochemistry equipment could be adapted for field use. These higher precision instruments (while not practical for field use) can verify the measurements made by the Aquamate.
- 1.3. Perform sample excavations at nominally five (5) and 10 years. Removals at these intervals will allow for the measurement of corrosion rates by mass-loss for verification with electrochemical data. This will also demonstrate the long-term robustness of the probes.
- 1.4. At 20-25 years of total exposure remove the remaining samples. This will allow for a true measurement of long-term corrosion rates of the alloys in these soil environments and provide verification of any measurements made.

2. Alternative Methods

- 2.1. Much of the variability in the corrosion data may be caused by corrosion and/or damage to the electrode surfaces. Investigation of alternative electrode materials and how they affect LPR measurements could help to develop a more robust probe that may provide more consistent, applicable readings of the underground environment.
- 2.2. Measurements of pH taken from field probes were largely ineffective. A more rigorous lab program to determine an effective measurement apparatus and technique for determining in-situ pH is needed in order to incorporate pH into a predictive model.
- 2.3. Laboratory measurements of corrosion rate utilizing the Miller soil box and steel coupons that are resurfaced after every measurement is time consuming and labor intensive. A more user friendly approach would be advantageous in establishing a standard practice based on this method.

REFERENCES

1. M. Romanoff, Underground Corrosion, National Bureau of Standards Circular 579, April 1957
2. J.B. Bushman, et al, "Soil Side Durability of Corrugated Steel Pipe", Final Report prepared by Corpro Companies, Inc. to the National Corrugated Steel Pipe Association, Washington, D.C., March 1991
3. J.L. Beaton and R.F. Stratfull, "Field Test for Estimating Service Life of Corrugated Metal Pipe Culverts", TRB Proceedings, Vol. 41, 1962, p. 255
4. R.A. King, "A Review of Soil Corrosiveness with Particular Reference to Reinforced Earth", Transport and Road Research Lab., Crowthorne, England, 1977
5. ASTM G 158, "Standard Guide for Three Methods of Assessing Buried Steel Tanks"
6. "Effect of Environmental Factors on Corrosion Induced Deterioration of Reinforced Concrete Bridge Structures," N. Thompson et.al. , paper No. 4, Corrosion 95, National Association of Corrosion Engineers, Houston, TX
7. J. Ellor, et al "An Investigation of Water Treatments for Mitigating Sulfide-Related Corrosion of Copper Alloy Condenser Tubes," paper 225, Corrosion 86, National Association of Corrosion Engineers, Houston, TX
8. FHWA Final Technical Report, "Characterization of the Environment," Fall 1999, DTFH61-92-C-00083
9. M. Romanoff, Underground Corrosion, National Bureau of Standards Circular 579, April 1957
10. N.D. Tomashov and Y.N. Mikhailovsky, "Corrosivity of Soil", *Corrosion*, Vol. 15, pp. 77t to 82t
11. National Bureau of Standards, "Study of Causes and Effects of Underground Corrosion", *Journal AWWA*, Dec. 1958, pp. 1581 to 1588
12. G.N. Scott, "*The Distribution of Soil Conductivities and Some Consequences*", *Corrosion*, August 1958, pp. 369t - 400t
13. G.N. Scott, "*A Theory for the Probability Distribution of Soil Conductivity*", *Corrosion*, Vol. 18, July 1962, pp. 215t - 252t
14. Palmer, J.D., "Soil Resistivity - Measurement and Analysis", *Materials Performance*, January 1974, pp. 41- 46
15. **Corrosion Engineering**, M. Fontana, McGraw-Hill, Inc. N.Y., N.Y., 1986, pp. 192-194
16. **Electrochemical Techniques for Corrosion Engineering**, R. Baboian (ed.), National Association of Corrosion Engineers, Houston, TX 1986
17. **Advances in Corrosion Protection by Organic Coatings**, Volume 89-13, The Electrochemical Society, Pennington, NJ 1989, pp. 373-394
18. private, CONFIDENTIAL, internal Corpro Correspondence
19. F. Wenner, "A Method of Measuring Earth Resistivity", Scientific Papers of the Bureau of Standards No. 258, October 11, 1915, Department of Commerce, Washington, DC
20. H.H. Uhlig and R.W. Revie, **Corrosion and Corrosion Control, 3rd Ed.**, John Wiley & Sons, NY, 1985, p. 424
21. Shreier, Corrosion, Vol. 2, John Wiley & Sons, New York, 1972, pp. 11:108
22. M.J. Wilmott, et al, "Soil Probe Measures Several Properties to Predict Corrosion", *Oil & Gas Journal*, April 3, 1995, pp. 54 – 58
23. ASTM, American Society for Testing and Materials, West Conshohocken, PA
24. AASHTO, American Association of State Highway and Transportation Officials, Washington, DC
25. California Department of Transportation, Division of New Technology and Materials Research, Sacramento, CA
26. ASTM G-57 "Standard test method for field measurement of soil resistivity using the Wenner four-electrode method," 1995, American Society for Testing and Materials, West Conshohocken, PA.
27. AASHTO T-288 "Determining minimum laboratory soil resistivity," 1996, American Association of State Highway Transportation Officials, Washington, DC.
28. California Test 643 "Method for estimating the service life of steel culverts," California Department of Transportation, Sacramento, CA, 1993.

29. A. L. Page, R.H. Miller, and D.R. Ckeeney "Methods for Soil Analysis," American Society of Agronomy, 1982.
30. M.J. Wilmott, et al, "Soil Probe Measures Several Properties to Predict Corrosion", Oil & Gas Journal, April 3, 1995, pp. 54 – 58.
31. F. Wenner, "A Method of Measuring Earth Resistivity", Scientific Papers of the Bureau of Standards No. 258, October 11, 1915, Department of Commerce, Washington, DC.
32. H.H. Uhlig and R.W. Revie, Corrosion and Corrosion Control, 3rd Ed., John Wiley & Sons, NY, 1985, p. 424.
33. H. E. Barnes, "Soil Investigation Employing a New Method of Layer Value Determination for Earth Resistivity Interpretation," National Academy of Sciences NRC Bulletin No. 65, 1952, Washington, DC.
34. ASTM G-59, "Practice for Conducting Potentiodynamic Polarization Resistance Measurements," 1995, American Society for Testing and Materials, West Conshohocken, PA.
35. Keller, G. V., Frischknecht, F. C., "Electrical Methods in Geophysical Prospecting," Pergamon Press, 1966.
36. Wait, J. R., "A Note on the Electromagnetic Response of a Stratified Earth," Geophysics, V. 27, (1962), pp 382-85.
37. McNeill, J. D., "Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers," Technical Note No. 6, (October 1980) Geonics Ltd., Mississauga, Ontario, Canada.

APPENDIX A

LABORATORY METHODS FOR RESISTIVITY AND CORROSION RATE

MODIFIED PROCEDURE FOR DETERMINATION OF SOIL RESISTIVITY AND CORROSION RATE

Corrpro Companies, Inc.

1. SCOPE

- 1.1** This procedure describes methods for the evaluation of soil resistance and corrosion rate using a standard Miller soil box (ASTM G57). The actual equipment and procedures are discussed below.

2. REFERENCED DOCUMENTS

2.1 ASTM Standards:

G57-95a(2001) Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method

PART I

INITIAL PREPARATION OF TEST SAMPLES

3. SCOPE

- 3.1** The following describes the method for preparing soil and corrosion samples to be used for resistivity and corrosion rate testing.

4. APPARATUS

- 4.1** Any non-metallic vessel of suitable size for thorough mixing of the soil sample. See 5.1 for minimum size.
- 4.2** De-ionized Water
- 4.3** *Corrosion Samples* – 1.5" x 1" x 1/4" carbon steel coupons (2 per test)
- 4.4** Drill with No. 29 Bit
- 4.5** 8/32" Bottoming Tap
- 4.6** Acetone
- 4.7** Two-part epoxy adhesive
- 4.8** Abrasive Blast Cabinet with 120 grit Glass Bead Abrasive
- 4.9** 8/32" x 1/2" machine screws with nuts (x2)
- 4.10** Miller Soil Box

5. SAMPLE SIZE

- 5.1** The volume of soil material required to perform the test is approximately 800mL

6. INITIAL PREPARATION OF TEST SAMPLES

SOIL SAMPLES

- 6.1** Soil is prepared in accordance with ASTM G57. A comprehensive description of this procedure follows.
 - 6.1.1** Place sample into a non-metallic container of suitable size for thorough mixing of your sample size.
 - 6.1.2** Remove large debris/particles (i.e., rocks) from the soil using a No. 8 (2.36mm) sieve.
 - 6.1.3** Using DI or other water prepare test sample for evaluation.
 - 6.1.3.1** For saturated soil testing, mix the soil in this container in a 1:1 ratio (by volume) of DI water to soil.
 - 6.2** Prepare corrosion rate sample in accordance with the procedure below.

CORROSION RATE SAMPLES

- 6.3** Carbon steel is the typical corrosion specimen used for these tests.
 - 6.3.1** Other materials of interest may also be evaluated, although the validity of corrosion rate obtained from these samples has not been confirmed. When using the Aquamate, the multiplier for the corrosion rate will have to be changed to account for the different metal. A detailed procedure for preparing carbon steel corrosion samples follows.
 - 6.3.2** Ensure corrosion samples have a final dimension of 1-1/2" x 1" x 1/4".
 - 6.3.3** Mark the location where the hole in the soil box lines up with the coupon, generally 3/4" across and 1/2" down on the coupon.
 - 6.3.4** Using a No. 29 bit drill approximately 2/3 of the way (1/5") into the 1/4" steel coupon.
 - 6.3.5** The hole is then tapped with an 8/32 thread size so a corresponding machine screw can be fastened into the steel coupon.
 - 6.3.6** The coupon is then blasted with glass bead abrasive (120-grit or finer) to give a clean surface.

- 6.3.7 The corrosion sample is rinsed with DI water and acetone and allowed to dry.
- 6.3.8 Once dry, the coupon edges are coated with a two-part epoxy adhesive to prevent exposure in the measurement circuit.
- 6.3.9 After full cure of the epoxy, the actual surface area of the exposed face of the coupon is measured and used for corrosion rate analysis.
- 6.3.10 The sample is rinsed again in DI water and acetone to remove any contaminants. The sample should only be handled using a clean gloved hand from this point forward.
- 6.3.11 The holes at either the end of the soil box are drilled out to accommodate the 8/32 screw for attaching the steel coupons.
- 6.3.12 When the coupons and box are dry attach the steel coupons to either end by putting the drilled side of the coupon towards the screw hole in the soil box and fastening with the 8/32 machine screw (nut already attached).
- 6.3.13 Use the nut on the machine screw to maintain a snug fit between the coupon and the end of the Miller Soil Box (do not over tighten this screw as it may crack the acrylic box or loosen the steel coupon interrupting electrical contact).

PART II

MEASUREMENT OF SOIL RESISTIVITY

7. SCOPE

- 7.1 This section describes the method for determining soil resistivity.

8. APPARATUS

- 8.1 *Resistance meter* – The Nilsson 400 Soil Resistance meter is recommended for this measurement.
- 8.2 Modified Miller Soil Box (see above steps 6.2 to 6.3.13)
- 8.3 Test leads with banana plug at one end and alligator or similar clip at the other (minimum 4 per test)

9. PROCEDURE

- 9.1 Prior to testing ensure that the soil box and contacts are clean of foreign debris, foreign matter or corrosion before filling with soil.
- 9.2 For non-saturated soil: remove the brass pins from the center of the box before adding soil sample.
- 9.3 Fill the soil box with the “as-is condition” sample, making sure the compaction in the box resembles that of the ground where the sample was obtained.
- 9.4 Using the Nilsson 400 meter in conjunction with the modified Miller soil box, clip the c1 and c2 leads to the screws attached to the removable corrosion samples at the far ends of the soil box.
- 9.5 Attach p1 and p2 leads to the brass pins in the center of the box corresponding to the locations of c1 and c2.
- 9.6 For steps on operating the Nilsson 400 meter, see Corpro Companies, Inc. “*Field Method for Measuring Corrosion Rate in Soils*” Sections 6.4 to 6.7.

PART III

DETERMINATION OF CORROSION RATE

10. SCOPE

- 10.1 This section describes the method for determining the instantaneous corrosion rate of the steel coupons in the soil samples.

11. APPARATUS

- 11.1 *Corrosion rate meter* – The Aquamate CORRATER meter is recommended for this measurement.
- 11.2 Aquamate cable assembly
- 11.3 Modified Miller Soil Box – As-is immediately following the procedure described in Section 9.

12. PROCEDURE

- 12.1 Continuing when the resistivity test ends, remove the p1 and p2 leads from the soil box.
- 12.2 Leave the c1 and c2 leads connected and attach the other end of each lead to one of the clips on the Aquamate cable assembly (one separate connection per lead).
- 12.3 Turn the Aquamate on by pressing the “on” button.

- 12.4 The battery level will be shown; to show that there is still battery life left. The settings on the Aquamate can be adjusted based on the material being measured (see user manual for adjustments).
- 12.5 Press the configure key and use the arrows to scroll through the list, for carbon steel the multiplier should be 1. The multiplier can be modified to account for the different surface area or it can be multiplied after the test is completed, since this will change with every coupon that is a different size.
- 12.6 Make sure the conductivity measurement is turned on.
- 12.7 Press the “MEAS” button to begin measurements once the display reads “Ready to read probe”.
- 12.8 Leave the test undisturbed until the Aquamate results are displayed (it usually takes between five and ten minutes per sample).
- 12.9 When finished, copy down the corrosion rate, conductivity, and imbalance. If the Aquamate turns off, press the “on” button and the “DISPLAY” button to obtain the results from the current test.

PART IV

TREATMENT OF USED CORROSION SAMPLES

13. SCOPE

- 13.1 This section describes the procedure for handling used corrosion samples.

14. APPARATUS

- 14.1 Modified Miller Soil Box with used corrosion samples (after completion of Section 12)
- 14.2 De-ionized Water
- 14.3 Acetone
- 14.4 Abrasive Blast Cabinet with 120 grit Glass Bead Abrasive
- 14.5 8/32” x 1/2” machine screws with nuts (x2)

15. PROCEDURE

- 15.1 Corrosion samples are removed from the Miller Soil Box at the completion of each measurement. If additional measurements are to be made on these samples their surface must be cleaned from all corrosion products and prepared for additional testing in accordance with the procedure below.
- 15.2 The steel coupons are removed from the Miller Soil Box at the completion of each measurement.
- 15.3 Using fresh 120-grit glass bead abrasive blast the surface of the samples.
- 15.4 Rinse the coupons with DI water and acetone and allow to dry.
- 15.5 When the coupons and box are dry re-attach the steel coupons to either end by putting the drilled side of the coupon towards the screw hole in the soil box and fastening with the 8/32 machine screw (nut already attached).
- 15.6 Use the nut on the machine screw to maintain a snug fit between the coupon and the end of the Miller Soil Box (do not over tighten this screw as it may crack the acrylic box or loosen the steel coupon interrupting electrical contact).

16. PRECAUTIONS

- 16.1 Be sure to use clean corrosion samples for each new measurement.

17. REPORT

- 17.1 As specified in 9.7, report resistivity as measured resistance multiplied by a factor of unity (1) for a standard Miller soil box. Other boxes may require a different factor.
- 17.2 The corrosion rate obtained for the Aquamate is normalized to a surface area of 5 cm². To find the corrosion rate of the sample being evaluated, the surface area must be corrected. The following equation is used to correct the corrosion rate equation.

$$CR = CR_{Aquamate} * \frac{5}{X}$$

Where CR_{Aquamate} is the corrosion rate read from the Aquamate and X is the surface area of the electrodes used (calculated in step 6.3.9 above) and is in cm².

18. PRECISION AND BIAS

- 18.1 Data is not available at this time.

APPENDIX B

pH Measurement Comparison and Method

Table 8: pH Method Comparison

Issue	AASHTO 289	ASTM G51	ASTM D4972	Corrpro Standard
Sample Moisture	Air dry soil, or dry soil in a drying apparatus at less than 60C, then add distilled water to sample until water mass equals soil mass (30g apiece)	Measure soil as-is	Air dry soil, then add distilled water until soil and water mass are equal (10g apiece)	Measure soil moisture content, then add deaerated water until water mass equals soil mass (10g apiece)
Buffer Sol'ns	Standard pH 4, 7, 10 sol'ns	Standard pH 4, 7, 8 sol'ns	0.05 M Acid Potassium Phthalate buffer, 0.025 M Phosphate buffer	2 commercially available sol'ns (pH 4 and 7) checked against 0.01 M Borax sol'n pH 9.18 at 25C
Frequency of Meter Calibration	Prior to session	Linearity of response - prior to session and periodically. Accuracy of response - prior to session, every 30 minutes during session	Prior to session	Before and after session, at least every 24 measurements during session
Temperature	Meter adjusted to reflect soil temperature	Meter calibrated with buffers within 10C of soil temp and within 5C of each other	Sample measured at 15 to 25C	No mention
Electrode Type	One or two electrode	Glass-calomel combination or single	Glass-calomel or Ag/AgCl	Separate pH electrodes and single junction reference electrodes
Sample Location	Lab	Field preferred, lab if necessary with sample preservation	Lab	Field and/or lab
Sieving	No. 10 sieve	None	No. 10 sieve	None
CaCl₂ measurement	No	No	Yes	No

PROCEDURE FOR MEASURING pH OF SOIL SAMPLES

Corrpro Companies, Inc.

1. SCOPE

1.1 This procedure describes a method for determining the pH of soil samples for use in corrosion testing.

2. REFERENCED DOCUMENTS

2.1 APHA (ibid.) Method 150.1 pH (Electrometric).

2.2 ASTM (ibid.) Vol. 04.09 Soil and Rock (II), Standard test method for pH of soils, method D 4972-89 pp. 115-117, 1994.

PART I

INITIAL PREPARATION OF TEST SAMPLES

3. SCOPE

3.1 This procedure describes the method for preparing soil samples for pH measurement. It includes a measurement of soil moisture content.

4. APPARATUS

4.1 Disposable aluminum drying dishes

4.2 Electric forced air drying oven capable of continued heating to 150°C

4.3 Electronic laboratory balance with 0.01 gram resolution.

4.4 Stainless steel spatula

4.5 Standard weights (NIST Class S or better)

4.6 100mL plastic beaker

4.7 *De-aerated water* – de-aerated water is obtained by boiling distilled or de-ionized water for at least 10 minutes and then immediately capping the container before the water cools. The cap is left tightened at all times except when actually transferring water to the sample.

5. SAMPLE SIZE

5.1 The amount of soil material required to perform this test is approximately 40 to 60 grams.

6. INITIAL PREPARATION OF TEST SAMPLES

6.1 Ensure that the lab scale is level.

6.2 Check the accuracy of the scale using the standard NIST traceable weights.

6.3 Dispense approximately 40 to 60 grams of soil into an aluminum drying dish.

6.4 If the sample contains particles of a size greater than 2mm (~1/16-inch), note on the test report that the sample contains gravel. If particles are present of a size greater than 10mm (~3/8-inch), remove them by hand.

6.5 Note the final weight of the sample.

6.6 Heat the sample at 110°C for 6 to 12 hours, or until a constant weight is obtained.

6.7 Record the dry weight of the sample and calculate moisture content by the following formula:

$$\%moisture = (gross\ wet\ wt. - gross\ dry\ wt.)/(gross\ dry\ weight - tare\ wt.)*100$$

Where

%moisture = Total moisture content of the soil sample expressed as a percentage by mass of the dry soil weight

Gross wet wt. = total weight of the sample and dish before drying

Gross dry wt. = total weight of the sample and dish after drying

Tare wt. = weight of the dish

6.8 Dispense a new soil sample that contains 10 grams of dry soil, the total mass of which is calculated as follows:

$$\text{Mass of new sample} = 10g + (10g * \% \text{moisture})$$

For example, if the moisture percentage is 25%, then 12.5 grams of wet soil is placed in the beaker.

6.9 Add sufficient de-aerated water to the beaker to bring the total mass of the sample to 20.0 grams. This gives a mixture of 10 grams of soil and 10 grams of water.

6.10 Stir the soil-water mixture until the soil is thoroughly dispersed.

6.10.1 In the case of particularly heavy clay samples or samples high in organic matter that cannot be dispersed in 10 grams of water, add an additional 10 grams of de-aerated water to the mixture. The error introduced by the additional water should be less than the error resulting from incomplete dispersion.

6.11 After completely dispersing the sample, let it stand for at least 30 minutes.

PART II

DETERMINATION OF SOIL pH

7. SCOPE

7.1 This section describes the procedure for measuring soil pH.

8. APPARATUS

8.1 A research grade pH/selective ion/millivolt meter.

8.2 Separate pH electrodes and single junction reference electrodes. Because the pH electrode has a relatively short life, keep a stock of 4 to 6 on hand at all times. Similarly, spare single junction reference electrodes should be kept available.

8.3 Filling solution for the reference electrode.

8.4 Commercial stock pH buffer solutions – pH 4.00 and 7.00.

8.5 Sodium tetraborate (borax) solution 0.01 M

8.6 Distilled water

9. PROCEDURE

9.1 Calibrate the pH meter as per the manufacturer's instructions for a bracketed calibration using the two commercial buffer solutions, and verify that the borax solution has a pH of 9.18 at 25°C.

9.2 Gently swirl the beaker containing the soil-water suspension and tip slightly to one side, permitting the larger soil and gravel particles to slide out of the way.

9.3 Immerse the pH and reference electrodes in the supernatant suspension.

9.4 Allow the pH reading to stabilize. This may take a few minutes.

9.5 Once the reading is stable, gently swirl the beaker (with the electrodes still inserted) and observe the reading. If the pH reading changes by more than 0.05 pH units, then a stable reading has not been achieved, and the swirling and stabilizing process must be repeated.

9.6 When a stable reading is obtained, remove the pH and reference electrodes and rinse them with distilled water.

9.7 Recheck the pH meter at the end of the session to the commercial buffer solutions and the borax solution.

9.8 In the case of multiple measurements, the pH meter should be checked at least every 24 measurements. The readings should not drift more than 0.02 to 0.03 pH units from the original readings.

10. PRECAUTIONS

10.1 Periodically check for damage to electrodes.

10.2 Be sure to maintain and store electrodes according to manufacturer's instructions.

11. REPORT

11.1 Record soil moisture content to the nearest 0.1%.

11.2 Record solution pH to the nearest 0.01 pH unit.

12. PRECISION AND BIAS

APPENDIX C

SOIL ANALYSIS

CLIENT: National Cooperative Hiway Research Program	ENGINEER: William Shepperson III
PROJECT: 21-06, NCHRP-2	TECHNICIAN: Nancy Jacob
OFFICE: OCEAN CITY	DATE RECEIVED: 11/11/04
JOB #: 83706	DATE OUT: 11/16/04

LABORATORY ELECTROLYTE ANALYSIS

CLIENT: National Cooperative Hiway Research Program	ENGINEER: William Shepperson III
PROJECT: 21-06, NCHRP	TECHNICIAN: Nancy Jacob
OFFICE: Ocean City	DATE RECEIVED: 11/11/04
JOB #: 83706	DATE OUT: 11/16/04

63

LABORATORY ELECTROLYTE ANALYSIS

CLIENT: National Cooperative Hiway Research Program	ENGINEER: William Shepperson III
PROJECT: CA-4, CA-8, CA-25, CA-30 & NY-4, NY-8, NY-25, NY-30	TECHNICIAN: Nancy Jacob
OFFICE: OCEAN CITY	DATE RECEIVED: 01/28/2005
JOB #: 83706	DATE OUT:

SAMPLE ID	MOISTURE %	pH	CHLORIDE ppm	SULFIDE ppm	CONDUCTIVITY mmhos	Calculated		SOIL TYPE	SOIL COLOR
						RESISTIVITY ohm-cm			
CA-4	5.90	8.4	37	0.0	290	3,500		Fine, sharp rocks	Gray-black & brown
CA-8	6.50	6.0	81	0.0	520	1,900		Igneous rocks	Dark gray & brown
CA-25-5A	51.00	8.8	2,300	0.4	7,900	130		Clay	Gray
CA-25-5B	43.00	8.4	2,600	0.3	8,300	120		Clay	Gray & brown
CA-25-5E	31.00	8.9	1,500	0.0	4,900	200		Clay	Gray & brown
CA-25-5F	28.00	7.5	2,500	0.0	8,400	120		Clay	Light brown
CA-30-7B	28.00	7.6	2,500	0.0	8,900	110		Clay	Light brown
CA-30-7C	28.00	7.5	2,700	0.0	9,100	110		Clay	Light brown
NY-4	18.00	6.3	230	0.0	710	1,400		Clay loam	Gray-brown
NY-8	13.00	7.9	220	0.0	520	1,900		Clay loam	Gray-brown
NY-25	10.00	8.0	50	0.0	400	2,500		Silty clay	Gray & brown
NY-30	7.80	8.1	10	0.0	1,200	830		Silty clay	Gray

LABORATORY ELECTROLYTE ANALYSIS

CLIENT: National Cooperative Hiway Research Program	ENGINEER: William Shepperson III
PROJECT: CA-4, CA-8, CA-25, CA-30 & NY-4, NY-8, NY-25, NY-30	TECHNICIAN: Nancy Jacob
OFFICE: Ocean City	DATE RECEIVED: 01/28/2005
JOB #: 83706	DATE OUT:

SAMPLE ID	REDOX POTENTIAL			4 PIN RESISTIVITY		as is 2 Pin Corrosion Rate		saturated 2 Pin Corrosion Rate	
	as is # 1	as is # 2	saturated	as is	saturated	mpy	imbalance	mpy	imbalance
CA-4	210	180	240	12,000	1,600	0.02	0.00	0.25	0.11
CA-8	230	210	230	10,000	2,000	0.05	0.03	0.33	0.20
CA-25-5A	-230	-220	16	140	130	1.00	3.19	0.84	6.30
CA-25-5B	-170	-220	66	120	110	1.33	0.03	1.35	0.09
CA-25-5E	-45	-62	48	220	210	1.98	1.52	2.47	0.00
CA-25-5F	170	210	240	140	130	2.06	1.77	2.34	0.54
CA-30-7B	150	230	260	120	120	2.26	0.94	1.72	2.74
CA-30-7C	190	190	280	240	120	1.77	0.40	2.23	0.80
NY-4	230	250	340	3,400	1,900	0.42	0.15	0.53	0.22
NY-8	240	270	290	7,100	2,900	0.14	0.03	0.31	0.28
NY-25	320	320	230	10,000	3,300	0.05	0.01	0.24	0.15
NY-30	180	190	220	15,000	1,800	0.04	0.04	0.15	0.06
Yellow = There was not enough sample to fill the soil box completely. The box was filled 1/8 " to 1/16 " from the top.									

KEY: S4 = NJ, 4-foot; S22 = NJ 22-foot, S29 = NJ 29-foot, O3 = Ohio 3-foot, 14 = Illinois 4-foot, 18 = Illinois 8-foot, 122 = Illinois 22-foot, 129 = Illinois 29-foot, CA-4 = California 4-foot, CA-8 = California 8-foot, CA-25-xx = California 25-foot (xx is the sample number), CA-30-xx = California 30-foot (xx is the sample number), NY-4 = New York 4-foot, NY-8 = New York 8-foot, NY-25 = New York 25-foot, NY-30 = New York 30-foot.

APPENDIX D

FHWA AND GERMAN SOIL CORROSIVITY RATINGS

Resistivity Range ohm-cm	Steel Corrodibility	Years to Penetrate Sheet Steel
<500	very severe	1-5
500-1,000	severe	5-10
1,000-2,000	severe to moderate	10-15
2,000-5,000	moderate to slight	15-20
5,000-10,000	slight	>20
10,000-1,000,000	slight to none	

Figure 1 Corrosion Assessment Table reproduced from *Practical Handbook of Corrosion Control in Soils* (Bradford, 2000)

¹ Hepfner, Jon J., "Statewide Corrosivity Study on Corrugated Steel Culvert Pipe", FHWA/MT-01-001/8148, November 2001, p. 6.

German Method²

² Shreir, L.L.; Jarman, R.A.; Burstein, G.T., “Corrosion (3rd Edition)” Volume 1, Elsevier, 1994, p. 2:85.

Table 2.20 Soil Corrosivity Assessment Technique from the German Gas and Water Works Engineers' Association Standard (DVGW GW9)

<i>Item</i>	<i>Measured Value</i>	<i>Marks</i>
Soil composition	Calcareous, marly limestone	+2
	Sandy marl, not stratified sand	
	Loam, sandy loam (loam content 75% or less) marly	0
	loam, sandy claysoil (silt content 75% or less)	-2
	Clay, marly clay, humus,	-4
Ground-water level at buried position	Peat, thick loam, marshy soil	0
	None	-1
	Exist	-2
	Vary	0
Resistivity	10,000 ohm. cm or more	-1
	10,000-5,000	-2
	5,000-2,300	-3
	2,300-1,000	-4
	1,000 or less	0
Moisture content	20% or less	-1
	20% or more	0
pH	6 or more	-2
	6 or less	0
Sulphide and hydrogen sulphide	None	-2
	Trace	-4
	Exist	+2
Carbonate	5% or more	+1
	5-1	0
	1 or less	0
Chloride	100 mg/kg or less	-1
	100 mg/kg more	0
Sulphate	200 mg/kg or less	-1
	200-500	-2
	500-1,000	-3
	1,000 or more	0
Cinder and coke	None	-4
	Exist	

Soil is regarded as non-corrosive if the total of the above is 0 or higher; Slightly corrosive if 0 to -4; corrosive if -5 to -10 and very corrosive if -10 or less.

APPENDIX G

Field Method for Corrosion Rate Measurement

FIELD METHOD FOR MEASURING CORROSION RATE IN SOILS

Corrpro Companies, Inc.

1. SCOPE

- 1.1 This procedure describes field methods for measuring Corrosion Rate, Conductivity, Resistivity, Corrosive Pitting Tendency (Imbalance), and pH of soils at Corrpro's NCHRP 21-06 installation sites.

2. REFERENCED DOCUMENTS

- 2.1 Corrpro Companies, Inc. standard NCHRP 21-06 data collection forms (tailored to individual sites).

3. APPARATUS

- 3.1 Aquamate CORRATER corrosion meter with associated 2-clip wire assembly and calibration probe.
3.2 Nilsson 400 soil resistance meter with associated 4-clip wire set.
3.3 Digital multi-meter capable of measuring millivolts DC with associated 2-clip wire set.
3.4 Clock or stopwatch

PART I

CORROSION RATE, CONDUCTIVITY, AND IMBALANCE

4. SCOPE

- 4.1 This section describes the procedure for using the Aquamate CORRATER to measure instantaneous corrosion rate, conductivity, and imbalance of soil through buried LPR probes.

5. PROCEDURE

5.1 Calibration

- 5.1.1 Attach the red calibration probe to the Aquamate.
5.1.2 Turn on the Aquamate. A battery life readout will briefly display. Ensure sufficient battery life and replace the unit's battery (9V) if necessary.
5.1.3 Press "CONFIG" and cycle through the parameters with the arrow keys. The parameters should read:

PROBE MULT = 1.00

CYCLE TIME = 2.0

ELEM STYLE = STANDARD

PROBE TYPE = 2 ELEC

ADVANCED = NO

- 5.1.4 When parameters have been confirmed, press "DISPLAY", then press "MEAS" and wait for readings to appear. This should take approximately 2 minutes.
5.1.5 Compare measured values to the desired values printed on the calibration probe and record on the data sheet for Box A.
5.1.6 Detach calibration probe from the Aquamate and attach clip leads.
5.2 Measurements
5.2.1 Attach clip leads to junction box terminations in Box A as indicated on the data sheet for the site being surveyed. For example, red Aquamate lead 1 attached to junction box terminal 1, black Aquamate lead 2 attached to junction box terminal 2 to take the first reading on LPR probe #1.
5.2.2 At this point the Aquamate should still be displaying the calibration readings. Press "MEAS" to take the first junction reading.
5.2.2.1 The Aquamate meter has an automatic off feature to extend battery life. If the unit has switched off, restart and wait for the "Ready" screen, then press "MEAS".
5.2.3 When the readings appear, record them in the appropriate fields of the data sheet.
5.2.3.1 If the unit switches off before the values are recorded, switch the unit back on, wait for the "Ready" screen, then press "DISPLAY" to display the previous reading.
5.2.4 Repeat steps 5.2.1 to 5.2.3 for subsequent termination pairs.
5.2.5 When all readings are complete, repeat the calibration procedure and record the values on the sheet for the last box measured. If at any time during the measurement process it is necessary to replace the battery, repeat the calibration procedure and record the values on the appropriate data sheet.
5.3 Due to the time required for each Aquamate measurement, the procedures in Parts II and III can be performed concurrently with the procedure above.

PART II

RESISTIVITY

6. PROCEDURE

- 6.1 Attach the set of 4 leads to the Nilsson soil resistance meter.
- 6.2 Observe the Battery Check light for signs of low battery life.
- 6.3 Connect clip leads to the junction box terminations in Box A as indicated on the data sheet for the site being surveyed.
- 6.4 Move the switch to the "Low" position and observe the gauge.
- 6.5 Adjust primary dial until gauge points to center. If center cannot be reached by adjustment of primary dial, switch secondary dial up or down accordingly and try again.
- 6.6 When gauge points to center, move switch to "High" and adjust primary dial so that the gauge points to center.
- 6.7 When center reading has been achieved on "high" setting, record the resistance level on the data sheet by multiplying the primary dial reading (between 1 and 10) by the secondary dial reading.
- 6.8 Repeat steps 6.3 to 6.7 for subsequent termination pairs.

PART III

pH

7. PROCEDURE

- 7.1 Attach leads to the digital multi-meter.
- 7.2 Ensure multi-meter batteries have sufficient life for the task.
- 7.3 Set multi-meter to read millivolts DC.
- 7.4 Record current time (HH:MM) in the appropriate field on the data sheet for Box A of the site being surveyed.
- 7.5 Attach leads to first termination pair in Box A as indicated on the data sheet for the site being surveyed.
- 7.5.1 NOTE: Termination pairs used in Parts I and II will not be used for pH measurements. Not all probes will have terminations for pH measurements.
- 7.6 Immediately record the value displayed.
- 7.7 With the leads still attached to the termination pair, wait one minute, then record the time and displayed value in the appropriate fields of the data sheet.
- 7.8 Repeat step 7.7 four (4) additional times.
- 7.9 Repeat steps 7.4 to 7.8 for subsequent termination pairs.

8. PRECAUTIONS

- 8.1 Be sure to check for loose connections in each junction box before taking readings.
- 8.2 Pay close attention to time while recording pH readings. Multi-tasking makes the above processes more efficient, but at the risk of missing a pH measurement.
- 8.3 Be sure to have at least one extra battery on hand for the Aquamate in particular. It will drain batteries quickly.

9. REPORT

- 9.1 To calculate the actual corrosion rate from the rate measured with the Aquamate:

$$C = C_m * 1.517$$

Where

C = Actual Corrosion Rate in mpy

C_m = Measured corrosion rate in mpy

- 9.2 The Conductivity (μ mhos/cm) and Imbalance (mpy) values are recorded as displayed by the Aquamate.

- 9.3 To calculate resistivity of the soil from the direct resistance reading given by the Nilsson meter:

$$\rho = R_c * 18 = R_d * 42$$

Where

ρ = Resistivity in ohm-cm

R_c = Resistance measured with cylinder probe in ohms

R_d = Resistance measured with disposable LPR probe in ohms

9.4 To calculate pH from the measured potentials:

$$pH = ((V \div 1000) + 0.0134) \div 0.0576$$

Where

V = Measured potential in millivolts

10. PRECISION AND BIAS

10.1 Data is unavailable at this time.

APPENDIX H

SURVEY INFORMATION

DOT QUESTIONNAIRE INFORMATION

Questionnaire Template – 2 pages

Responses – General Information – 1 page

Responses – Threshold Values for Soil Resistivity and pH – 5 pages

Responses – Resistivity Measurement Instrumentation – 2 pages

Responses – Additional Comments – 11 pages

NCHRP PROJECT No. 21-06
Corrpro Companies, Inc., Chantilly, Virginia
Tel: 703-679-9220; Fax: 703-679-9230; email: corrprova@aol.com

SURVEY QUESTIONNAIRE ON SOIL RESISTIVITY AND pH MEASUREMENTS

Name of Organization Responding to Survey: _____

Address: _____

Tel: _____ Fax: _____ Email: _____

Name of Person Responding to Survey: _____

Position/Title: _____

(1) Does your organization perform soil resistivity and/or pH tests? Yes ☐ No ☐

(2) If yes, what do you use resistivity and pH measurements for?

	Resistivity	pH
Culverts	<input type="radio"/>	<input type="radio"/>
Pilings	<input type="radio"/>	<input type="radio"/>
Piping	<input type="radio"/>	<input type="radio"/>
MSE walls	<input type="radio"/>	<input type="radio"/>
Other _____	<input type="radio"/>	<input type="radio"/>

(3) Do you have or follow any test specifications for either test? Yes ☐ No ☐

(4) If yes, what is the preferred test specification?

	Resistivity		pH
ASTM	<input type="radio"/>	ASTM	<input type="radio"/>
AASHTO	<input type="radio"/>	AASHTO	<input type="radio"/>
In-House	<input type="radio"/>	In-House	<input type="radio"/>
Other _____	<input type="radio"/>	Other _____	<input type="radio"/>

(5) Please state reason for choosing preferred test specification

(6) What is the level of precision expected by your organization for resistivity and pH data (given the variation in field practices, equipment nuances, etc.)?

	Resistivity		pH
0 - 5%	<input type="radio"/>	0 - 5%	<input type="radio"/>
5 - 10%	<input type="radio"/>	5 - 10%	<input type="radio"/>
Other _____	<input type="radio"/>	Other _____	<input type="radio"/>

(7) Is resistivity and/or pH data used in any decision making process? Yes ☐ No ☐

(8) If yes, please provide brief information

NCHRP PROJECT No. 21-06
Corrpro Companies, Inc., Chantilly, Virginia
Tel: 703-679-9220; Fax: 703-679-9230; email: corrprova@aol.com

SURVEY QUESTIONNAIRE ON SOIL RESISTIVITY AND pH MEASUREMENTS

(9) Please provide the following information for resistivity and pH instruments used:

Resistivity instrument

Manufacturer: _____ Model: _____
Year of manufacture: _____ No of eletrodes: _____
Signal frequency: _____ Signal waveform: _____
Signal voltage: _____ Electrode material: _____
Soil sample preparation: _____

Instrument Reliability: Excellent ☐ Good ☐ Fair ☐ Poor ☐

pH instrument

Manufacturer: _____ Model: _____
Year of manufacture: _____ Type of buffers: _____
Type of electrode: _____ Type of indicator: _____
Soil sample preparation: _____

Instrument Reliability: Excellent ☐ Good ☐ Fair ☐ Poor ☐

PLEASE SEND RESPONSE BY FAX OR EMAIL TO:

Dr. Moavin Islam
Corrpro Companies, Inc., Chantilly, Virginia
Tel: 703-679-9220; Fax: 703-679-9230; email: mislam@corrpro.com

YOUR INPUT IN SINCERELY APPRECIATED

Response to Survey Questionnaire: General Information

State	Perform testing		Who performs tests				Structure life prediction		Corrosion Assessment		Materials Selection		Use of Coatings		CP Design		Other		Preferred Test Specification	
	Res.	pH	Consult	Out-Lab	Contract	In-house	Res.	pH	Res.	pH	Res.	pH	Res.	pH	Res.	pH	Res.	pH	Resistivity	pH
Alabama	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	N	N	N	N	in-house & CADOT 643	in-house 291
Alaska	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	AASHTO T288	AASHTO T289
Arkansas	N	N	Y	N	N	N	N	N	Y	Y	N	N	Y	Y	N	N	N	N	ASTM & AASHTO	ASTM & AASHTO
Colorado	N	Y	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	ASTM	AASHTO
Connecticut	Y	Y	N	Y	Y	N	N	N	Y	Y	Y	N	Y	Y	N	N	N	N	AASHTO T288-911	AASHTO T289-911
Florida	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	in-house	in-house
Georgia	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	N	N	N	N	in-house, std methods	in-house, std methods
Hawaii	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	in-house	in-house
Idaho	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	Y	N	Y	N	N	N	AASHTO	AASHTO
Illinois	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	N	NA	NA
Indiana	N	Y	Y	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	NA	Cornell Method 960
Kansas	Y	Y	N	N	N	Y	Y	Y	N	N	Y	Y	N	N	N	N	N	N	ASTM G57-78	ASTM, AASHTO
Maryland	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	N	N	AASHTO M-288	ASTM G51
Michigan	Y	Y	N	N	N	Y	N	N	N	N	Y	Y	N	N	N	N	N	N	AASHTO T288	AASHTO T289
Minnesota	N	N	N	N	N	Y	Y	N	Y	N	Y	Y	N	N	N	N	N	N	ASTM & Chem lab	ASTM & Chem lab
Mississippi	Y	Y	N	N	N	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	NA	NA
Missouri	Y	Y	N	Y	Y	N	N	N	N	N	N	Y	N	N	N	N	MSE & RSS Structures		Ca DOT 643	California DOT 643
Montana (Const)	Y	N	N	N	N	Y	Y	N	Y	N	Y	N	Y	N	Y	N	N	N	ASTM, AASHTO	NA
Montana	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	in-house	in-house
Nebraska	Y	Y	N	Y	Y	Y	N	N	Y	Y	Y	Y	N	N	N	N	N	N	in-house	in-house
Nevada	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	AASHTO , NVT-235B	in-house NVT-238A
New Hampshire	Y	Y	N	Y	N	N	N	N	N	N	Y	Y	N	N	N	N	N	N	ASTM, AASHTO	ASTM, AASHTO
New Jersey	N	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	NA	NA
New Mexico	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	Y	Y	N	N	N	N	CaDOT 643	California DOT 643
New York	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	N	N	N	N	to meet specs		AASHTO T288	AASHTO T289
North Dakota	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	NA	NA
Oregon	Y	Y	N	N	N	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	N	N	ASTM , TM107	inhouse TM107
Pennsylvania	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	PTM-133, Ca DOT 643B	in-house PTM-208
Puerto Rico	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	ASTM	ASTM
South Carolina	N	Y	N	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	NA	AASHTO T289
South Dakota	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	NA	NA
Texas	Y	Y	N	N	N	Y	N	N	N	N	Y	Y	N	N	N	N	N	N	in-house Tex-129-E	in-house Tex-128-E
Utah	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	AASHTO T-288	AASHTO T-289
Washington	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	in-house	in-house
West Virginia	Y	Y	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	N	N	N	AASHTO	AASHTO
Wyoming	Y	Y	N	N	N	Y	Y	N	Y	N	Y	N	N	N	N	N	N	N	ASTM, AASHTO	AASHTO T289

% responded NO 24% 14% 78% 76% 86% 24% 54% 62% 38% 38% 30% 24% 65% 57% 92% 95%

% responded YES 76% 86% 22% 24% 14% 76% 46% 38% 62% 62% 70% 76% 35% 43% 8% 5%

Response to Survey Questionnaire: Threshold Values for Soil Resistivity and pH

Component	Parameter	Alabama	Alaska	Arkansas	Colorado	Connecticut	Florida	Georgia
Culverts	Resistivity	>3000 ohm-cm	>3000 ohm-cm	NR	NR	NR	Y	see sheet
	pH	5-10	5 to 10	NR	Y	NR	Y	see sheet
Pilings	Resistivity	>3000 ohm-cm	>3000 ohm-cm	NR	NR	Y	Y	NR
	pH	5-10	5 to 10	NR	NR	Y	Y	NR
Piping	Resistivity	NR	NR	NR	NR	NR	Y	see sheet
	pH	NR	NR	NR	NR	NR	Y	see sheet
MSE Walls	Resistivity	>3000 ohm-cm	>3000 ohm-cm	Y	NR	3000 ohm-cm	Y	>3000
	pH	5-10	5 to 10	Y	NR	5-10	Y	6 to 9.5
Reinforced Concrete Foundation	Resistivity	NR	>3000 ohm-cm	NR	NR	NR	Y	NR
	pH	NR	5 to 10	NR	Y	NR	Y	NR
Underground Storage Tanks	Resistivity	NR	NR	NR	NR	NR	Y	NR
	pH	NR	NR	NR	NR	NR	Y	NR
Other	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	NR

Notes:

NR = no response

Y = yes (value not mentioned)

Response to Survey Questionnaire: Threshold Values for Soil Resistivity and pH (continued)

Component	Parameter	Hawaii	Idaho	Illinois	Indiana	Kansas	Maryland	Michigan
Culverts	Resistivity	Y	1000	NR	NR	Y	NR	NR
	pH	Y	6 to 8	3	5-8.5	Y	NR	NR
Pilings	Resistivity	NR	NR	2000	NR	NR	>3000 ohm-cm	NR
	pH	NR	NR	4	NR	NR	Y	NR
Piping	Resistivity	NR	1000	2000	NR	NR	Y	NR
	pH	NR	6 to 8	4	5-8.5	NR	Y	NR
MSE Walls	Resistivity	Y	3000	2000	NR	NR	Y	3000 min
	pH	Y	4.5 to 9.5	4	NR	NR	3-9	5-10
Reinforced Concrete Foundation	Resistivity	NR	1000	NR	NR	NR	Y	NR
	pH	NR	5 to 12	3	NR	NR	Y	NR
Underground Storage Tanks	Resistivity	NR	NR	2000	NR	NR	NR	NR
	pH	NR	NR	4	NR	NR	Y	NR
Other	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	Soil Nailing 5-7.5 for vegetation	NR

Notes:

NR = no response

Y = yes (value not mentioned)

Response to Survey Questionnaire: Threshold Values for Soil Resistivity and pH (continued)

Component	Parameter	Minnesota	Mississippi	Missouri	Montana (C)	Montana	Nebraska	Nevada
Culverts	Resistivity	NR	1000	NR	3000	2200	Y	1000min
	pH	NR	4	NR	NR	5-8.5	Y	5 to 9.5
Pilings	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	NR
Piping	Resistivity	NR	NR	NR	NR	NR	NR	1000min
	pH	NR	NR	NR	NR	NR	NR	5 to 9.5
MSE Walls	Resistivity	FHWA Rec.	NR	>3000 ohm-cm	5000	NR	Y	3000min
	pH	NR	NR	3<x<9	NR	NR	Y	5 to 10
Reinforced Concrete Foundations	Resistivity	NR	NR	NR	5000	NR	NR	1000min
	pH	NR	NR	NR	5<x<10	NR	NR	5 to 9.5
Underground Storage Tanks	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	NR
Other	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	5-9 OK	NR	NR	NR	NR	NR	NR

Notes:

NR = no response

Y = yes (value not mentioned)

Response to Survey Questionnaire: Threshold Values for Soil Resistivity and pH (continued)

Component	Parameter	New Hampshire	New Jersey	New Mexico	New York	North Dakota	Oregon	Pennsylvania
Culverts	Resistivity	NR	NR	Y	NR	NR	2000	NR
	pH	NR	NR	Y	5 to 10	NR	4.5	4
Pilings	Resistivity	NR	NR	NR	NR	NR	NR	10000
	pH	NR	NR	NR	NR	NR	NR	5.5
Piping	Resistivity	NR	NR	NR	NR	NR	NR	6000
	pH	NR	NR	NR	5 to 10	NR	NR	5.5
MSE Walls	Resistivity	3000min	NR	3000	>3000	NR	2000	NR
	pH	5 to 10	Y	5 to 10	5 to 10	NR	4.5	5.5
Reinforced Concrete Foundation	Resistivity	Ohm-cm	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	4
Underground Storage Tanks	Resistivity	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	NR
Other	Resistivity	NR	NR	NR	NR	NR	NR	Aluminum Structures 500
	pH	NR	NR	NR	NR	NR	NR	Aluminum Structures 4

Notes:

NR = no response

Y = yes (value not mentioned)

Response to Survey Questionnaire: Threshold Values for Soil Resistivity and pH (continued)

Component	Parameter	Puerto Rico	South Carolina	South Dakota	Texas	Utah	Washington	West Virginia	Wyoming
Culverts	Resistivity	NR	NR	Y	NR	Y	1000	NR	Y
	pH	NR	NR	Y	NR	Y	57x78.5	Y	Y
Pilings	Resistivity	NR	NR	Y	NR	NR	NR	NR	Y
	pH	NR	NR	Y	NR	NR	NR	NR	Y
Piping	Resistivity	NR	NR	NR	NR	NR	NR	NR	NR
	pH	NR	NR	NR	NR	NR	NR	NR	NR
MSE Walls	Resistivity	Y	NR	Y	1500 min	NR	3000	Y	NR
	pH	Y	3.0-9.0	NR	5.5 to 10	NR	57x78.0	Y	NR
Reinforced Concrete Foundation	Resistivity	NR	NR	NR	NR	NR	NR	NR	Y
	pH	NR	NR	NR	NR	NR	NR	NR	Y
Underground Storage Tanks	Resistivity	NR	NR	Y	NR	NR	1000	NR	NR
	pH	NR	NR	Y	NR	NR	57x78.5	NR	NR
Other	Resistivity	Soil Nailing	NR	NR	NR	NR	NR	NR	All facility structures
	pH	Soil Nailing	NR	NR	NR	NR	NR	NR	All facility structures

Notes:

NR = no response

Y = yes (value not mentioned)

Response to Survey Questionnaire: Resistivity Measurement Instrumentation

State	Manufacturer	Model	Year of Manufacture	No. of Pins	Signal Frequency	Signal Waveform	Signal Voltage	Electrode Material	Instrument Reliability
Alabama	NR	NR	NR	NR	NR	NR	NR	NR	NR
Alaska	Soiltest	Strata Scout	NR	NR	NR	NR	NR	NR	good
Arkansas	NR	NR	NR	NR	NR	NR	NR	NR	NR
Colorado	NR	NR	NR	NR	NR	NR	NR	NR	NR
Connecticut	NR	NR	NR	NR	NR	NR	NR	NR	NR
Florida	MC Miller	Miller Soil Box	Inventory varies	NR	NR	NR	NR	Brass	NR
Georgia	Fisher Scientific	AB 30	1999	NR	12V / 500mA	NR	NR	NR	excellent
Hawaii	Associated Research	Vibroground 293	1974	NR	97 CPS	0-10000 PCCM	NR	Steel	good
Hawaii	MC Miller	Miller Soil Box	1974	NR	NR	NR	NR	steel	NR
Idaho	AGRA	MARK II	1999	NR	NR	NR	NR	stainless steel	NR
Illinois	Nilsson Electric Lab.	NR	NR	NR	NR	NR	NR	NR	excellent
Illinois	MC Miller	NR	NR	NR	NR	NR	NR	NR	NR
Indiana	NR	NR	NR	NR	NR	NR	NR	NR	NR
Kansas	Nilsson Electric Lab.	400	1994	4	NR	NR	NR	NR	good
Kansas	MC Miller	400	1994	NR	NR	NR	NR	stainless steel	NR
Maryland	Nilsson Electric Lab.	400	2000	4	NR	NR	NR	brass	excellent
Maryland	MC Miller	37006	2000	NR	NR	NR	NR	brass	NR
Michigan	Beckman	RA-2A Conductivity Meter	NR	2	NR	NR	NR	NR	Excellent
Minnesota	NR	NR	NR	NR	NR	NR	NR	NR	NR
Mississippi	NR	NR	NR	NR	NR	NR	NR	NR	NR
Missouri	NR	NR	NR	NR	NR	NR	NR	NR	NR
Montana (C)	Nilsson Electric Lab.	400	NR	4, 18"x.25" Diam.	97Hz	square	DC	stainless steel	good
Montana (C)	In-house fabricated	NR	NR	NR	NR	NR	NR	SS box (factor=10)	NR
Montana	Orion	150	1997	NR	NR	NR	NR	Epoxy/Graphite	good
Nebraska	Beckman	SMB-1 Soil Moisture Bridge	NR	NR	NR	NR	NR	NR	NR
Nevada	Cole-Parmer	5800-05 Solution Analyzer	1993	Platinum based	NR	NR	NR	NR	Excellent
New Hampshire	NR	NR	NR	NR	NR	NR	NR	NR	NR
New Jersey	NR	NR	NR	NR	NR	NR	NR	NR	NR
New Mexico	NR	NR	NR	NR	NR	NR	NR	NR	NR
New York	in-house per AASHTO T-288	NR	1990	NR	NR	NR	NR	stainless steel	NR
North Dakota	NR	NR	NR	NR	NR	NR	NR	NR	NR
Oregon	Associated Research	Vibroground 293	approx. 1980	used w/ soil box only	97 CPS	NR	125	brass pin, SS current plates	excellent
Oregon	MC Miller	soil box	1998	NR	NR	NR	NR	brass pin, SS current plates	NR
Pennsylvania	NR	NR	NR	NR	NR	NR	NR	NR	NR
Puerto Rico	NR	NR	NR	NR	NR	NR	NR	NR	NR
South Carolina	NR	NR	NR	NR	NR	NR	NR	NR	NR
South Dakota	NR	NR	NR	NR	NR	NR	NR	NR	NR
Texas	Nilsson Electric Lab.	400	NR	NR	NR	NR	NR	NR	good
Texas	in-house per to Tex-129-E	NR	NR	NR	NR	NR	NR	NR	NR
Utah	NR	NR	NR	NR	NR	NR	NR	NR	NR
Washington	Nilsson Electric Lab.	400	NR	NR	NR	NR	NR	Brass	NR
West Virginia	Nilsson Electric Lab.	400	NR	NR	NR	NR	NR	NR	NR
Wyoming	Nilsson Electric Lab.	400	NR	4	NR	NR	NR	Brass	good
Wyoming	MC Miller	Miller Soil Box	NR	NR	NR	NR	NR	Brass	NR

NR = no response

Response to Survey Questionnaire: pH Measurement Instrumentation

State	Manufacturer	Model	Year of Manufacture	Type of Buffers	Type of Electrode	Type of Indicator	Instrument Reliability
Alabama	Hach One	NR	1996	Baxter pH4 and pH7	pH electrode	NR	good
Alaska	Corning	313	1996	NR	3 more combo	NR	Excellent
Arkansas	NR	NR	NR	NR	NR	NR	NR
Colorado	NR	NR	NR	NR	NR	NR	NR
Connecticut	NR	NR	NR	NR	NR	NR	NR
Florida	HANNR Instruments	pHep3	Varies	analytical grade pH 4 & 10	Hand held	Potentiometric	Excellent
Georgia	Beckman	211389	1997	4, 7, 10	standard	SB 101-4 Fisher Sci	Excellent
Hawaii	HANNR Instruments	PHEP3 with ATC	Nov-96	pH 7	glass bulb	digital	good
Hawaii	NR	NR	NR	NR	NR	NR	NR
Idaho	Fisher Scientific	AR-15	1999	4, 7, 10	glass/field effect transistor	640x480 LCD	good
Illinois	Corning	NR	NR	NR	Oirion electrode	NR	good
Illinois	NR	NR	NR	NR	NR	NR	NR
Indiana	Orion	NR	1986	powder 7.0	gel-filled	probe	good
Kansas	Cole-Parmer	pH Testr 2	1999	NR	Ag/AgCl	NR	good
Kansas	NR	NR	NR	NR	NR	NR	NR
Maryland	Orion	SA 720	NR	potassium, phosphate pH4 & pH7	Ross Sure Flow Onfon	NR	Excellent
Maryland	NR	NR	NR	NR	NR	NR	NR
Michigan	Cole-Parmer	pH Testr 1 59000-00	NR	NR	Hand held	LCD Digital	Excellent
Minnesota	NR	NR	NR	NR	NR	NR	NR
Mississippi	NR	NR	NR	NR	NR	NR	NR
Missouri	NR	NR	NR	NR	NR	NR	NR
Montana (C)	NR	NR	NR	NR	NR	NR	NR
Montana (C)	NR	NR	NR	NR	NR	NR	NR
Montana	Mettler	DL12	1994	Buffer Solutions 4, 7, 10	Universal Glass	NR	good
Nebraska	Orion	901	NR	Orion pH4 to pH11	Beckman	NR	Excellent
Nevada	Cole-Parmer	5800-05 Solution Analyzer	1993	Beckman 4-7-10	Cole-Parmer	digital	NR
New Hampshire	NR	NR	NR	NR	NR	NR	NR
New Jersey	NR	NR	NR	NR	NR	NR	NR
New Mexico	NR	NR	NR	NR	NR	NR	NR
New York	Mettler/Toledo	MP-220	2000	4, 7, 10	Combination	direct read	excellent
North Dakota	NR	NR	NR	NR	NR	NR	NR
Oregon	Controls International	37008	1997	liquid pH4, pH7, pH10	gel-filled, epoxy bodied	digital	excellent
Oregon	NR	NR	NR	NR	NR	NR	NR
Pennsylvania	NR	NR	NR	NR	NR	NR	NR
Puerto Rico	NR	NR	NR	NR	NR	NR	NR
South Carolina	Corning	350	1994	Liquid 4, 7, 10	Combination	NR	Excellent
South Dakota	NR	NR	NR	NR	NR	NR	NR
Texas	in-house Tex-128-E	NR	NR	NR	NR	NR	good
Texas	NR	NR	NR	NR	NR	NR	NR
Utah	NR	NR	NR	NR	NR	NR	NR
Washington	VWR	3000	1994	VWR #34170 - 127, 130, 133	Orion 9207BN, Ag/AgCl ge	digital	good
West Virginia	Orion	230A	1992	4, 7, 10	gel-filled triode	NR	Excellent
Wyoming	Orion	960	1995	Orion	Orion	NR	Excellent
Wyoming	NR	NR	NR	NR	NR	NR	NR

NR = no response

State	Please indicate what action is taken if resistivity and pH do not conform to threshold values	Please state reason(s) for choosing preferred test specification.
Alabama		
Alaska	1. Find another source 2. Redesign	lab familiarity
Arkansas		
Colorado	Colorado DOT does not have a test specification available	
Connecticut	backfill material is not accepted if it does not meet threshold values	Test methods as recommended by AASHTO Standard Bridge Design Specification
Florida	higher class of concrete used: increase in metal gage and/or use of coatings	
Georgia	For culverts and pipe: product will not be used. The solution is usually to use concrete, HDPE or PVC pipe. For MSE walls: backfill must meet these requirements before it is allowed to be used.	
Hawaii		
Idaho	for pipes or culverts, use different types. For backfill of MSE, reject material	
Illinois	A potentiodynamic scan might be required of the environmental conditions, including water, water-soil mixture, and general characteristics of the river or creek (pH; specific ionic content; conductivity; whether particulates or sediment is carried by the water).	Specifications of choice would be sent on a case-by-case basis. Generally this would be done only for projects where severe deterioration was previously experienced and the Department would have its contractors, consultants or an outside laboratory do the work. Presently, in-house expertise is limited to a few persons and is already stretched beyond capacity.
Indiana	use a bituminous coating on metal pipes	only thing we have ever used
Kansas	If the values indicate that the life of Aluminized pipe will be less than 50 years concrete or plastic will be specified. The life of the pipe is determined using the "Estimated Service Life Based on pH and Resistivity for Aluminized CSP" nomograph developed by the Florida DOT.	Typical tests performed by metal pipe manufacturers.
Maryland	don't use material that may be susceptible to an aggressive subsurface situation	availability of an instrument. known industry wide.

Michigan	find another source of backfill for MSE wall	
Minnesota	use other material in the given environment, i.e. geosynthetics for steelstrips in MSE fills and wood chips or geofoam used where tires may be a problem	conformance with national standards
Mississippi	for metal culverts used on cross drains, resistivity threshold is 10,000. If the soil survey shows the conditions are less than the threshold values metal pipe is not recommended for use in that project	
Missouri	the select granular material is rejected and another source must be used.	
Montana (C)	pH and resistivity are often combined in corrosion rate equations to estimate pipe life.	TDR and Wenner 4-pin testing field methods are good for in situ determination; however, these methods provide only a "snapshot" of the soil characteristics at a given time and for a given set of soil, water, and environmental conditions. Of the laboratory test methods, several agricultural or soil physics based methods exist for determination of soil resistivity; however, these methods typically only focus on fluid extracted from a soil/water mixture and are not representative of a soil and water medium. AASHTO T288 is more repeatable and reasonable than the ASTM G57 or CalTrans soil box methods. CalTrans and AASHTO are similar; however, CalTrans does not specify a specific "seasoning time" prior to testing at the initial moisture content which has an effect on the minimum resistivity. AASHTO is also favored over ASTM because ASTM specifies a soil slurry to be used as the testing medium, and slurry state may not replicate field conditions.
Montana	Specifications are on additional sheet entitled Corrosive Soils Evaluations	
Nebraska	#5 (d) Certification by contractor, based on testing by independent lab. Measurements are used on structures that are metallic reinforcement elements. #6 NDOR uses ranges, see attached copy of pages 500 and 501 of NDOR Standard Specification for Highway Construction Manual.	These are the same tests that are required for our aggregates.
Nevada	material is not allowed to be used as backfill	NDOT test method developed for speed. Perform over 1400 soil tests annually, use AASHTO T288 as a referee test in cases of dispute.

New Hampshire	backfill material is not accepted, without approval of the engineer	recommended in FHWA demo project guide specifications for MSE wall backfill materials
New Jersey	decision on a case by case basis	
New Mexico	if resistivity and pH do not meet specifications the backfill material is changed or a different culvert material is used.	
New York	if resistivity is between 1000 and 3000 ohm-cm, additional testing (sulfates, chlorides) is performed. If resistivity is below 1000, the material is rejected.	is nationally recognized standard.
North Dakota		
Oregon	for MSE, if resistivity <5000 chloride and sulfate tests taken. For culvert, if below threshold galvanized steel not to be used.	based on a Fed study for MSE wall backfil.
Pennsylvania	Some limits are threshold values where other materials would be used. Some limits are values where a sacrificial thickness would be added to the base metal thickness, or protective coatings would be used. Our Design Manual lays out our criteria.	The test methods noted above are for in-house testing. Other test specifications (AASHTO or ASTM) may be used by consultants and their outside labs during the design phase.
Puerto Rico		
South Carolina	Retaining wall design is reevaluated for other possible configurations.	It is an AASHTO test procedure recognized as part of accreditation program.
South Dakota		
Texas	select backfill for MSE wall is rejected	Corrosion resistance. The test procedures requested above can be found on the internet at www.dot.state.tx.us , Business, TxDOT Manuals, Materials and Tests, Manual of Testing Procedures, Soils.
Utah		UDOT corrosion equations were developed using specific test protocol which if not followed will not allow repeaytable test results.
Washington	alter material used	historical usage
West Virginia	The test results are used to determine the type of pipe or coatings required. For MSE WALLS the tests are performed to determine if a backfill material is satisfactory to use.	We try to use AASHTO whenever possibe.
Wyoming	Different types of materials are recommended for use depending on the test values obtained for resistivity and pH.	We use ASTM or AASHTO specifications for uniformity and standardization.

State	Soil sample preparation		If more than one resistivity or pH	
	Resistivity	pH	Resistivity	pH
Alabama		deionized water extraction		
Alaska		Corning		
Arkansas				
Colorado				
Connecticut				
Florida	used in conjunction with Nilsson model 400 resistance meter			
Georgia				
Hawaii	prepare 1000 gram of soil sample passing No. 8 sieve	mix 50 gr. Of soil sample & 50 gr. Of distilled water in glass beaker. Immerse probe until display is stable		
Idaho	as per AASHTO 288	as per AASHTO 289		
Illinois				
Indiana		material passing a #10 sieve		only one used
Kansas	Sieve dry soil add 30 ml of water and mix after each test. Continue to add water, 20 ml and test until resistivity reaches lowest value. Soil box samples are rarely used. ASTM G57-78	Mix approximately 50 ml of soil with 50 ml of distilled water, stir allow to settle out then test water for pH.		
Maryland	dried, graded to no.10 material	ASTM requirements		prefer pH which is a simple test based on pH test results. If above desirable limit, then may run resistivity tes.
Michigan	according to AASHOT T288	according to AASHOT T 289		

Minnesota				
Mississippi				
Missouri				
Montana (C)	AASHTO T288			
Montana	one part soil to two parts distilled water	saturated paste		
Nebraska	Dried at 50 degrees C, crushed, passed through No. 8 sieve.	Dried at 50 degrees C, crushed and passed through No. 8 sieve		
Nevada				
New Hampshire				
New Jersey				
New Mexico				
New York	AASHTO T288	AASHTO T289		
North Dakota				
Oregon	air dry soil, mix, crush (without crushing rocks), sieve over a 2.36mm (#8) sieve.	air dry soil, mix, crush (w/o crushing rocks), sieve over a 4.75mm (#4) sieve.		
Pennsylvania				
Puerto Rico				
South Carolina		AASHTO T289		

South Dakota				
Texas	According to Tex-129-E	According to Tex-128-E		Any meter meeting the test procedure apparatus requirements is acceptable.
Utah				
Washington				
West Virginia	Material is ground to -200	Material is ground to -200		
Wyoming		50 grams of soil with 50 grams of water		

State	Briefly describe if any in-house modifications have been developed for any of the test procedures or result interpretation method
Alabama	
Alaska	
Arkansas	
Colorado	
Connecticut	
Florida	
Georgia	
Hawaii	
Idaho	
Illinois	
Indiana	
Kansas	For the soil pH 50 ml of soil are placed in a beaker and 100 ml of distilled water is added. The material is then mixed, allowed to stand for a short time and the pH is tested.
Maryland	
Michigan	
Minnesota	
Mississippi	
Missouri	
Montana (C)	Research is in progress to develop a reliable test method that models in situ soil conditions and can be correlated to observed corrosion and case studies
Montana	

Nebraska	<p>Question 12, Note (1) - For galvanized steel the pH of the soil and water where it is used should be 6.0 to 8.0. For galvanized steel the minimum soil resistivity should be equal to or greater than 2500 ohms/per cubic centimeter. For aluminum coated steel the pH of the soil and water where it is used should be 5.0 to 9.0. For aluminum coated steel the minimum soil resistivity should be equal to or greater than 1500 ohms/per cubic centimeter. (Information provided by Stan Karel, Physical Tests Supervisor, voice: 402.479.3849; email: skarel@dor.state.ne.us)</p> <p>Question 10, Note (2) - Test Methods: pH: AASHTO M-288 and Resistivity: AASHTO M-289. Question 13 Note (3) NDOR has the capacity to do some tests in-house, but mainly accept contractor's certification. Note (4) Type of electrode: Futural Quartz Reference Electrode and Futura Glass Indicating Electrode. (Information for questions #13 - #15 and Notes (2) - (4) provided by Bruce Norton, Chemical Tests Manager, voice: 402.479.4758; email: bnorton@dor.state.ne.us.)</p>
Nevada	
New Hampshire	NHDOT specifications require contractor building MSE structure to provide Certificate of Compliance certifying that the select granular material meets the specified electrochemical values
New Jersey	
New Mexico	
New York	
North Dakota	
Oregon	ASTM G57 is a fairly vague test method and does not include pH testing, creating the need for our own TM107
Pennsylvania	
Puerto Rico	
South Carolina	
South Dakota	South Dakota uses a soil database developed in conjunction with the Soil Conservation Service as part of their soil mapping projects for each county. Their publications include a section on Engineering Properties of Soils which characterizes each soil type with respect to potential corrosivity based on pH, resistivity and sulfate, in regard to both metal and PCC in contact with each soil type. We have a compiled list of typical soils with a corrosivity rating which is used to decide on culverts and other components on or below ground surface. Occasionally, pH and resistivity data are obtained for special situations but never on a routine basis.
Texas	Help us improve our corrosion specification for MSE retaining wall reinforcement.
Utah	Corrosion issues in Utah are driven by the fact that being a "great basin" state and an arid climate pH is essentially always greater than 7 and thus a different set of reactions etc. are driving the corrosion environment.
Washington	
West Virginia	
Wyoming	Use 1/2 the weight of soil with 1/2 the volume of water in increments for resistivity measurements.

State	Please give any additional comments or information on instruments and procedures used or on any of the preceding questions
Alabama	attached procedures for selecting roadway pipe type
Alaska	
Arkansas	
Colorado	
Connecticut	
Florida	
Georgia	Q6-culverts & pipe: Corrugated Steel Pipe resistivity is >8000 ohm/cm & pH is b/w 6-10.5; Corrugated aluminum resistivity >1500 ohms/cm & pH b/w 4.5-9; Corrugated Steel resistivity is >3000 ohms/cm & pH is b/w 5-9
Hawaii	
Idaho	pH limits for other types of pipe ... READ SHEET!!!
Illinois	Because there are a variety of instruments to choose from, it is especially important that electrodes and calibration media be selected which can be readily made and/or obtained, and have reliably purity and results. The correlation between 4-pin testing and soil box sampling is very important.
Indiana	
Kansas	Water is also tested for total dissolved solids and pH for metal pipe installation. Cole-Parmer TDS testers are presently in use.
Maryland	
Michigan	
Minnesota	seldom do this type of testing unless have reason to believe may need to check it as in case of the mine tailings used as borrow material. pH, soluble salts, extractable potassium and phosphorus are done on a routine basis. Soluble salt is measured by a conductivity method. Soil resistivity has only been run once in the last 10+ yrs. Other testing may have been done my MN Road Research people but no response was submitted. The response was coordinated with Reasearch, Chem. Lab, Geotechnical Engineering and Bridge
Mississippi	
Missouri	
Montana (C)	You may wish to query the following laboratories as they provide the private consultants with "resistivity" data: Alpine Analytical, Helena, Montana; Energy Laboratories, Billings, Montana; and Advanced Terra Testing, Lakewood, Colorado
Montana	
Nebraska	
Nevada	
New Hampshire	

New Jersey	
New Mexico	
New York	We would like to determine if the values stated in our specifications are realistic, and provide performance comparable to the model we use to design MSES structures.
North Dakota	
Oregon	
Pennsylvania	I'm not clear what the intent/scope of the research is, so I'm commenting from that standpoint. I'm not convinced that accelerated testing for corrosion is predictive of actual long-term degradation. I would like to see more clear guidelines on soil side vs. water side parameters for metal culvert corrosion rates, limits for thermoplastic pipes if needed, and clear, cost-effective, constructable guidelines for mitigation measures, including additives for concretes, linings, coatings, etc. for all material types.
Puerto Rico	
South Carolina	
South Dakota	
Texas	
Utah	yes, any info you may accumulate having to do with the corrosion of Aluminized Type II materials in the alkaline environment.
Washington	
West Virginia	
Wyoming	

State	Is there any specific outcome(s) to this research that would assist you or others within your organization in corrosion control matters?
Alabama	
Alaska	sea water corrosion rates
Arkansas	
Colorado	
Connecticut	
Florida	uniform standards for test site location, conducting tests and interpreting results
Georgia	
Hawaii	
Idaho	
Illinois	The establishment of a standardized ASTM procedure for instrument calibration and field & laboratory use would be very helpful. This would be subsequently adopted by AASHTO. DOTs rely heavily on standard methods to minimize contention and permit contractors or consultants that primarily operate in other states to bid on projects.
Indiana	
Kansas	
Maryland	hope to improve capabilities to match the best construction material for a particular subsurface situation. Understanding the available testing equipment, techniques, and practices will assist MD SHA in making these types of decisions. Also like to do this at minimal cost and time while maintaining high quality test results.
Michigan	
Minnesota	
Mississippi	
Missouri	
Montana (C)	
Montana	
Nebraska	
Nevada	
New Hampshire	
New Jersey	
New Mexico	
New York	
North Dakota	
Oregon	
Pennsylvania	
Puerto Rico	
South Carolina	
South Dakota	
Texas	
Utah	
Washington	
West Virginia	
Wyoming	