NCHRP Research Report 958 Pre-Publication Draft— Subject to Revision

Improved Test Methods and Practices for Characterizing Steel Corrosion Potential of Earthen Materials

Kenneth L. Fishman McMahon & Mann Consulting Engineering and Geology, P.C. Buffalo, NY

> Soheil Nazaria Shane Walker Arturo Bronson The University of Texas at El Paso El Paso, TX

> > June 2020

DISCLAIMER

The opinions and conclusions expressed or implied in this document are those of the researchers who performed the research. They are not necessarily those of the program sponsors; the FHWA; the Transportation Research Board; or the National Academies of Sciences, Engineering, and Medicine. The information contained in this document was taken directly from the submission of the authors. This material has not been edited by the Transportation Research Board.

SPECIAL NOTE: This document IS NOT an official publication of the Transportation Research Board or the National Academies of Sciences, Engineering, and Medicine. A final, edited version of this document will be released at a later date.

> The National Academies of SCIENCES • ENGINEERING • MEDICINE

> > TRANSPORTATION RESEARCH BOARD



NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply endorsement by TRB and any of its program sponsors of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

DISCLAIMER

To facilitate more timely dissemination of research findings, this pre-publication document is taken directly from the submission of the research agency. The material has not been edited by TRB. The opinions and conclusions expressed or implied in this document are those of the researchers who performed the research. They are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; the FHWA; or the program sponsors.

The Transportation Research Board, the National Academies, and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

This pre-publication document IS NOT an official publication of the Cooperative Research Programs; the Transportation Research Board; or the National Academies of Sciences, Engineering, and Medicine.

Recommended citation: Fishman, K. L., S. Nazarian, S. Walker, and A. Bronson. 2020. *Improved Test Methods and Practices for Characterizing Steel Corrosion Potential of Earthen Materials*. Prepublication draft of NCHRP Research Report 958. Transportation Research Board, Washington, D.C.



Summary	1
Chapter 1. Background	7
1.1. Introduction	7
1.2. Research Objectives	7
1.3. Review of Current Practices for the Characterization of Corrosion Potential of	Q
Earthen Materials	ð
1.3.1 Factors Affecting the Corrosion Potential of Geomaterials	ð
1.3.2 Current Laboratory Test Methods.	9
1.3.2.1 Comparison of Different Resistivity Test Methods	10
1.3.3 Limitations of Current Test Methods	15
1.4. Knowledge Gaps and Study Purpose	15
Chapter 2. Research Approach	16
2.1. Introduction	16
2.2. Phase I	16
2.2.1 Task 1 – Information Search	16
2.2.2 Task 2 – Identify Limitations of Approaches for Characterizing Materials	16
2.2.3 Task 3 – Developed Detailed Work Plan	16
2.2.4 Task 4 – Submit Interim Report	16
2.3. Phase II	17
2.3.1 Task 5 – Conduct Work Plan Approved in Task 4	17
2.3.2 Task 6 – Prepare Work Plan for Field Trials	17
2.4. Phase III	17
2.4.1 Task 7 – Implement Work Plan for Field Trials	17
2.4.2 Task 8 – Propose Protocol	17
2.4.3 Task 9 – Prepare Final Report	17
Chapter 3. Laboratory Measurements (Phase II)	18
3.1. Introduction	18
3.2. Description of Data Set	18
3.3. Comparison of Results from Different Test Methods	22
3.3.1 Resistivity	22
3.3.1.1 Precision/Repeatability for Individual Test Methods	23
3.3.1.2 Comparison of Different Resistivity Tests with AASHTO T-288 (2016)	24
3.3.2 Salt Contents	29
3.3.2.1 Correlations between Salt Contents and Resistivity	
3.3.3 Measurements of pH	
3.4. Characterization of Corrosion Potential and Correlations with Corrosion Rates	36
3.4.1 Correlation between Resistivity and Performance Data	37
3 4 1 1 Performance of Galvanized Steel	38
3.4.1.2 Performance of Plain Steel	41
3 4 2 Classification of Soil Corrosivity	
3 4 2 1 Characterization Scheme	
3 4 2 2 Correlation between Results of Characterization Scheme and	······ T
Performance Data	46
3.5. Recommended Protocol	49

Contents

Chapter 4. Field Measurements (Phase III)	51
4.1. Introduction	
4.2. Description of Data Set	51
4.3. Results	55
4.3.1 Resistivity – Soil Boxes	55
4.3.2 Resistivity – Field Tests using Wenner Technique	57
4.3.3 Other Electrochemical Properties	63
4.4. Comments and Suggestions from Owners	65
4.5. Conclusions	66
Chapter 5. Conclusions and Needs for Future Research	68
Chapter 5. Conclusions and Needs for Future Research 5.1. Main Conclusions	68
Chapter 5. Conclusions and Needs for Future Research 5.1. Main Conclusions 5.2. Recommendations for Future Research	68 68 69
Chapter 5. Conclusions and Needs for Future Research 5.1. Main Conclusions 5.2. Recommendations for Future Research References	68 68 69 72
 Chapter 5. Conclusions and Needs for Future Research	68 68 69 72
 Chapter 5. Conclusions and Needs for Future Research	

List of Figures

Figure 1-1 Resistivity measurement using a two-electrode soil box.	12
Figure 1-2 Resistivity versus moisture contents (adapted from McCarter, W.J. (1984)).	12
Figure 1-3 Procedure to perform a typical leach test.	14
Figure 3-1 Characteristics of the sample domain used in the laboratory investigations.	21
Figure 3-2 Summary of the test results for measuring resistivity/conductivity	23
(a) precision	
(b) bias with respect to AASHTO T-288.	
Figure 3-3 Comparisons of soil box test results relative to AASHTO T-288.	25
Figure 3-4 Statistics of resistivity test bias with respect to AASHTO T-288 (2016)	
(a) bias means and standard deviations	25
(b) coefficients of variation (COV = $\sigma_{\text{bias}}/\mu_{\text{bias}}$)	26
Figure 3-5 Resistivity measurements from samples with different textures	
(a) mean bias	27
(b) coefficients of variation	28
Figure 3-6 Tests for measurements of salt content, and observations of precision.	30
Figure 3-7 Correlation between salt content measurements from Tex-620-M	
and AASHTO T-290 & T-291.	31
Figure 3-8 Summary of the test results for measuring pH	35
(a) precision	
(b) bias with respect to AASHTO T-289 (2018)	
Figure 3-9 Comparisons of pH measurements relative to AASHTO T-289 (2018).	36
Figure 3-10 Galvanized steel corrosion rates and resistivity measurements from	
Samples with more than 22% passing the No.10 sieve	
(via AASHTO T-288 (2016))	39
Figure 3-11 Galvanized steel corrosion rates and measurements of resistivity	
from samples with less than 22% passing the No.10 sieve	
(via Tex-129-M)	40
Figure 3-12 Galvanized steel corrosion rates and measurements of resistivity from	
worldwide data. Testing with AASHTO T-288 (2016) from samples	4.1
with more than 22% passing the No.10 sieve	41
Figure 3-13 Plain steel corrosion rates and measurements of resistivity from	
AASH10 1-288 (2016) and samples with more than	40
22% passing the No.10 sieve.	42
Figure 5-14 Flowchart of the proposed protocol.	50
Figure 4-1 Locations and coordinates of construction sites.	55 54
Figure 4-2 Oradation curves from different sources.	54
(a) Schematic	55
(a) Schematic (b) Test Set up	55
(b) Test Set-up Figure 4.4 Comparison of registivity regults obtained from modified soil how tests	56
Figure 4-5 The Wenner 4-probe technique	50
(a) Schematic	57
(h) Test setup in the field	58
Figure 4-6 Locations, zones and directions for performing soil resistivity measurements	50

(a) San Antonio, TX	58
(b) El Paso, TX	59
(c) Buffalo, NY	59
(d) Schroon, NY	59
Figure 4-7 Results from in-situ testing.	
(a) San Antonio, TX – parallel to reinforcements	60
(b) San Antonio, TX – perpendicular to reinforcements	60
(c) El Paso, TX – parallel to reinforcements	60
(d) El Paso, TX – perpendicular to reinforcements	60
(e) Buffalo, NY – parallel to pavement	61
(f) Buffalo, NY – perpendicular to pavement	61
(g) Schroon, NY – parallel to pavement	61
(h) Schroon, NY – perpendicular to pavement	61
Figure 4-8 In-situ measurement of moisture content at Schroon, NY.	62
Figure 4-9 Extrapolating the moisture-resistivity curves to determine the resistivity	
at in-situ moisture content for the site in Buffalo, NY.	63
Figure 4-10 Comparison of chloride content results obtained from samples collected	
from the sites and sources	64
Figure 4-11 Comparison of sulfate content results obtained from samples collected	
from the sites and sources	65
Figure 4-12 A mixer used in at Soils Engineering Laboratory of NYSDOT	66
Figure B-1 Histogram of bias in salt measurements fromTex-620-M	89
Figure B-2 Correlation between bias in salt measurements fromTex-620-M	
and percent passing the No. 10 sieve used to characterize the sample.	90
Figure B-3 Correlation of bias from Tex-129-M with respect to scaling parameter.	93

List of Tables

9
13
14
19
28
33
33
38
44
45
45
47
47
48
48
52
54
63
64
83
84
85
85
86
87
88

Author Acknowledgements

The research reported herein was performed under NCHRP Project 21-11 by McMahon & Mann Consulting Engineering and Geology, P.C. (McMahon & Mann) and the University of Texas at El Paso (UTEP). Dr. K.L. Fishman, P.E. from McMahon & Mann was the principal investigator and Professors S. Nazarian, S. Walker, and A. Bronson from UTEP were co-principal investigators. Personnel from McMahon & Mann including Messrs. Cody Coonradt, Jim Bojarski, P.E., Chad Giesler, Jon Whiting, Brad Armstrong, P.E., and Ms. Kaitlyn Murray, P.E. and Sonia Pang assisted with the literature review, sampling, and data analyses for the project. Dr. Hamid Fakhri from McMahon & Mann was instrumental in implementing the verification study conducted in Phase III of this research and in preparing this report.

We are grateful to the many graduate and undergraduate research assistants from UTEP who undertook the extensive laboratory test program that was a large part this research including Jose Luis Arciniega Aguilar, Diana Cabrara, Troy Svede, Mathew Gonzales, Luisa Morales, Daniela Hernandez, Yadira Calderas, Miguel Perez, and Luis Lemus. The lab technicians from UTEP including Jose Garibay, Sergio Rocha, and Cesar Tirado are also acknowledged for their contributions to the laboratory test program as well as for collecting information from the Texas sites incorporated into the implementation study conducted during Phase III.

We received considerable assistance to procure samples of fill for the laboratory test program from the New York State Department of Transportation (NYSDOT), the North Carolina Department of Transportation (NCDOT), the Florida Department of Transportation (FDOT), the Expanded Shale, Clay and Slate Institute (ECSI) and from contactors and aggregate suppliers in New York, South Carolina; British Columbia, Canada, and Alberta, Canada. Samples of fill were obtained from in service MSE structures and involved the use of excavation equipment, drilling equipment, traffic control, associated crews and utility clearances that were donated as part of the assistance provided by these agencies.

Personnel from these agencies who contributed include Joe DiGregorio, P.E., (NYSDOT, Structure Foundations Section Supervisor), Chris Nebral P.E. (NYSDOT, Geotechnical Engineering Bureau, Geotechnical Engineer), Joe SantaMaria, P.E. and Tim Wolff, P.E. (NYSDOT, Region 2, Regional and Assistant Geotechnical Engineer), Darryl Byers, P.E. (NYSDOT, Region 4, Geotechnical Engineer), Todd Nelson, P.E. (NYSDOT, Region 5, Geotechnical Engineer), John Wheeler (NYSDOT, Region 8, Construction), Aquifer Drilling and Testing, Inc. (NYSDOT, Region 8, drilling contractor); Messrs. Brian Hunter, Cabell Garbee, and Todd Whittington (NCDOT, Materials and Test Unit); Dr. Mohammed Mulla, P.E., and Messrs. Scott Hidden, P.E. and John Pilipchuk P.E. (NCDOT, Geotechnical Engineering Unit), Messr. Kyle Brashear, (QA Supervisor, North Carolina East District, Martin Marietta, Clark Quarry, New Bern, North Carolina); Messr. Rodrigo Herrera, P.E. (FDOT, Structures Design Office), Dr. David Horhota (FDOT, State Geotechnical Materials Engineer), Messr. Ron Simmons (FDOT, State Materials Office), and the FDOT District 5, Ocala Operations Office; Messr. John Johnson, P.E., (Project Manager, CDM Smith, Inc., SCDOT, Horry County DPW), Messr. Brian Bennett (Project

Manager, Windley Contacting, Ltd., British Columbia, CA); Messr. Barre Johnson (Kiewit Graham Ledcor Constructors, Calgary, Alberta CA); and Messrs. Bill Wolfe and Jack Moore (ESCSI).

Ms. Monica Ruiz and Messr. Richard Izzo (TXDOT); Messrs. Mathew Van Wicklen and Jacob Fuentes, P.E. (Raba Kistner Consultants, Inc.); Messrs. Joe DiGregorio, P.E., (NYSDOT, Structure Foundations Section Supervisor) and Brett Dening, (NYSDOT Soils Engineering Laboratory Supervisor) graciously facilitated access to sites included in the implementation study for Phase III, provided much needed background information for the sites, and performed sampling and laboratory testing for comparison with the results from the research team.

The authors are sincerely grateful to the members of the Association for Mechanically Stabilized Earth (AMSE) for the helpful comments, discussions and feedback during the course of this research.

SUMMARY

Study Purpose

NCHRP Project 21-11 aims to assess and improve the current methods for characterizing the steel corrosion potential of earthen materials. Electrochemical properties of earthen materials such as electrical resistivity, pH, salt concentrations, and organic contents are commonly used to characterize the corrosion potential of buried metal elements that are in direct contact with the surrounding soil. AASHTO test standards, adopted in the early 1990s, are among the most common practices in the United States to determine the electrochemical properties of earthen materials. However, these methods do not consider the vastly different characteristics of earthen materials used in infrastructure construction, nor do they distinguish issues inherent to particular applications. AASHTO T-288 (2016) requires a portion of the fill finer than the No. 10 sieve to determine the resistivity of specimens compacted within a relatively small soil box. This gradation affects the conductivity of the soil by altering the soil texture and may lead to resistivity results which are different than the original soil (i.e., resistivity of a fine grain soil is generally lower than a coarse grain soil). Hence, the limitations associated with the current AASHTO test standards must be recognized and alternatives need to be considered to address these limitations.

The main product from this research is a test protocol for sampling, testing, and charactering the steel corrosion potential of earthen materials. The specific research objectives are: (1) to identify, sample, and characterize representative earthen materials; (2) to determine the effects of different electrochemical measurement techniques and different specimen preparation procedures (e.g., aggregate size) on the measured electrochemical properties of the soil and leachate samples; (3) to establish links between laboratory and field measurements for proper interpretation of laboratory test results; and (4) to develop a test protocol and corresponding characterization of corrosion potential that more accurately reflects the corrosivity of earthen materials compared to the conventional methods.

Approach

We performed this study in three phases. Phase I (Literature review) includes a search and review of existing information, synthesis of national and international practices, the identification and prioritization of knowledge gaps, and preparation of a draft protocol for sampling, testing, and evaluating steel corrosivity of earthen materials. Phase II (Evaluation) includes a systematic study of alternative test methods for measuring electrochemical properties in the laboratory, algorithms for assessment of the corrosion potential of earthen materials, and further development of the protocol. Phase III (Validations), evaluates the practicality of the proposed protocol and alternative laboratory test methods (investigated in Phase II).

We studied alternative laboratory test procedures for measuring electrochemical properties of soils applied to a sampling domain incorporating a broad range of materials (mostly those commonly used in MSE wall constructions). The data included characterization of different sample sources (e.g., maximum particle size and gradation) along with the measurements of geochemical and electrochemical properties of the samples including resistivity, pH, chloride, and sulfate contents.

We documented performance data (i.e., corrosion rates) of plain and galvanized steel specimens, embedded in 19 of these sources. While electrochemical test results were used to characterize the corrosion potential of each source, the performance data were used to correlate these characterizations to the corrosion rates.

Alternatives to AASHTO tests to measure soil resistivity include ASTM G-187 (2018), Tex-129-E (1999), Tex-129-M, ASTM WK24261, SCT 143 (2008) and Tex-620-M. Resistivity test methods are of two general types that include (1) measurements of voltage drop in response to an applied current passing through the compacted soil sample in a soil box (galvanostatic test), or (2) conductivity measurements on aqueous solutions extracted from soil samples (leachates). Other differences between the tests are in terms of sample treatments that may include sieving, air drying, heating, methods of mixing, time of settling/curing, and filtering. Test methods ASTM WK24261 and Tex-129-M are new test methods (under development) that are currently being considered for implementation by ASTM and TxDOT. Tex-129-E (1999) is the current TxDOT standard that may be superseded by Tex-129-M.

In general, tests for pH and salt content are performed on extracts obtained after diluting a small soil sample with deionized water. Specific details of specimen preparation such as the size of the soil sample, fraction of soil included in the sample (e.g., portion finer than sieve No. 10), dilution ratio, soaking period, method and time of mixing, and filtration of solids vary amongst the different test procedures. These factors can significantly affect the obtained electrochemical results.

Alternatives to AASHTO tests for measurement of pH include ASTM D4972 (2019), SCT 143 (2008), Tex-128-E (1999), Tex-620-M, a procedure developed by CorrTest and described as part of NCHRP Project 21-06 (2009), and a new test method which is currently under consideration by ASTM Committee D18. The latter two test methods and Tex-620-M are applicable to measure the pH for relatively coarse-grained materials, while the other tests are more applicable to measure pH for finer materials.

Alternatives to AASHTO tests to measure soluble salt contents include Tex-620-J (2005) and Tex-620-M. In addition, ASTM D4327 (2017) provides a more robust technique which uses ionexchange chromatography (IC) to determine soluble salt contents including chloride and sulfate ion content as well as other anions that are more applicable to drinking and wastewaters. This technique can be applied to the samples that are prepared in accordance with AASHTO T-290 (2016) and AASHTO T-291 (2013). In addition, the sulfate and chloride contents can be determined from the same specimen when using IC.

We compared results obtained from different test procedures in terms of (a) precision/repeatability of the results, (b) bias of the results compared to those obtained from the current AASHTO tests, and (c) trends we identified from the data. We made these comparisons to check whether any of the procedures perform better than others in terms of repeatability, precision, and bias. We also identify cases where the results from different test methods are similar, and where the results are different. For cases where differences in results are observed, we performed further analyses to identify the best result for characterizing the steel corrosion potential.

Precision and Bias

Resistivity

- The best precisions are observed from Tex-620-J (2005), Tex-129-E (1999), Tex-129-M, and Tex-620-M with repeatability ranging from 6.8% to 7.6%.
- The precisions from the other test methods are less with repeatability ranging between 9.1% and 13.2%. Results from ASTM WK24261, with a repeatability of 13.2%, have the poorest repeatability compared to the other test methods for resistivity.
- Results from tests performed on leachates extracted from soil-water mixtures (Tex-620-J (2005), Tex-620-M, and SCT 143 (2008)) have repeatability comparable to what is achieved from the soil box tests (Tex-129-M, Tex-129-E (1999), ASTM G-187 (2018), AASHTO T-288 (2016), and ASTM WK24261).
- Results obtained from the Texas modified procedures for the measurement of resistivity/conductivity (Tex-129-M and Tex-620-M) have improved repeatability compared to those obtained from AASHTO T-288 (2016), SCT 143 (2008), ASTM G-187 (2018), and ASTM WK24261.
- The mean bias is approximately one for Tex-129-E (1999) with a coefficient of variation (COV) of 22%. The results from Tex-129-E (1999) and AASHTO T-288 (2016) were close because of the similarities between these test methods. The two tests differ in terms of the sieve size used to separate the specimen from the sample (No. 8 vs. No. 10) and the 12-hour curing period prescribed by AASHTO T-288 (2016) for the first moisture increment. For the sand and gravel materials that were tested in this study, these differences did not have a significant impact on the results. Other test procedures show mean bias values that are noticeably higher than 1.00 (as high as 5.22 in Tex-620-M) with COVs generally higher than 50%.
- The mean bias is greater for test procedures that involve coarser gradations (i.e., ASTM G-187 (2018), Tex-129-M, and ASTM WK24261). ASTM G-187 (2018) includes particle sizes up to 1/4", but Tex-129-M and ASTM WK 24261 both include particle sizes up to 1 3/4". This is reflected in the mean bias values, which are higher for results obtained from ASTM WK 24261 and Tex-129-M compared to those from ASTM G-187 (2018). The bias from ASTM WK24261 is higher than that from Tex-129-M due to the manner in which measurements are taken after the sample is drained for ASTM WK24261.
- We grouped the data from each test method according to the fineness of the samples (fine sand, coarse sand, and gravel). We observed that, as the coarseness of the sample increases, the mean bias and the COV increase. Considering materials characterized as fine sand, and results from the soil-box tests, the average mean bias is close to one with a relatively low COV (average COV = 8%). On the other hand, the biases for coarse sand and gravel are 1.6 and 3.1, respectively considering results from Tex-129-M which includes coarse particles within the test specimen. Also, the COV_{bias} increase incrementally for materials characterized as coarse sands and gravels, where COVs in excess of 30% are observed.
- The mean biases for the tests on compacted soil specimens and tests performed with leachates are 2.13 and 2.95, respectively. We expected the observed differences because we cannot include the effects from tortuosity using conductivity measurements from leachate.

• Biases from tests on the leachates are all greater than one, even for samples that are separated into finer components (e.g., for Tex-620-J (2005) the sample is separated on a No. 40 sieve). This is due to the different dilution ratios and methods of mixing and extracting leachates used in different leaching tests compared to soil box tests.

Salt Content

- Precision/repeatability is similar among test methods for measurements of salt contents.
- Higher salt contents are measured via Tex-620-J (2005) compared to the AASHTO tests; salt contents from Tex-620-M are generally lower than other test methods.
- The best correlations between salt contents and resistivity measurements are obtained from the AASHTO test standards.

pН

- Measurements of pH from Tex-620-M are less repeatable compared to measurements from other test methods investigated in this study.
- In general, Tex-620-M renders pH values that are higher compared to those obtained from the other test methods investigated in the study.
- Results from NCHRP 21-06 (2009) are more repeatable and do not have a significant bias compared to AASHTO T-289 (2018).

Correlation with CR

We used the coefficient of determination, R^2 , between the corrosion rate and resistivity measurements as an index to rank the accuracy of the obtained results from each of the resistivity tests that were included in the test program. Resistivity is often considered to be an indicator of corrosivity as this single parameter is correlated with numerous factors that play roles in corrosion reactions, including salt and moisture contents (King 1977; Romanoff 1957).

The data set for the regression analysis included measurements from 19 sample sources incorporating 28 measurements of corrosion rates. Observed corrosion rates included 18 data points from galvanized steel specimens and 10 data points from plain steel specimens. Measurements presented herein are the maximum observed from each site/source. We use the maximums to consider the durability of the most vulnerable elements. The data set included the in-situ measurements of corrosion rates and corrosion rates measured from laboratory tests.

We conclude that results from Tex-129-M apply well to materials with less than approximately 22% passing the No.10 sieve. For materials with more than 22 percent passing a No.10 sieve, AASHTO T-288 is appropriate for the measurement of resistivity. We used these observations to develop the proposed protocol presented in Appendix A.

Recommended Protocol

We incorporated recommendations into the proposed protocol that are based upon results from our analyses of the data collected in Phase II. We summarized the proposed protocol in the form of a flowchart shown in Figure 3-14. The characteristics of the materials are described in terms of

grading number (GN) and the percentage passing the No. 10 sieve. In general, the proposed protocol describes the application of the current AASHTO test series for samples with GN > 3, or if the percent passing the No.10 sieve is greater than 25%. Otherwise, if the GN < 3, and the percent passing the No.10 sieve is less than 25%, the Texas modified procedures are recommended (i.e., Tex-129-M and Tex-620-M).

Implementation Study

During Phase III of NCHRP Project 21-11, we cooperated with selected transportation agencies whereby the recommended protocol was implemented as a "shadow specification." The data included characterization of different sample sources (e.g., maximum particle size and gradation) along with the measurements of geochemical and electrochemical properties of the samples including resistivity, pH, chloride, and sulfate contents (i.e., the total salt content). The Wenner 4-probe technique (according to ASTM G57 (2012) and Wenner (1915)) was used in the field for measurement of electrical resistivity. Representative samples of fill were collected from the site or from the source. The samples were subject to electrochemical tests in the laboratory using Texas modified and AASHTO test procedures. We also evaluated the practicality and implementation of the suggested protocol through the interaction with laboratories engaged in electrochemical testing, and suppliers/owners in different states.

Data from the implementation study allowed us to compare the results obtained by different labs using the same test standards. We also performed in-situ measurements of resistivity for comparison with laboratory measurements that were obtained from specimens with the same gradation as the material placed in the field and measured at similar moisture contents.

The information and the data we have obtained from the implementation of Phase III of NCHRP Project 21-11 show the effects of reinforcements on the measurements of fill resistivity, and the benefits of orientating the lines for the Wenner 4-probe test perpendicular to the reinforcements. These data also showed the variability that is inherent to the measurements and the effects of reinforcements on these variations. We have also observed a correspondence between laboratory and field measurements of resistivity.

The experience and data collected from implementing the proposed protocol on active construction projects indicate that the modified test procedures and the test protocol for improved characterization of corrosion potential are easier to implement compared to the traditional methods. The owners/contractors were able to perform the modified test procedures, and with few exceptions could acquire the equipment needed to perform these tests. Recommendations as to which test procedures should be applied to the characterizations of corrosivity were found to be clear and easy to implement.

Organization of the Report

NCHRP Project 21-11 aims to assess and improve the current methods for characterizing the steel corrosion potential of earthen materials. The main goal of this research is to develop test protocols to promote characterization of corrosion potential for earthen materials consistent with in-service conditions and observations of field performance. This report describes the results, data collection and interpretation, conclusions and recommendations from NCHRP Project 21-11.

Chapter 1 is a summary of the advantages and shortcomings associated with the current test methods and practices for assessing the corrosivity of earthen materials (Phase I). Chapter 2 summarizes the research approaches used to achieve the main goal of the study. That chapter also summarizes the objectives and research tasks included in each phase of the project. In Chapter 3, we describe the sample domain used in the laboratory program and the results obtained from the laboratory measurements. That chapter includes discussions and comparisons between the measurements of electrochemical properties obtained from different test methods with a focus on development of recommendations and protocols for sampling and testing earthen materials and characterizing steel corrosion potential. In Chapter 4, we describe cooperation with owners/contactors and implementation of our recommendations and proposed protocol as a "shadow specification" on active construction projects. This is followed by the comparison of the laboratory test results obtained from different labs and samples from the same source. We also propose improvements to current practices for in-situ measurements of resistivity and comparisons between results from laboratory and field measurements. Chapter 5 includes conclusions and recommendations for future research.

Chapter 1. Background

1.1. Introduction

Electrochemical properties of earthen materials such as electrical resistivity, pH, salt concentrations and organic contents are commonly used to characterize their corrosion potential. AASHTO test standards, adopted in the early 1990s, are among the most common practices in the United States to determine the electrochemical properties of earthen materials. However, the AASHTO test methods do not apply to all earthen materials that encompass a broad range of physical and electrochemical characteristics, nor do they distinguish issues inherent to particular types of infrastructure construction. For example, AASHTO T-288 (2016) is used to determine the minimum resistivity (ρ_{min}) of earthen materials at a saturated or slurry state. However, a slurry state does not represent a condition that occurs during the effective service lives of earth retaining structures. The minimum resistivity obtained from such a test is not representative of the resistivity of earthen materials experienced at any time during the service lives of metal elements placed within them. Also, AASHTO T-288 (2016) specifies how test specimens are prepared by separating the sample into fractions according to particle size and only including the fraction passing the No. 10 sieve in the test specimen. Resistivity measurements for earthen materials are affected by soil texture, thus including only the finer portion of the sample within the test specimen renders resistivity measurements that are different from what would be measured if all of the particle sizes inherent to the sample were included. The AASHTO tests may not be appropriate for determining the corrosivity of coarser types of earthen materials and do not consider practical limits on moisture contents that may be experienced in the field. Results from the current AASHTO practices cannot be interpreted beyond establishing a common reference point to compare the corrosivity of different soils under laboratory conditions. This research evaluates alternative test methods that may be more appropriate for particular applications (e.g., MSE Walls), and will consider a wider range of fill types incorporating larger particle sizes.

1.2. Research Objectives

The main goal of this research is to develop a test protocol for characterizing the in-service steel corrosion potential of earthen materials. The objectives needed to achieve this goal include: (1) identifying, sampling, and characterizing representative earthen materials; (2) determining the effects of different electrochemical measurement techniques and different specimen preparation procedures (e.g., aggregate size) on the measured electrochemical properties of compacted soil or leachates extracted from the solid samples; (3) establishing links between laboratory and field measurements for proper interpretation of laboratory test results; and (4) developing a test protocol and corresponding characterization of corrosion potential that more accurately reflects the corrosivity of earthen materials compared to the conventional methods. In pursuit of these objectives, we addressed a number of questions and technical challenges, including:

- a. Quantifying sampling and testing errors associated with measurements of electrochemical properties considering:
 - a. diversity in the site and environmental conditions, earthen materials used in construction, and construction practices, and
 - b. variations in test procedures to measure electrochemical properties.

- b. Evaluating how the compositions of earthen materials and water chemistry affect measurements of electrochemical properties considering:
 - a. porosity, mineralogy, and texture (tortuosity) of earthen materials, and
 - b. the relevance of laboratory tests, test parameters and sample preparation techniques to the actual field conditions/applications.
- c. Relating laboratory measurements of electrochemical properties to performance observed from field measurements, considering:
 - a. how well sampling strategies and the end points for laboratory measurements (e.g., the final moisture content) apply to the specific field conditions;
 - b. material characterizations that are consistent with the available field performance data;
 - c. the reliability of laboratory and field tests;
 - d. service life design and asset management practices for transportation infrastructure; and
 - e. barriers to implementation.

1.3. Review of Current Practices for the Characterization of Corrosion Potential of Earthen Materials

This section summarizes the current test methods used to evaluate the corrosivity of earthen materials and presents the suggested interpretation of results. Laboratory tests for measurements of a) electrical resistivity b) chloride content c) sulfate content, and d) pH were included in the investigation. Sample preparations and limitations associated with each test method are also presented in this section.

1.3.1 Factors Affecting the Corrosion Potential of Geomaterials

Several electrochemical parameters influence the corrosivity of an earthen material, including electrical resistivity, degree of saturation, pH, dissolved salts (ions), and redox potential (Elias 1990). These properties can also be affected by contamination from constituents not typically components of soil including less common minerals from mining, and contamination from natural petroleum or manmade fertilizers. The effects from contaminants were not directly included in this study. Most salts are active participants in the corrosion reaction with the exception of carbonate, which forms an adherent protective scale on the surface of most metals and inhibits corrosion rate. According to the literature, chloride, sulfate, and sulfide are the major components promoting corrosion in steel reinforcements embedded in earthen materials/concretes (Ahmad 2003; Romanoff 1957). Given its relationship to salt content, Romanoff (1957) and King (1977) established resistivity as the most significant indicator of corrosion of metals in soils and water:

- 1) Key factors are temperature, oxygen concentration, resistivity, pH, carbonate scaling tendency, acids, alkalis, salts, soil particle size distribution, porosity, water content, and microbial activity.
- 2) The maximum corrosion occurs at a critical moisture content in a soil mass., Above the critical moisture content corrosion rate is controlled by the conductivity of the soil/water mixture (i.e., activation controlled or the rate by which electrons from the metal are transferred to oxygen

molecules through the electrolyte). Below the critical moisture content corrosion rate is diffusion controlled (i.e., controlled by the rate of oxygen diffusion towards the metal surface).

- 3) Generally, higher annual rainfall and higher temperatures produce groundwater that is highly corrosive (as temperature increases, the ion mobility and corrosivity increases).
- 4) Carbonate scaling can contribute to reduced corrosion rates, so the presence of carbonates should be considered for determining corrosivity of soils and water.
- 5) Other properties of water such as dissolved oxygen content may need to be considered for precise determination of corrosion potential.
- 6) Besides chloride, sulfate can also break down the protective passive film (or carbonate scaling) and cause pitting corrosion (William 2009). Hence, observations of the performances of metals in contact with earthen materials with higher sulfate contents, but low chloride contents, are needed to improve characterizations of corrosion potential.
- 7) The observed elevated corrosion rates at sites not initially characterized as aggressive due to the soil/water properties were mainly attributed to microbial induced corrosion (MIC). MIC is expected to be more significant in marine environments, warmer climates, and for metal in contact with soils that have a high organics content. MIC can be mitigated via use of engineered, free draining fill that is free of organics, and placement of metals in soils above the water table where there is an abundance of oxygen.

1.3.2 Current Laboratory Test Methods

Most transportation agencies evaluate electrochemical properties of earthen materials using current AASHTO laboratory test standards, which were adopted in the early 1990s. Specified test methods to measure the electrochemical properties of geomaterials are AASHTO T-288 (2016) (resistivity measurement), AASHTO T-289 (2018) (pH measurement), AASHTO T-290 (2016) (soluble sulfate content measurement), and AASHTO T-291 (2013) (soluble chloride content measurement). AASHTO describes the electrochemical requirements for fill material to be suitable for MSE wall construction as shown in Table 1-1.

Parameter	Acceptable range	AASHTO standard
Minimum resistivity	$> 3000 \Omega\text{-cm}$	T-288 (2016)
pH	5 - 10	T-289 (2018)
Sulfate content	< 200 ppm	T-290 (2016)
Chloride content	< 100 ppm	T-291 (2013)

 Table 1-1
 AASHTO requirements for the fill materials in MSE walls.

Alternatives to AASHTO tests to measure soil resistivity include ASTM G187 (2018), Tex-129-E (1999), Tex-129-M, ASTM WK 24621, and SCT 143 (2008). Resistivity test methods are of two general types that include (1) measurements of voltage drop in response to an applied current passing through specimens that are compacted in a soil box (galvanostatic test), or (2) conductivity measurements on aqueous solutions extracted from solid samples (leachates). Other differences between the tests are in terms of sample treatments that may include sieving, air drying, heating, methods of mixing, time of settling/curing, and filtering.

Test methods ASTM WK 24621 and Tex-129-M are new test methods (under development during the course of this research, 2016-2019) considered for implementation by ASTM and TxDOT.

Tex-129-E (1999) was the TxDOT standard that will be superseded by Tex-129-M. Tex-129-M is an improvement compared to Tex-129-E as it applies to testing coarse graded samples including gravel. For Tex-129-E larger particles were crushed to render specimens with all particles passing a #8 sieve. However, the geochemical behavior and electrochemical properties of crushed particles are not representative of the larger sized particles from which they were derived, and the electrochemical and geochemical activity that occurs on the surfaces of the larger particles (Bronson et al. 2013). The test procedure described in Tex-129-M allows all particle sizes up to a maximum of 1 ³/₄ inches to be include in the test specimen, and relative to Tex-129-E larger sized boxes are employed to accommodate testing coarse samples. ASTM WK 24621 also applies to coarse graded samples.

In general, tests for pH and salt content are performed on extracts obtained after diluting a small solid sample with deionized (DI) water. Specific details of specimen preparation vary amongst the different test procedures such as the size of the solid sample, fraction of earthen material included in the test specimen (e.g., portion finer than No. 10 sieve), dilution ratio, soaking period, method and time of mixing, and filtration of solids. These factors can significantly affect the obtained electrochemical results.

Alternatives to AASHTO tests for measurement of pH include ASTM D 4972 (2019), SCT 143 (2008), Tex-128-E (1999), Tex-620-M, a test procedure developed at CorrTest and described as part of NCHRP Project 21-06 (2009), and a new test method for determining pH of lightweight aggregates which was being considered by ASTM Committee D18 during the course of this research. The latter two test methods and Tex-620-M are applicable for measuring the pH of relatively coarse-grained materials, while the other tests are more applicable to finer materials.

Alternatives to AASHTO tests to measure soluble salt contents include Tex-620-J (2005) and Tex-620-M. In addition, ASTM D4327 (2017) provides a more robust technique which uses ion exchange chromatography (IC) to determine the soluble salt content. This technique can be applied to the samples that are prepared in accordance with AASHTO T-290 (2016) and AASHTO T-291 (2013). In addition, the sulfate and chloride contents can be determined from the same specimen.

We reviewed state DOT standard specifications to identify their practices for measuring electrochemical properties of earthen materials and detailed results are presented in Appendix B. Twenty-two states use AASHTO test methods, three states referenced multiple test methods, one state publishes modifications to the AASHTO methods, 12 states do not use the AASHTO methods, 15 states use different electrochemical requirements, and one state references FHWA guidance instead of AASHTO specifications for their practice.

1.3.2.1 Comparison of Different Resistivity Test Methods

Tests for measurement of soil resistivity include those performed on extracts, or on compacted specimens at moisture contents that include as-received and saturated. Resistivity measurements may be made in-situ or in the laboratory. Laboratory measurements have the advantage that the moisture content in the soil box is controllable. In order to obtain a comparable resistivity that is independent of seasonal and other variations in soil-moisture content, resistivity should be determined under the most adverse condition (e.g., at saturation). The resistivity measured in the

water-saturated soil box does not necessarily represent the actual site conditions, but provides a baseline for comparing the corrosivity of different earthen materials, and is considered as the minimum resistivity in this study.

AASHTO T-288 (2016), ASTM G-187 (2018), Tex-129-E (1999), Tex-129-M and ASTM WK 24621 are test methods for measurements of resistivity on compacted specimens. Tests performed on compacted specimens are useful to investigate the influence of moisture content, level of compaction, and particle size distribution (i.e., tortuosity of the current flow path) on specimen resistivity.

Figure 1-1 shows the typical process for resistivity measurements of earthen materials using a twoelectrode soil box used in AASHTO T-288 (2016). A sample size that includes about 1500 g of air-dried materials finer than No. 10 sieve is required for testing.

- The soil sample is placed in an acrylic plastic soil box (Figure 1-1 (a)) in layers and compacted using finger pressure (Figure 1-1 (b)). The soil box has inner dimensions of 150 mm × 100 mm × 45 mm (length × width × height).
- In order to provide a proper electrical contact between the resistivity meter and the soil, two stainless steel plates with dimensions of $150 \text{ mm} \times 45 \text{ mm}$ are affixed to the side walls of the soil box (distance between stainless steel electrodes = 100 mm).
- A measured amount of distilled or DI water, with a resistivity greater than 20,000 Ω -cm, is gradually added to the soil sample.
- The resistivity meter is then connected to the stainless-steel electrodes, as shown in Figure 1-1 (e), and an alternating current (AC) consisting of a square wave with a frequency of 97 Hz is passed through the soil sample.
- The electrical resistance is measured from the corresponding voltage drop between the two electrodes. The resistivity of the soil sample is computed by multiplying the resistance by the soil box factor, which is a function of the geometry of the box.

The process is repeated by remixing the soil sample with increasing amounts of distilled or DI water to produce resistivity measurements at various moisture contents (up to saturation state, shown in Figure 1-1 (d)). A plot of resistivity versus moisture content renders the minimum resistivity and corresponding moisture content (Figure 1-2).



Figure 1-1 Resistivity measurement using a two-electrode soil box.

AASHTO T-288 (2016), ASTM G187 (2018), ASTM WK 24621, Tex-129-E (1999), and Tex-129-M differ in terms of sample treatments (whether or not the sample is dried before distilled water is added in increments), the particle size distribution of the specimen, the manner in which the soil sample is mixed with water, and the moisture conditions during the test. In Table 1-2 we summarize the differences between different test methods in terms of sample treatment and specimen preparations. In the present research, the results from different test methods are compared to those from the relevant AASHTO standards, which serve as the nominal values. In case of soil resistivity, we make these comparisons with respect to data from the AASHTO T-288 (2016) test.



Figure 1-2 Resistivity versus moisture contents (adapted from McCarter, W.J. (1984)).

Test methods	Air/oven dry	Moisture condition		
AASHTO T-288 (2016)	air/oven dried at 60º C	< 2 mm; crushing not allowed	water added incrementally, mixed thoroughly, placed in box; 1 st increment cures for 12 hrs.	water added in increments until saturated or until reaching a minimum resistivity
ASTM G- 187 (2018)	No	Debris and particles > 1/4 inches removed	unless tested as-received, water is added and mixed as soil is placed within the box; no curing	as-received or saturated
ASTM WK 24621	No, soaked for 24 hrs. prior to testing	all sizes	similar to ASTM G-187, but aggregates have been soaked	as received/saturated then drained
Tex-129-E (1999)	oven-dried at 60° C	< 2.36 mm; crushing allowed	water added incrementally, mixed thoroughly, placed in box; no curing	water added in increments until saturated
Tex-129-M	air/oven dried at 60º C	all sizes	water added incrementally, mixed thoroughly, placed in box; no curing	water added in increments until saturated

 Table 1-2
 Comparison of different resistivity test methods in terms of sample treatment.

Test methods performed on aqueous extracts for measurement of resistivity/conductivity include Tex-620-M, the USGS Field Leach Test (Hageman 2007) and SCT 143 (2008). Leachate tests commonly include (a) preparing measured amounts of material for testing, (b) adding a measured volume of DI water to the sample, (c) agitating the mixture (simultaneous heating in some of the test methods), and (d) measuring pH, temperature, and conductivity of the aqueous solution (see Figure 1-3). The samples are syphoned via syringes and filtered before conducting the analytical tests using IC to determine the sulfate and chloride contents.

The USGS Field Leach Test (USGS FLT) applies to poorly graded sands, gravels, and aggregate mixtures. This test measures the conductivity of leachate and has the advantage that the same sample may be used for measurements of resistivity, pH, chloride, and sulfate contents. However, this test may not render meaningful results for well graded materials, where the tortuosity of the path between the particles affects the current flow and the obtained resistivity measurement.

Different test methods such as SCT 143 (2008), Tex-620-J and Tex-620-M differ with respect to sample preparations that may include sample size, dilution ratio (the weight ratio of DI water added to the soil sample), the manner in which samples are mixed with water, and whether or not the extract is filtered before the test. Table 1-3 summarizes the differences between these test methods in terms of sample preparation.



Figure 1-3 Procedure to perform a typical leach test.(a) prepare measured amounts of material,(b) add DI, (c) agitate, (d) make measurements

Table 1-3	Differences in	test methods	performed	on extracts	(leachates).
-----------	----------------	--------------	-----------	-------------	--------------

Test methods	Sample size (g)	(W:S) ¹	Mixing method	Settling time (hr.)	Filtration
SCT 143	2000	1:1	Mixed then stand for 30 minutes, agitate for 3 minutes at 0, 2- and 4-hour intervals	20	Yes
Tex-620-J	30 (separated on the #4 sieve and then pulverized to pass a #40 sieve)	10:1	Heat sample to 150°F and digest on hot plate for approximately 16 hours stirring periodically	none	Yes
Tex-620-M	100 (dried)	10:1	shake vigorously for 30 minutes	1	No; tip of electrode placed 5 cm deep into the mixture

 1 W:S = water to solids ratio (by weight).

1.3.3 Limitations of Current Test Methods

AASHTO T-288 (2016), T-289 (2018), T-290 (2016) and T-291 (2013) are performed on specimens that are separated from the sample on the No. 10 sieve. In particular, for coarse fills with little to no material passing the No. 10 sieve, a sufficient amount of fines for testing might be obtained from sieving a large quantity of the material. This process is impractical and may lead to inaccurate results, especially for gravel fills that have very little fine materials. Unless some breakage is anticipated during placement and compaction, crushing of larger aggregates to obtain the finer fraction is neither appropriate, nor allowed by the AASHTO test standards. This is because most of the soluble ions are concentrated on the surfaces of the particles (diffusions of ions through the particles are negligible). Testing the finer fractions are significant sources of soluble salts. This is not necessarily the case when using coarse fills that have very little, or no, material finer than the No. 10 sieve. In that case an alternative method of test should be considered.

1.4. Knowledge Gaps and Study Purpose

Gaps in knowledge that need to be addressed before we can recommend alternative test methods for measurements of electrochemical properties are summarized with the following questions:

- How fine does the material need to be before testing the fraction passing the No. 10 sieve is appropriate?
- How coarse should the material be before testing an aqueous extract for resistivity is appropriate?
- How do results obtained from different test methods compare?
- What is the precision and bias for individual test methods?
- How well does the proposed characterization of corrosion potential correlate with performance/observed corrosion rates?

Chapter 2. Research Approach

2.1. Introduction

We performed this study in three phases including nine tasks. Phase I, consisting of Tasks 1 through 4, included a search and review of existing information, synthesis of national and international practices, the identification and prioritization of knowledge gaps, and preparation of a draft protocol for sampling, testing and evaluating steel corrosivity of earthen materials. Phase II (Evaluation), consisting of Tasks 5 and 6, included a systematic study of alternative test methods for measuring electrochemical properties in the laboratory, algorithms for assessment of the corrosion potential of earthen materials, and further development of the protocol. During Phase III, (Validations) including Tasks 7 through 9, we evaluated the practicality of the proposed protocol and alternative laboratory test methods (from Phase II), validated and modified the proposed protocol as necessary, and facilitated implementation of the suggested laboratory test methods in the field. Brief descriptions of all tasks are presented in the following sections.

2.2. Phase I

2.2.1 Task 1 – Information Search

Task 1 consisted of three subtasks, (1) compilation of relevant literature, (2) documentation of differences between alternative test procedures, and (3) identification of the best practice for applying each test procedure depending upon material type and the environment and/or site conditions associated with particular applications. Based on that information, we developed a preliminary draft protocol with guidance for selection of test methods and assessing the corrosion potential of earthen materials, and a work plan to address the knowledge gaps that we identified.

2.2.2 Task 2 – Identify Limitations of Approaches for Characterizing Materials

We reviewed different practices to characterize the corrosion potential of earthen materials adopted by transportation agencies, and we identified the limitations associated with different practices.

2.2.3 Task 3 – Developed Detailed Work Plan

We prepared detailed plans for sampling and a program of laboratory tests to address the limitations of different practices that we identified in Task 2.

2.2.4 Task 4 – Submit Interim Report

We submitted an Interim Report summarizing the results, conclusions, preliminary draft protocol, and recommended work plans developed from Tasks 1 through 3. The Interim Report was submitted to NCHRP in January 2017.

2.3. Phase II

2.3.1 Task 5 – Conduct Work Plan Approved in Task 4

Following the NCHRP review of our Interim Report, we implemented the approved work plan developed in Task 3. This task included analyses of results from alternative laboratory tests for measuring the electrochemical properties of earthen materials. We recommended use of new or improved methods for sampling and testing based on the interpretations from these data and incorporated this information into the draft protocol.

2.3.2 Task 6 – Prepare Work Plan for Field Trials

We made plans to implement the proposed protocol as a "shadow specification" in cooperation with owners/contractors on active construction projects. This step was necessary to refine the test methods and analysis procedures based on working conditions, and to assess the practical limitations of the proposed specifications.

2.4. Phase III

2.4.1 Task 7 – Implement Work Plan for Field Trials

We implemented the workplan developed and approved in Task 6. During Task 7 we evaluated the practicality and ease-of-use of the new procedures through the interaction with laboratories engaged in testing electrochemical properties of earthen materials, suppliers of MSE wall systems and owners. We used the outcomes from Task 7 to determine whether the main technical goal of the research project for better characterization of corrosion potential as compared to the traditional methods was met.

2.4.2 Task 8 – Propose Protocol

We updated the draft protocol based on the findings and experiences from Task 7.

2.4.3 Task 9 – Prepare Final Report

This final report summarizes the findings of NCHRP 21-11 project including:

- Review of the most important parameters affecting the corrosion potential of earthen materials.
- Review of current laboratory and field practices to characterize the corrosion potential of earthen materials as well as identifying the limitations associated with each practice.
- Development of a protocol for improved sampling and testing of earthen materials.
- Recommended alternatives to the current AASHTO test procedures (AASHTO T 288-12 2016) in accordance with the recommended test protocol.
- Discussion of deficiencies in present knowledge and recommendations for future work.

Chapter 3. Laboratory Measurements (Phase II)

The following sections describe the sampling and testing program we implemented during Phase II. We used data from the laboratory test program to study the precision and bias of measurements from different test procedures. We also compared the measurements from electrochemical properties to observations of corrosion rates with respect to the same sources to evaluate the veracity of the corresponding characterizations of corrosion potential. We used this information to develop recommendations and propose protocols for sampling earthen materials, proper testing, and characterizations of corrosion potentials.

3.1. Introduction

The objectives of Phase II were to determine when test results from the current AASHTO test procedures are most applicable to characterize the steel corrosion potential of earthen materials and when alternative test methods for measurements of geochemical and electrochemical properties should be applied. During Phase II, we studied alternative laboratory test procedures for measuring the electrochemical properties of soils applied to a sampling domain incorporating a broad range of materials (mostly those commonly used in MSE wall constructions). The data include characterization of different sample sources (e.g., maximum particle size and gradation) along with the measurements of geochemical and electrochemical properties of the samples including resistivity, pH, and chloride and sulfate contents. In this chapter, we summarize the laboratory data obtained from 27 different samples of earthen materials. We documented performance data (i.e., corrosion rates) of plain and galvanized steel specimens, embedded in 19 of these sources. While electrochemical test results were used to characterize the corrosion potential of each source, the performance data were used to correlate these characterizations to the corrosion rates.

We compared the results from applying different test standards with those obtained from equivalent AASHTO tests and identified the reasons for the observed differences (i.e., the AASHTO tests were used as a reference). A brief description of the data set used in this chapter (the 27 different material samples) is presented in the next section. This is followed by the key results obtained from different test methods in the form of resistivity/conductivity, pH, and chloride/sulfate content. Finally, we discuss the trends observed within the data sets and compare the results from the alternatives with the results from AASHTO test methods. The test procedures and details about precisions and biases are tabulated and presented in Appendix B. Salient details are presented in what follows.

3.2. Description of Data Set

Table 3-1 summarizes the materials that were included in the laboratory test program for NCHRP 21-11, and their sources. We collected samples from various sources throughout North America for the laboratory test program. These sources were from New York (5 sources), North Carolina (3), South Carolina (2), Florida (1), Louisiana (1), Arkansas (1), Texas (10), British Columbia (1), and Calgary (1). Overall, we obtained 27 samples from these 25 sites. The minerology of aggregate sources included limestone (13), granite (2), sandstone (1), natural sands/silica (6), glacial till (1)

		Fine				Medium											Coarse							
	Florida	EL Paso MSE	M-U-D NY	South Carolina LWF	РІР	South Carolina GB	Pharr TX	Beaufort NC	Rochester NY	El Paso TX	Calgary AB	Prince George BC	Ashdown AR	Temple TX	Sprain Brook NY	Raleigh NC	Garden City TX	Maple Rd NY	Wake Forest NC	Round Rock TX	El Paso Coarse MSE	Louisiana LWF Crushed	Waco TX	Bastrop TX
TYPE /USCS	Sand/SP	Sand/SP	Sand/SP	Expanded Clay/SW	Sand/SW	Limestone/SW	Limestone/SP	Limestone/GP	Sand/SP	Limestone/SW	Sand/GW	Glacial Till/GW	Sandstone/GW	Limestone/GW	Limestone/GW	Granite/GP	Limestone/GP	Limestone/GW	Granite/GP	Limestone/GP	Limestone/GP	expanded clay/SW	Limestone/GW	Limestone/GP
LATITUDE	29°10'44.60"N	31°44'30.5"N	43° 8'12.86"N	33°41'4.49"N	41° 2'16.19"N	33°41'4.49"N	31°56'15.7"N	34°43'37.57"N	43° 6'36.33"N	31°56'15.7"N	50°53'33.50"N	53°38'35.60"N	33°46'18.5"N	31°06'11.0"N	41° 3'44.43"N	35°52'24.89"N	31°51'39.9"N	42°59'28.56"N	35°57'55.56"N		31°47'16.8"N			
LONGITUDE	82° 8'40.85"W	106°22'26.6"W	75°16'14.39"W	78°57'35.90"W	73°56'58.68"W	78°57'35.90"W	106°32'38.8"W	76°39'51.89"W	77°36'0.36"W	106°32'38.8"W	114° 3'15.88"W	122°39'54.35"W	94°10'54.0"W	97°21'32.2"W	73°48'25.95"W	78°34'6.30"W	101°35'32.2"W	78°47'18.76"W	78°32'30.93"W		106°31'13.6"W			
UNDER ASPHALT/CONCRETE	Samples were taken from within the median, near a corrosion monitoring station established by FDOT in 1997.		Samples retrieved from beneath a paved median, near a corrosion monitoring station during construction (2000) by NYSDOT.	Samples were taken from within the median while corrosion monitoring stations were being installed one year after construction (2016). LWF was located beneath the granular base that caped the top of the MSE wall fill.	Samples taken from borings advanced beneath the shoulder of the pavement and into the MSE fill, near the locations of corrosion monitoring stations installed by NVSDOT during construction (2000).	Samples were taken from within the median while corrosion monitoring stations were being installed one year after construction (2016). GB was placed as a cap over the expanded clay LWF.		Sample was obtained from the quary that was the source during construction. NCDOT installed Stations within the MSE wall fill during construction (2016).	Samples taken from borings advanced beneath the shoulder of the pavement and into the MSE fill, near a corrosion monitoring station that was installed after construction (1980) by NYSDOT in 2000.		Samples were obtained from a test embahkment constructed from the same sources of materials used to construct the MSE walls.	Samples taken from side hill cut near corrosion monitoring stations that were installed to monitor the performance of hollow bar soil nails that serve to stabilize the cut.	2		Samples were taken from test pits advanced beneath the paved shoulder. Metal loss and corrosion rates were observed from reinforcement samples that were exhumed and examined after the wall failure.	Samples were taken from test pits advanced behind the sloping wing walls of the abuttment for the locations of corrosion installed behind the abuttments by NCDOT during construction (2004).		Samples were taken from test pits advanced behind the slopping wing walls of the abutment for the viaduct, near the bacations of corrosion monitoring stations installed behind the abutments after the wall was constructed (1986) by NYSDOT in 1988.	Samples were taken from test pits advanced behind the sloping wingwalls of the abutment for the viaduct, near the locations of corrosion monitoring stations installed behind the abutments by NCDOT during construction (2005).					
DRAINAGE INLET NEARBY	No subdrain behind the wall.	Sample was taken from within an existing MSE wall. UTEP installed corrosion monitoring stations at this site.	Pavement edge drains and drainage inlets are located within the MSE fill.	Subdrains and drainage inlets located within MSE fill at some locations.	Subdrains are located within the median carrying stormwater to the low end of the approach, away from the abutments.	Subdrains and drainage inlets located within MSE fill at some locations.	Sample came from a quarry (Terra Firma Materials) and was sampled from a stock pile.	No drainage inlets were observed along the MSE walls.	Drainage inlets located behind the wall face.	Sample came from a quarry (Jobe Avispa Quarry) and was sampled from a stock pile. Corrosion rate measurements were obtained from laboratory measurements on steel specimens embedded within material from the stockpile sample.	Subsurface drainage is installed behind the MSE wall face.	Drainage inlets are installed at several locations along the tops of the soil nail walls.	Sample came from quary (Hanson Aggregates) and was sampled from a stock pile. Corrosion rate were obtained from laboratory measurements on steel specimens embedded within material from the stockpile sample.	Sample was taken fron an MSE wall that was deconstructed.	Drainage inlets are included within the embankment behind the wall and though to have contributed to the failure in 2016	I Drainage inlets are located within the median.	Sample came from quary (Laredo Paving, Garden City and was sampled from a stock pile. Corrosion rate measurements were obtained from laboratory measurements on laboratory measurements on steel specimens embedded within material from the stockpile sample.) No noticeable drainage inlet behind MSE wall.	Drainage inlets capture runoff from the viaduct and direct the water away from the walls.	Sample was taken from a MSE wall that was deconstructed	Sample was taken from existing MSE wall and UTEP installed corrosion monitoring stations at this site.	Sample sent to UTEP from producer in Louisiana. This sample was tested as-is, and after crushing.		
WATER RUNOFF	Surface runoff from the pavement is directed to the side slopes of the approach embankment. The viaduct spans across a railway and there are no surface waters nearby. The surroung area is relatively flat.		Paved median was originally constructed to be sloped away from the MSE wall face, but ponded water was observed. Super- elevation of the highway pavement also directs water towards the median in some locations.	Subdrains installed within the median direct stormwater to the low end of the approach (away from the abutments). The surrounding area is relatively flat.	Surfacewater directed to the paved shoulders and into drainage inlets. The viaduct crosses a creek and the bases of the MSE walls are within the stream banks.	Subdrains installed within the median direct stormwater to the low end of the approach (away from the abutments). The surrounding area is relatively flat.		Stormwater directed towards the MSE wall face due to the pavement superelevation. The surrounding area is relatively flat. Waterway is in front of the abutments and the edges of the approach are within a coastal wetland.	Subdrains direct stormwater away from the viaduct and abutments. Ranoff from the superelevated bridge decks will travel towards DJ's or to embankment slopes along the bases of the walls. Surrounding area is relatively flat.		Stormwater is directed down the side slopes of the approach embankment or collected at a point behind the abutment and directed into the pavement subdrain.	Storm and meltwaters will run down the surface of the hilisde behind the soil nail wall and into a swale at the top of the wall. The svale directs water to DI's that run down the face of the soil nail wall and discharge into the Frazier River in front of the wall.			Stormwater runoff follows along the superelevated paved shoulders to the drainage inlets located within the median or at the shoulder.	Stormwater runoff collected by the DI's is directed away from the wall		Stormwater runoff is collected from the end of the bridge deck and directed down the embankment slopes via a subdrain. The topography surrounding the site is relatively flat.	Stormwater runoff will be captured by sloping wingwall. This is a raised embankment and the topography of the surrounding area is flat.					
LOCATION ON WALL	MSE wall is an in-line abutment spanning between two bridge approaches and a median.		MSE walls serve as the abutment facing and as a grade separation along the approach. The in- line abutment spans the median.	MSE walls support the approaches to the viaduct, and include a facing that spans the median that separates this divided highway.	MSE walls support the approaches and serve as facing at the viaduct abutments. A creek flows in front of the abutments.	MSE walls support the approaches to the viaduct, and include a facing that spans the median that separates this divided highway.		MSE walls support the approach to the viaduct crossing the intercoastal waterway.	MSE walls support the approach and serve as facing to the abutments for a viaduct that crosses several highways at an intersection.		The MSE wall serves as an abutment to the viaduct which crosses a highway.	2000 feet long soil nail wall supports a side hill cut parallel to the Frazier River below the wall.			MSE walls support the approaches and the abutment to a viaduct.	MSE walls serve as abutments to the viaduct with sloping wingwalls.		MSE walls serve as abutments to the viaduct with sloping wingwalls.	MSE walls serve as abutments to the viaduct with sloping wingwalls.					
HIGH CHLORIDE/SULFATE?	Extremely low Chloride and Sulfate Content	Low Chloride and Sulfate content	Extremely low Chloride and Sulfate content	Extremely high Sulfate content and low Chloride content	High Chloride content, over acceptance limit. Low Sulfate content.	High Sulfate content over acceptance limit and extremely low Chloride content	Extremely low Chloride content and low Sulfate content		Extremely high Chloride content and low Sulfate content	High Sulfate and Chloride content over acceptance limit	Extremely high Sulfate content and low Chloride content	Extremely low Chloride and Sulfate content	Extremely low Chloride content and low Sulfate content	Low Sulfate and Chloride content	High Chloride content over acceptance limit and low Sulfate content	Extremely low sulfate and chloride ion content	High Sulfate conten just below acceptance limit and high Chloride content above acceptance limit	t High sulfate and low chloride ion content	Extremely low Chloride and Sulfate content	Extremely low Chloride content and low Sulfate content	Extremely low Chloride and Sulfate content	Extremely low Chloride and Sulfate content	Extremely low Chloride and Sulfate content	Extremely low Chloride and Sulfate content

and expanded clay light weight fill (2). In addition, we collected three separate samples from different depths at the Palisade Interstate Parkway (PIP) site in Orangeburg, New York.

We present details of each sample in Figure 3-1 in terms of (a) composition, (b) grading number (GN), and (c) percentage passing the No. 10 sieve. The samples represent a broad range of gradations and compositions ranging from fine sand to coarse, clean, and open-graded, gravel. The composition is described in terms of the percentages of gravel (% retained on ¼ inch sieve), coarse to medium sand (passing ¼ inch and retained on the No. 40 sieve), fine sand (passing the No. 200 sieve) and fines (% passing the No. 200 sieve). Sieve analyses were conducted in accordance with Tex-110-E whereby the percent passing the No. 200 sieve was determined by dry sieving. We summarize the composition of the materials as follows:

- Three samples were predominately (i.e., more than 50%) fine sand,
- Six samples were predominately coarse to medium sands,
- Two samples were mixtures of fine and coarse particles, where none of the components were equal to or greater than 50% of the total,
- Sixteen samples were predominately gravel varying from sandy gravels to clean and open graded gravels with no sand content, and
- None of the samples had more than 5% passing the No. 200 sieve.

The grading number (GN) expresses the coarseness of the sample with a number ranging from 0 to 7. The GN is computed using Equation (3-1) (Oman 2004):

$$GN = 1/100 \times (PP_{1in} + PP_{\frac{3}{4}in} + PP_{\frac{3}{8}in} + PP_{\#4} + PP_{\#10} + PP_{\#40} + PP_{\#200})$$
(3-1)

where PP signifies percent passing. The value of GN increases with respect to fineness of the sample. For example, GN equal to 0 represents a very coarse sample (> 1"), and GN equal to 7 represents a sample in which 100% of the material passes the No. 200 sieve. Values of GN in this study ranged between 0.15 and 5.65, with an approximate median of 3 (i.e., about half of the samples had GN greater than 3 and the rest had GN smaller than 3). In this study samples with GN < 3 are gravels, in which less than 12 percent of the sample (% by weight) passes the No. 40 sieve (i.e., includes little fine sand).

The percentage passing the No. 10 sieve (2 mm) is of particular interest because the current test procedures for measurements of electrochemical properties specified by AASHTO are performed on the samples after they have been separated on a No. 10 sieve. We summarize the $PP_{\#10}$ from the sample domain as follows:

- Five samples had $PP_{\#10} > 60$;
- Twelve samples had $25 < PP_{\#10} < 60$;
- Three samples had $10 < PP_{\#10} < 25$; and
- Seven samples had PP_{#10} <10



(c) Percent passing No. 10 sieve

Figure 3-1 Characteristics of the sample domain used in the laboratory investigations.

3.3. Comparison of Results from Different Test Methods

We compared results obtained from different test procedures in terms of: (a) precision/repeatability, (b) bias relative to those obtained from the current AASHTO tests, and (c) trends we identified from the data. We made these comparisons to check whether any of the procedures perform better than others in terms of repeatability, precision, and bias. We also identify cases where the results from different test methods are similar, and where the results are different. For cases where differences in results are observed, we performed further analyses to identify the best result for characterizing the steel corrosion potential. In this section, first, we describe the precision and bias from measurements of resistivity for different samples/specimens, then describe measurements of salt contents and pH. *Samples* in this report are considered to be the material that was retrieved from the source in bulk (i.e., including all particle sizes), and *specimens* to be the portions of the *samples* that are prepared (e.g., passed through a certain sieve number) for testing as prescribed by a given test standard.

3.3.1 Resistivity

We summarize the statistics describing the precision observed from testing replicates and the bias of each test procedure with respect to AASHTO T-288 in Figure 3-2. The bar graphs and error bars shown in Figure 3-2 represent means and standard deviations, respectively (mean values are presented in an ascending order). Five of the test procedures, included on the left-hand side of Figure 3-2, directly measure the resistivity of a compacted soil specimen in a soil box. The remaining three test procedures, shown on the right-hand side of the figure, measure the conductivity of a leachate extracted from a soil/water solution (the resistivity of this solution is the reciprocal of conductivity).

Soil box tests allow for the effects on resistivity from level of compaction, moisture content, and texture of the soil to be investigated. Test methods performed on the specimens compacted in a soil box include AASHTO T-288 (2016), ASTM G-187 (2018), Tex-129-E (1999), Tex-129-M, and ASTM WK 24621. These test procedures vary in terms of the particle sizes included in the test specimen, the specimen preparations prior to testing, the size of the test box (depends on the maximum particle size), and the moisture content at which the minimum resistivity is reported (see Table B-2 in Appendix B for a summary of the different test procedures).

The process for determining the resistivity from a soil box test is described in Section 1.3.2.1 (see Figure 1-1). Tests involving measurements of conductivity from leachates extracted from the solids (Tex-620-J, Tex-620-M and SCDOT T-143) include (a) preparing a measured amount of dry material for testing, (b) adding a measured volume of distilled or DI water, and (c) measuring conductivity of the extracts. In leaching tests, differences include dilution ratios (i.e., mass of water per mass of soil), methods of agitation, and the resting times, at which no agitation is applied before starting the conductivity measurements. Resistivity of the leachate is computed as the reciprocal of conductivity. Results from leaching tests cannot be directly correlated to those obtained from compacted specimens. This is because other factors including tortuosity of the electrical current path through an actual compacted specimen significantly affect the resistivity measurements.



Figure 3-2 Summary of the test results for measuring resistivity/conductivity.

We discuss details about the precision and bias of the test results obtained from different test procedures in the following subsections.

3.3.1.1 Precision/Repeatability for Individual Test Methods

We tested three to five replicates from nine different samples, for each test method. The nine samples represent a range of characteristics in terms of coarseness (gradation), source, mineralogy, and corrosivity (range of resistivity). We tested five replicates using samples from Florida; South Carolina (light-weight fill); and El Paso, Texas. We tested three replicates from six more samples from Marcy-Utica-Deerfield (M-U-D), NY; South Carolina (granular base); Pharr, Texas; Rochester, NY; Raleigh, NC; and Wake, NC. We maintained consistency between replicates by controlling the gradation of each replicate. We broke each sample down into individual grain size components and then recombined them into replicates such that that each satisfied the overall

gradation of the sample. We did this to minimize the effects of sample error on the test results such that the variation in results was mostly related to differences among the test procedures.

We computed the mean (μ), standard deviation (σ), and coefficient of variation (COV = σ/μ) from the results obtained from each set of replicates. We generated further statistics from the replicate COVs to obtain the means (μ_{cov}) and standard deviations (σ_{cov}) of the COVs observed between samples. We used the coefficients of variation between measurements to describe the precision of each test method with a ranking index (RI) as shown in Equation (3-2).

$$RI = \mu_{COV} + \sigma_{COV}$$
(3-2)

Lower RIs correspond to better repeatability of the results for a given test method. In Figure 3-2 (a), the RI values correspond to the upper limit of the error bars. The obtained RIs of the resistivity test methods range between 6.8 and 13.2 percent.

We made the following observations from the laboratory resistivity test data:

- The lowest RIs (best repeatability) are observed from Tex-620-J (2005), Tex-129-E (1999), Tex-129-M, and Tex-620-M with RI values ranging from 6.8% to 7.6%.
- The RIs from the other test methods are higher, ranging between 9.1% and 13.2%. Results from ASTM WK 24621, with an RI of 13.2%, have the poorest repeatability compared to the other test methods for resistivity.
- Results from tests performed on leachate extracted from a soil water mixture (Tex-620-J (2005), Tex-620-M and SCT 143 (2008)) have repeatability comparable to what is achieved from the soil box tests (Tex-129-M, Tex-129-E (1999), ASTM G-187 (2018), AASHTO T-288 (2016), and ASTM WK 24621).
- Results obtained from the Texas modified procedures for measurement of resistivity/conductivity (Tex-129-M and Tex-620-M) have better repeatability compared to the results obtained from AASHTO T-288 (2016), SCT 143 (2008), ASTM G-187 (2018), and ASTM WK 24621.

In the following section we compare resistivity measurements from alternative test procedures to the AASHTO tests and identify data trends.

3.3.1.2 Comparison of Different Resistivity Tests with AASHTO T-288 (2016)

We have plotted resistivity test results from Tex-129-E (1999), ASTM G-187 (2018), Tex-129-M, and ASTM WK 24621 against the resistivities obtained from the AASHTO T-288 standard (2016) in Figure 3-3. In general, the data appear to be positivity correlated; meaning materials with relatively higher resistivity values via AASHTO T-288 (2016) also showed high resistivity values via the alternative test procedures. An important observation is that the resistivities from Tex-129-E (1999) and ASTM G-187 (2018) are more strongly correlated to those obtained from AASHTO T-288 (2016) (Figure 3-3 (a) and Figure 3-3 (b)) compared to the resistivities from Tex-129-M and ASTM WK 24621 (Figure 3-3 (c) and Figure 3-3 (d)).



Figure 3-3 Comparisons of soil box test results relative to AASHTO T-288.

We normalized data from alternative test methods with respect to results obtained from the same samples tested via AASHTO T-288 (2016). We define the ratio between results from an alternative test method to that from AASHTO T-288 (2016) as the bias for the alternative test method. In Figure 3-4 we summarize the bias statistics from the alternative test procedures, where the bars represent the mean bias (μ_{bias}) in Figure 3-4 (a), and the coefficient of variation of the bias (COV_{bias}) in Figure 3-4 (b). The whiskers in Figure 3-4 (a) represent the standard deviations of the biases (σ_{Bias}).



(a) bias means and standard deviations



Figure 3-4 Statistics of resistivity test bias with respect to AASHTO T-288 (2016).

We make the following general conclusions based on the presentation of data in Figure 3-4:

- The mean bias is approximately one for Tex-129-E (1999) with a COV of 22%. These statistics are manifested in the relatively narrow band and proximity to the line of equal values depicted in Figure 3-3 (a). We expect results from Tex-129-E (1999) and AASHTO T-288 (2016) to be close because of the similarities between these test methods. The two tests differ in terms of the sieve size used to separate the specimen from the sample (No. 8 vs. No. 10) and the 12-hour curing period prescribed by AASHTO T-288 (2016) for the first moisture increment. For the materials tested in this study, these differences did not have a significant impact on the results. Other test procedures show mean bias values that are noticeably higher than 1.00 (as high as 5.22 in Tex-620-M) with COVs generally higher than 50%.
- The mean bias is greater for test procedures that involve coarser gradations (i.e., ASTM G-187 (2018), Tex-129-M, and ASTM WK 24621). ASTM G-187 (2018) includes particle sizes up to 1/4", but Tex-129-M and ASTM WK 24621 both include particle sizes up to 1 3/4". This is reflected in the mean bias values, which are higher for results obtained from ASTM WK 24621 and Tex-129-M compared to those from ASTM G-187 (2018). The bias from ASTM WK 24621 is higher than that from Tex-129-M due to the manner in which measurements are taken after the sample is drained for ASTM WK 24621.
- The mean bias for the tests on compacted soil specimens and tests performed with leachates are 2.13 and 2.95, respectively. We expect differences between results obtained with these techniques because we cannot include the effects from tortuosity using conductivity measurements from leachate.
- Biases from tests on leachate are all greater than one, even for samples that are separated into finer components (e.g., for Tex-620-J (2005) the sample is separated on a No. 40 sieve). This is due to the different dilution ratios, and methods of mixing and extracting leachates used in different leaching tests compared to soil box tests.

We grouped the data from each test method according to the fineness of the samples (fine sand, coarse sand, and gravel), as previously described in Figure 3-1. We summarized these data in Figure 3-5 including the mean (Figure 3-5 (a)) and coefficient of variation (Figure 3-5 (b)) of the bias observed from all samples included in each fineness group. We could not perform SCT 143 (2008), with fine samples due to the lack of settlement of the finer particles during the specified standing time. We conclude that, as the coarseness of the sample increases, the mean bias and the COV increase. Considering the materials characterized as fine sand, and results from soil-box tests, the average bias is close to one with a relatively low COV (average COV = 8%). On the other hand, the biases for coarse sand and gravel are 1.6 and 3.1, respectively, considering results from Tex-129-M which includes coarse particles within the test specimen. Also, the COV_{bias} increases incrementally for materials characterized as coarse sands and gravels, where COVs in excess of 30% are observed.

The means of the biases of the results from leaching tests performed on fine samples are higher than one, due to the manner in which samples are diluted for leaching, compared to the moisture contents that prevail for compacted, saturated samples. For compacted samples, the moisture contents are generally less than 50% by weight, but dilution ratios as high as 10:1 (water: solids) are commonly used for leaching tests. The bias from Tex-620-M is more than twice the bias from Tex-129-M. Since the same specimen gradation is included in the both tests, the observed differences are due to the manner in which leachate is prepared and tested for Tex-620-M compared to tests conducted on compacted specimens (Tex-129-M). The mean biases of the test results from Tex-620-J (2005) do not trend with respect to coarseness of the sample. This is because the sample is separated on a No. 40 sieve, and only the finer portion is included in the test specimen.



(a) mean bias


⁽b) coefficients of variation

Figure 3-5 Resistivity measurements from samples with different textures.

We identified trends within the data to reconcile the variability (high COVs) of the bias from testing coarse sand and gravel materials. These trends distinguish parameters that influence the resistivity of geomaterials and describe how parameters correlate with the measured values. The bias of Tex-129-M and ASTM WK 24621 with respect to AASHTO T-288 (2016) were investigated in this study using a model developed at The University of Texas at El Paso (Arciniega et al., 2018; 2019).

The model shows how resistivity of soil can be described in terms of sample gradations and salt ion concentrations. We derived non-dimensional scaling parameters from this model that show how results from different resistivity test procedures may be compared and correlated to one another (the model and the bias statistics are presented in Appendix B). We reviewed these correlations to identify trends in the data that are then related to easily observed material characteristics as shown in Table 3-2.

Sample	Sample Bias < 1.5		1.5 < Bi	ias < 3.0	Bias > 3		
Types	GN	PP#10	GN	PP#10	GN	PP#10	
Gravel	-	-	2.0 - 3.0	6 - 40	3.0 - 3.6	24 - 40	
Coarse Sand	4.5 - 4.8	60 - 70	3.9 - 4.5	50 - 60	-	-	
Fine Sand	5.0 - 6.7	> 80	-	-	-	-	

Table 3-2 Resistivity test bias correspondence with GN and PP_{#10}.

We draw the following conclusions based on the information presented in Table 3-2:

- If the sample has more than 60 percent passing a No. 10 sieve, then bias is close to one, and results from testing in accordance with Tex-129-M and AASHTO T-288 (2016) are similar.
- When the grading number of the sample is greater than 3 and there is less than 40 percent passing the No. 10 sieve, the bias in resistance measurements is greater than 3 (higher bias).

Thus, a relatively large difference in results is obtained with Tex-129-M compared to AASHTO T-288 (2016) from materials with these characteristics. In general, these can be described as gravels with significant amounts of coarse and fine sand, where the percent gravel is approximately 50% and the coarse sand component is approximately 30%.

Tex-129-M appears to be a good alternative to AASHTO T-288 (2016) to evaluate the effect of the coarseness and gradation of the sample on measurements of resistivity. The test procedure is like AASHTO T-288 (2016) and considers how moisture content and degree of saturation affects the resistivity of a compacted sample.

3.3.2 Salt Contents

In Figure 3-6, we summarize the precisions of salt content measurements observed from testing replicates. The samples and replicates are the same as those described for evaluating the precision of resistivity tests and identified in Section 3.3.1. The bar graphs and whiskers in Figure 3-6 represent μ_{COV} and σ_{cov} , respectively. We have included measurements of salt contents via AASHTO T-290 (2016), AASHTO T-291 (2013), Tex-620-J (2005), and Tex-620-M. A common measurement technique (Ion Chromatography) was applied for all test standards, such that the comparisons presented herein depict differences due to sample preparations including dilution ratios and methods of mixing.

For the comparison between results from different test methods described here, we measured chloride and sulfate ion concentrations via the IC method for all of the test procedures. The ASTM D4327 (2017) standard, is employed to simultaneously measure chloride and sulfate concentrations as well as other anions (e.g., bicarbonate anion) using the ion-exchange chromatograph. Ion chromatography is a more accurate and reproducible technique for measuring salt concentrations compared to traditional methods (e.g., titrations, photo-spectrometry). The IC method is more automated, less expensive, and indicates potential interferences, which are not identified by the current AASHTO tests. However, sample treatments described in AASHTO T-290 and T-291 are needed to prepare an extract for IC measurements.

We only included samples with salt contents greater than 10 mg/kg (ppm) for computations of the COV statistics (μ_{cov} and σ_{cov}). These include two samples from South Carolina (LWF and GB), one sample from Rochester, NY, and one sample from El Paso, TX. Measurements less than 10 mg/kg are not reliable because the resolution of the measurement device is large compared to the measurements. We make the following observations based on the COV statistics depicted in Figure 3-6:

- Differences between precision and repeatability among the tests are more distinct between the tests for chloride compared to those from measurements of sulfate.
- For sulfate measurements, AASHTO T-290 (2016) rendered repeatability equal to or better than the other test methods that were evaluated.
- Measurements of chloride from Tex-620-M are less repeatable compared to other methods.



Figure 3-6 Tests for measurements of salt content, and observations of precision (only included results from testing sulfate and chloride with > 10 mg/kg, n=4).

Salt contents measured via Tex-620-J (2005) were high compared to those from Tex-620-M and the AASHTO tests because of the method used for the sample preparation, which includes pulverizing the sample to pass a No. 40 sieve and heating to 150°F before extracting the leachate. Tex-620-J (2005) was originally used by TxDOT for measurements of chloride contents in concrete samples. Although TxDOT has applied this test for evaluating fills for MSE walls, it does not appear to be applicable. Therefore, data from Tex-620-J (2005) will not be included in the forthcoming comparisons. We will discuss and compare results obtained from the AASHTO (AASHTO T-290 (2016) (sulfate) and T-291 (2013) (chloride)) and Texas modified procedures (Tex-620-M) in what follows.

We tested 26 samples, in which 21 samples were tested via AASHTO and Texas modified procedures and five samples were only tested via Tex-620-M. The five coarse samples were not tested via AASHTO tests because of the lack of sufficient constituents passing the No. 10 sieve. We compare salt contents obtained from Tex-620-M and AASHTO tests in Figure 3-7. Except for samples with a high content of particles passing a No. 10 sieve, the Tex-620-M procedure renders lower salt contents compared to AASHTO tests. This is due to the larger particle sizes included in Tex-620-M compared to the AASHTO tests that are performed on the finer fraction of the sample (passing a No. 10 sieve). The black dotted line, which shows the best fit for sulfate measurements by Tex-620-M ($R^2 = 0.79$), indicates that sulfate content measured by Tex-620-M are approximately 70 percent of those measured by AASHTO tests. Similarly, chloride contents measured by Tex-620-M ($R^2 = 0.76$) are approximately 50 percent of those measured by AASHTO tests.

For measurements of low salt content ($\leq 10 \text{ mg/kg}$), results from Tex-620-M agree well with those from AASHTO tests. There are also a few measurements at higher salt contents where the results from the three tests are approximately the same. There are four observations where sulfate contents measured via Tex-620-M are significantly lower than those measured by AASHTO T-290 (2016) (about one-fifth).



Figure 3-7 Correlation between salt content measurements from Tex-620-M and AASHTO T-290 & T-291.

We computed bias as the ratio of "equivalent total salt content" obtained from Tex-620-M divided by the "equivalent total salt content" computed from the results of AAAHTO T-290 (2016) and T-291 (2013). Equivalent total salt contents consider the combining power of chloride and sulfate in solution in terms of their milliequivalent units, and is useful to check trends between salt content and resistivity, as we describe in the next subsection. In general, lower salt contents are measured via the modified test procedures so the bias is less than one. The lowest values of bias are from samples that have a low percentage of particles passing a No. 10 sieve.

We identified the trend in bias with respect to percent passing the No. 10 sieve for each sample as follows:

- The lowest biases are from samples with less than 25 percent passing a No. 10 sieve.
- For samples with more than 60 percent of the particles passing a No. 10 sieve, the bias is close to one. For these samples, the fines and fine sand components dominate the leaching of salts from samples tested via either the AASHTO or Texas modified procedures.
- Other factors, in addition to the percent passing the #10 sieve, that are related to the test technique may also affect the bias. Higher dilution ratios and different methods of mixing may render measurements of salt contents from Tex-620-M that are higher compared to AASHTO T-290 (2016) and T-291 (2013) even for samples with a large fraction passing a No. 10 sieve.

3.3.2.1 Correlations between Salt Contents and Resistivity

Salts affect the electrical resistivity of an aqueous solution because salts dissociate into their components (ions) when dissolved in water and create an electrically conductive solution. The resistivity decreases as the solution becomes more concentrated with ions (higher ion mobility).

Thus, measurements of resistivity are negatively correlated with the measurements of salt content. We evaluated correlations between salt content and resistivity measurements to assess the veracity of these measurements. If the results do not show a consistent trend between the salt contents and resistivity, then the tests used for measurements of salt contents or electrical resistivity may not provide a true measurement. This may also be related to the unknown presence of other ions, besides chloride or sulfate ions, that affect the measured resistivity.

We paired resistivity measurements with the measurements of salt contents. Data pairings between resistivities and salt contents include the AASHTO test series (AASHTO T-288 (2016) for resistivity and T-290 (2016) and T-291 (2013) for measurements of salt contents), the current TxDOT test procedures (Tex-129-E (1999) and Tex-620-J (2005)), and the proposed TxDOT modified test procedures (Tex-129-M and Tex-620-M). ASTM tests for measurements of resistivity, including ASTM G-187 (2018) and ASTM WK 24621, are paired with salt contents measured via AASHTO T-290 (2016)/T-291 (2013) and Tex-620-M, respectively. In this manner, test results from measurements of resistivity and salt concentrations are performed on specimens that have been separated from the sample into similar particle sizes before testing. For Tex-620-M, conductivity/resistivity and salt content measurements were performed on the same specimen. This is unique compared to measurements of resistivity from compacted soil specimens paired with salt contents measured from leachate.

We performed regression analysis to assess the coefficients of correlation (R^2) between the resistivity and salt content measurements (mg/kg). A power law, as shown in the Equation (3-3), was found to provide the best fit to the data. For Equation 3, chloride and sulfate ion contents were combined to render equivalent salt contents in terms of mg/kg as described in Appendix B.

$$\rho \left(\Omega - cm \right) = A \left(\frac{mg}{kg} \right)^{-B}$$
(3-3)

We summarized the model parameters and coefficients of correlation for each of the pairings in Table 3-3. The highest coefficient of correlation ($R^2 = 0.79$) is achieved comparing the results from salt content and conductivity measurements using the Tex-620-M procedure. The coefficients of correlation from measurements of resistivity on compacted soil specimens are lower and range from 0.36 to 0.64. The best correlations from resistivity measurements observed on compacted soil specimens are with the AASHTO test series ($R^2 = 0.64$), and the worst are from testing with ASTM WK 24621 and Tex-620-M ($R^2 = 0.36$).

Test procedures	Α	В	R ²			
Leachate						
Tex-620-M conductivity and salt	122,000	0.53	0.79			
Soil box						
AASHTO T-288/T-290/T-291	27,000	0.47	0.64			
ASTM G-187 and AASHTO T-290/T-291	22,000	0.35	0.50			
Tex-129-E and Tex-620-J	48,000	0.49	0.52			
Tex-129-M and Tex-620-M	41,000	0.47	0.43			
ASTM WK 24621 and Tex-620-M	57,000	0.44	0.36			

Table 3-3 Resistivity model parameters (ppm of salts).

Subsequently, AASHTO test procedures were applied to samples with at least 22 percent passing a No. 10 sieve, and the Texas modified procedures to samples with less than 22 percent passing a No. 10 sieve. This resulted in improved correlations between resistivity and salt contents.

We performed similar analyses using milliequivalent units to express the salt contents (mEq instead of ppm). We also included measurements of alkalinity in terms of part per million of CaCO₃ for the calculation of mEq units, in which the carbonate ions are considered as another salt component in the sample mixtures. Alkalinity is commonly determined as the capacity of water to buffer acids (acid-neutralizing capacity of water), where the major acid buffer constituents in water are bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions. Table 3-4 shows the correlations obtained using mEq units. By comparing the determination coefficients in Table 3-3 and Table 3-4, utilizing mEq units results in significant improvements in the correlations. If we consider data parings from Tex-129-M and Tex-620-M, R² increases from 0.43 to 0.59; and for measurements of both conductivity and salt via Tex-620-M, R² increases from 0.79 to 0.88.

Test procedures	Α	B	\mathbb{R}^2				
Leachate							
Tex-620-M conductivity and salt	142,105	-1.13	0.88				
Soil box							
AASHTO T-288/T-290/T-291	13,500	-0.82	0.64				
Tex-129-M and Tex-620-M	57,000	-1.12	0.59				

Table 3-4 Resistivity model parameters (mEq of chloride, sulfate and alkalinity).

We draw the following conclusions from the results presented in this section:

- Precision/repeatability are similar between test methods for measurements of salt contents.
- Higher salt contents are measured via Tex-620-J (2005) compared to the AASHTO tests; salt contents from Tex-620-M are generally lower than others.
- The best correlations between salt content and resistivity measured on a compacted specimen are obtained from the AASHTO test standards.
- Milliequivalent units are the best way to express salt contents and to allow consideration of the effects from other salts besides chloride and sulfate on the resistivity measurements.

3.3.3 Measurements of pH

We have summarized the statistics describing the precision observed from testing replicates and the bias of each test procedure with respect to AASHTO T-289 (2018) in Figure 3-8. Precision is observed from testing replicates from the same nine sources as those described for resistivity testing and measurements of salt contents. The test procedures for measuring pH vary in terms of (1) whether or not the sample is air-dried, (2) the particle sizes included in the test specimen, (3) the dilution ratios used in the sample preparation, (4) methods of mixing water with the sample including whether or not the mixture is heated, and (5) the period that the soil-water mixture is allowed to stand before making the first measurement.

In Figure 3-8, the bar graphs and whiskers represent means and standard deviations, respectively; the means and standard deviations are in pH units. The pH values measured from all samples range between 7.6 and 9.5. The mean of the measurements from AASHTO T-289 (2018) is 8.34, which means that a COV of 1% corresponds to an average standard deviation difference of approximately 0.08 pH units. Higher pH values are measured via Tex-620-M with a mean pH value of 8.95.

Based on the data shown in Figure 3-8, the repeatability of the different measurement techniques is similar between the test procedures described by NCHRP 21-06 (2009), Tex-620-J (2005), and Tex-128-E (1999). Tex-620-J (2005) and Tex-128-E (1999) are similar in terms of the particle sizes included in the test specimens, the use of higher dilution ratios, and the heat applied during the mixing procedure. Application of heat appears to improve the repeatability of the test results. However, there are significant differences between these procedures and the NCHRP 21-06 (2009) procedure. In NCHRP 21-06 (2009), heat is not applied during mixing, and this is the only procedure whereby the sample is not air-dried as a part of sample preparations. Including moisture, which has been a part of the mixture over time, may result in more consistent extractions and corresponding measurements of pH from NCHRP 21-06 (2009).

ASTM D 4972 (2019) and AASHTO T-289 (2018) have lower, but similar repeatability. These procedures are similar except for the methods of mixing. However, the two procedures differ from previously discussed methods in terms of dilution ratios (1:1) and mixing the sample without the application of heat. The poorest repeatability is observed from measurements of pH obtained via Tex-620-M, which incorporates gravel sized particles within the test specimen.

Figure 3-8(b) shows that, except for Tex-620-M, the bias of results from all of the test methods with respect to data from AASHTO T 289 are close to one. The biases of the results from Tex-620-M were observed to increase with respect to sample coarseness; i.e., the bias from testing a gravel sample is higher compared to that from a sample which includes coarse or fine sands. We plotted results from measurements of pH in Figure 3-9, whereby pH values obtained from Tex-620-J (2005), NCHRP 21-06 (2009), ASTM D 4972 (2019), Tex-128-E (1999), and Tex-620-M (vertical axes) are compared to those from AASHTO T-289 (2018) (horizontal axes). From Figure 3-9 we observe that the pH values measured by Tex-620-J (2005) and NCHRP 21-06 (2009) are lower, measurements from ASTM D 4972 (2019) are nearly equal, and measurements from Tex-128-E (1999) and Tex-620-M are higher compared to measurements from AASHTO T-289 (2018). Other methods render a stronger correlation with results from AASHTO T-289 (2018) ($R^2 > 0.6$), compared to the correlation with Tex-620-M ($R^2 = 0.33$).

We draw the following conclusions from the results presented in this section:

- Measurements of pH from Tex-620-M are less repeatable compared to measurements from other test methods investigated in this study.
- In general, Tex-620-M renders pH values that are higher compared to those obtained from the other test methods investigated in the study.
- Results from NCHRP 21-06 (2009) are more repeatable compared to AASHTO T-289 (2018) and do not have a significant bias with respect to results obtained from AASHTO T-289 (2018).





Figure 3-8 Summary of the test results for measuring pH.



Figure 3-9 Comparisons of pH measurements relative to AASHTO T-289 (2018).

3.4. Characterization of Corrosion Potential and Correlations with Corrosion Rates

In the previous sections, we compared results from testing samples in accordance with current AASHTO tests and other alternative procedures for preparing specimens and making measurements. Given the better precision observed from results with the Tex-129-M test and its similarities with the AASHTO T-288 test procedure, we considered Tex-129-M as an alternative to AASHTO T-288 for testing coarse materials. Based on the distribution of bias in the results we made the following observations:

- When more than 60% of the sample is passing a No.10 sieve, similar results are obtained from measurements of resistivity and salt content via current test standards or the modified Texas procedures (Tex-129-M for resistivity and Tex-620-M for salt contents).
- Significant differences in measurements of resistivity and salt content were observed for materials having less than approximately 25% passing a No.10 sieve.
- The largest differences were observed from testing sandy gravels with 3.0 < GN < 4.0 and less than 40 % passing a No.10 sieve.

3.4.1 Correlation between Resistivity and Performance Data

Up to this point, we have focused on identifying differences between test results and the factors affecting these differences. The next step is to determine whether and when measurements that are different from AASHTO T-288 (2016) may render a better result. We modeled performance by relating observations of performance to site conditions, and identifying parameters that provide the best correlations with performance data. In this case, performance is in terms of the durability of earth reinforcements as quantified by observations of metal losses and corrosion rates (CR). Site conditions include the environment surrounding the earth reinforcements, most notably resistivity of the fills or native soils. We used the coefficient of determination, R², between the corrosion rate and resistivity measurements as an index to rank the accuracy of the results from each of the resistivity tests that were included in the test program. Resistivity is often considered to be an indicator of corrosivity as this single parameter is correlated with numerous factors that affect corrosion reactions, including salt and moisture contents (King 1977; Romanoff 1957).

The data set for the regression analysis includes measurements from 19 sample sources incorporating 28 measurements of corrosion rates. Observed corrosion rates include 18 data points from galvanized steel specimens and 10 data points from plain steel specimens. Measurements presented herein are the maximum observed from each site/source. We use the maximums to consider the durability of the most vulnerable elements. The data set includes in-situ corrosion rate measurements from the field and corrosion rates measured from laboratory tests.

In-situ measurements of corrosion rates from field studies involved variable moisture contents and corrosion rate measurements from locations near the tops and bases of the MSE walls. We used the linear polarization resistance (LPR) technique (Jones 1996; Tait 1994) for in-situ measurements of corrosion rates. As many as 30 samples were monitored at a given site and the maximum values were observed from sample locations where conditions for corrosion were more severe (e.g., higher moisture contents, cycles of wetting and drying, availability of oxygen). Laboratory tests included samples embedded within fills under the most severe conditions that may be encountered in the field. Moisture contents were maintained near optimum moisture contents for corrosion rates are considered to be extremes/maximums compared to what is likely to occur in the field.

In general, corrosion rates tend to attenuate with respect to time when conditions favor the development of a protective scale on the steel surface, however the majority of the attenuation occurs within the first year (Romanoff 1957). Corrosion rate measurements presented herein are from samples that have been embedded in fill for at least one year (i.e., with relatively stabilized corrosion rates). Considering each of the resistivity test methods, we plotted measurements of

corrosion rates versus measurements of resistivity for plain steel and galvanized elements separately. We obtained the best fit to the data using the power law shown in Equation (3-4). Table 3-5 summarizes the regression coefficients (A and B) and the coefficient of determination (\mathbb{R}^2) obtained from each regression analysis. We will discuss these data by grouping them according to the gradation of the specimens prepared for testing.

$$CR\left(\frac{\mu m}{yr}\right) = A \times \rho(\Omega \cdot cm)^{-B}$$
 (3-4)

Group I includes results from AASHTO T-288 (2016), Tex-129-E (1999) and ASTM G-187 (2018). For Group I, samples were separated and the finer portion (passing a No.8, No.10 or ¹/₄ inch sieve) was included in the specimen for measurement of resistivity. Group II included tests whereby the specimen was more representative of the source, including particle sizes up to 1-3/4" (Tex-129-M, ASTM WK 24621, Tex-620-M).

We observed that Group I tests render better correlations for galvanized steel and Group II tests render better correlations for plain steel specimens. This may be because galvanized surfaces are more uniform compared to the surfaces of plain steel specimens. Correlations between resistivity and corrosion rates are affected by the variability of the soil samples and the specimens included in Group II have more variability compared to Group I. The characteristics of the metal along the surface of plain steel are more variable and compared to those with galvanized steel the correlations are less affected by the uniformity of the finer specimens included in Group I. The characteristics is and the speciment of the surface of plain steel are more variable and compared to those with galvanized steel the correlations are less affected by the uniformity of the finer specimens included in Group I. The correlation with respect to the performances of galvanized and plain steels are discussed in the following subsections.

	Tost Mathad	Ga	Galvanized steel			plain Steel		
	Test Miethou	Α	В	\mathbb{R}^2	Α	В	R ²	
	AASHTO T-288	9,945	0.93	0.46	9,073	0.90	0.20	
Group 1	Тех-129-Е	12,380	0.95	0.38	1,492	0.70	0.08	
	ASTM G-187	24,613	1.00	0.40	386,844	1.30	0.16	
	Tex-129-M	1,102	0.67	0.19	55,542	1.05	0.31	
Group 2	ASTM WK 24621	9,169	0.88	0.33	88,746	1.08	0.27	
	Tex-620-M	140,664	1.11	0.32	467,000	1.16	0.30	

Table 3-5 Regression of observed corrosion rates and resistivity measurements.

3.4.1.1 Performance of Galvanized Steel

For Group I, corrosion rates from galvanized elements are negatively correlated with resistivity $(0.38 < R^2 < 0.46)$. The regression coefficient, *B*, is very similar between the different test methods ranging from 0.90 to 1.3. The *A* coefficient is more than twice as high for ASTM G-187 (2018) compared to those from AASHTO T-288 (2016) or Tex-129-E (1999) (i.e., results from ASTM G-187 correlate to higher corrosion rates). This is directly related to the bias of the resistivity measurements from ASTM G-187 (2018) compared to AASHTO T-288 (2016).

For Group II, corrosion rates do not correlate as well with corrosion rate measurements compared to the correlations obtained from Group I. These correlations can be described as low to moderate $(0.19 < R^2 < 0.33)$. The lower degrees of correlation are because the tests in Group I, and the AASHTO T-288 test in particular, are suited to a broader range of materials compared to the range of materials for which results from Tex-129-M and other tests in Group II are applicable.

Better correlations are obtained by culling the data set to only include materials that have more than 22 percent passing a No.10 sieve in the test results from AASHTO T-288, and only include those with less than 22 percent passing in the test results from Tex-129-M. The selection of a threshold of 22 percent is consistent with the observation that trends between the salt contents and resistivity measurements are more prevalent when materials are grouped based on whether or not there are more than 22 percent passing a No.10 sieve, as discussed in Section 3.3.2 and the high bias values that are observed from measurements of resistivity and salt contents when the percent passing a #10 is less than 22% as discussed in Sections 3.3.1.2 and 3.3.2. In the proposed protocol, in Section 3.5 and Appendix A, the threshold of 22% is rounded up to 25%. There are seven samples within the Phase II test program with less than 22 percent passing a No.10 sieve and corresponding measurements of corrosion rate. These include samples from Wake Forest, NC; San Antonio Texas; Bastrop Texas; Maple Road, Amherst; New York; Waco, Texas; Garden City Texas; and samples of coarse aggregate from an MSE wall in El Paso Texas. We show the correlations corresponding to AASHTO T-288 (2016) and Tex-129-M in Figure 3-10 and Figure 3-11, respectively.



Figure 3-10 Galvanized steel corrosion rates and resistivity measurements from samples with more than 22% passing the No.10 sieve (via AASHTO T-288 (2016)).



Figure 3-11 Galvanized steel corrosion rates and measurements of resistivity from samples with less than 22% passing the No.10 sieve (via Tex-129-M).

Figure 3-10 depicts data from AASHTO T-288 (2016) not including the coarse samples. The data collected for the lightweight fill (LWF, which was primarily expanded clay) from South Carolina was also removed. LWF samples were considered different from natural materials due to their absorption and chemical compositions. The regression showed some improvement, $R^2 = 0.50$, compared to the case where all of the samples are included, $R^2 = 0.46$. The regression coefficients were changed (A= 2733 and B = 0.73) such that the computed corrosion rates were different. We observed that corrosion rate measurements became more disperse with decreasing resistivity, which caused the regression to decrease.

Figure 3-11 depicts data from application of Tex-129-M to samples with less than 22% passing a No.10 sieve. Compared to Figure 3-10 and the resistivity measurements from AASHTO T 288 (with > 22% passing #10), lower corrosion rates are depicted in Figure 3-11 for all levels of resistivity measured via Tex-129-M (with < 22% passing #10). Corrosion rate measurements from Waco Texas, and an MSE wall in El Paso Texas with coarse fill are very low (<< 1 μ m/yr). The low measurements of corrosion rates are likely due to the fact that these were field measurements from sites that were very dry (desert locations) at the time of measurements. Thus, the resistivity measurements obtained from samples that are saturated do not apply very well to these data.

More data including measurements of corrosion rates and resistivity from sites located throughout North America and Europe are available from a database catalogued as part of NCHRP 24-28 (Fishman and Withiam, 2011). These data include the maximum corrosion rates observed from each site. However, the resistivity measurements from Tex-129-M are not available for this data set. We culled these data such that coarse samples with less than 22 percent passing a No.10 sieve were removed from the data set. The culled data are presented in Figure 3-12 with 36 data points

including 10 data points coincident with the samples included in the Phase II laboratory testing for this study (NCHRP 21-11).



Figure 3-12 Galvanized steel corrosion rates and measurements of resistivity from worldwide data. Testing with AASHTO T-288 (2016) from samples with more than 22% passing the No.10 sieve.

Regression analysis using the data from Figure 3-12 showed similar regression coefficients and correlations compared to the data presented in Figure 3-10 that only includes data collected from Phase II of this study. The regression from the broader database renders A = 5267 compared to A = 2733; B = 0.84 compared to B = 0.73, and $R^2 = 0.62$ compared to $R^2 = 0.50$. We used these sets of coefficients with Equation (3-4) and resistivity between 200 Ω -cm and 50,000 Ω -cm as input. Differences in computed corrosion rates were within 3 µm/yr. for computed corrosion rates in excess of 15 µm/yr. and the difference decreases to 0.5 µm/yr. for computed corrosion rates of approximately 1 µm/yr. These similarities indicate that the model is robust and fits well to the data that were not included in the set initially used to determine regression coefficients. This provides confidence that the model obtained from regression analysis is not limited to describing those data collected in the Phase II of this project, and has a broader application.

3.4.1.2 Performance of Plain Steel

We consider the correlations between test results from Group I and corrosion rates measured on plain steel specimens to be low ($0.08 < R^2 < 0.20$). This may be due to the paucity of corrosion rate measurements available from plain steel specimens placed within MSE wall fill. The correlation using results from Tex-129-M is better ($R^2 = 0.31$), and considered moderately correlated (because, $0.25 < R^2 < 0.49$).

Figure 3-13 depicts data from correlating results of AASHTO T-288 to measurements of corrosion rate on plain steel specimens for samples with more than 22% passing the No.10 sieve. We achieved a good correlation ($R^2 = 0.4$) with outliers removed, whereby higher corrosion rates are

observed (Prince George, BC Canada and M-U-D, NY). The correlation coefficients from this regression are A = 1470 and B = 0.68.

There are only two data points with corrosion rate measurements and resistivity measured via Tex-129-M for materials with less than 22% passing the No.10 sieve. For these two points, the higher corrosion rate corresponds to the lower measurement of resistivity.



Figure 3-13 Plain steel corrosion rates and measurements of resistivity from AASHTO T-288 (2016) and samples with more than 22% passing the No.10 sieve.

We conclude that results from Tex-129-M apply well to materials with less than approximately 22% passing the No.10 sieve. For materials with more than 22 percent passing a No.10 sieve, AASHTO T-288 is appropriate for measurement of resistivity. We used these observations to develop the proposed protocol discussed in Section 3.5 and presented in Appendix A.

3.4.2 Classification of Soil Corrosivity

3.4.2.1 Characterization Scheme

Proper characterization of corrosion potential needs to consider the nature and physical characteristics of the material, its electrochemical properties, and various factors related to the site conditions. Characterizations of corrosion potential may be done by setting threshold limits for individual electrochemical parameters (e.g., electrical resistivity, pH, sulfate, and chloride content) similar to AASHTO, or may involve ranking according to a multivariate approach. A number of schemes exist for screening and characterizing corrosion potential of earthen materials. These schemes are often developed for specific applications (e.g., MSE walls, piles, culverts, and pipelines) that may involve aspects of the installations, site conditions, and electrochemical properties. Some of the most common schemes that use a multivariate approach are summarized below:

- German Gas and Water Works Engineers' Association Standard (DVGW GW9), which is one of the earliest corrosion assessment methods applied to pipeline construction in Europe (Shreir et al. 1994).
- Eyre and Lewis (1987), modified the German scheme, which was then adopted in a slightly revised form by the UK Highways Agency in their Design Manual for Roads and Bridges (2000). However, this revised scheme does not consider the beneficial effect from the presence of carbonates on corrosivity, which was originally included in DVGM GW9.
- Jones (1985) developed a method for characterizing the corrosivity of soils considering a number of variables related to soil type, site conditions, and electrochemical properties.
- The standard method used in Great Britain (GB) to assess the design life requirements of buried galvanized steel structures; culverts in particular, is based on a multi-variate classification system which rates different environments in contact with the structure according to their corrosivity (Brady and McMahon, 1994). The classification scheme used in GB considers characteristics of the soil including mechanical properties described in terms of particle size, and plasticity; and electrochemical parameters including resistivity, pH, and the presence of sulfate, chloride and sulfide.

In this study we focus on the application of AASHTO criteria to characterize corrosion potential (presented in Table 1-1) and the DVGW GW9, which considers the protective effects associated with the presence of carbonates. Table 3-6 presents the DVGW GW9's characterization scheme, in which a number of factors are involved in the corrosivity assessment including physical and electrochemical properties of the earthen material (soil), site conditions, ground water levels, and the presence of industrial fills. Points/marks are assigned for each factor and the marks are summed to calculate an overall score. This score is used to assess corrosivity, in which lower (more negative) scores indicate more severe corrosion conditions. The scheme considers the benefits (positive score) from the presence of carbonates on the corrosion behavior of buried metals. The sum of the points assigned to each category can range from a best of +4 to a worst case of -25. From this overall score and using Table 3-7 and Table 3-8, corrosivity and expected corrosion rates can be evaluated.

Item	Measured value	Marks		
	Calcareous, marly limestone, sandy marl, not stratified sand	+2		
Soil composition	Loam, sandy loam (loam content 75% or less) marly loam, sandy clay soil (silt content 75% or less)	0		
	Clay, marly clay, humus	-2		
	Peat, thick loam, marshy soil	-4		
Ground water	None	0		
level at buried position	Exist			
	Vary	-2		
	>10,000 Ω-cm	0		
	5,000 – 10,000 Ω-cm	-1		
Resistivity	2,300 – 5,000 Ω-cm	-2		
	1,000 – 2,300 Ω-cm	-3		
	< 1,000 Ω-cm	-4		
Moisture	< 20%	0		
content	> 20%	-1		
aIJ	>6	0		
рн	< 6	-2		

Table 3-6 Characterization scheme from DVGW GW9 (continued).

Item	Measured value	Marks
Sulfide and	None	0
hydrogen	Trace	-2
sulfide	Exist	-4
	> 5%	+2
Carbonate	1% - 5%	+1
	< 1%	0
011 1	< 100 mg/kg	0
Chioride	> 100 mg/kg	-1
	< 200 mg/kg	0
Culfata	200 mg/kg – 500 mg/kg	-1
Sunate	500 mg/kg – 1,000 mg/kg	-2
	> 1,000 mg/kg	-3
Cinder and	None	0
coke	Exist	-4

Total score	Category	ory Soil corrosivity Risk deep/wide pitting		Risk general corrosion
≥ 0	Ia	Virtually not corrosive	Very low	Very low
0 to -4	Ib	Slightly corrosive	Low	Very low
-5 to -10	II	Corrosive	Medium	Low
< -10	III	Highly corrosive	High	Medium

Table 3-7 Soil corrosivity/aggressiveness (for carbon steel) DIN 50 929 Part 3.

Table 3-8 Expected corrosion forms/rates (for carbon steel) DIN 50 929 Part 3.

Total score	Category	General corrosion rate (µm/yr.)	Range (µm/yr.) Localized (pitting) corrosion rate (µm/yr.)		Range (µm/yr.)
≥ 0	Ia	5	2.5 - 10	30	15 - 60
0 to -4	Ib	10	5 - 20	60	30 - 120
-5 to -10	II	20	10 - 40	200	100 - 400
< -10	III	60	30 - 120	400	200 - 800

We computed corrosion indices using the DVGW GW9 scheme for all sample sources included in Phase II of the test program. We incorporated multiple electrochemical measurements from earth materials including pH, resistivity, and soluble chloride and sulfate ion contents to compute a corrosivity index. Correspondingly, we computed corrosivity indices with results from the AASHTO test series, current TXDOT test procedures, proposed modified TXDOT test procedures and data from ASTM test procedures.

We also computed indices according to the following criteria for application of the appropriate electrochemical test methods. We selected the appropriate test standards depending on the character of the material under test, and based upon the percent passing the No.10 sieve.

- If the sample has more than 25 percent passing a N.10 sieve or a GN <3, then AASHTO T-288 (2016) applies;
- If the sample has less than 25% passing the #10 sieve, and GN greater than 3, then Tex-129-M is applied.

The GN is included with the screening to restrict use of Tex-129-M to coarse textured samples with a relatively high gravel content.

We compared the characterizations of corrosivity with measurements of corrosion rate from galvanized and plain steel elements. In what follows, we will compare correlations with performance considering characterizations of corrosivity from DVGW GW9. Characterizations based solely on resistivity, as discussed in Section 3.4.1, are also included in the comparisons.

3.4.2.2 Correlation between Results of Characterization Scheme and Performance Data

Formulas determined from regression analysis do not depict how corrosion rates vary within selected ranges of resistivity, or other material characteristics. Alternatively, data clusters are useful to quantify the variations and uncertainties associated with data within selected regions of a sample domain. A data cluster is a group of objects that are more similar to each other compared to those in other groups (clusters). In this context, clusters are in terms of similar material characteristics (e.g., gradation, maximum particle size, electrochemistry, or corrosivity index). We will identify distinct ranges of performance, as measured by corrosion rates that are associated with each data cluster.

We are using cluster analysis to demonstrate the advantage of the proposed protocol over existing test standards for characterizing the steel corrosivity of earthen materials. In Table 3-9, we present data clusters that are arranged according to resistivity measured via AASHTO T-288, Tex-129-M or ASTM WK 24621 as prescribed in the last section. ASTM WK 24621 is applied to expanded clay, for which the particles are porous, and the 24-hour soaking period included in the ASTM WK 24621 procedure allows moisture to be absorbed before the test. This assures that all measurements are made with moisture occupying the pore spaces within the solid particles. We grouped resistivity measurements (ρ) into three clusters as $\rho > 10,000 \ \Omega$ -cm, $3000 \ \Omega$ -cm $< \rho < 10,000 \ \Omega$ -cm; and $1000 \ \Omega$ -cm $< \rho < 3000 \ \Omega$ -cm. We observed distinctly different ranges of corrosion rate measurements within these defined clusters for galvanized and plain steel elements.

Corresponding ranges of corrosion rates, that we show in Table 3-10 are similar to those described in DIN 50 929 Part 3 (Brady and McMahon, 1994) corresponding to noncorrosive, slightly corrosive, and corrosive conditions. Two exclusions are evident out of 28 measurements depicted in Table 3-9 (these exclusions are marked with red colored texts).

In Table 3-11 we present data clusters that are arranged according to corrosivity index as determined from DVGW-GW9. We grouped the corrosivity indices ($\Sigma(I)$) into three clusters as $\Sigma(I) \ge 0, -3 \le \Sigma(I) < 0; -5 \le \Sigma(I) < -3$. Table 3-12 describes the ranges of corrosion rates corresponding to each cluster. Compared to the clustering with resistivity measurements, these clusters result in a tighter range of observed performance within each cluster. We observed four exclusions that are marked in red in Table 3-11.

		~~~		Test method	0	C (um	R /vr.)
Cluster	Sample	GN	<b>PP</b> #10	(proposed protocol)	(Ω-cm)	Galv.	Plain
0	San Antonio, TX	0.18	2	Tex-129-M	42666	1.0	NA ^A
о, п	Wake Forest, NC	2.21	8	Tex-129-M	31651	0.3	< 0.1
10, -ci	Bastrop, TX	0.15	2	Tex-129-M	24155	0.4	NA
∧ G	Ocala, FL	5.65	91	AASHTO T-288	16535	1.8	3.8
d	Ashdown, AR	2.88	36	AASHTO T-288	13958	1.8 ^B	NA
I	M-U-D, NY	5.24	82	AASHTO T-288	9064	4.8	39
0,000 Ω	LWF, South Carolina	4.83	68	ASTM WK 24621	7045	1.2	8.4
	Maple Rd., NY	2.50	22	Tex-129-M	3817	3.7	16
$\sim$ 1	TTC, NC	3.51	24	AASHTO T-288	5056	5.8	1.6
ςμ	Waco, TX	1.26	7	Tex-129-M	4499	0.3	NA
n <	Prince George, BC	2.89	32	AASHTO T-288	4527	NA	20
-ct	Garden City, TX	2.52	22	Tex-129-M	3613	4.3	NA
C (	El Paso Coarse/MSE	0.22	2	Tex-129-M	3307	0.2	NA
000	El Paso Fine/MSE	5.52	87	AASHTO T-288	3026	21 ^C	NA
3	GB, South Carolina	4.48	56	AASHTO T-288	2486	3.2 ^D	5.8
n	PIP, NY	4.62	61	AASHTO T-288	1872	37	30
$\mathbf{D}^{C}$	Sprain Brook Pkwy, NY	2.54	27	AASHTO T-288	1720	33	NA
00C	Quarry; El Paso, TX	3.64	41	AASHTO T-288	914	14.8	NA
1( 3(	Rochester, NY	3.85	49	AASHTO T-288	679	9.6	20

Table 3-9 Data clustering according to resistivity and observed rates of corrosion.

 A NA = not available

^B CR measured from moist and saturated samples. Results is from moist samples to be consistent with other measurements presented in this table. Measurement from saturated sample is  $7.7 \,\mu$ m/yr.

^C This reading is from the top of the MSE wall. The CR measured near the base of the MSE wall was much lower,  $2.1 \mu m/yr$ .

^D One outlier equal to 35  $\mu$ m/yr. that appears to be dubious. Next highest is 3.2  $\mu$ m/yr.

Table 3-10 Ranges of corrosion rate according to resistivity.

Degistivity alugtang	Observed corrosion rates, CR				
Resistivity clusters	Galvanized steel	Plain steel			
ρ > 10,000 Ω-cm	$CR < 2 \mu m/yr.$	$CR < 5 \ \mu m/yr.$			
$3000 \ \Omega$ -cm < ρ < 10,000 $\Omega$ -cm	0 μm/yr. < CR < 6 μm/yr.	$1.0 \ \mu m/yr. < CR < 20 \ \mu m/yr.$			
1000 Ω-cm $< \rho < 3000$ Ω-cm	10 μm/yr. < CR < 35 μm/yr.	$10 \ \mu m/yr. < CR < 40 \ \mu m/yr.$			

Cluster	Sample	GN	<b>PP</b> #10	Test method (proposed	Corros. Rank ^A	C (um	R /vr.)
	~~~ <b>r</b> ~~		#10	protocol)	$\Sigma(\mathbf{I})$	Galv.	Plain
sive 0	San Antonio, TX	0.18	2	Tex-129-M		1.0	NA ^B
	Wake Forest, NC	2.21	8	Tex-129-M	2	0.3	< 0.1
	Bastrop, TX	0.15	2	Tex-129-M	2	0.4	NA
	Ashdown, AR	2.88	36	AASHTO T-288	2	1.8 ^C	NA
rro ≥	TTC, NC	3.51	24	AASHTO T-288	1	5.8	1.6
co (I)	Ocala, FL	5.65	91	AASHTO T-288	0	1.8	3.8
Not	LWF, South Carolina	4.83	68	ASTM WK 24621	0	1.2	8.4
	El Paso Coarse/MSE	0.22	2	Tex-129-M	0	0.2	NA
	Waco, TX	1.26	7	Tex-129-M	0	0.3	NA
htly sive (I) < 0	M-U-D, NY	5.24	82	AASHTO T-288	-1	4.8	39
	Garden City, TX	2.52	22	Tex-129-M	-1	4.3	NA
	GB, South Carolina	4.48	56	AASHTO T-288	-1	3.2 ^D	5.8
llig orrc	Maple Rd., NY	2.50	22	Tex-129-M	-2	3.7	16
3 C S	El Paso Fine/MSE	5.52	87	AASHTO T-288	-2	21 ^E	NA
1	Prince George, BC	2.89	32	AASHTO T-288	-3	NA	20
osive (I)< -3	PIP, NY	4.62	61	AASHTO T-288	-4	37	30
	Sprain Brook Pkwy, NY	2.54	27	AASHTO T-288	-4	33	NA
≤∑	Quarry; El Paso, TX	3.64	41	AASHTO T-288	-4	14.8	NA
-5 <u>-</u>	Rochester, NY	3.85	49	AASHTO T-288	-5	9.6	20

Table 3-11 Data clustering relating corrosivity rankings^A to observed rates of corrosion.

^A German Method DVGW-GW9

^B NA = not available

^C CR measured from moist and saturated samples. Results is from moist samples to be consistent with other measurements presented in this table. Measurement from saturated sample is 7.7 μ m/yr.

^D One outlier equal to 35 μ m/yr. that appears to be dubious. Next highest is 3.2 μ m/yr.

^E This reading is from the top of the MSE wall. The CR measured near the base of the MSE wall was much lower, $2.1 \,\mu$ m/yr.

Table 3-12 Ranges of corrosion rate and corresponding ranges of $\Sigma(I)$.

Corrosivity	Observed corrosion rates, CR					Observed corrosion rates, CR				
clusters	Galvanized steel	Plain steel								
$\sum(I) \ge 0$	$CR < 2 \ \mu m/yr.$	$CR < 5 \ \mu m/yr.$								
$-3 \leq \sum(I) < 0$	$2 \mu m/yr. < CR < 5 \mu m/yr.$	5 μ m/yr. < CR < 20 μ m/yr.								
$-5 \le \sum(I) < -3$	$10 \ \mu m/yr. < CR < 35 \ \mu m/yr.$	$20 \ \mu m/yr. < CR < 40 \ \mu m/yr.$								

After we apply clustering to these data, the benefits of the proposed protocol are apparent. We observe distinct clusters of data that can be useful for relating characterizations of corrosivity to performance.

3.5. Recommended Protocol

We incorporated recommendations into the proposed protocol (presented in Appendix A) that are based upon results from our analyses of the data collected in Phase II. We summarized the proposed protocol in the form of a flowchart shown in Figure 3-14. In general, the proposed protocol describes application of the current AASHTO test series for samples with GN > 3, <u>or</u> if the percent passing the No.10 sieve is greater than 25%. Otherwise, if the GN < 3, <u>and</u> the percent passing the No.10 sieve is less than 25%, the Texas modified procedures are recommended (i.e., Tex-129-M and Tex-620-M).

We considered four factors to select methods for the proposed protocol including a) precision and repeatability of the test methods, b) compatibility between parameters (e.g., salt contents and resistivity), c) correlations between geochemical and electrochemical properties, corrosivity and corrosion rates, and d) the utility of the test results. All of these factors support the implementation of the AASHTO and Texas modified procedures within the proposed protocol.

The statistics included in the evaluation of the test methods describe the repeatability of the test results and correlations between measurements of corrosivity/resistivity and corrosion rates. These statistics demonstrate that the proposed protocol renders results that correlate best with observations of corrosion rates, although observed differences are not large. Also, the repeatability of the Texas modified test series is the best compared to the other test methods. This is partially used to justify recommending the AASHTO test series and the Texas modified test series in the proposed protocol. Other considerations include the observed trends between parameters such as salt contents and resistivity and the utility of the test results, which favors use of the AASHTO or Texas modified tests.

Coefficients of correlation and the statistics of the measurements are not the only factors considered in the selection of test recommendations. There are benefits to obtaining the relationship between moisture content and resistivity. These benefits include the ability to relate laboratory and field measurements of resistivity where the field moisture content is known. Correlation between laboratory and field measurements also requires that the gradation of the material tested in the laboratory and in the field are similar. Tex-129-M satisfies these needs because the test specifies that resistivity measurements be obtained for a range of moisture contents up to saturation, and the test includes all particle sizes up to $1\frac{3}{4}$ inches.

ASTM G-187 (2018) is only performed at moisture contents corresponding to as-received or saturated, and only includes particle sizes up to $\frac{1}{4}$ inches. Therefore, for the MSE wall application, ASTM G-187 (2018) is not as desirable as Tex-129-M. ASTM G-187 may be desirable for other applications where water content is not variable with respect to time or is maintained at particular levels such as always saturated.

ASTM WK 24621 is also not applicable to a range of moisture contents but may apply to some materials that drain freely. ASTM WK 24621 may be particularly applicable for materials that absorb moisture, because saturation requires soaking. and a 24-hour soaking period is specified by WK 24621.



Figure 3-14 Flow chart of the proposed protocol.

Chapter 4. Field Measurements (Phase III)

4.1. Introduction

During Phase III of NCHRP Project 21-11 we cooperated with selected transportation agencies whereby the recommended protocol was implemented as a "shadow specification." The data include characterization of different sample sources (e.g., maximum particle size and gradation) along with the measurements of geochemical and electrochemical properties of the samples including resistivity, pH, and chloride and sulfate contents (i.e., the total salt content). The Wenner 4-probe technique (according to ASTM G57 (2012) and Wenner (1915)) was used in the field for measurement of electrical resistivity and representative material samples were collected from the *site* or from the *source* to perform electrochemical tests in the laboratory using Texas modified and AASHTO test procedures.

In this chapter, we summarize the field and laboratory test results obtained from four active construction projects in cooperation with two owners (Texas and New York DOTs), four different geotechnical testing laboratories (UTEP, McMahon & Mann, NYSDOOT and TXDOT), and four general contractors. The main focus of this chapter is to determine whether the main technical goal of the research project for better characterization of corrosion potential using the suggested protocol as compared to the traditional methods has been met. We also evaluate the practicality and implementation of the suggested protocol through the interaction with laboratories engaged in the electrochemical testing, and suppliers/owners in different states.

We present a brief description of the data obtained in pursuit of Phase III in the following section. This is followed by the key results obtained from different test methods in the form of resistivity obtained from the Wenner 4-probe test (used in the field), and laboratory measurements including resistivity pH, and chloride/sulfate contents. Finally, we present a detailed discussion of the trends observed within the data sets and comparison between the field and the laboratory measurements.

4.2. Description of Data Set

Two sites in Texas and two sites in New York were included in the field verification study including sites located in San Antonio, TX; El Paso, TX; Buffalo, NY; and Schroon, NY. We sampled materials from the sources and at the sites for laboratory testing. Split samples were sent to The University of Texas at El Paso and state DOT geotechnical laboratories to determine gradation, resistivity, pH, salt and sulfate contents. Table 4-1 summarizes the laboratory tests performed on the samples obtained from the site and the source by the owner and/or the research group at The University of Texas at El Paso.

	Samples			
	Site	Source		
Owners (state DOTs)	_1	measurements of ρ, [Cl ⁻] and [SO ₄] content, and pH using Texas modified and AASHTO procedures		
Research group (UTEP)	Texas modified and ASSHTO procedures ²	Texas modified and AASHTO procedures		

Table 4-1 Laboratory tests performed on the site and source samples.

¹No tests were performed by the owners on the site samples.

² Field resistivity tests were performed using the Wenner 4-probe technique (according to ASTM G57 (2012)).

The site in San Antonio, Texas involved construction of MSE walls at the intersection of IH10 East and Ackerman Road (Figure 4-1 (a)), where the MSE wall fill was a coarse, open graded gravel produced locally by Hanson Aggregates (Lehigh Hanson Company 2019). Limestone was mined at the quarry to produce the aggregates for MSE wall fill.

Similar to the San Antonio Site, the site in El Paso, Texas involved construction of MSE walls at the intersection of Montana Avenue and Lee Trevino Drive (Figure 4-1 (b)). The MSE fill at this site was a medium grain, well-graded, sand.

We selected two quarries from the New York State (NYS) inventory to include in our evaluation; one from the eastern part of the state (Peckham Quarry, NYSDOT Region 1), and one from the western part of the state (Enterprise Stone & Lime, NYSDOT Region 5). The sources from the eastern and western parts of the state were granite and limestone quarries, respectively. The two sources produced well-graded gravels that included significant sand components. These materials meet the requirements for pavement subbase in NYS.

The material sourced from NYSDOT Region 5 was used in a bridge reconstruction project in Tonawanda, NY (near Buffalo, NY) along the I290 West where it crosses the Niagara Frontier Transportation Authority Property (Figure 4-1 (c)). The fill was placed as subbase beneath the shoulder backing at the west end of the bridge. The shoulder backing was compacted to a thickness of approximately 12 inches and was approximately 5 feet wide. Although this material was used in an application where corrosivity was not an issue, the NYSDOT sampled and tested the material similar to what is specified for MSE wall fill.

Material from NYSDOT Region 1 was also used in a bridge reconstruction project along I87N, near Exit 28 in Schroon, New York (Figure 4-1 (d)). Although this material could potentially be a source of MSE wall fill, for this project material was placed as subbase beneath the shoulder along the approach sections. The material was compacted to a final lift thickness of approximately 15 inches and had been in place for less than a week during our site visit.





(b) El Paso, TX



(c) Buffalo, NY



(d) Schroon, NY Figure 4-1 Locations and coordinates of construction sites¹.

¹ The photos from El Paso, Buffalo, and Schroon sites are older Google Earth images that do not depict construction activities at these locations.

In Figure 4-2, we present the gradation curves for the different materials sampled from the sites cited in this chapter. In Table 4-2, we summarize salient details of each sample in terms of aggregate size, grading number, and USCS classification to describe the characteristics of the sample domain used in the field and laboratory tests. Given the details from Table 4-2 (GN and $PP_{\#10}$), and from the suggested protocol (Appendix A - also summarized in Figure 3-14), samples from Buffalo and El Paso should be evaluated using the current AASHTO tests (passing No. 10 sieve) and samples from San Antonio and Schroon should be evaluated using modified procedures, which includes larger particles within the test specimens.



Figure 4-2 Gradation curves from different sites.

	NMAS ¹ (in)	PP ² _{1/4"} (%)	PP _{#10} (%)	PP _{#200} (%)	Cu ³	C _c ⁴	USCS classification	GN ⁵
San Antonio, TX	2	0	0	0	1.48	0.97	GP	0.13
El Paso, TX	0.25	94	70	0	6.52	1.04	SW	4.55
Buffalo, NY	1	49	31	0	20.00	0.99	GW	3.07
Schroon, NY	2	17	10	0	11.01	2.51	GW	1.70

Table 4-2 Summary of gradation from different sources.

¹NMAS = nominal maximum aggregate size

² PP = percentage passing

³ C_u = Uniformity coefficient $\left(\frac{D60}{D10}\right)$

⁴ C_c = Coefficient of curvature
$$\left(\frac{(D30)^2}{D60 \times D10}\right)$$

 5 GN = grading number

4.3. Results

4.3.1 Resistivity – Soil Boxes

In Figure 4-3, we show the laboratory measurement of soil resistivity using the modified soil box for the samples retrieved from the sources and the sites included in Phase III. The equipment used for laboratory measurement of resistivity included: 1) Soil Resistance Meter, M.C. Miller, Model: 400D and 2) Potentiostat, Gamry Instruments, Model Reference 600. The potentiostat showed repeatability of about 10% - 15%. The M.C. Miller device showed repeatability of about 1%. Hence, we present the results obtained from the M.C. Miller device in what follows.

We present laboratory measurements of resistivity from samples retrieved from sources and sites in Buffalo, NY; Schroon, NY; San Antonio, TX; and El Paso, TX in Figure 4-4. Figure 4-4 includes the results from testing samples, via AASHTO T-288 (2016) and Tex-129-M and data obtained by owners/contractors as well as by UTEP (NCHRP Research Team). The data presented in Figure 4-4 show relatively good agreements between the resistivity measurements from samples retrieved from the sources (tested by UTEP and owners) and those obtained from the sites (tested by UTEP). An exception to this observation is the site sample from Schroon, NY tested via Tex-129-M (resistivity = 9300 Ω -cm in Figure 4-4). This result appears to be low compared to the other test results obtained from the source and tested via Tex-129-M, and is not higher than the results obtained via AASHTO T-288 (2016). This is unusual as measurements of resistivity via Tex-129-M M are generally higher than those obtained via AASHTO T-288 with the same sample, as depicted by the bias that was shown in Figure 3-4 and 3-5 and discussed in Section 3.3.1.2.



(a) Schematic¹

¹ C_1 and C_2 = current terminals; P_1 and P_2 = potential terminals



(b) Test setup Figure 4-3 Resistivity measurement using modified soil box (DAQ = data acquisition system).



Figure 4-4 Comparison of resistivity results obtained from modified soil box tests¹.

¹ The owner (TXDOT) from two of the sites (El Paso and San Antonio) did not provide results from resistivity testing in accordance with Tex-129-M. TXDOT provided data from testing in accordance with AASHTO T 288 for the San Antonio site, but not for the El Paso site.

4.3.2 Resistivity – Field Tests using Wenner Technique

We performed in-situ resistivity measurements at each site using the Wenner 4-probe technique, as described by ASTM G-57 (2012) and Wenner (1915). In addition, in-situ measurements of moisture content and density were made using a nuclear density gauge (Troxler, Model 3440 – shown in Figure 4-8) and samples were collected from the site for further laboratory investigations. The equipment used for resistivity measurements included: 1) Advanced Earth Ground Tester GEO, Fluke, Model 1625-2, 2) Soil Resistance Meter, Nilsson Electrical Laboratory INC., Model 400, 3) Soil Resistance Meter, M.C. Miller, Model: 400D, and 4) Potentiostat, Gamry Instruments, Model Reference 600. The resistivity values presented in this research are mainly from those obtained from M.C. Miller, Model: 400D, as it provides the most stable resistivity readings.

In Figure 4-5 we show the typical test setup for performing the Wenner 4-probe measurement. We used a penetration depth of the probes ("b") of 6 inches for all measurements and varied the spacing between the probes, ("a") as 6 inches, 12 inches, and 24 inches. The spacing determines the depth covered by the measurements. For resistivity measurements in MSE walls, we selected test locations perpendicular and parallel to the reinforcement strips. For resistivity measurements along the shoulder (or shoulder back) of roads, we selected measurement lines perpendicular and parallel to the pavement. Figure 4-6 is a schematic that depicts the locations, zones, and directions of resistivity measurements at each site.





(b) Test setup in the field Figure 4-5 The Wenner 4-probe technique.







Figure 4-6 Locations, zones and directions for performing soil resistivity measurements.

At locations where the soil appeared to be very dry (e.g., in the MSE wall in San Antonio, TX), we added water in small amounts (less than 200 ml) to the soil next to the probes to improve the electrical conductivity between the probes and the soil. In this case, samples for measuring moisture content and electrochemical properties of the soil were collected farther away from the wet region of the soil. These samples were sealed and stored in double ZiplockTM plastic bags to prevent evaporation and contamination.

According to Wenner (1915), the resistance reading (*R*) can be converted to the resistivity (ρ) at different probe penetrations (*b*) and different spacings (*a*), using Equation (4-1).

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{2a}{\sqrt{4a^2 + 4b^2}}}$$
(4-1)

When the penetration depth of the probes is small in comparison to the spacing among them (b < 0.05 a), Equation (4-1) can be simplified as Equation (4-2), which is the formula cited by the ASTM G57 standard (2012). Since the penetration depth in this research (6 inches) is clearly greater than 5% of the spacing between the probes, we used the original formula by Wenner (1915) (Equation (4-1)) to determine the numerical resistivity values in the field.

$$\rho = 2\pi a R \tag{4-2}$$

We show resistivity measurements as a function of depth for different sites at directions parallel or perpendicular to the reinforcements (or pavements) in Figure 4-7. These data include measurements from lines/locations spaced approximately 15 feet apart. Each line/location is a total of 6 feet long and includes resistivity measurements at probe spacings of 0.5, 1.0, and 2.0 feet. At some locations the one- or two-feet probe spacing could not be achieved due to space constraints to place the probes.







h) Schroon, NY - perpendicular to pavement

Figure 4-7 Results from in-situ testing (determined from Equation (4-1)).

Figure 4-7 allows us to compare the data obtained from different sites, and from fills that incorporate metal reinforcements and those that do not. Based on the data shown in Figure 4-7, we made the following observations:

- The resistivity measurements from the San Antonio site were very high; greater than 1,000,000 Ω -cm, and within the range of 5,000,000 to 35,000,000 Ω -cm. This is due to the extremely dry conditions at this site.
- Data from the MSE wall site in San Antonio show higher variations between measurements taken at different locations compared to the data obtained from the other sites. This might be related to the extremely dry conditions at the site (with moisture content less than 1%) as the operators had to add water in small amounts to the fill (next to the probes) to improve the electrical connection between the probes and the fill. Addition of water and the high evaporation rate at this site might be the main reasons for the relatively large variations in the resistivity measurements.
- Measurements from the San Antonio and El Paso sites depict higher resistivity values from lines orientated perpendicular to the MSE reinforcements compared to the measurements from lines orientated parallel with the reinforcements. This can be explained by the fact that the steel reinforcement provides an easy path for current in the longitudinal direction causing a reduction in the resistivity readings when the alignment of the pins for resistivity measurements are orientated parallel (longitudinal) with the reinforcements.
- Considering the measurements from the New York sites that were performed within the shoulder areas of the pavement, measurements with lines perpendicular or parallel to the pavement are similar to each other (no steel reinforcements in the subbase materials).
- In general, the resistivity measurements from the site in San Antonio increase with respect to depth, but the data from New York sites generally decrease with respect to depth. This

observation may be related to the significantly higher effect of the reinforcements in reducing the resistivity at 0.5 feet depth compared to that at 2.0 feet depth (i.e., having one layer of reinforcement in a 0.5-feet thick material has a more significant charge carrying effect compared to that over a thickness of 2.0). In addition, the measurements at depths of 2.0 feet from the subbases studied at the New York sites reflect the presence of subgrade material beneath the 12 to 15 inches of subbase material that was placed for these projects (i.e., materials at the New York sites are not homogeneous over the two feet depth of measurements).

- The resistivity measurements from the site in El Paso remains relatively constant with respect to depth, which is different than the increasing trend observed in the data from San Antonio. This could be attributed to the high moisture content of the fill in El Paso (with the average moisture content of 7.3%), which dominates over the effect of reinforcements (described above). In addition, the lower variations in the resistivity measurements from El Paso can be explained by the higher moisture content of the fill at this site.
- Higher resistivities were observed from measurements at the site in Schroon, NY compared to those from the site in Buffalo, NY. This is consistent with laboratory measurements of resistivity.

We measured the in-situ moisture contents at the Schroon, Buffalo, and El Paso sites as approximately 3.0, 2.5, and 7.3 percent by weight, respectively. Figure 4-8 shows one of the insitu moisture content measurement at Schroon, NY, performed by the NYSDOT (the owner) using a nuclear density gauge. UTEP and the NYSDOT tested samples from the sources and sites in accordance with Tex-129-M, which includes the larger soil box and all of the particle sizes in the test specimen. We extrapolated the moisture-resistivity curves obtained from these laboratory tests to moisture contents of 3.0, 2.5, and 7.3 percent as shown in Figure 4-9, and compared these values to the field/in-situ measurements at depths of 6 inches. We obtained a good comparison as shown in Table 4-3. The average error was approximately 11%.



Figure 4-8 In-situ measurement of moisture content at Schroon, NY.



Figure 4-9 Extrapolating the moisture-resistivity curves to determine the resistivity at in-situ moisture content for the site in Buffalo, NY.

Table 4-3 In-situ (Wenner 4-probe) and laboratory (modified soil box) measurements¹.

	In-situ range (Ω-cm)	Laboratory (Ω-cm)
El Paso, TX	8000 - 22,000	11,600
Buffalo, NY	30,000 - 54,000	38,400
Schroon, NY	60,000 - 115,000	95,000

4.3.3 Other Electrochemical Properties

We present laboratory measurements of chloride and sulfate contents from samples retrieved from sources and sites in Buffalo, NY; Schroon, NY; San Antonio, TX; and El Paso, TX in Figure 4-10 and Figure 4-11, respectively. These graphs include the results from testing samples via AASHTO T-290 (2016), AASHTO T-291 (2013) and Tex-620-M. The data show good agreements between measurements from samples retrieved from the sources and those obtained from the sites. In most cases the chloride and sulfate contents determined by Tex-620-M are lower than those obtained by AASHTO test procedures. An exception to this observation is seen with the source from Buffalo, NY, where the sulfate content from Tex-620-M appears to be higher than that from AASHTO T-290 (2016). However, the measurement of sulfate content via AASHTO T 290 for the site sample is higher compared to the results from testing the source. The measurement of sulfate content via AASHTO T 290 from the source sample appears to be anomalous and too low and is not considered in the comparisons of results.

We show the results of electrochemical tests performed on the samples retrieved from the sites and from the sources in Table 4-4. The laboratory results of the resistivity tests were discussed in

¹ Because of the unusually high resistivity measurements at the San Antonio site (Figure 4-7 (a) and (b)), we did not include the comparisons between laboratory and in-situ measurements in this Table.
Figure 4-4. Considering the AASHTO requirements for fills in MSE walls (presented in Table 1), the material from Buffalo, NY, is characterized as corrosive but other materials are noncorrosive.

	Protocol	Resistivity (Ω-cm)	рН	[Cl ⁻] (mg/kg)	[SO ₄] (mg/kg)	Corrosive
San Antonio, TX	Modified Tests	53,300	9.0	1	1	No
El Paso, TX	AASHTO	3,650	9.0	49	40	No
Buffalo, NY	AASHTO	2,233	7.7	14	311	Yes
Schroon, NY	AASHTO	10,433	8.3	15	53	No

Table 4-4 Characterization of corrosion potential¹.

Note: The values marked in red do not meet current AASHTO requirements for MSE wall fill.



¹ The presented values in this Table are average of site and source.



4.4. Comments and Suggestions from Owners

We exchanged information with the New York State DOT (NYSDOT) geotechnical and environmental engineering laboratories and noted their comments and suggestions for proper implementation of the proposed protocol. Since the Texas DOT participated in the development of the modified test procedures, they offered no additional comments. We summarized the main comments/suggestions that we received from NYSDOT below:

- 1. When testing compacted specimens, add increments of moisture after removing the specimens from the box and use a mixer (similar to Figure 4-12) to obtain a good distribution of moisture throughout the specimen (i.e., do not add water directly to the compacted specimen within the soil box).
- 2. The moisture increment corresponding to 100 percent saturation is easily obtained from weight measurements of the compacted soil specimen after each increment. The increment at which the wet weight of the material begins to decrease occurs near saturation.
- 3. For AASHTO T-288 and Tex-129-M compare the resistivity measurements obtained when the specimen reaches saturation (ρ_{sat}) to the minimum resistivity (ρ_{min}) obtained by increasing the moisture content until reaching the absolute minimum resistivity. However, for moisture contents in excess of those needed to achieve 100 percent saturation, we are not testing a compacted specimen, rather we are testing a slurry. This comparison provides useful information to estimate the behavior of the material in the worst-case scenarios and to determine the possible underestimation/overestimation of the reported resistivity.
- 4. Resistivity tests with coarse samples in the 20 lb. box and preparing the samples and testing in accordance with Tex-129-M was feasible (required a reasonable amount of time and effort).

- 5. A bottle roller is not standard equipment for a geotechnical lab and other methods of mixing should be implemented for measuring salt contents and pH in accordance with Tex-620-M.
- 6. Mixing times for the tests on leachates for measurements of pH and salt contents should be kept to a maximum of 30 minutes.
- 7. Use a template to properly align pins for performing the Wenner 4-probe test.
- 8. The Wenner 4-probe test is relatively easy to implement and can be used on active construction projects. Resistivity meters built specifically for this test, similar to the M.C. Miller Resistivity Meter, should be employed due to their ease of use, field ruggedness and efficiencies (i.e., although the results obtained from the Gamry device were in good agreement with the M.C. Miller device, it was a relatively time consuming process to make a measurement with the Gamry device).



Figure 4-12 A mixer used at Soils Engineering Laboratory of NYSDOT.

4.5. Conclusions

We made the following observations from the data we collected in cooperation with owners/contractors as part of Phase III:

- We observed higher variations in results between laboratories that were testing similar samples compared to the variations observed from resistivity measurements made with samples retrieved from the sources before construction, and from the site during construction. This is because, in general, samples retrieved from the site or the source were similar.
- The variations we observed during the field studies included in Phase III were higher than the variations that we observed from testing replicates with the same operator/laboratory during Phase II. This is expected because of variabilities that exist between laboratory practices and the errors due to variations between samples. We intentionally limited the

variations between samples when we implemented the laboratory test program for Phase II, which mitigated the sampling error.

- Reinforcements affect the in-situ measurements of resistivity from MSE wall fills.
- Reinforcements appear to have the least effect on measurements of resistivity if the lines for the Wenner 4-probe test are orientated perpendicular to the reinforcements.
- We observed good correspondence between laboratory and field measurements of resistivity when the laboratory tests are conducted on compacted specimens with the same particle sizes, gradation and moisture content as the in-place fill, and considering the in-place moisture content of the fill.

The experience and data collected from implementing the proposed protocol on active construction projects indicate that the modified test procedures and the test protocol for improved characterization of corrosion potential are easier to implement compared to the traditional methods. The owners/contractors were able to perform the modified test procedures, and with few exceptions could acquire the equipment needed to perform these tests.

Chapter 5. Conclusions and Needs for Future Research

5.1. Main Conclusions

We have proposed a protocol describing best practices for sampling, testing, and characterizing the steel corrosion potential of earthen materials. The protocol incorporates alternatives to the current AASHTO test standards for measuring electrochemical properties including resistivity, pH, chloride and sulfate ion contents. We developed the protocol from a review of current test procedures and practices, a program of laboratory testing that included a broad range of materials and test alternatives, and observations of corrosion rates from galvanized and plain steel elements subject to corrosion.

The current AASHTO test procedures are limited to testing materials that incorporate a significant amount of material passing a No.10 sieve. Modified test standards considered as alternatives to the AASHTO tests include Tex-129-M and Tex-620-M for measurements of resistivity and salt contents, respectively. Unlike the AASHTO tests, these alternatives incorporate larger sized particles within the test specimens. We selected Tex-129-M and Tex-620-M from a suite of candidates based on the precision and repeatability of the results observed from the laboratory test program, the utility of the test results, and the observed performances of plain and galvanized steel elements subjected to corrosion within these materials.

Conceptually, there is a threshold (i.e., PP_{#10}), beyond which the portion of the material finer than the No. 10 sieve controls the performance and the ability of corrosion currents¹ to flow through the materials. The finer particles have higher salt contents and lower resistivities compared to the measurements obtained from the bulk samples. If there is sufficient material passing the No. 10 sieve, then the corrosion currents will be concentrated along paths where the finer materials are concentrated (i.e., current follows the path of least resistance). Hence, the corrosivity is affected more by the properties of the finer portions compared to the bulk properties of the material. We concluded that results from Tex-129-M apply well to the materials with less than approximately 22 percent passing the No.10 sieve. For materials with more than 22 percent passing a No.10 sieve, AASHTO T-288 is appropriate for the measurement of resistivity. We used these observations to develop the proposed protocol presented in Appendix A, where the 22 percent threshold is rounded up to 25 percent passing a No. 10 sieve.

In general, the proposed protocol describes the application of the current AASHTO test series for samples with grading number (GN) > 3, <u>or</u> if the percent passing the No.10 sieve is greater than 25%. Otherwise, if the GN < 3, <u>and</u> the percent passing the No.10 sieve is less than 25%, the Texas modified procedures are recommended (i.e., Tex-129-M and Tex-620-M). The GN is included with the screening to restrict the use of Tex-129-M to coarse-textured samples with a relatively high gravel content.

We grouped the materials included in this study into clusters based on ranges of resistivity and according to corrosion indices determined from the German Method (DVGW-GW9) for characterizing corrosivity. The German Method is a multivariate approach for classifying

¹ Corrosion current is the electrical current produced in the medium (in this case soil) during the corrosion process.

corrosivity that considers the electrochemical properties of the relevant earthen materials, site conditions, and the presence of carbonates or industrial by-products. We selected ranges of resistivity and corrosion indices corresponding to noncorrosive, mildly corrosive, and moderately to severely corrosive conditions. We compared corrosion rates measured from plain and galvanized steel elements to the rates cited in the literature corresponding to the given corrosivity descriptions. We observed relatively good comparisons, when test results were applied according to the proposed protocol.

We cooperated with selected transportation agencies, whereby the recommended protocol was implemented as a "shadow specification." The data included characterization of different sample sources (e.g., maximum particle size and gradation) along with the measurements of geochemical and electrochemical properties of the samples including resistivity, pH, chloride, and sulfate contents. A program of in-situ testing that included the Wenner 4-probe technique (according to ASTM G57 (2012) and Wenner (1915)) was used in the field for measurement of electrical resistivity. This was followed by collecting the representative material samples from the site and from the source to perform electrochemical tests in the laboratory using modified and current AASHTO test procedures. We also evaluated the practicality and implementation of the suggested protocol through the interaction with laboratories engaged in electrochemical testing, and suppliers/owners in different states including UTEP, McMahon & Mann, NYSDOT and TXDOT (AASHTO Tests only).

The experience and data collected from implementing the proposed protocol on active construction projects indicate that the modified test procedures and the test protocol for improved characterization of corrosion potential are easy to implement compared to the traditional methods. The owners/contractors were able to perform the modified test procedures, and with few exceptions could acquire the equipment needed to perform these tests. Recommendations as to which test procedures should be applied to the characterizations of corrosivity were found to be clear and easy to implement.

5.2. Recommendations for Future Research

1. The test program described in this study included materials that may be described as sands and gravels that did not incorporate more than 5 percent passing a No. 200 sieve. This sample domain was relevant to MSE wall construction practices. However, this sample domain was not representative of earthen materials encountered in other applications that may include installations of piles, culverts, and drainage pipes. Also, in some states materials with more than 15% passing a No. 200 sieve are common in MSE wall constructions. Thus, more data are needed to evaluate the characterization of steel corrosion potential for earthen materials with significant fine contents (material passing a No. 200 sieve, i.e., silt and clay fractions). Additionally, more data are needed to distinguish between the effects of silty fines compared to clayey fines on the corrosion potential. In some cases, the endpoints for resistivity tests may need to be modified depending on the nature and the application of the material. For some materials and applications, the proper test endpoint is when the material is saturated, and in other cases the endpoint needs to be when the lowest (minimum) resistivity is reached. The latter definition for endpoint means that the specimen may be in a slurry state at the end of the test, which is not a "compacted" specimen. In this study the endpoint for resistivity testing was at the point of saturation.

- 2. Further research is needed to consider the use of nonconventional materials in construction that may include industrial by-products, recycled materials, or lightweight fills. The compositions, chemical, and electrochemical properties of these materials are significantly different from soils. Hence, special test considerations and sample preparations need to be developed for proper measurements of electrochemical properties.
- 3. For this study, we used observations of the performance of metal elements embedded within earthen materials from laboratory measurements of corrosion rates in addition to insitu measurements from in-service soil reinforcements. Laboratory tests are an efficient means of obtaining data from a number of different fill types. More data are needed to expand the performance database and to refine the characterizations of corrosivity and capabilities for service life modeling. We suggest that an extensive program of laboratory tests verified with field measurements be undertaken to expand the performance database.
- 4. More data from field testing using the Wenner 4-probe technique are necessary. Results from field testing may be useful to decide if collecting more samples from the site and laboratory testing are necessary. If the results from field testing match the laboratory measurements from Tex-129-M, at similar levels of moisture content, then this indicates that the materials that were sampled and tested prior to construction are similar to those that were delivered to the site and placed during construction. If the results do not match, then more samples should be selected from the source and the site for further laboratory testing and confirmation that materials that are not corrosive are being placed at the site. At this point, we only have data from four sites, and more data and experiences are needed to validate this approach.
- 5. Additional implementation activities are needed to promote the recommended protocol, transfer information about the sampling and testing described in the protocol, and interact with AASHTO committees and the State DOTs to consider the modified practices. We suggest the following activities for promoting the implementation of the proposed protocol:
 - Combine all of the required information including the protocol and the specifications into one modified test standard. This may include modifications and enhancements to the current AASHTO Standards.
 - Prepare course materials, guidebooks, and laboratory demonstrations for training.
 - Conduct inter-lab tests to obtain more data on the precision and repeatability of the tests included in the proposed protocol.
 - Attend and make presentations at AASHTO Committee and FHWA regional meetings to engage the state DOTs and transfer knowledge that was gained in pursuit of NCHRP 21-11 and the proposed protocol.
 - Engage the construction industry including contractors that often select fills for construction, and suppliers of MSE wall systems that promote the use of good construction practices and specifications. This can be accomplished via interactions

with various industry groups including the Association for Mechanically Stabilized Earth (AMSE) and the Associated General Contractors of America (AGC).

• Engage the FHWA to assist in deployment of these practices. This may include updates to existing documents published by FHWA that describe corrosion and degradation of soil reinforcements, culverts, etc. and sampling and testing of fill materials. (e.g. FHWA-NHI-09-087, Elias et al., 2009).

References

- AASHTO T 288-12 (2016). "Determining minimum laboratory soil resistivity." American Association of State Highway and Transportation Officials, Washington, DC.
- AASHTO T 289-91 (2018). "Determining pH of soil for use in corrosion testing." American Association of State Highway and Transportation Officials, Washington, DC.
- AASHTO T 290-95 (2016). "Determining water-soluble sulfate ion content insoil." American Association of State Highway and Transportation Officials, Washington, DC.
- AASHTO T 291-94 (2013). "Determining water-woluble chloride ion content insoil." American Association of State Highway and Transportation Officials, Washington, DC.
- Ahmad, S. (2003). "Reinforcement corrosion in concrete structures, its monitoring and service life prediction—a review." *Cement and Concrete Composites*, 25(4-5), 459-471.
- Arciniega, J.L., Walker, W. S., Nazarian, S., and Fishman, K. L. (2018). "A Process for Optimizing Gradation of Marginal Backfill of Mechanically Stabilized Earth Walls to Achieve Acceptable Resistivity," <u>Transportation Research Record</u>, Journal of the Transportation Research Board, Vol. 2672, Issue 52, Sage Publications, Washington, DC, 7 p.
- Arciniega, J.L., Walker, W. S., Nazarian, S., and Fishman, K. L. (2019). "A Model for Estimating Resistivity of In-Service Backfill of Mechanically Stabilized Earth Walls Based on Minimum Resistivity and Degree of Saturation," <u>Transportation Research Record</u>, Journal of the Transportation Research Board, https://doi.org/10.1177/0361198118825121, 7 p.
- ASTM D4327-17 (2017). "Standard test method for anions in water by suppressed ion chromatography." ASTM International, West Conshohocken, PA.
- ASTM D4972-19 (2019). "Standard test methods for pH of soils." ASTM International, West Conshohocken, PA.
- ASTM G57-06 (2012). "Standard test method for field measurement of soil resistivity using the Wenner four-electrode method." ASTM International, West Conshohocken, PA.
- ASTM WK24621 (2015). "Measurement of Coarse Aggreate Resistivity Using the Two-Eelctrode Soil Box," Draft Documet, 08-28-2015, for consideration by ASTM Subcommittee C-09.20.
- ASTM G187-18 (2018). "Standard test method for measurement of soil resistivity using the twoelectrode soil box method." ASTM International, West Conshohocken, PA.
- Brady, K.C. and McMahon, W. (1994), "The Durability of Corrugated Steel Buried Structures," Transportation Research Laboratory, UK.
- Bronson, A., Rocha, S., Nazarian, S., Borrock, D.M. (2013), "Characterization of Coarse Backfill Materials for Prevention of Corrosion of MSE Metallic Wall Reinforcement," Report No. FHWA/TX 11/0-6359-1, National Technical Information Service, Springfield, Virginia, 137p.
- Elias, V. (1990). "Durability/corrosion of soil reinforced structures." *FHWA-RD-89-186*, Office of Engineering and Highway Operations, R&D, McLean, VA.
- Elias V., Fishman, K.L., Christopher, B.R. and Berg, R.R. (2009) "Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes," Report FHWA-NHI-09-087, National Highway Institute, Federal Highway Administration, Washington, D.C.

- Eyre, D. and Lewis, D.A. (1987), "Soil Corrosivity Assessment," Contractor Report 54, Transportation Road Research Laboratory, UK.
- Fishman, K.L. and Withiam, J.L. (2011). "LRFD Metal Loss and Service-Life Strength Reduction Factors for Metal-Reinforced Systems," NCHRP Report 675, National Academy Press, Washington, D.C., 105p.
- Hageman, P.L. (2007), "U.S. Geological Survey Field Leach Test for Assessing Water Reactivity and Leaching Potential of Mine Wastes, Soils, and Other Geologic and Environmental Materials," U.S. Geologic Survey Techniques and Methods, Book 5, Chapter D3, U.S. Department of the Interior, U.S. Geologic Survey, Reston, VA, 14 p.
- Highway Agency, United Kingdom (2000), "Design Manual for Roads and Bridges", BD 42/00, Vol. 2, Section 1, Part 2. < <u>http://www.standardsforhighways.co.uk/ha/standards/</u> > (Oct 21, 2019).
- Jones, C.J.F.P. (1985), "Durability," Chapter 10, Earth Reinforcements and Soil Structures, Butterworths, London, pp. 138.
- Jones, D. A. (1996). *Principles and Prevention of Corrosion*, Prentice Hall, Upper Saddle River, NJ, 40-74.
- King, R. (1977). "A review of soil corrosiveness with particular reference to reinforced earth." *TRRL Supplementary Report 316*, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.
- Lehigh Hanson Company (2019). "Crushed stone materials." <<u>https://www.lehighhanson.com/products/aggregates/crushed-stone</u> >. (Oct 16, 2019).
- McCarter, W. J. (1984). "The electrical resistivity characteristics of compacted clays." *Geotechnique*, 34(2), 263-267.
- NCHRP 21-06 (2009). "Corrosion in the Soil Environment: Soil Resistivity and pH Measurements," Draft Final Report, prepared by William S. Vilda III, Corrpro Companies, Inc., Ocean CIty Research Group, Ocean City, NJ, Janaury 2009, 106 pp.
- Oman, M. (2004). "Advancement of grading & base material testing." Office of Materials, Minnesota Department of Transportation, Maplewood, MN, USA.
- Page, A. (1982). *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*, American Society of Agronomy.
- Rehm, G. (1980). "The service life of reinforced earth structures from a corrosion technology standpoint." The Reinforced Earth Company (RECO), Vienna, VA.
- Romanoff, M. (1957). *Underground Corrosion*, National Bureau of Standards, Circular 579, U.S. Department of Commerce, Washington, DC.
- Sagues, A., Poor, N. D., Caseres, L., and Akhoondan, M. (2009). "Development of a rational method for predicting corrosion rates of metals in soils and waters." *Report No. BD497*, National Technical Information Service, Springfield, Virginia.
- Shreir, L.L., Jarman, R.A., and Barstein, G.T. (1994), *Corrosion*, 3rd Edition, Vol. 1, Elsevier, p. 2:85.
- SCT 143 (2008). "Method of preparing coarse aggregate sample for pH and resistivity testing in the laboratory." South Carolina Department of Transportation (SCDOT), Columbia, SC.
- Siddharthan, R. V., Thornley, J., and Luke, B. (2010). "Investigation of corrosion of MSE walls in Nevada." *Research No. 2009-03*, University of Nevada, Reno, Reno, NV.
- Tait, W. S. (1994). An Introduction to Electrochemical Corrosion Testing for Practicing Engineers and Scientists, PairODocs, Racine, WI.

- Tex-110-E (1999). "Particle Size Analysis of Soils," Texas Department of Transportation, Austin, TX.
- Tex-128-E (1999). "Determining soil pH." Texas Department of Transportation (TxDOT), Austin, TX.
- Tex-129-E (1999). "Measuring the resistivity of soil materials." Texas Department of Transportation (TxDOT), Austin, TX.
- Tex-129-M (2018). "Test Procedure for Measuring the Resistivity of Soils and Aggregates," Texas Department of Transportation (TxDOT), Austin, TX.
- Tex-620-J (2005). "Determining chloride and sulfate contents in soil." Texas Department of Transportation (TxDOT), Austin, TX.
- Tex-620-M (2018). "Test Procedure for Determining the Conductivity, pH, Sulfate Contnet, and Chloride Content of Soil and Coarse Aggregate," Texas Department of Transportation (TxDOT), Austin, TX.
- Wenner, F. (1915). "A method for measuring earth resistivity." *Journal of the washington academy of sciences*, 5(16), 561-563.
- William, V. (2009). "Corrosion in the soil environment: soil resistivity and pH measurements." *NCHRP 21-06*, National Cooperative Highway Research Program, Washington, DC.

Appendix A. Test Protocols – Recommended Electrochemical Test Methods to Evaluate the Corrosion Potential of Earthen Materials

1. Introduction

1.1. This protocol is focused on characterizing the steel corrosion potential of earthen materials.

1.2. Corrosion performance of black and galvanized steel elements embedded in earthen materials are considered.

1.3. Corrosion potential considers the electrochemical properties of earthen materials, site conditions, metal type, and applications that may include mechanically stabilized earth (MSE), soil nails (SN), steel (and reinforced concrete) piles and culverts and drainage pipes.

1.4. Earthen materials incorporate soils and aggregates that may include crushed rock or native soils that are excavated and processed to meet specified gradations.

1.5. Earthen materials may be native (in situ), existing fills or newly placed fills. Fills may be from native materials excavated and used "as-is" or may be native materials that are excavated and processed.

1.6. Earthen materials are characterized in terms of maximum particle size, gradation, fines content, plasticity index, and mineralogy.

1.7. Native soils are earthen materials that are in their natural state and have not been disturbed by excavation and processed to satisfy a specific gradation.

1.8. Newly placed materials are fills that will be, or are being, placed during construction.

1.9. Existing materials are earthen materials that are in place prior to construction and may include old fills or native (in situ) materials.

1.10. Although many test techniques and standards exist for the measurement of electrochemical properties of earthen materials (including resistivity, pH, and chloride and sulfate contents), not all test methods are suitable for all types of earthen materials and applications. Test methods for measurement of electrochemical properties must be selected based on the nature and character of the earthen material. In addition, practicality of each test considering the site conditions and accuracy of the results should be considered before selecting any test methods/standards.

1.11. Site conditions include topography, details of constructed facilities, the location of the water table, drainage conditions, climate (temperature, humidity, etc.).

1.12. The protocol describes different applications (MSE, SN, piles, culverts, and drainage pipe) and the factors that may affect steel corrosion in these applications.

1.13. The protocol describes sampling procedures and requirements for characterizing corrosion potential of earthen materials.

1.14. The protocol refers to the most common test standards for the measurement of electrochemical properties including resistivity, pH, and concentration of chloride, and sulfate.

1.15. The protocol describes different schemes for characterizing the corrosion potential of earthen materials.

2. Referenced Documents

2.1. AASHTO Standards

T-27 Sieve Analysis of Fine and Coarse Aggregates;

T-88 Particle Size Analysis of Soils;

T-89 Determining the Liquid Limit of Soils;

T-90 Determining the Plastic Limit and Plasticity Index of Soils;

T-288 Determining Minimum Laboratory Soil Resistivity;

T-289 Determining pH of Soil for Use in Corrosion Testing;

T-290 Determining Water-Soluble Sulfate Ion Content in Soil;

T-291 Determining Water-Soluble Chloride Ion Content in Soil;

R026 Standard Practice for Assessment of Corrosion of Steel Piling for Non-Marine Applications; and

LRFD Bridge Design Specifications

2.2. ASTM Standards

D2419 Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate;

D4327 Standard Test Method for Anions in Water by Suppressed Ion Chromatography;

G57 Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method; and

D4220 Standard Practices for Preserving and Transporting Soil Samples

2.3. TXDOT

Tex-129-M Test Procedure for Measuring the Resistivity of Soils and Aggregates; and

Tex-620-M Test Procedure for Determining the Conductivity, pH, Sulfate Content and Chloride Content of Soil and Coarse Aggregate

2.4. NCHRP

NCHRP Report 477 Appendix A, "Recommended Practice for Evaluating Metal Tensioned Systems Used in Geotechnical Applications."

NCHRP Report 474, "Service Life of Culverts."

2.5. FHWA/NHI

FHWA-NHI-09-087, "Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes." November 2009, 155 pp.

FHWA-NHI-16-009, "Geotechnical Engineering Circular No. 12 – Design and Construction of Driven Pile Foundations," September 2016, 563 pp.

FHWA-NHI-14-007, "Geotechnical Engineering Circular No. 7 – Soil Nail Walls Reference Manual," February 2015, 425 pp.

French National Project Clouterre (1991), "Recommendations Clouterre 1991 (English Translation)," Federal Highway Administration, Washington, D.C., 321pp.

Samtani, N. C. and Nowatzki, E. A. (2006), "Hollow-Core Soil Nails State-of-the-Practice," FHWA Report Unassigned, Office of Bridge Technology, Federal Highway Administration, Washington. D.C., 51pp.

Samtani, N. C. and Nowatzki, E. A. (2010), "Hollow Bar Soil Nails Review of Corrosion Factors and Mitigation Practice," Report FHWA-CFL/TD-10-002, Federal Highway Administration, Central Federal Lands Highway Division, Lakewood, CO., 82pp.

2.6. Post-Tensioning Institute (PTI)

Recommendations for Prestressed Rock and Soil Anchors

3. Identify Application

3.1. Mechanically stabilized earth walls (MSEW) are fill walls (i.e. bottom-up construction) consisting of alternating layers of compacted fill and soil reinforcement elements fixed to a wall facing forming a composite soil structure. Soil reinforcements may be metallic or geosynthetic and fill sources include mined sands and gravels, or processed aggregates, that should not be corrosive when metallic reinforcements are used. Fills commonly used in MSE construction have textures that range between fine silty sand and coarse aggregate, are relatively homogenous and often free draining. Fill materials are compacted during construction at near optimum moisture contents and maximum density as determined by laboratory and in situ testing, or until sufficient interlock is achieved as indicated by proof rolling in the case of coarse aggregate fills.

3.2. Soil nails (SN) are closely spaced reinforcements that are drilled and grouted into existing earthen materials via top-down construction to form a composite structure that includes a shotcrete facing. Soil nails may be solid steel bars or hollow bar soil nails (HBSN). Solid bar soil nails (SBSN) may include Class I or II corrosion protection (PTI) depending upon the corrosivity of the existing soils and whether the installation is considered permanent or temporary. HBSNs employ sacrificial steel and are surrounded by grout. However, because of the brittleness of the grout and the inevitable formation of microcracks in tension, and the possibility of soil intrusion into the hole, the degree to which the grout protects the HBSN is uncertain. Thus, the electrochemical properties of the existing soils are important factors affecting the service-life design of the SBSN and HBSN.

3.3. Piles are deep foundation elements that may include steel piles that are hammered or predrilled into the existing soils. They may penetrate through different soil layers (and the water table) with different electrochemical properties. Where grades have been raised there may be industrial fill near the surface. Corrosion problems have been observed near the surface where industrial fills have been placed and the groundwater table fluctuates near the interface between the fill and native ground. In addition, different soil layers have different oxygen contents (above and below the water table), which provides the electromotive force required for corrosion.

3.4. Culverts/drainage pipes are conduits that collect or direct stormwater, provide drainage to embankments and roadways, and allow embankments and roadways to cross streams or creek beds. They are installed within existing or newly placed soils and may be plastic, reinforced concrete, or metal sections. Although bedding and structural backfill are usually placed during construction, often the surrounding existing soil determines the corrosion levels in culverts/drainage pipes. For culverts, corrosion may occur on the both the water, and soil sides.

4. Relevant Characteristics of Earthen Materials

4.1. Nature – Best practices vary depending upon the nature of earthen materials. Sampling and laboratory testing are recommended from potential sources of newly placed materials. Field tests (in-place testing) along with sampling and laboratory testing are recommended for existing materials and during construction with newly placed materials.

4.2. Unconventional fills – May incorporate lightweight or recycled materials. These may include recycled concrete, slag, cinder ash, or lightweight materials such as foamed glass, expanded clay, expanded slate or expanded shale. There is not much known about the factors affecting the behavior of unconventional fills and additional studies are needed to investigate and adapt test procedures for the measurement of electrochemical properties and for characterizing corrosion potential of these materials. This protocol does not address testing and characterizing corrosion potential for unconventional fills.

4.3. Size/gradation – The texture of earthen materials may be coarse or fine. Also, depending on the gradation, the material may be free draining or not free draining. For laboratory testing, the maximum particle size and the gradation of the sample affect the sample size requirements and the appropriate testing conditions. For tests on leachate, the maximum particle size and the gradation affect the required dilution ratios and mixing procedure. Best practices are to select test standards including sample treatments and specimen preparations that are best suited to the texture of the sample.

4.4. Minerology – Carbonates, pyritic minerals, siliceous minerals, and clay may be present and affect the performance of metal elements and the characterization of corrosion potential. Descriptions of the parent rock types and knowledge of the corresponding mineralogy are useful to discern the presence of these constituents. Quarries identify their parent rock types, which can also be identified from bedrock geology maps, provided the location of the source is known. Best practices are to characterize mineralogy based on the knowledge of the source.

4.4. Anaerobic conditions and the presence of sulfate-reducing bacteria may contribute to microbial induced corrosion (MIC). For example, soils underlying marsh, bogs, and swamps or exposed to marine environments are highly corrosive for this reason. Best practices are to identify

conditions where there will be a lack of oxygen within materials that incorporate organics and sulfate and to consider the possibility of MIC, i.e. recognize that corrosion can occur in the absence of oxygen. We recommend in situ measurements of the oxygen reduction potential (ORD), when possible for susceptible sites, to identify if aerobic or anaerobic conditions prevail in situ.

4.5 Contaminants – Earthen materials may become contaminated from polluted groundwater, runoff from fertilized fields, infiltration of deicing salts, or contaminated stormwater during the service life of the metal elements. Best practices for characterizing corrosion potential should consider that properties of earthen materials may be altered over time due to the presence of contaminants.

5. Requirements for Sampling and Testing

5.1. The number of samples. Sampling requirements depend on the homogeneity of the source and the precision of the test procedure. Recommended sampling intervals for MSE fill are described in FHWA-NHI-09-087, Table 2-2, "Recommended Sampling Protocol for Electrochemical Testing of MSE Wall Fill." These recommendations may also apply to other applications involving newly placed materials.

5.1.1. For existing soils see the in-situ sampling techniques described in Section 5.5.

5.1.2. Best practices for sampling "in place" materials will be identified. This will include the application of the Wenner 4-probe test as described in ASTM G57 with limited sampling for laboratory testing and comparisons between in situ and laboratory test results.

5.2. Sample preparations. Sample treatments and specimen preparations including separations into different sized fractions, additions and mixing with water, and curing period vary with respect to different test procedures. Best practices depend upon the nature of the material as described in Section 6.

5.3. Storage. Samples may be stored prior to testing. Best practices for storing samples including storage temperatures, storage times, and requirements for storage containers are specified in the test standards.

5.4. Temperature. Temperatures of the sample maintained during the test may have an effect on the test results. Best practices are described in the test standards for making temperature measurements and correcting measurements to a given reference temperature.

5.5. Samples may be obtained from the source, stockpiles, or after placement. Existing materials may be sampled in situ with a split spoon sampler, from auger cuttings, test pits, or other means of retrieving soil samples from the subsurface.

5.5.1. Soil or groundwater samples should be retrieved that are representative of materials surrounding the metal elements of interest. Several representative soil samples may need to be obtained if conditions vary along the lengths of the elements.

5.5.2. Care should be taken during sampling to avoid contamination of the soil samples and the loss of moisture during storage and transportation to the laboratory. The intent, precautions, and procedures of ASTM D 4220 (Group B) are applicable to this protocol.

5.5.3. Collect soil samples from depths of at least 3 ft. below the water table if not to the end of the element unless organics are present. If organics are present, MIC is a concern, however, MIC has not been observed from depths below 50 feet. Therefore, if MIC is a concern, retrieve samples from depths down to 50 feet if not to the end of the element.

6. Methods of Testing

Figure A-1, attached to the end of this protocol, is a flowchart describing the characterization of earthen materials and the selection of the appropriate test procedures and standards for measurements of electrochemical properties as described in Sections 6.1 through 6.4.

6.1. Material Characterization. Identify the physical characteristics of the material including gradation (AASHTO T-27 or T-88), and Atterberg limits (AASHTO T-89 and T-90).

6.1.1. Determine the grading number (GN) and the percent passing a number 10 sieve,

where

 $GN = 1/100 * (PP_{1 in} + PP_{3/4 in} + PP_{3/8 in} + PP_{\#4} + PP_{\#10} + PP_{\#40} + PP_{\#200})$

and PP signifies percent passing. The GN is often used to characterize the coarseness of aggregates used for highway construction.

6.1.2. For materials with more than 15% passing the number 10 sieve, determine the Atterberg limits, which are useful to limit the clay content of the finer fraction (PI < 6). Best practices also include the use of the sand equivalent test (SE) to evaluate if the fine particles included in an earthen material are clay-like or inert (e.g. SE > 12).

6.2. pH – Materials should be sampled and tested in the laboratory via AASHTO T-289 or Tex-620-M to determine the pH. Details of storage, transport, temperature control, and sample treatments need to be followed as described by these procedures.

6.2.1. Measure pH in accordance with AASHTO T-289 if the GN >3, or if the percent passing the No. 10 Sieve is greater than 25%.

6.2.2. Measure pH in accordance with Tex-620-M if the GN < 3, and if the percent passing a No. 10 Sieve is less than 25%.

6.3. Chloride and sulfate - Ion exchange chromatography (IC) (e.g. ASTM D4327) is the preferred test technique for measuring chloride and sulfate ion concentrations. This test has the advantage that measurements of sulfate and chloride concentrations are performed with a single sample and the method includes a means to assess interferences that may affect the measurements. Measurements made on the aliquot are relatively rapid compared to the methods employed for AASHTO T-290 and T-291. ASTM D4327 only includes testing of anions in water. Other test procedures need to be followed to extract soluble chloride and sulfate from the surfaces of soil particles and preparation of the aliquot for testing.

6.3.1. AASHTO T-290 and T-291 describe procedures for preparing an extract and then ASTM D4327 may be followed for measurements of sulfate and chloride ion contents from the aliquot. The best practice is to express the salt contents with respect to the total weight of the soil sample, rather than the total volume of the aliquot.

6.3.2. Tex-620-M describes procedures for leaching extractions and also specifies chloride and sulfate measurements via IC.

6.3.3. Measure salt contents (chloride and sulfate) in accordance with AASHTO T-290 and T-291 if the GN >3, or if the percent passing the No. 10 Sieve is greater than 25%.

6.3.4. Measure salt contents in accordance with Tex-620-M if the GN < 3, and if the percent passing a No. 10 Sieve is less than 25%.

6.4. Resistivity – Both laboratory and field measurements are recommended. Moisture, compaction conditions, and treatments can be controlled for laboratory testing. Field tests provide measurements under in situ conditions and a larger volume of soil is included from field measurements compared to laboratory tests. Field tests are useful to characterize performance at different times (seasons) during service.

6.4.1. Newly placed material – Laboratory tests

6.4.1.1. AASHTO T 288 applies to sands, fine sands, silty sands, clayey sands, silt, clay, silty clay, and clayey silts. The method describes testing at increasing moisture contents until reaching a "minimum" resistivity. Testing soils at moisture contents beyond saturation may relate to conditions for the waterside of culverts but is not relevant to other applications (e.g. MSE fills). Thus, in many applications the moisture content at 100% saturation should be considered the endpoint for AASHTO T288. Density and degree of saturation are important parameters relating to soil resistivity, but compaction is not a variable for the current test standard. Dry density should be determined based on measurements of water content and the weight of material in the box after compaction. Dry density and moisture content are used to verify when the degree of saturation has reached 100%.

6.4.1.2. Tex-129-M measures the resistivity of soil materials in a two-electrode soil box, which is sized according to the nominal maximum particle size of the material being tested. Thus, this test applies to soils with any gradation, up to a maximum particle size of 1 3/4 inches. Increments of moisture are applied during the test, similar to AASHTO T 288, however, particle sizes up to 1 3/4 inches are included in the specimen. The material is not separated prior to testing and the entire gradation is included in the test.

6.4.1.3. Measure resistivity in accordance with AASHTO T 288 if the GN >3 or if the percent passing the No. 10 Sieve is greater than 25%.

6.4.1.4. Measure resistivity in accordance with Tex-129-M if the GN < 3, and if the percent passing a No. 10 Sieve is less than 25%.

6.4.2. In situ field test

6.4.2.1. ASTM G57 Wenner/Schlumberger array is recommended for in situ testing of materials surrounding culvert locations, piles, and soil nails at different depths due to its simplicity and efficiency. This test may also be applied to measure resistivity of MSE wall fill during or after construction. Best practice is to compare the results from the Wenner test with those obtained from the laboratory tests (soil boxes) at the same moisture contents. In situ resistivity measurements should be collected using lines orientated perpendicular to the longitudinal axis of the reinforcements and should include approximately five tests per lift using electrode spacing that are approximately equal to the lift thickness.

7. Screening/Characterization

The goal of sampling and testing earthen materials described in this protocol is for proper characterization of corrosion potential. A number of schemes exist for screening and characterizing corrosion potential of earthen materials, and these are often developed for specific applications that may include aspects of the installations, site conditions and electrochemical properties. These schemes may (1) apply statistics to the data to forecast corrosivity, (2) set threshold values for electrochemical measurements to identify corrosive conditions, or (3) consider a number of variables that incorporate site conditions and electrochemical properties of earthen materials in the assessment of corrosion potential.

7.1. Percentiles – Define the threshold for the percentile value (e.g. 90th percentile) for electrochemical parameters such as resistivity. This approach is applied by the US Bureau of Land Reclamation to assess the level of corrosion protection needed for pipeline installations.

7.2. Parameter thresholds – Limits on electrochemical parameters including resistivity, pH, chloride and sulfate contents. If any one of the parameters is not within prescribed thresholds the material is considered corrosive. The AASHTO LRFD Bridge Design Specifications specify thresholds and limits for resistivity, pH, and salt contents to identify MSE wall fills that will not be corrosive towards galvanized steel reinforcements.

7.3. Rating/multi-variant – e.g. German Gas and Water Works Standard DVGW GW9. The German Gas and Water Works Engineers' Association Standard (DVGW GW9) is one of the earliest corrosion assessment methods and has been applied to pipeline construction in Europe. A number of categories are included in the assessment that incorporates physical and electrochemical properties of the earthen material (soil) and site conditions that include groundwater levels and the presence of industrial fills. Points/marks are assigned for each category depending on values for the relevant parameters and the marks are summed to render an overall score. The score is used to assess corrosivity with lower (more negative) scores correlated with increasing levels of corrosivity. The scheme considers the benefits from the presence of carbonates on the corrosion behavior of buried metals, which is unique compared to other schemes.

Appendix B. Details of Laboratory Measurements

State Practices

State transportation agencies (e.g., DOTs) currently use a wide variety of electrochemical test standards for characterizing the steel corrosion potential of earthen materials. We performed a review of state DOT standard specifications and other state publications for information regarding corrosion of MSE reinforcements. A summary of state DOT practices is presented in Table B-1. Twenty-two of the states were found to generally follow AASHTO requirements and use AASHTO test methods, three states referenced multiple test methods, one state publishes modifications to the AASHTO methods, 12 states do not use the AASHTO methods, 15 states use different electrochemical requirements, and one state uses FHWA guidance instead of AASHTO as a reference in the state specifications. A state may be included in multiple categories, for instance California uses different test methods and different electrochemical requirements and is included in both counts.

Reference tests	States		
States using AASHTO tests and requirements	Alaska, Indiana, Iowa, Maine, Michigan***, Mississippi, Montana***, Nebraska, Nevada**, New Jersey, New York (MSE Inspection Manual), North Carolina (Fine Aggregate Only), North Dakota***, Ohio**, Oklahoma*, Rhode Island***, South Dakota***, Vermont***, Virginia, Washington D.C.***, West Virginia**, Wisconsin*		
States referencing multiple methods	Connecticut****, Delaware, South Carolina		
States using modified AASHTO test methods	Illinois		
States using different test methods	Arizona, California, Colorado, Delaware, Florida, Kansas, Kentucky, Louisiana, New York (Stand. Specs.), Pennsylvania***, Texas, Washington**		
States using different electrochemical requirements	Arizona, California, Colorado, Florida, Georgia*, Illinois, Kansas, Kentucky, Louisiana, Missouri, New Mexico, New York (Stand. Specs.), South Carolina, Texas, Washington		
States using FHWA-NHI-09-087	Minnesota		

Table B-1. Summary of state practices.

* test methods not stated explicitly

** Chloride and sulfate tests are waived if resistivity is greater than 5000 Ω -cm

*** AASHTO stated as design standards

**** Ranges not stated

Summary of Resistivity Tests

Table B-2 shows the summary of resistivity tests used in this research in terms of specimen preparation, precision (μ_{cov} and σ_{cov}) and bias (μ and σ) with respect to the results of AASHTO T-288 (2016).

Test	Salient details		Precision		Bias w.r.t. AASHTO T-288	
Soil box tests	Measure resistivity (ρ) of compacted specimens	μ _{cov}	σcov	μ	σ	
AASHTO T-288 (2016)	Sample passing No. 10 sieve, incremental addition of water (10% by weight), curing for 12 hours, compacting the specimen into the soil box and measuring the resistance. Keep adding water until reaching ρ_{min} or ρ_{sat}	4.6	4.5 ¹	-	-	
ASTM G- 187 (2018)	Scalp material greater than $\frac{1}{4}$ inch, saturating the specimen while compacting in a soil box and measuring resistivity at saturation, ρ_{sat} . Saturation is determined visually	5.3	4.5	1.4	0.4	
ASTM WK 24621	Include particle sizes up to 1 ³ ⁄ ₄ inches , curing for 24 hours, compacted specimen into the soil box. The specimen is allowed to drain before making the resistance readings	7.4	5.8	3.8	5.1	
Tex-129-E (1999)	Similar to AASHTO T-288 except the material is separated on a No. 8 sieve before testing	3.2	4.3	1.1	0.2	
Tex-129-M	Include particle sizes up to 1 $\frac{3}{4}$ inches, sample is removed from the box after each measurement and re-mixed with additional water, test continues until the additional moisture cannot be absorbed and the specimen has reached either ρ_{min} or ρ_{sat}	4.8	2.8	2.3	1.9	
Leaching tests	Measure conductivity (κ) of aqueous solution	µcov	σ _{cov}	μ	σ	
SCT 143 (2008)	Include particle sizes up to 1 ¾ inches , diluting the sample at a 1:1 ratio, agitating for 3-minutes at the 30-minute, 2-hour and 4-hour intervals, standing for 20 hours and filtering the sample before conductivity measurements	4.9	4.5	1.9	1.7	
Tex-620-J (2005)	Sample passing No. 40 sieve, diluting the sample at a 10:1 ratio, heating to 140°F while stirring every hour for 12 hours, measuring conductivity of the mixture	4.9	1.9	1.6	0.9	
Tex-620-M	Include particle sizes up to 1 ³ / ₄ inches , diluting the sample at a 10:1 ratio, mixed for 60 minutes, not allowed to stand before the conductivity measurements	4.5	3.1	5.2	3.4	

Table B-2. Summary of resistivity tests, precision, and l	oias.
---	-------

¹ In this study precision for AASHTO 288 was determined using 100% saturation as the end point.

Comparison of Different Resistivity Tests with AASHTO T-288

Test method	μ_{bias}	σ _{bias}	$\text{COV}_{\text{bias}}(\%) = \sigma_{\text{bias}} \mu_{\text{bias}}$
Tex-129-E	1.07	0.24	22
ASTM G-187	1.41	0.44	31
Tex-129-M	2.28	1.96	86
ASTM WK 24621	3.75	5.10	136
Tex-620-J	1.69	0.96	57
SC T-143	1.95	1.72	88
Tex-620-M	5.22	3.41	65

Table B-3. Statistics of resistivity test bias with respect to AASHTO T-288 (2016).

Table B-4. Bias of resistivity measurements from samples with different texture.

	Fine sand		Coarse sand		Gravel	
Test method	μbias	COV _{bias} (%)	$\mu_{ ext{bias}}$	COV _{bias} (%)	μbias	COV _{bias} (%)
Tex-129-E	1.0	11	1.2	18	1.0	26
ASTM G-187	1.0	12	1.6	25	1.4	35
Tex-129-M	0.9	3	1.6	56	3.1	77
ASTM WK 24621	0.9	6	2.0	40	5.8	116
Tex-620-J	1.3	56	1.8	58	1.7	59
SC T-143 ¹	-	-	0.9	96	2.6	72
Tex-620-M	2.2	44	4.6	72	6.5	53

¹could not perform SCT 143 (2008) with fine samples due to the lack of settlement of the finer particles during the specified standing time.

Summary of Tests to Measure Salt Contents

Table B-5 shows the summary of tests used in this research to determine sulfate and chloride contents. This table summarizes each test in terms of specimen preparation and precision COV (μ_{cov} and σ_{cov}).

Sulfate content					
Test	Caliant dataila		Precision ¹ COV (%)		
Test	Salient details	μ_{cov}	$\sigma_{ m cov}$		
AASHTO T- 290 (2016)	Sample passing a No. 10 sieve , diluting the sample at 3:1 ratio, mixing in a flask, centrifuging and filtering the sample and measuring sulfate ion content using spectrophotometry or ion chromatography (IC)	10.1	5.6		
Tex-620-J (2005)	Sample passing a No. 40 sieve , diluting the sample at 10:1 ratio, heating to 140°F while stirring every hour for 12 hours and measure sulfate and chloride ion contents via IC	11.8	7.6		
Tex-620-M	Include particle sizes up to 1 ³ / ₄ ³ , diluting the sample at 10:1 ratio, mixing for 60 minutes, not allowed to stand, filtering before the sulfate and chloride measurements via IC	10.7	5.9		
	Chloride				
AASHTO T- 291 (2013)	Sample passing a No. 10 sieve , diluting the sample at 3:1 ratio, mixing in a flask for 20 seconds, after one-hour repeat shaking, centrifuging and filtering the sample then measuring chloride content by titration or IC	7.5	5.4		
Tex-620-J	Sample passing a No. 40 sieve , diluting the sample at 10:1 ratio, heating to 140°F while stirring every hour for 12 hours, filtering the sample and measuring the sulfate and chloride contents via IC	3.7	2.5		
Tex-620-M	Include particle sizes up to 1 ³ / ₄ ³ , diluting the sample at 10:1 ratio, mixing for 60 minutes, not allowed to stand, filtering before the sulfate and chloride contents measurements via IC	12.9 ²	6		

Table B-5. Tests for measurements of salt content, and observations of precision.

¹ Only included results from testing sulfate and chloride with > 10 mg/kg

² Outlier from SC LWF removed

Summary of Tests to pH

Table B-6 shows the summary of tests used in this research to determine pH of the aqueous solutions. This table summarizes each test in terms of specimen preparation, precision COV (μ_{cov} and σ_{cov}) and bias with respect to AASHTO T-289 (2018).

TEST	Salient Details	Precision COV (%)		Bias w.r.t. T-289 (2018)	
		μ _{cov}	σ _{cov}	μ	σ
AASHTO T-289 (2018)	Sample passing a No. 10 sieve , air drying, a 30-gram specimen is taken, diluting the sample at 1:1 ratio, stand for a minimum of 1 hr. while stirring every 10 to 15 minutes then measuring the pH of the slurry specimen	1.0	1.0	-	-
ASTM D 4972 (2019)	Sample passing a No. 10 sieve , air drying, a 10-gram specimen is taken, diluting the sample at 1:1 ratio, mixed thoroughly and standing for 1 hr. then measuring the pH of the partially settled suspension	1.1	0.6	0.99	0.03
NCHRP 21-06 (2009)	Particles larger than 3/8 in. are removed from the sample by hand. The moisture content of the sample is determined but the sample is <u>not</u> air-dried, diluting the sample at 1:1 ratio, stirring thoroughly to disperse the soil, standing for 30 minutes then the pH of the supernatant is measured	0.7	0.5	0.98	0.03
Tex-128-E (1999)	Sample passing a No. 40 sieve , air drying, adding 200 ml of DI water to the sample, heating to 112°F - 140°F, diluting 30-gram of heated dry soil at 5:1 dilution ratio, stirring initially and every 15 minutes for 1 hour thereafter, <u>not</u> allowed to stand then measuring the pH of the suspension	0.9	0.5	1.03	0.03
Tex-620-J (2005)	Sample is air-dried and the portion of the sample passing a No. 4 sieve (crushed as necessary) is pulverized to pass a No. 40 sieve , diluting 30-gram of sample at 10:1 dilution ratio, heating to 150°F and stirring, allowing to digest for 15 to 18 hours, the mixture is <u>not</u> allowed to stand then pH of the suspension is measured	0.9	0.3	0.97	0.04
Tex-620-M	Particle sizes up to 1 ³ / ₄ inches are included in the specimen, air-drying and diluting at 10:1 ratio, agitating for 60 minutes the mixture is <u>not</u> allowed to stand then pH of the suspension is measured	1.2	1.7	1.1	0.04

Table B-6. Summary of tests for pH and observations of precision and bias.
--

Salt Contents

Table B-7 is a summary of the samples with general descriptions of results from testing via the AASHTO and the Texas modified procedures. Results are described as 1) low salt contents with sulfate and chloride contents < 50 mg/kg; (2) both sulfate and chloride contents > \approx 50 mg/kg, (3) high sulfate (> 50 mg/kg) and low chloride contents (< 50 mg/kg); and (4) high chloride (> 50 mg/kg) and low sulfate contents (< 50 mg/kg).

C: 4.	Results				
Site	AASHTO	Texas Modified			
Ocala, Florida	Low salt ¹	Low salt			
M-U-D, NYS	Low salt	Low salt			
Pharr, TX	Low salt	Low salt			
Prince George, BC	Low salt	Low salt			
Ashdown. AR	Low salt	Low salt			
Raleigh, NC	Low salt	Low salt			
Temple, TX	$SO_4(41) + Cl^{-}(22)$	Low salt			
MSE Coarse, El Paso, TX	$SO_4(145) + Cl^{-}(85)$	Low salt			
PIP 5', NYS	$SO_4(56) + Cl^{-}(172)$	$SO_4(26) + Cl^{-}(65)$			
PIP 10', NYS	$SO_4(60) + Cl^{-}(137)$	$SO_4(76) + Cl^{-}(105)$			
PIP 15', NYS	$SO_4(71) + Cl^{-}(190)$	$SO_4(97) + Cl^{-}(204)$			
MSE Fine, El Paso, TX	$SO_4(67) + Cl^{-}(45)$	$SO_4(91) + Cl^{-}(43)$			
Quarry, El Paso, TX	$SO_4(312) + Cl^{-}(204)$	$SO_4(214) + Cl^{-}(121)$			
Maple Rd., NYS	High SO ₄ (153); Low Cl ⁻ (43)	Low salt			
LWF-Crushed, LA	High SO ₄ (155); Low Cl ⁻ (14)	High SO ₄ (81); Low Cl ⁻ (4)			
Granular Base, SC	High SO ₄ (280); Low Cl ⁻ (6)	Low salt			
Round Rock, TX	High SO ₄ (305); Low Cl ⁻ (16)	Low salt			
LWF, SC	High SO ₄ (397); Low Cl ⁻ (15)	High SO ₄ (427); Low Cl ⁻ (21)			
Calgary, BC	High SO ₄ (809); Low Cl ⁻ (11)	High SO ₄ (652); Low Cl ⁻ (9)			
Sprain Brook, NY	Low SO ₄ (63); High Cl ⁻ (341)	Low SO ₄ (51); High Cl ⁻ (153)			
Rochester, NY	Low SO ₄ (45); High Cl ⁻ (361)	Low SO ₄ (22); High Cl ⁻ (145)			
Wake, NC	NA	Low salt			
LWF Uncrushed, LA	NA	Low salt			
Waco, TX	NA	Low salt			
Bastrop	NA	Low salt			
Garden City, TX	NA	$SO_4(197) + Cl^{-}(113)$			

Table B-7. Summary of salt contents measured via AASHTO and Texas modified procedures.

¹ Low salt = total salt content (sulfate + chloride) is less than 50 mg/kg.

Data in Table B-7 indicate the results between the AASHTO and Texas modified test procedures are similar for 16 out of 21 samples. Differences include five samples where data from Tex-620-M indicate low salt contents but data from the AASHTO tests indicate total salt contents greater than 50 mg/kg or high sulfate contents. In each case where differences are observed, the finer sand component of the sample is limited and minimal fine sand is included within the Tex-620-M specimen. Four of the samples with different results are gravels with less than 30 % passing a #10 sieve (Temple, TX; Maple Rd., NY; Round Rock, TX; and El Paso, TX –MSE Coarse) and one is a coarse sand with less than 20 % passing the #40 sieve (South Carolina, GB).

Results from testing coarse samples with less than 8 % passing a # 10 sieve via Tex-620-M (but not via AASHTO T-290 and 291) show low salt contents. The sample from Garden City Texas with higher chloride and sulfate ion contents has 22 % passing a #10 sieve. The Garden City sample does not have a corresponding AASHTO test result.

Bias Statistics

We computed bias as the ratio of "equivalent total salt content" obtained from Tex-620-M divided by the "equivalent total salt content" computed from the results of AAAHTO T-290 (2016) and T-291 (2013). Equivalent total salt contents consider the combining power of chloride and sulfate in solution in terms of their milliequivalent units, and is useful to check trends between salt content and resistivity. The milliequivalent of an electrolyte is the mass proportion (mg/kg) divided by the equivalent molecular weight, whereby 1 mEq/kg of Cl⁻ is equal to 0.74 mEq /kg of sulfate (SO₄⁻²). We convert the chloride and sulfate contents to an equivalent total content in terms of chloride as 0.65 (SO₄ (mg/kg)) + Cl⁻ (mg/kg).

In general, lower salt contents are measured via the modified test procedures so the bias is less than one. Figure B-1 is a histogram depicting the distribution of the bias. The bias ranges between 0.1 and 2.3, with mean bias, μ_{bias} , equal to 0.72 and coefficient of variation (COV_{bias}) equal to 65 percent. The highest bias corresponds to the sample from Ocala, Florida that has a very low salt content (< 10 mg/kg). Low salt contents (<10 mg/kg) are affected by the sensitivity of the measurements, and the measurements are more uncertain compared to when higher salt contents are measured. The lowest values of bias are from samples that have a low percentage of particles passing a No. 10 sieve.



Figure B-1 Histogram of bias in salt measurements from Tex-620-M.

We identified the trend in bias with respect to percent passing the No. 10 sieve for each sample as shown in Figure B-2. After two outliers are removed including the sample from Ocala, Florida and the sample of granular base from South Carolina, a good correlation ($R^2 = 0.76$) is observed between the remaining 19 data points. The Ocala data point was an outlier due to the low salt content and the South Carolina GB sample exhibits a bias that is too low considering other samples with similar medium to fine sand (% passing No. 10) content. The lowest biases are from samples

with less than 25 percent passing a No. 10 sieve. For samples with more than 60 percent of the particles passing a No. 10 sieve, the bias is close to, or greater, than one. For these samples, the fines and fine sand components dominate the leaching of salts from samples tested via either the AASHTO or Texas modified procedures. Higher dilution ratios and different methods of mixing may render measurements of salt contents from Tex-620-M that are higher compared to AASHTO T-290 (2016) and T-291 (2013) for samples with a large fraction passing a No. 10 sieve.



Figure B-2 Correlation between bias in salt measurements fromTex-620-M and percent passing the No. 10 sieve used to characterize the sample.

Concepts of Resistivity Bias

Arciniega et al., 2018; 2019 at The University of Texas, El Paso (UTEP) developed relationships describing how the resistivity of a soil sample (ρ) can be computed based upon physicochemical characteristics including gradation, degree of saturation, and the leaching potential of cations and anions present on the surfaces of the soil particles. That relationship is of the form:

$$\rho = \left(\frac{w_g}{\rho_g} + \frac{w_{cs}}{\rho_{cs}} + \frac{w_{fs}}{\rho_{fs}} + \frac{w_f}{\rho_f}\right)^{-1}$$
(B-1)

where w_g, w_{cs}, w_{fs}, w_f , are the percent by weight of the constituents including gravel (g), coarse sand (cs), fine sand (fs) and fines (f), and ρ are resistivities of the constituent geomaterials including gravel (ρ_g), coarse sand (ρ_{cs}), fine sand (ρ_{fs}), and fines (ρ_f) For a degree of saturation equal to 100 percent, the resistivity of a saturated geomaterial (ρ_{sgm}) can be approximated as:

$$\rho_{sgm} \sim \frac{\tau_{pw}}{\kappa_{pw} n_{gm}} \tag{B-2}$$

where τ_{pw} is the tortuosity of the pore water in the system, κ_{pw} is the electrical conductivity of the porewater, and n_{gm} is the porosity of the geomaterial/constituent.

The electrochemistry of the porewater solution (κ_{pw}) is computed based upon the leaching potential including the molar concentration (c_i) of soluble ions including sulfate and chloride ions (i), the electrical charge of the ions (z_i eq/mol) and the ionic diffusivity (D_i) as follows:

$$\kappa_{pw} = \frac{F^2}{R_g T} \sum_i D_i z_i c_i \tag{B-3}$$

where F is Faraday's constant (96,485 C/eq), R_g is the molar gas constant, T is the solution temperature, and \sum is to sum the effects from all ions (i), including cations (e.g., sodium, calcium, magnesium, potassium, etc.) and anions (e.g., sulfate, chloride, bicarbonate, etc.). Because the density of water in these conditions is approximately 1 kg/L, the concentration of each ion is approximately equal to the mass concentration or "salt content" (w_i , mg of ion per kg of soil) divided by the dilution factor (DF, kg of water per kg of soil).

Most of the soluble ions are extracted (leached) from the surfaces of the geomaterial particles (with negligible contribution by diffusion from within the geomaterial particles, except for very porous materials such as expanded clays), so the amounts of ions that can be extracted generally depend upon the external surface areas of the particles and the surface concentration of ions. If we idealize the solid particles to be shaped as spheres such that the surface area of each particle size (j) is πd_j^2 , and if we assume an even surface concentration (Γ_i , mol/m²) of each ion across all particle sizes, then we can write:

$$\kappa_{pw} \propto \frac{1}{\rho_{sgm} \, n_{gm}} \propto \Sigma \, c_i \propto \Sigma \frac{w_i}{DF} \propto \Sigma \, \Gamma_i \, d_j^2$$
 (B-4)

We can use a characteristic particle size (e.g., d_{max} , d_{85} , d_{50} , d_{10}) as a scalar representative of the specific-surface-area weighted-average particle size, where d_{max} is the maximum particle size, and d_{85} , d_{50} , and d_{10} are particle diameters with 85, 50, and 10 percent passing, respectively. (Note that, as a particle size distribution approaches ideal uniformity, all of these characteristic sizes converge.)

Tortuosity, τ_{pw} , which affects the current path through the soil, depends upon the material gradation, degree of saturation, and the particle shapes, angularity, size and packing/porosity. We assume that tortuosity is inherent to the material characterization as fines, fine sand, coarse sand or gravel. Arciniega et al. (2019) confirmed this assumption and demonstrated fitting parameters for the tortuosity function that varied with respect to characteristics of the gradation. For example, proportionalities may be written for soils tested via Tex-129-M (entire gradation) and for AASHTO T-288 (2016) (fine to medium sand component). Compacted soil specimens tested according to Tex-129-M may include gravel, coarse sand, fine sand and fines. Thus, using Equations (B-1) and (B-2) with the proportionality from Equation (B-4), the resistivity as measured by Tex-129-M is proportional to the percentages of each constituent and their particle sizes as:

$$\rho_{(129-M)} \propto \frac{1}{n_{(129-M)}} \left(w_g d_g^2 + w_{cs} d_{cs}^2 + w_{fs} d_{fs}^2 + w_f d_f^2 \right)^{-1}$$
(B-5)

AASHTO T-288 (2016) specifies preparing compacted specimens from the portion of the sample passing a No. 10 sieve. Thus, the resistivity as measured by AASHTO T-288 (2016) is proportional to the effective diameter ($d_{\#10}$, not to be confused with d_{10}) and the porosity of the compacted specimen with 100 percent passing a No. 10 sieve (n_{T-288}) as follows:

$$\rho_{(T-288)} \propto \left(n_{(T-288)} \times 100 \% \times d_{\#10}^2 \right)^{-1}$$
(B-6)

The ratio (bias) of the results from Tex-129-M relative to results from AASHTO T-288 is determined from these proportionalities. This serves as a scaling parameter relating the bias of the resistance measurements to characteristics of the samples in terms of maximum particle size, gradation and compaction (porosity).

$$\frac{\rho_{129-M}}{\rho_{T-288}} \propto \frac{n_{(T-288)} (100 \%) d_{\#10}^2}{n_{(129-M)} (w_g d_g^2 + w_{cs} d_{cs}^2 + w_{fs} d_{fs}^2 + w_f d_f^2)}$$
(B-7)

We are considering the effective diameters to be the maximum diameter of the particles included in the constituent as follows.

 $\begin{array}{l} d_g = d_{max} \mbox{ of the sample} \\ d_{cs} \approx 0.25 \mbox{ inches corresponding to the 1/4 inch sieve} \\ d_{fs} \approx 0.017 \mbox{ inches corresponding to the #40 sieve} \\ d_{f} \approx 0.0028 \mbox{ inches corresponding to the #200 sieve} \\ d_{\#10} \approx 0.079 \mbox{ inches corresponding to the #10 sieve, and} \\ n_{T-288} \mbox{ is the porosity of the compacted specimen (passing No.10) tested via AASHTO T-288} \\ n_{129-M} \mbox{ is the porosity of the compacted specimen tested via Tex-129-M} \end{array}$

Figure B-3 depicts the trend of the bias considering results from Tex-129-M compared to those from AASHTO T-288. The scaling factor is determined from each sample and plotted along the x-axis. The data are grouped to distinguish results from tests performed with fine sand, coarse sand or gravel samples. The observed correlations demonstrate that the bias from resistivity measurements have trends that are dependent upon the size of the materials; the trends from testing gravel samples are different from those observed from testing coarse or fine sand, as shown in Figure B-3. The bias of results from Tex-129-M compared to those from AASHTO T-288 is observed to be greater than one, and usually less than three. For fine sand, the bias is close to 1, as expected, and appears to be a tail to the trend observed from coarse sand.

For the coarse sand, there is an increase in bias with respect to decreasing values of the scaling parameter (inversely proportional). We observe that for coarse sands, the scaling parameter tends to decrease as the gravel content increases and approaches 50 percent. For the case of coarse sand, gravel sized particles are not in direct contact with one another and are enclosed within a matrix of coarse and fine sand sized particles. Under these conditions, an increase in gravel-sized particles increases the tortuosity of the current path during measurement of resistivity, rendering higher measurements of resistivity for the Tex-129-M test compared to results from AASHTO T-288, and an increase in the bias. For coarse sand, the observed bias has a range mostly between 1 and 3.

For the gravel category, bias tends to be directly, rather than inversely proportional to the scaling parameter. For gravel materials, the scaling parameter increases due to the relative increase in the coarse sand (w_{cs}) component. For gravel type material, the gravel particles are in contact and the finer fractions (CS, FS and F) pack the spaces between the gravel particles. The gravel component is packed more tightly when the percent gravel is higher, and the percent of coarse sand and fine sand are relatively lower. As the gravel content of the samples decreases and the coarse sand content increases, the more efficient packing arrangement decreases porosity and increases the tortuosity of the current path. These factors affect a higher measurement of resistivity via the Tex-129-M test, which tends to increase the bias. For gravel materials, the observed bias ranges between 1 and 7, although most of the observed bias is between 1 and 3.



Figure B-3 Correlation of bias from Tex-129-M with respect to scaling parameter.