

2018-01-01

# Effects Of Gradation And Moisture Content On Resistivity Of Mechanically Stabilized Earth Wall Backfill Materials

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EFFECTS OF GRADATION AND MOISTURE CONTENT ON RESISTIVITY  
OF MECHANICALLY STABILIZED EARTH WALL BACKFILL  
MATERIALS

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## **Dedication**

I dedicate this thesis to my parents, whose continued support and motivation will continue to inspire me throughout my career.

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OF MECHANICALLY STABILIZED EARTH WALL BACKFILL  
MATERIALS

by

JOSE LUIS ARCINIEGA AGUILAR, EIT, BSCE

THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE

Department of Civil Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

August 2018

## **Acknowledgements**

I would like to express my gratitude towards my advisor Dr. Soheil Nazarian for his guidance throughout the fulfillment of my research and his quintessential advice and mentorship which have armed me with the tools to lead a successful career. I thank especially Dr. W. Shane Walker, who continuously lent his knowledge, time and concern in the development of this work. I also thank the rest of my thesis committee Dr. Ken Fishman and Dr. Arturo Bronson, without whose expertise and insight this work would not have been possible. I would also like to acknowledge the support and assistance from the faculty and students at The University of Texas at El Paso (UTEP) Center for Transportation Infrastructure Systems (CTIS), especially the lab manager, Mr. Jose Garibay, the center director Dr. Imad Abdallah, and students Mathew Gonzales, Luisa Morales, Troy Svede, Daniela Hernandez, Ivan Ramirez, and Diana Cabrera. I would also like to thank the Texas Department of Transportation (TxDOT) and the National Cooperative Highway Research Program (NCHRP) for providing funding and assistance that made this research possible.

Most importantly I would like to thank my parents, siblings, girlfriend, extended family and friends for their continued concern, support and strength throughout the completion of my education.

## **Abstract**

The service life of mechanically stabilized earth (MSE) walls depends on the corrosion rate of the metallic reinforcement used in their construction. The resistivity of the backfill aggregates needs to be measured accurately in order to estimate realistically the corrosion rate of the reinforcement. Resistivity testing is usually performed using the traditional soil box on the portion of the aggregates that passes a No. 10 or No. 8 sieve to either select or reject the backfill. For a more reasonable characterization of the corrosivity of coarse backfills, it is desirable to use their actual gradations. To that end, several resistivity boxes with dimensions that were double and quadruple of the original box were constructed. In addition to the three standard gradations specified by TxDOT, over twenty backfill materials sampled from sources throughout Texas were fractionated to fines, fine sand, coarse sand, and gravel. Resistivity tests were performed separately on each of these four constituents for each backfill. Test results demonstrated that the gradation and moisture content of the backfill significantly affect the measured resistivity. The results were then used to evaluate a relationship that would allow the estimation of the resistivity of any desired backfill gradations from the resistivity values of their four constituents (i.e., fines, fine sand, coarse sand, and gravel). The proposed model looks promising since the resistivity of the backfill composed of the actual gradation could be estimated with small uncertainty. The results of this study can potentially help highway agencies and contractors use a number of local quarries that are currently disqualified based on the resistivity values that obtained from only testing the materials passing No. 8/10 sieve. Lastly, the results were also used to develop a model that would allow the estimation of the resistivity of a given backfill knowing its minimum resistivity, porosity, and degree of saturation. The results were promising for estimating the resistivity of backfills at degrees of saturation higher than 50%, when the rate of corrosion becomes

a concern. The model can potentially be used to estimate the resistivity of in-service wall backfill from the minimum resistivity and moisture conditions.

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# Chapter 1: Introduction

## 1.1 Background

Mechanically stabilized earth (MSE) walls have been used widely as an economical alternative to traditional retaining walls. Figure 1.1 shows the composition of an MSE wall under construction, which consists of generally coarse backfill stabilized with reinforcement (usually galvanized steel) which are attached to precast concrete panels. Estimating the rate of corrosion of the metallic reinforcement is crucial for determining the service lives of MSE walls, and as such, an assessment of the corrosion potential of the aggregate used as backfill is required. The corrosion potential of the backfill is characterized in terms of its resistivity, soluble ion content, moisture content and the position of the water table.



FIGURE 1.1: TYPICAL MSE WALL UNDER CONSTRUCTION

## 1.2 Statement of Purpose

Current specifications used to measure resistivity measure only material passing the #8 or #10 sieve. There is concern that these specifications are not representative of materials used as backfill in MSE walls, as they often contain little to no particles passing these sieve sizes. Due to the dimensions of the box used to measure resistivity, it may be difficult to test accurately a representative sample since the aggregates used at the site can include aggregates up to 75 mm (3

in.) in diameter. The main purpose of the research reported here is to find a reliable way of testing the backfill used in the MSE walls in the laboratory that provides a more accurate representation of the field conditions. This would be achieved through the quantification of the effect that gradation and moisture have on the resistivity of a given backfill. With this goal, the possibility of estimating the resistivity knowing either of these parameters are explored. This process is culminated with the development of two practical empirical models. The first model attempts to estimate the resistivity of a given backfill material knowing its gradation and the resistivity of its major constituents (gravel, coarse sand, fine sand, and fines, as defined by the Unified Soil Classification System, USCS). The second model estimates the resistivity of an actual backfill knowing the degree of saturation and its laboratory measured minimum resistivity.

A model that can approximate the resistivity of an aggregate with a known gradation based on the resistivity values of the four constituents can have practical advantages, with the main advantage being the possibility of adjusting the gradation of a backfill to overcome the specified minimum resistivity. This could allow the selection of coarse materials that would traditionally have not be considered. Being able to estimate the resistivity based on the minimum resistivity of the backfill material and field moisture content can eventually be useful for field quality control based on resistivity and evaluating the corrosion potential of in-service walls under various climatic conditions, as it is done in the current mechanistic empirical pavement design.

### **1.3 Organization of Thesis**

This thesis contains seven chapters, including this current introductory chapter. Chapter 2 includes a brief review of the literature on the topics of resistivity as an estimation of corrosion potential, the effects of moisture content on corrosion rate and resistivity, as well as the use of current specifications to measure the resistivity of MSE wall backfill materials.

Chapter 3 summarizes the methodology used to carry out the laboratory testing performed in this study. This includes a description of the current methodology to measure resistivity, the process of validating a new specification to be potentially used to measure the resistivity of coarse aggregate, and a breakdown of all the laboratory testing performed. Chapter 4 includes a summary of the results obtained through laboratory testing. This includes the resistivity values for all the samples and the trends observed between different gradations and moisture contents.

Chapters 5 and 6 propose empirical models for estimating resistivity from gradation and moisture content, respectively. They include the process of derivation of said models, comparisons of modeled values to measured values, and an example of their potential usage as a proof of concept. Chapter 7 includes the conclusions and recommendations for future studies.

## Chapter 2: Review of Literature

### 2.1 Resistivity as an Estimation of Corrosion Potential

Romanoff and King (1957, 1977) indicated that resistivity was an intrinsic property of the material that could appropriately estimate the corrosion potential, since there is an inverse relationship with a material's resistivity and ionic concentration and ability to readily transmit electrons and corrosion rate is related to the soil's ability to transmit electrons (Doyle et al., 2003; Akpofure and Kehinde, 2006). As a result, many Departments of Transportations (DOTs) have established a limit for the resistivity of a material that can be used as backfill. The test is performed within a box with nominal dimensions of 150 mm x 100 mm x 45 mm (6 in. x 4 in. x 1 3/4 in.), with two stainless steel plates along the long sides as electrodes. Since the electrical resistance ( $R$ ) of a material between two electrodes is a function of the electrical resistivity ( $\rho$ ), the length between the electrodes ( $l$ ) and the cross sectional area ( $A$ ), the resistivity can be approximated as (Serway et al., 2000):

$$\rho = RA/l \quad (2.1)$$

By passing a 97 Hz square wave current through the two electrodes, the electrical resistance between the electrodes is measured to calculate the resistivity of the material. Elias et al. (2009) indicated there is little concern for corrosion in MSE walls when the material has a resistivity above 10,000  $\Omega \cdot \text{cm}$ . A material usually cannot be used as backfill if the resistivity of the material is below a certain level (*e.g.*, 3,000  $\Omega \cdot \text{cm}$  for TxDOT), as it would be regarded as having a high potential for corrosion.

## **2.2 Effect of Moisture Content on Corrosion Potential and Resistivity**

Moisture is another important parameter in the assessment of corrosion potential of in-service fills. Darbin (1986) observed that the maximum corrosion rates occurred at degrees of saturation between 60% and 85%. A survey by Elias (2000) of 14 California sites found that the degree of saturation of most backfills exceeded 65%. Therefore, it is critical to assess the moisture conditions in MSE wall fill as they are often at levels where corrosion becomes a concern. Borrock et al. (2013), through monitoring of 80 laboratory specimens for 27 months, concluded that the corrosion rate in dry specimens was minimal but was significant in wet specimens, and that the resistivity was well correlated with the rate of corrosion.

## **2.3 Use of Current Specifications to Characterize MSE Wall Backfill Materials**

There is a concern that the existing testing procedures are not representative of coarse-aggregate backfills. Procedures such as AASHTO T288 use material passing the No. 10 sieve, while material used in MSE walls typically contain only a small percentage that passes the No. 10 sieve. Thapalia et al. (2011) and Borrock et al. (2013) indicated that the portion that passes the No. 10 sieve was not indicative of the corrosion potential of the material used due to scarcity of such materials in the coarse backfills. This could result in rejection of materials that otherwise would have satisfied the specifications. Several recent studies (e.g., Adkins and Rutkowski (1998), Kuleza et al. (2016), Brady et al. (2016)) have attempted to relate field and lab resistivity measurements with limited success. Reasons for the poor comparisons include inconsistency between field and lab testing, field testing at optimum moisture content or lower versus lab testing at 100% saturation and beyond, and the actual fill materials versus lab gradation (e.g., passing sieve No. 8).



## Chapter 3: Methodology

### 3.1 Existing Methodology

In this research, the resistivity of backfill materials was analyzed with a method based on the Texas Department of Transportation (TxDOT) test procedure Tex-129-E (2014), which is similar to AASHTO T-288 (2016). The main difference between the two protocols is that Tex-129-E specifies analyzing material passing No. 8 (2.4 mm) sieve, while AASHTO T-288 specifies analyzing material passing No. 10 (2 mm) sieve.

Figure 3.1 shows the process followed in this research. 1.3 kg (2.9 lb) of sample that passed No. 8 sieve was prepared. The material was compacted to the brim of the resistivity soil box (see Figure 1), taking the excess off from the surface with a straight edge. The compacted specimen was weighed (for calculating the density of the sample) and the resistivity was measured using a soil resistance meter. Deionized (DI) water was then added in increments of 50 mL (0.11 lb) for sand soils and 100 mL (0.22 lb) for clay soils.

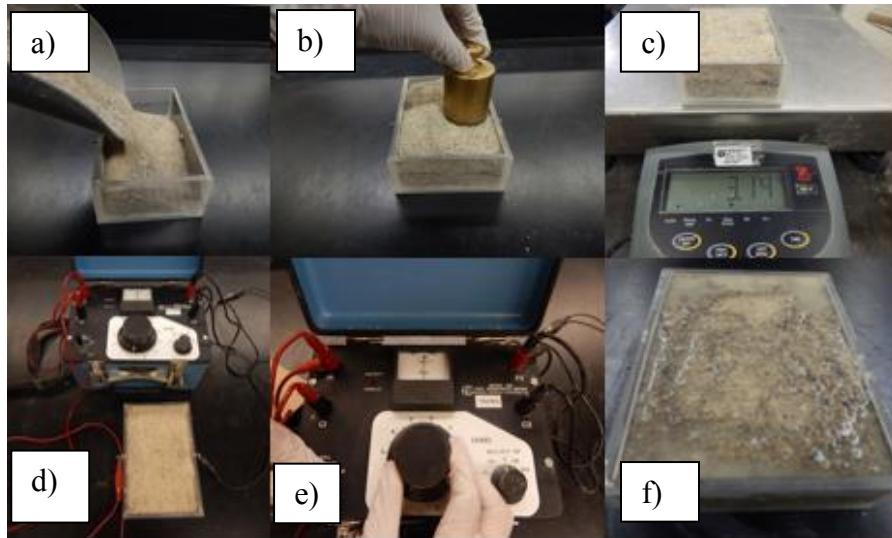


Figure 3.1: Procedure for performing Tex-129-E: (a)Filling the soil box, (b) Compacting the sample, (c) weighing the sample, (d) connecting apparatus to the soil box, (e) Obtaining a reading, (f) Sample at saturation

Each increment of water was a repeat of the testing cycle, taking the material out of the box, mixing in additional water and compacting. It has been found that the minimum resistivity happens at the worst case scenario for the aggregate, which is when the sample is at 100% saturation. By basing the specifications of the aggregates on the assumed worst case scenario it is possible to judge and select materials based on the specified 3000  $\Omega$  -cm limit while maintaining a conservative measurement as compared to the conditions on the field.

### **3.2 Summary of Testing**

Figure 3.2a shows the grain-size distributions of the samples for either Type AS, Type BS, or Type DS. All gradations included only materials finer than the 75 mm (3 in.) sieve. As also shown in Figure 3.2a, Type AS materials contained less than 50% materials passing the 12.7 mm (0.5 in.) sieve, less than 15% passing the No.40 sieve, and less than 5% passing No. 200 sieve. Type BS materials contained less than 60% passing No. 40 sieve and less than 15% passing the No. 200 sieve. Type DS backfills contained less than 15% passing the 9.5 mm (3/8 in.) sieve and less than 5% passing the No. 200 sieve. The gradations used for this study were designed to have distributions that passed through the middle of the acceptable ranges prescribed by TxDOT. The weight fractions of these gradations are shown in Figure 3.2b and are listed in Table 3.1. Type AS contained a higher proportion of the intermediate particles and a small fraction of fines (about 1%), while Type DS had a gap-graded distribution with a high fraction of gravel and low fraction of sand and fines with the fines fraction also being low (2%). Type BS material was a well-graded material with a relatively high fraction of fines (8%). In addition to these three gradations, the backfill material was fractionated into gravel, coarse sand, fine sand, and fines as per USCS. Gravel is defined as particles between the 75 mm (3 in.) and No. 4 sieves, coarse sand between the No. 4 and No. 40 sieves, fine sand between the No. 40 and No. 200 sieves, and fines passing the

No. 200 sieve. The resistivity tests were also performed on materials passing the No. 8 sieve as required by Tex-129-E.

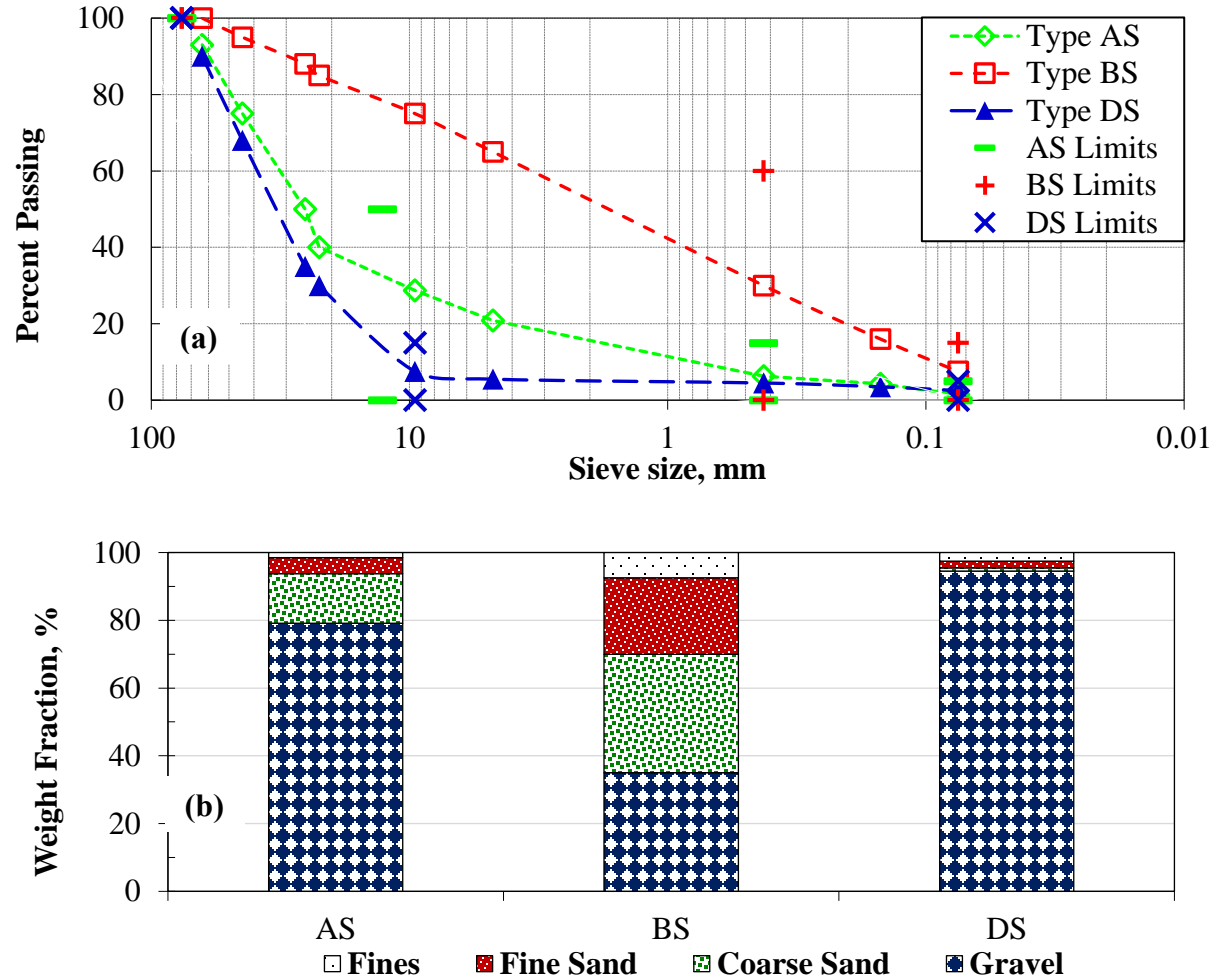


Figure 3.2: (a) Cumulative Size Distributions and (b) Composition by Weight Fractions for Type AS, BS, and DS Gradations.

Table 3.1: Composition by Weight Fraction for Type AS, BS, and DS Gradations.

Constituent	Distribution of Weights		
	AS	BS	DS
Gravel	79%	35%	95%
Coarse sand	15%	35%	1%
Fine sand	5%	22%	2%
Fines	1%	8%	2%

### 3.3 Modified Procedure

Two additional resistivity boxes with the dimensions two and four times the original box size were built to accommodate testing of coarse aggregates (see Figure 3.3). The box with the double dimensions was used to test coarse sand, while the box with quadruple dimension was used to test gravel and TxDOT gradations of AS, BS, and DS. The amount of material used and DI added were proportioned in order to give the same relation by volume as in the original size test procedure. That is, material and water amounts used in the double-dimension box were eight times the original, and material and water amounts used in the quadruple-dimension box were 64 times the original.

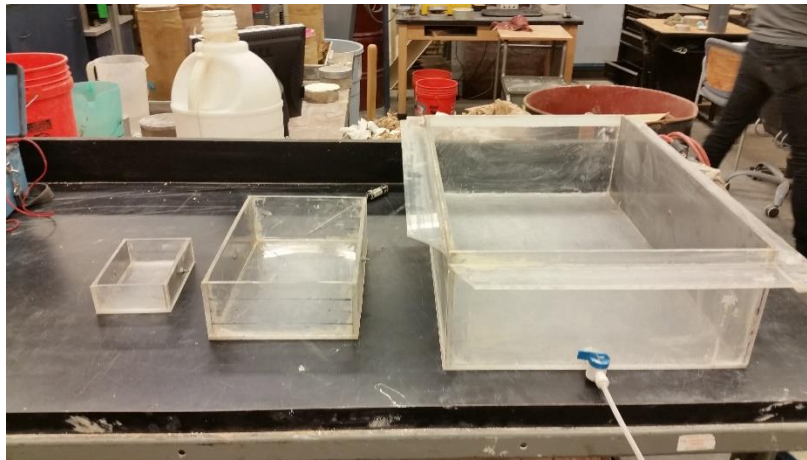


Figure 3.3: Original, Doubled Dimension, and Quadrupled Dimension Resistivity Soil Boxes.

Figure 3.4 compares the resistivity of a limestone backfill using the materials passing the No. 8 (Tex-129-E procedure) sieve in all the three box sizes against the degree of saturation. The results are generally consistent, as judged by the low coefficient of variation (COV) and high coefficient of determination ( $R^2$ ). The resistivity decreases with the increase in moisture content. Performing this test confirmed that it was possible to obtain consistent results across the three box sizes and that the tests were repeatable. The dependence of the resistivity on the backfill degree

of saturation is of importance as well. Based on this information, a new specification, named Tex-129-M, was developed that allowed the use of these increased dimension boxes.

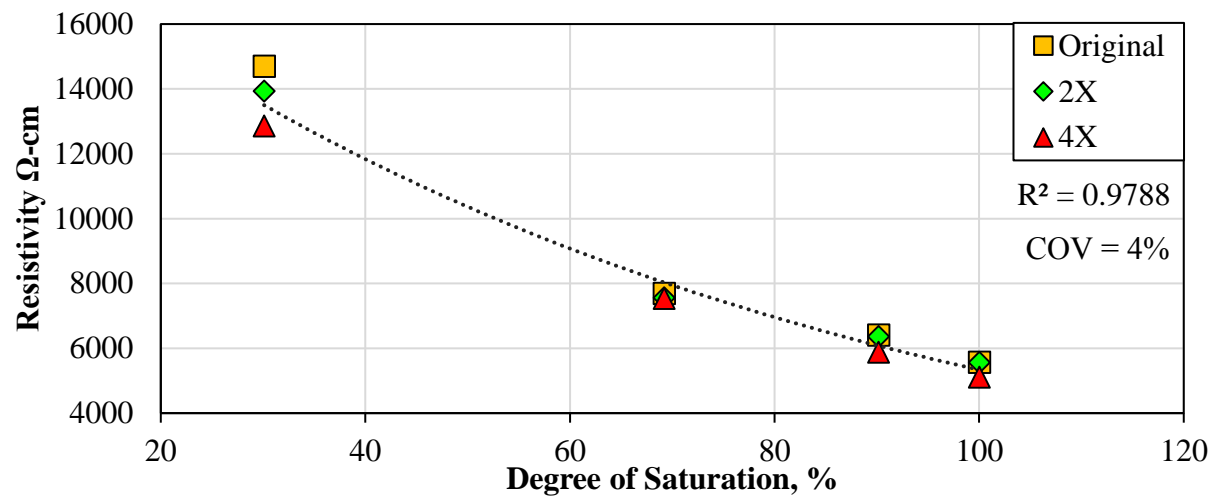


Figure 3.4:- Resistivity vs. Degree of Saturation across three box sizes

## Chapter 4: Results and Analyses

### 4.1 Minimum Resistivity Results and Trends with Gradation

Table 4.1 summarizes the observed minimum resistivity values of the eighteen materials tested using the methodology described. The resistivity values below 3,000  $\Omega\cdot\text{cm}$  are shown in red, while the resistivity values above 10,000  $\Omega\cdot\text{cm}$  are shown in green. Five of the 18 materials (28%) had a Tex-129-E minimum resistivity less than 3,000  $\Omega\cdot\text{cm}$ , but only 9% of the materials with the AS, BS, and DS gradations had a minimum resistivity less than 3,000  $\Omega\cdot\text{cm}$ . Thus, for the 18 materials and three gradations analyzed in this research, approximately 19% of the materials with the AS, BS, and DS gradations would not be allowed for use as backfill based on Tex-129-E but would meet the 3,000  $\Omega\cdot\text{cm}$  limit if the actual gradation was tested. Half of the resistivity values of the fine sand and two-thirds of the resistivity values of the fines were less than 3,000  $\Omega\cdot\text{cm}$ , which suggests that most of the soluble ionic content is in the fine sand and fines fractions. All gradations or size fractions for material L had a minimum resistivity less than 3,000  $\Omega\cdot\text{cm}$ .

Figure 4.1a shows the box plots and cumulative distribution plots of all the two electrode minimum resistivity measurements. In general, the resistivity values were greater over a larger range in the coarse (AS and DS) gradations than for the standard gradations recommended in Tex-129-E. The resistivity values from the current Tex-129-E procedure were more representative of the resistivity of the materials with the BS gradation. From the cumulative distribution curves in Figure 4.1b, more than 70% of the resistivity measurements from the AS and DS gradations were greater than 10,000  $\Omega\cdot\text{cm}$ . In contrast, less than 50% of the resistivity measurements from the BS gradation and close to 75% of the resistivity values with the current required gradation of Tex-129-E were less than 6,000  $\Omega\cdot\text{cm}$ . Around 30% of the measurements from the original Tex-129-E

procedure were below the current acceptance limit of 3,000  $\Omega\cdot\text{cm}$ , much more than for the AS, BS and DS gradations.

Figure 4.1c shows the cross plot between the resistivity values from Tex-129-E and Tex-129-M procedures for the two-electrode resistivity. There is an overlap between the relationships of the resistivity values for the materials with the AS and DS gradations with the resistivity values from the standard procedure. From these plots, the resistivity measurements of the materials with the AS and DS gradations are on average three times greater than those obtained with the original procedure. The resistivity measurements on the materials with the BS gradations on the other hand are approximately 1.5 times greater than the results from Tex-129-E.

Table 4.1 Minimum Resistivity of Measured Samples by Gradation

Material	Minimum Resistivity, $\Omega\cdot\text{cm}$							
	Tex-129-E	AS	BS	DS	Gravel	Coarse Sand	Fine Sand	Fines
A	5,534	17,336	5,334	22,403	29,337	12,802	2,334	1,867
B	4,001	17,869	6,668	26,670	27,737	6,801	4,467	2,200
C	5,334	14,402	6,934	20,003	37,338	10,668	3,067	3,400
D	4,867	20,803	10,935	20,003	28,004	33,338	2,800	2,667
E	36,671	37,338	10,135	45,339	48,006	34,671	6,934	4,067
F	8,001	23,203	10,935	29,337	34,671	12,268	6,668	5,134
G	4,201	20,269	9,335	26,670	22,936	11,201	5,067	3,600
H	2,600	4,001	4,001	4,001	13,068	3,867	2,267	2,267
I	3,134	5,601	2,667	5,334	13,068	3,200	1,267	867
J	2,267	8,268	3,200	12,802	18,669	7,468	1,734	1,400
K	800	3,467	2,160	7,201	8,001	2,000	1,133	1,267
L	1,334	2,667	2,374	2,667	2,934	2,534	1,267	1,400
M	16,002	50,673	25,337	37,338	66,675	29,337	9,335	3,267
N	5,334	16,002	5,334	19,202	24,536	12,002	5,201	1,867
O	9,335	29,337	10,935	37,338	109,347	25,337	5,467	3,667
P	7,334	14,669	7,468	14,935	19,202	8,134	4,601	2,534
Q	3,000	8,001	3,467	9,601	13,335	3,734	1,800	1,534
R	1,867	12,268	5,067	16,002	17,069	4,934	2,534	1,667

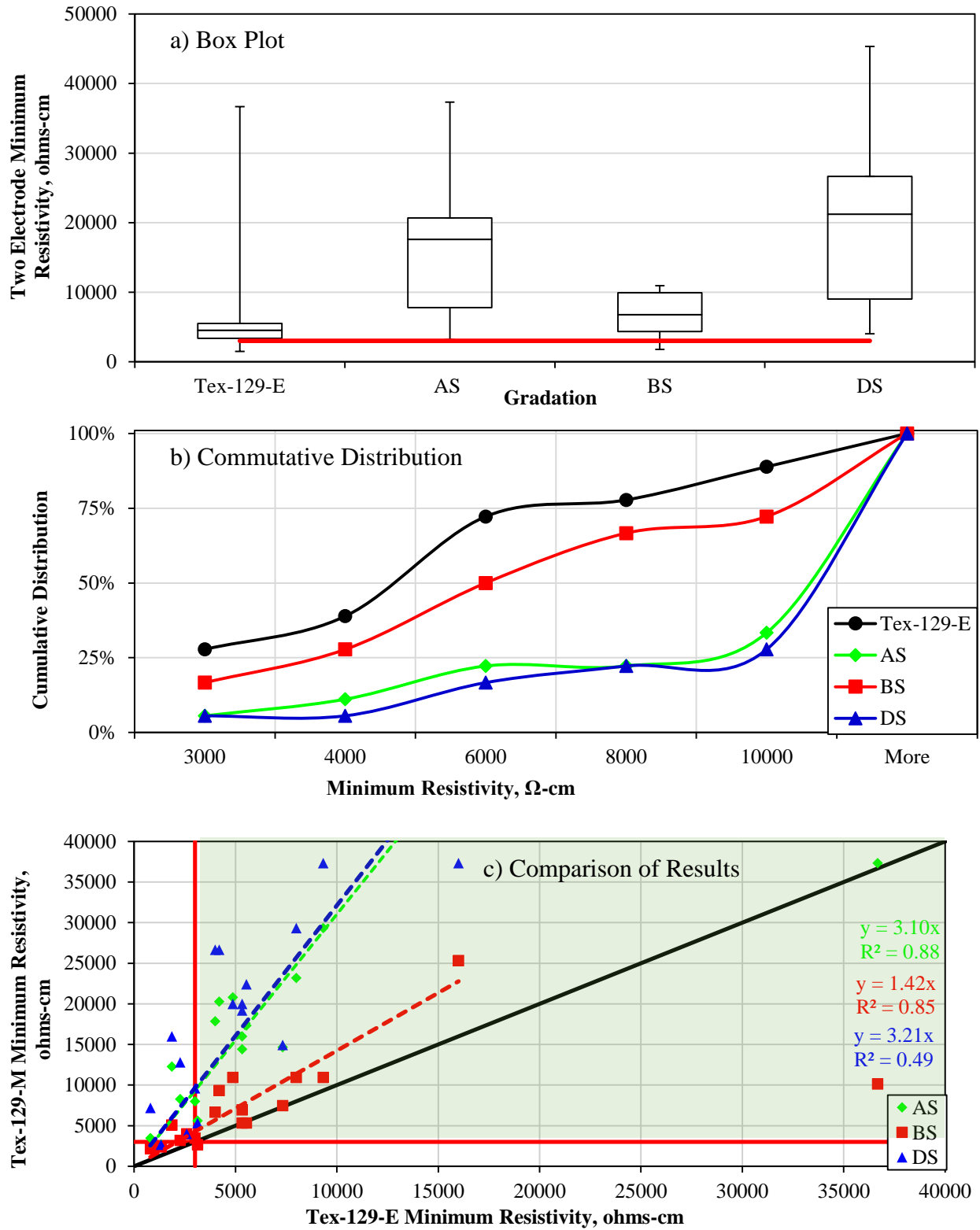


Figure 4.1- Comparison of Results from Two Electrode Minimum Resistivity



Figure 4.2 shows the average minimum resistivity of all 18 materials normalized by Tex-129-E per gradation (AS, BS, and DS) and size fraction (gravel, coarse sand, fine sand, and fines). Materials with a Type DS gradation had a higher average resistivity than with a Type AS gradation, while the materials with Type AS and DS gradations exhibited a higher average resistivity than Type BS. Within the constituent size fractions, the resistivity decreased as the particle size decreased. Again, the fine sand and fines had lower average resistivity values than the gravel and coarse sand (and lower than the fraction tested in Tex-129-E). This pattern indicates that most of the soluble ionic content is in these size fractions, and thus, the materials with the Type BS gradation suffer a lower average resistivity relative to the AS and DS gradations due to the higher weight fractions of the fine sand and fines.

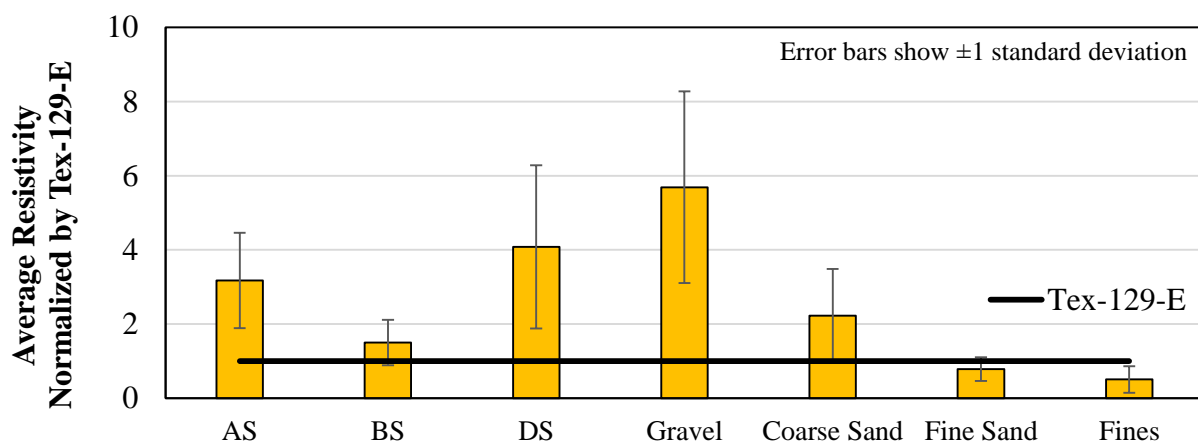


Figure 4.2: Average Resistivity Normalized by Tex-129-E.

#### 4.1 Resistivity Trends in Relation to Degree of Saturation

In order to predict how the variation in moisture content can affect the resistivity, and as a result the in service performance of MSE walls, laboratory resistivity measurements were carried out on 18 materials at varying moisture contents in addition to the minimum resistivity. Figure 4.3 shows the resistivity of the 18 materials normalized by the minimum resistivity of the respective sample per TxDOT gradation specifications (AS, BS, DS, Figure 4.3a) and USCS

material constituents (gravel, coarse sand, fine sand and fines, Figure 4.3b). In each case, an exponential decrease in resistivity is observed as a result of an increase in the degree of saturation. The resistivity measurements for degrees of saturation of 20% and less are significantly greater than the resistivity close to saturation with significant scatter. This can be attributed to the limitations of the resistivity methods in fairly dry materials. The resistivity measurements for the degrees of saturation of 50% and greater gradually decrease with the increase in the degree of saturation until they become asymptotic to their corresponding minimum resistivity values.

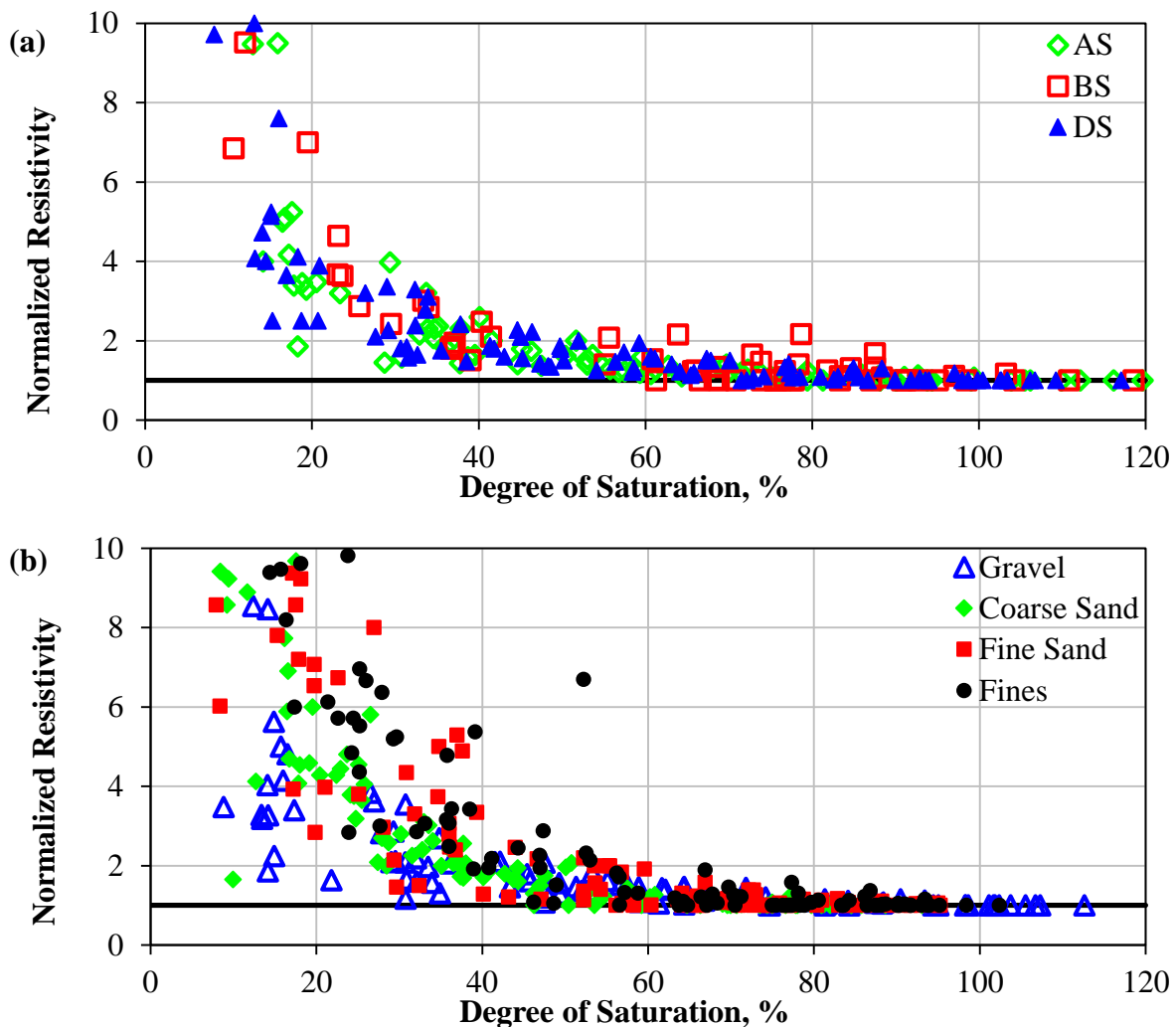


Figure 4.3: Normalized Resistivity versus Degree of Saturation for (a) Standard TxDOT Gradations and (b) USCS Material Constituents

## Chapter 5: Estimating Resistivity from Gradation

### 5.1 Developing a Model to Estimate Resistivity from Gradation

From the trends observed within the data, it was hypothesized that the total resistivity of a given material and gradation at saturation could be predicted as a function of the resistivity and weight fraction of the four constituent size fractions (*i.e.*, gravel, coarse sand, fine sand, and fines). This hypothesis assumes that the four constituents are effectively acting as resistors in parallel. An adaptation of the formula to estimate the total resistance of four parallel resistors in a circuit was used as:

$$\rho_{predicted} = (W_g/\rho_g + W_{cs}/\rho_{cs} + W_{fs}/\rho_{fs} + W_f/\rho_f)^{-1} \quad (5.1)$$

where  $W_i$  is the weight fraction of constituent  $i$ , and  $\rho_i$  is the minimum resistivity of the constituent.

### 5.2 Relationships Between Measured and Modeled Resistivity

The model presented in Equation 5.1 was tested using the minimum resistivity of the samples tested using the methodology described in previous chapters. The values obtained from that model are presented in Table 5.1. Figure 5.1 is the cross-plot of the predicted resistivity versus the measured resistivity (shown twice with different boundaries for reference in the interpretation of the data). Only resistivity values under 30,000  $\Omega \cdot \text{cm}$  were considered in the statistical analysis. With a coefficient of determination ( $R^2$  value) of 0.87 and a standard error of estimate (SEE) of 2288  $\Omega \cdot \text{cm}$ , the model can estimate the measured resistivity values reasonably well. The best-fit line produced by the data is very close to showing a one-to-one relationship (slope of 0.96). While there could be concern about the scatter that occurs at a resistivity above 10,000  $\Omega \cdot \text{cm}$ , these values

are beyond the critical range for corrosion mentioned before. When the resistivity is close to the acceptance limit of 3,000  $\Omega \cdot \text{cm}$ , the prediction errors are less than 20%.

Table 5.1: Predicted and Measured Resistivity Values

Material	AS Gradation Resistivity, $\Omega \cdot \text{cm}$		Gradation BS Resistivity, $\Omega \cdot \text{cm}$		Gradation DS Resistivity, $\Omega \cdot \text{cm}$	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
A	17336	14953	5334	5686	22403	18197
B	17869	14807	6668	6732	26670	19463
C	14402	18230	6934	7268	20003	24925
D	20803	18083	10935	7607	20003	19778
E	37338	31973	10135	14647	45339	34477
F	23203	22314	10935	11497	29337	27824
G	20269	16358	9335	8949	26670	18873
H	4001	7937	4001	4006	4001	10554
I	5601	6203	2667	2498	5334	8329
J	8268	9980	3200	4016	12802	12293
K	3467	4427	2160	2099	7201	6231
L	2667	2662	2374	2047	2667	2780
M	50673	37633	25337	15567	37338	41137
N	16002	16216	5334	7882	19202	17673
O	29337	38713	10935	12719	37338	51250
P	14669	13249	7468	7155	14935	15466
Q	8001	7420	3467	3403	9601	9905
R	12268	9632	5067	4440	16002	12456

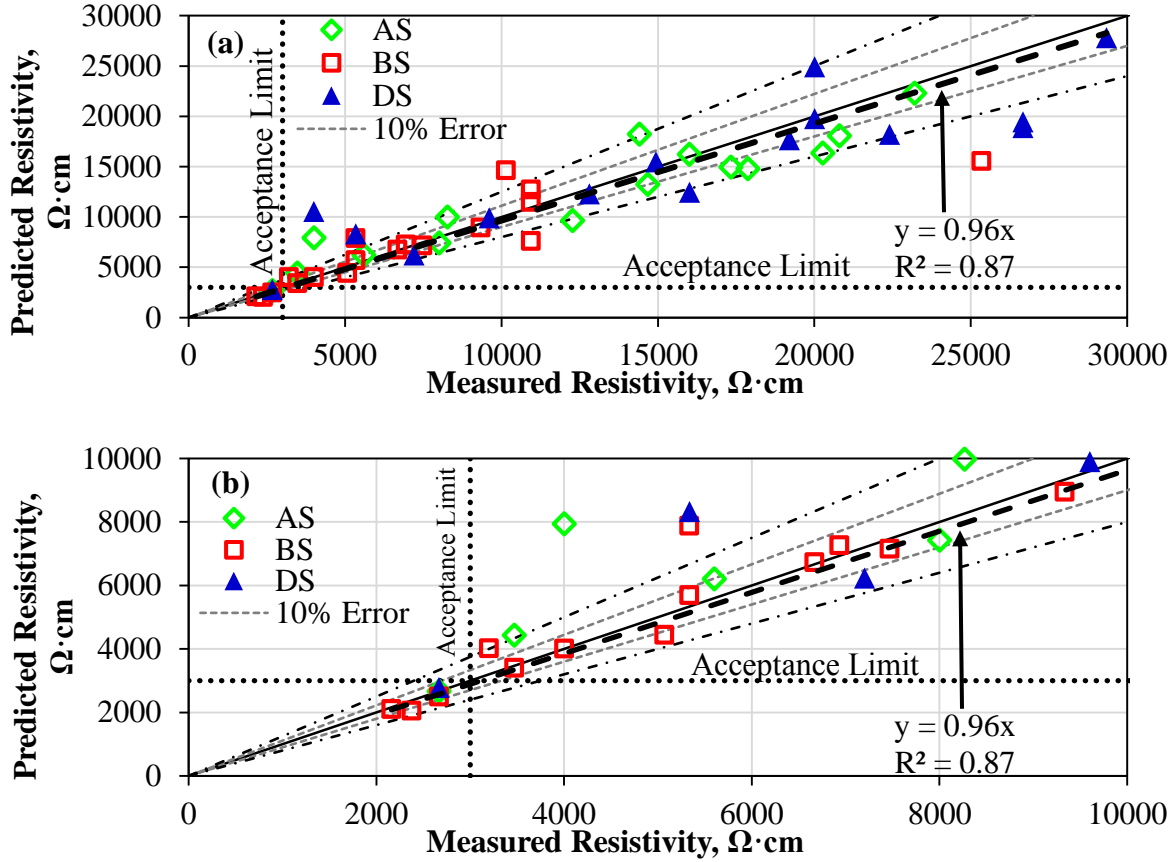


Figure 5.1: Predicted Resistivity Versus Measured Resistivity for (a) Resistivity less than 30,000  $\Omega \cdot \text{cm}$  and (b) Resistivity less than 10,000  $\Omega \cdot \text{cm}$ .

### 5.3 Characterizing Error in Estimations

As the cumulative distributions of the percentage of errors for different gradations show in Figure 5, the Equation 5.1 model appears to be slightly more accurate at predicting the resistivity of the materials with Type BS gradations than of the materials with the Type AS or Type DS gradations. Over 50% of the estimates for the materials with the BS gradation are within 10% error. For all three gradations, over 50% of the estimates are within a 20% of error and over 75% are within a 30% error. A very small percentage of the estimates had an error greater than 50%. The distributions of the errors appear to be consistent across the three gradations. This model appears to be useful to predict the resistivity of a given gradation as a function of constituent size

fractions that should be backed up by more direct testing. Regardless, the existence of a tool that reasonably approximates the resistivity of a material can provide a starting point for the empirical adjustment of its gradation in order to reduce the corrosion potential. Since the SEE is  $2288 \Omega \cdot \text{cm}$ , one can assume that any material with resistivity greater than  $5500 \Omega \cdot \text{cm}$  (a rounded approximation of the acceptance limit of  $3,000 \Omega \cdot \text{cm}$  plus SEE) obtained with this approximation should most probably pass the  $3,000 \Omega \cdot \text{cm}$  acceptance limit.

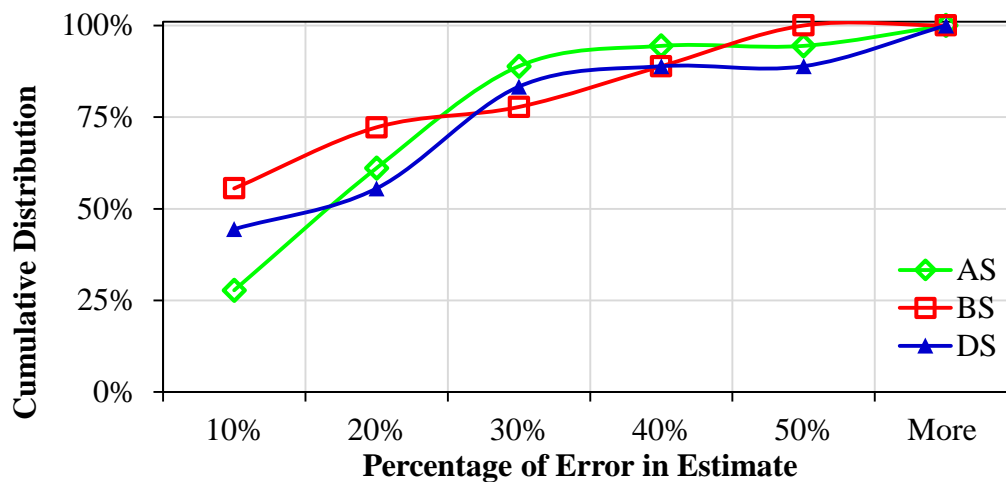


Figure 5.2: Cumulative Distribution of the Error in the Estimate of Resistivity per Gradation

#### 5.4 Practical Application

As reflected in Table 5.1, Material J would fail if analyzed by Tex-129-E or similar procedures (*e.g.*, AASHTO T-288) because the resistivity of  $2267 \Omega \cdot \text{cm}$  is less than the minimum  $3,000 \Omega \cdot \text{cm}$ . However, the material from this quarry can pass the resistivity requirements for Type AS and Type DS. The resistivity of the Type BS gradation for this material is just above the acceptance limit ( $3200 \Omega \cdot \text{cm}$ ) and could be subject to concern about corrosion. If the weight fractional composition of Type BS gradation of Material J could be changed from 35% gravel, 35% coarse sand, 22% fine sands, and 8% fines to 45% gravel, 45% coarse sand, 5% fine sand,

and 5% fines (compared in Figure 5.3), then the model predicts a resistivity value of 6715  $\Omega\cdot\text{cm}$ , which is above 3,000  $\Omega\cdot\text{cm}$  within a 2288  $\Omega\cdot\text{cm}$  SEE. One could prepare a sample and measure the resistivity of the proposed gradation using the modified two-electrode boxes to verify that it is in compliance with the specifications.

A concern for this model is the possibility of overestimating the resistivity, as this could result in the selection of a material that would have not passed the 3,000  $\Omega\cdot\text{cm}$  limit had it been measured directly. However, the error in the estimates seems to be greater when the resistivity is greater than 3,000  $\Omega\cdot\text{cm}$ , and the model predicts well for resistivity less than 3,000  $\Omega\cdot\text{cm}$ . Thus, the model is proposed as a viable way to estimate the resistivity of a backfill material through the gradation and the resistivity of the separate particle sizes that constitute it.

The main advantage of this model is that it would allow for the design of backfill aggregate size distribution through the adjustment of the gradation in an empirical manner. This could open up the possibility to use a variety of coarse materials that would otherwise not be considered for use as backfill. By reducing the weight fraction of finer particles, it could be possible to obtain a modified mixture of a material that satisfies the specifications set forth by the DOTs. Providing a method to design a backfill for a target resistivity changes significantly the current selection process for backfill in MSE wall. The materials are currently selected or rejected on a pass or fail manner in accordance to AASHTO T-288 or similar procedures. This model could effectively provide an easy medium for characterizing the corrosion potential of a material in terms of its gradation and composition and adjusting these parameters accordingly.

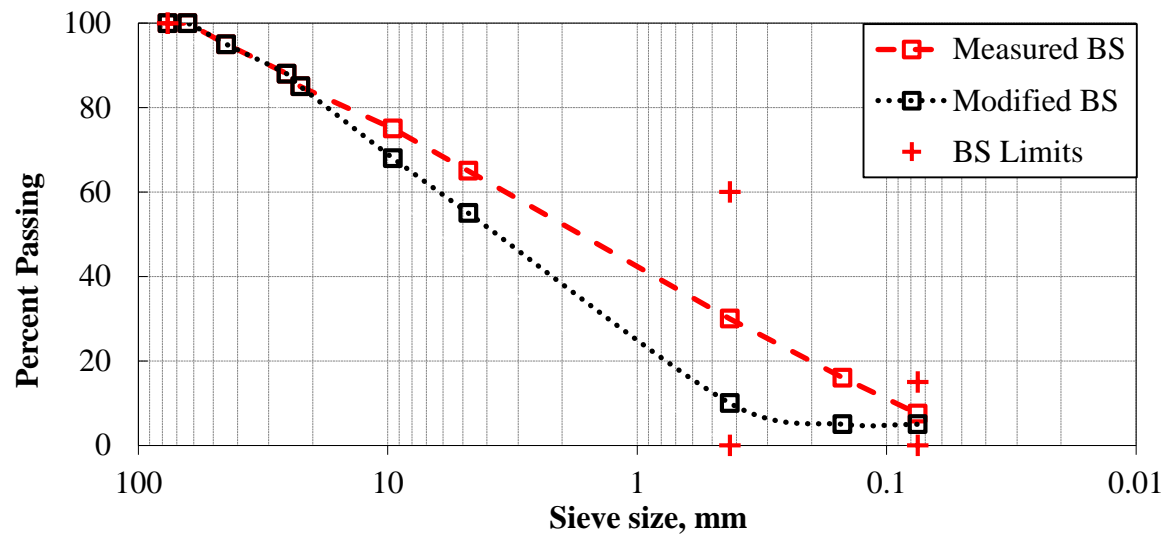


Figure 5.3: Size Distribution of Measured BS and Modified BS for Material J.



## Chapter 6: Estimating Resistivity from Degree of Saturation

### 6.1 Model Based on Empirical Observations

To estimate the resistivity at a given degree of saturation based on the minimum resistivity and field degree of saturation, the first assumption made was that the total resistivity of a material is a function of the resistivities ( $\rho$ ) of the solids, air, and pore water acting as parallel resistances and weighted by porosity ( $n$ ) and degree of saturation ( $S_r$ ), in the form of:

$$\rho_{material}^{-1} = \frac{\rho_{solids}^{-1}}{1-n} + \frac{\rho_{air}^{-1}}{n(1-S_r)} + \frac{\rho_{pore\ water}^{-1}}{n S_r} \quad (1)$$

As shown in Chapter 4, the resistivity values at degrees of saturation less than 20% were greater than 100 k $\Omega$ -cm, and therefore, no attempt was made to fit the resistivity values at a degree of saturation below 20%. For degrees of saturation greater than 20%, the resistivity of the air is assumed to be much greater than the resistivity of the solids, and the resistivity of the solids is much greater than the resistivity of the pore water, so the first two terms on the right hand side of Equation 1 are negligible compared to the third. Thus, the resistivity of the moist material is approximated as:

$$\rho_{material} = \frac{\tau_{pw}}{\kappa_{pw} * n * S_r} \quad (2)$$

where  $\tau_{pw}$  is the tortuosity of the pore water in the system and  $\kappa_{pw}$  is the electrical conductivity of the pore water (*i.e.*, the reciprocal of the resistivity of the pore water). Since the tortuosity of the pore water would be dependent on the amount of pore water present and there is uncertainty as to what exactly its effect would be on the resistivity of the material, the effect of the tortuosity of the pore water in the system and the degree of saturation was expressed as an exponential function with two fitting parameters ( $C_1$  and  $C_2$ ) in the form of:

$$\frac{\tau_{pw}}{S_r} = C_1 * 10^{-C_2 S_r} \quad (3)$$

In addition, the conductivity of the pore water at saturation was assumed to be equal to the measured minimum resistivity of the system, as shown in Equation 4.

$$\frac{1}{\kappa_{pw}(sat)} = \rho_{min} \quad (4)$$

Incorporating Equations 3 and 4 into Equation 2, yields the following relationship:

$$\rho_{material} = \frac{\rho_{min} * C_1 * 10^{-C_2 S_r}}{n} \quad (5)$$

This equation attempts to capture the relationship between degree of saturation and resistivity observed empirically.

The model presented in Equation 5 was tested using resistivity data collected at different moisture contents. Table 6.1 lists the values of the fitting parameters obtained through optimizations per gradation or constituent. These values were reached by first approximating them with a starting set of values, calculating a preliminary estimation of resistivity, and then minimizing the sum of the squares of differences between the measured and predicted resistivity values. The optimization of the model parameters was performed separately on the moisture conditions corresponding to degrees of saturation greater than 20% (to capture a broad spectrum of moisture contents) and greater than 50% (to obtain more accurate predictions for more corrosive conditions).

Table 6.1: Fitting Parameters Obtained through Optimization

Minimum Degree of Saturation, %	Fitting Parameter	Gradation of Backfill			Constituents as per US Classification System			
		AS	BS	DS	Gravel	Coarse Sand	Fine Sand	Fines
20	C <sub>1</sub>	1.16	3.14	1.38	1.30	4.66	4.26	20.69
	C <sub>2</sub>	0.57	1.15	0.55	0.55	1.58	1.48	2.58
50	C <sub>1</sub>	0.78	1.38	1.13	1.01	0.97	0.74	1.51
	C <sub>2</sub>	0.34	0.68	0.44	0.40	0.44	0.26	0.60

## 6.2 Relationships Between Measured and Modeled Resistivity

The relationships between the resistivity values estimated with the model using a minimum degree of saturation of 20% and corresponding measured resistivity values are presented in Figure 6.1a for the TxDOT gradations and Figure 6.1b for the USCS material constituents. Table 6.2 summarizes the slope, coefficient of determination ( $R^2$  value) and standard error of estimate (SEE) of the best fit line between the estimated and measured resistivity values for each of the seven gradations. The model works best for the materials with the coarser gradations such as AS, DS, and gravel. For these three gradations, the slopes of the best-fit lines between the estimated and measured values are greater than 0.9, and the  $R^2$  values are greater than 0.85. In contrast, for the finer aggregates, such as BS, the  $R^2$  values are less than 0.6 and as low as 0.43.

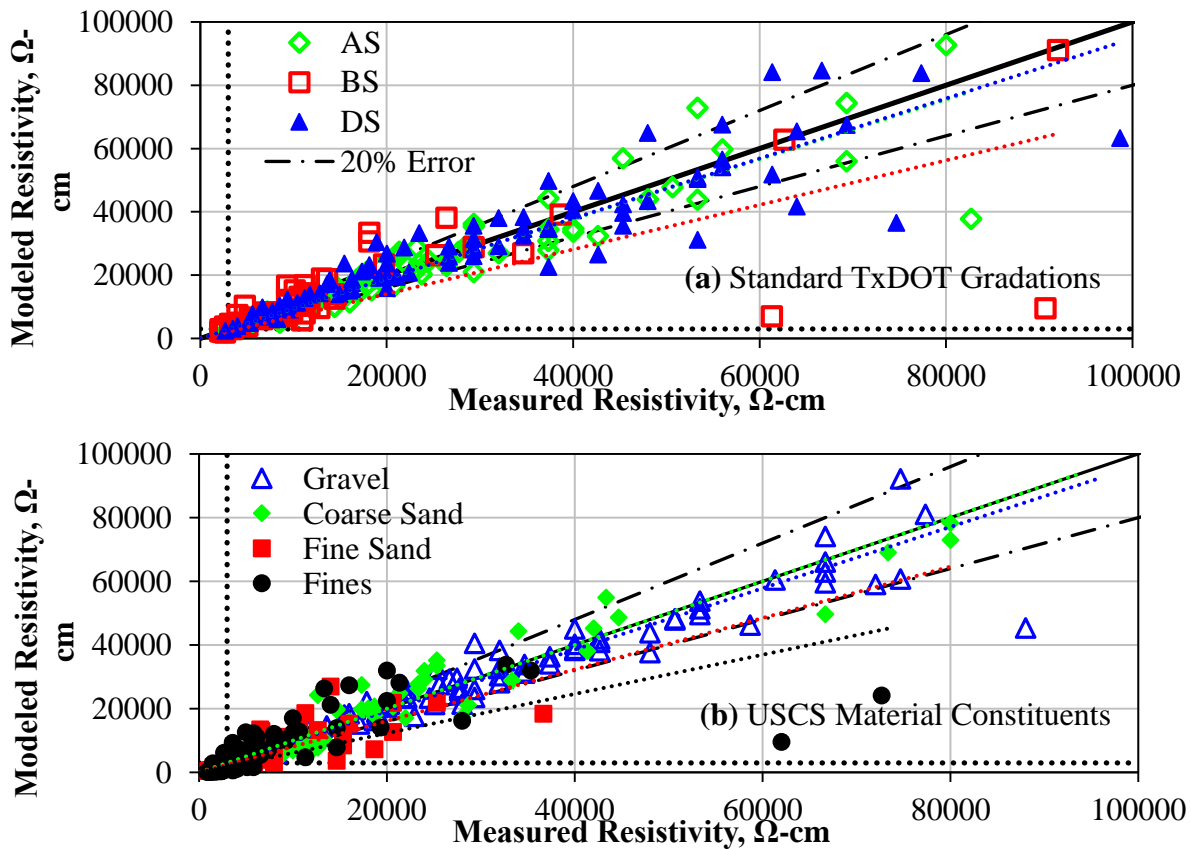


Figure 6.1: Predicted Resistivity versus Measured Resistivity for Fit with a Minimum Degree of Saturation of 20%

The relationships between the measured and estimated values with the model that only considers the resistivity values when their degrees of saturation are greater than 50% are shown in Figure 6.2. For all gradations, estimations of the resistivity as a function of degree of saturation greater than 50% are more accurate than the estimations of the resistivity as a function of degree of saturation greater than 20%.

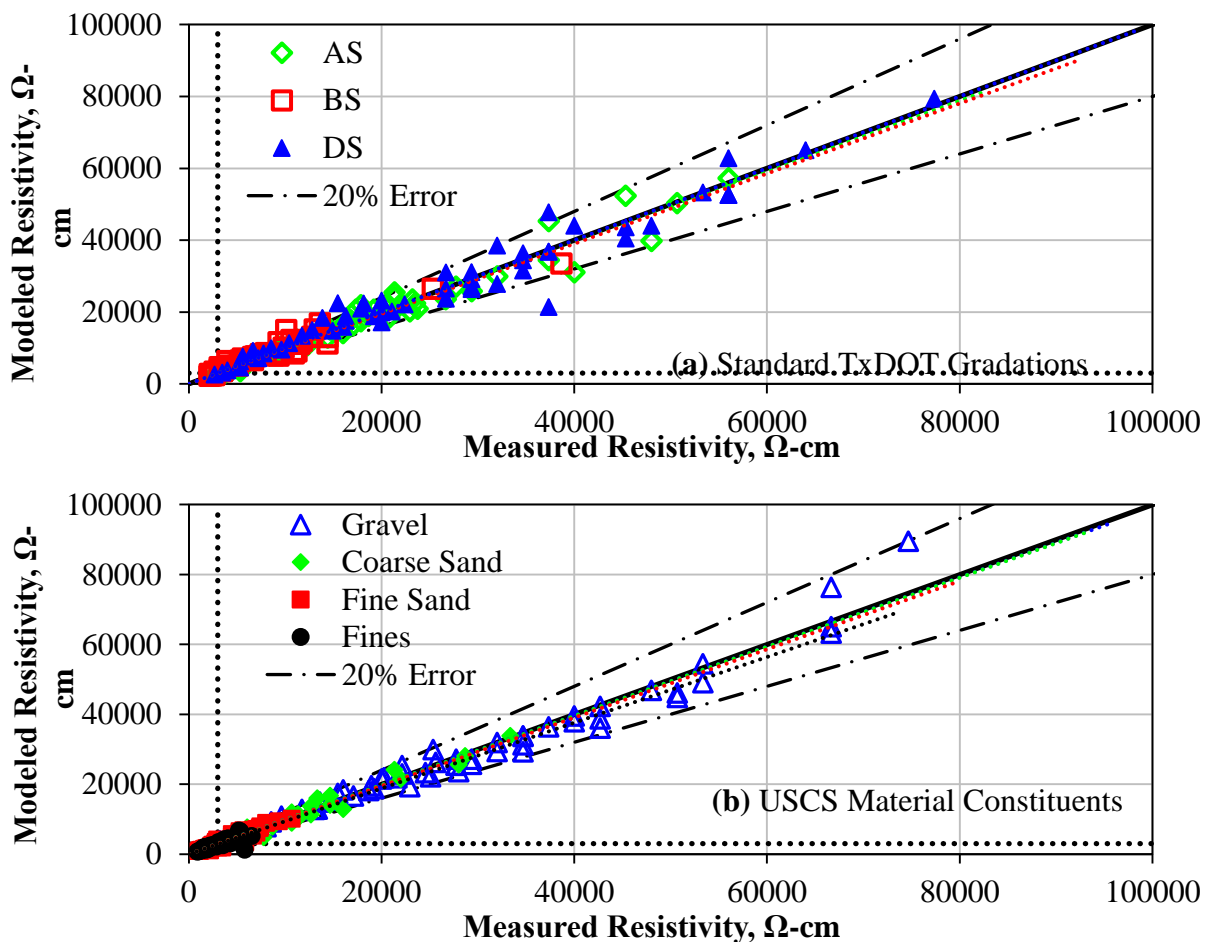


Figure 6.2: Predicted Resistivity versus Measured Resistivity for Fit with a Minimum Degree of Saturation of 50%

Table 6.2: Line of Best Fit Slope,  $R^2$ , and Standard Error of Estimate (SEE) Values

Minimum Degree of Saturation Considered	Best Fit Parameters	Gradation of Backfill			Constituents as per US Classification System			
		AS	BS	DS	Gravel	Coarse Sand	Fine Sand	Fines
20%	Slope	0.94	0.70	0.95	0.96	1.00	0.81	0.62
	$R^2$	0.85	0.43	0.79	0.87	0.94	0.63	0.39
	SEE, $\Omega$ -cm	7063	13484	9069	7565	4823	3653	7964
50%	Slope	0.99	0.98	1.00	0.99	0.99	0.98	0.94
	$R^2$	0.92	0.96	0.95	0.96	0.97	0.92	0.73
	SEE, $\Omega$ -cm	2710	1693	3757	3490	1253	672	747

### 6.3 Characterizing Error in Estimations

The cumulative distributions of error in estimating resistivity are shown in Figure 6.3 for each gradation and constituent where the error is defined as the absolute difference between the measured and estimated values divided by the measured value. Figure 6.3a shows the error distributions for the standard TxDOT gradations and Figure 6.3b for the USCS material constituents for the model where the degrees of saturation are greater than 20%. More than 75% of the estimates for the materials with the Type AS gradation and gravel exhibit errors of 20% or less. For all three gradations and gravel, over 50% of the estimates are within a 20% error, and over 70% of the estimations are within 30% error. A small fraction of the estimates had errors greater than 40%. The distributions of the errors appear to be consistent across the three gradations and gravel. Conversely, there appears to be a large amount of error in predicting the resistivity of coarse sand, fine sand, and fines, and of these coarse sand shows the least error, with over 50% of the estimates within 30% error. For fine sand, over 50% of the estimates had an error greater than 40%, and for fines nearly 75% of the estimates had an error greater than 40%. These errors seem

to indicate that when the degree of saturation is between 20% and 50% the model works better for coarser aggregates.

The cumulative distributions of error from the model optimized for degrees of saturation above 50% are shown in Figure 6.4a for the standard TxDOT gradations and Figure 6.4b for the USCS material constituents. The model appears to have similar levels of accuracy across all gradations and constituents, and is generally an improvement over the greater than 20% saturation fit. Over 50% of all estimates are within 10% error, and approximately 75% of the estimations are within 20% error. The superiority of the models for degree of saturation greater than 50% is more apparent for the finer samples. This could lead to the recommendation that the fit using degree of saturation greater than 20% be used for coarse aggregates, due to the fact that it allows for the prediction of a broader range of moisture levels. For use with fine aggregates, the model optimized with resistivity values for degree of saturation greater than 50% is recommended due to greater accuracy.

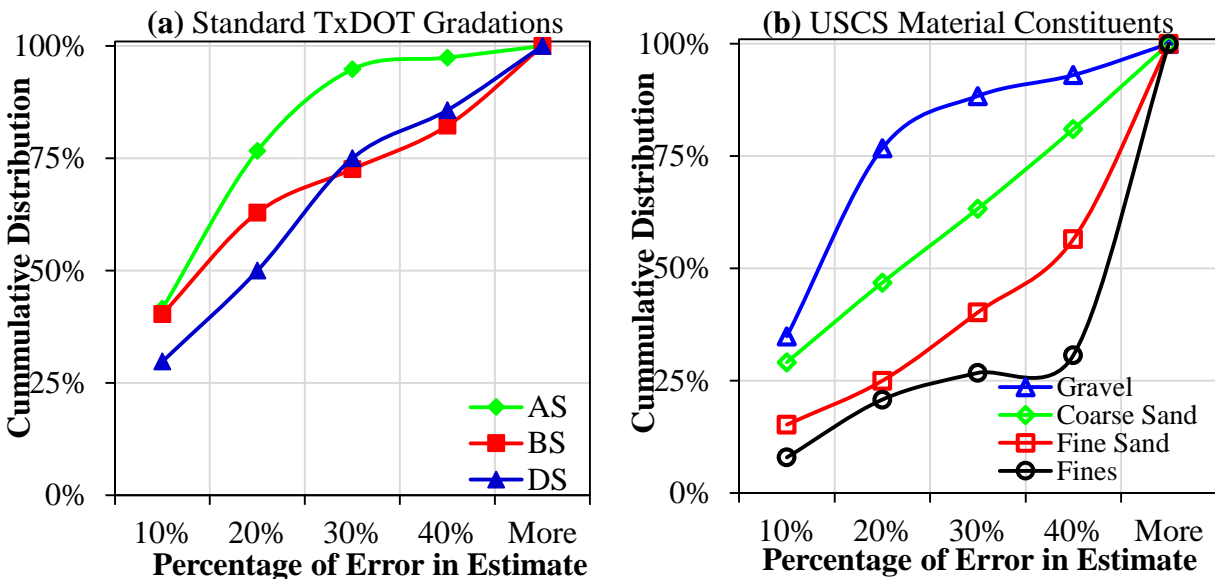


Figure 6.3: Cumulative Distribution of Error in the Estimate of Resistivity using Degrees of Saturation above 20%

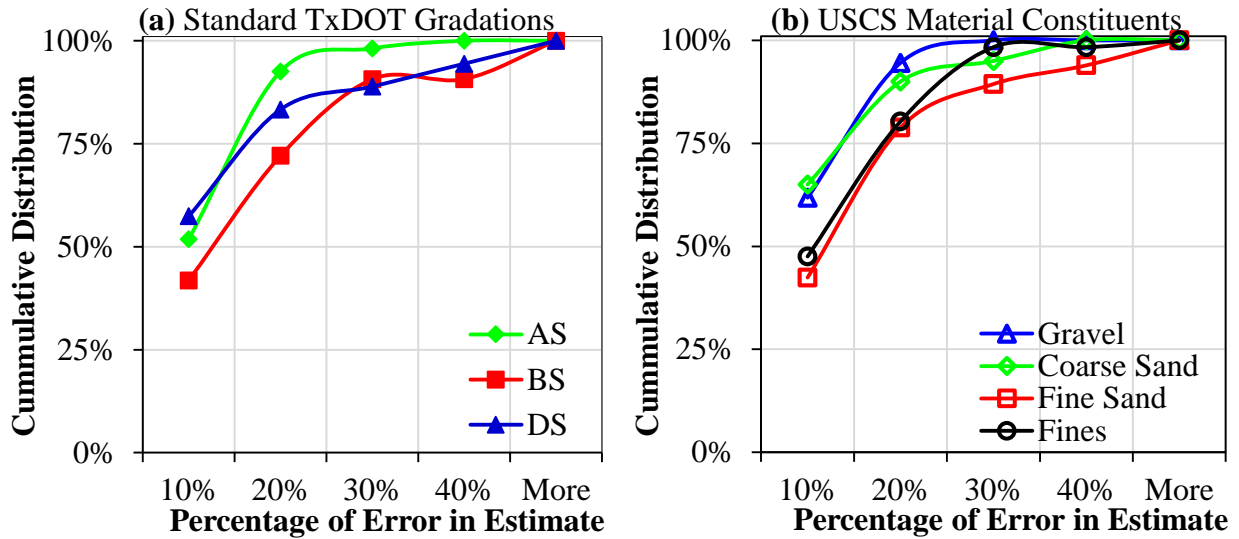


Figure 6.4: Cumulative Distribution of Error in the Estimate of Resistivity using Degrees of Saturation above 50%

#### 6.4 Test of Reasonableness

In addition to the 18 materials mentioned before, the resistivity tests were carried out on five additional materials used as backfill behind the walls in Texas using Tex-129-M. Since these measurements were not used in the development of the models, they were used to test the reasonableness of the models for use with other backfills. Figure 6.5 shows the grain-size distribution curves of the five materials. Backfills A, B, D, and E resembled Type AS gradation, while Material C was a sandy backfill.

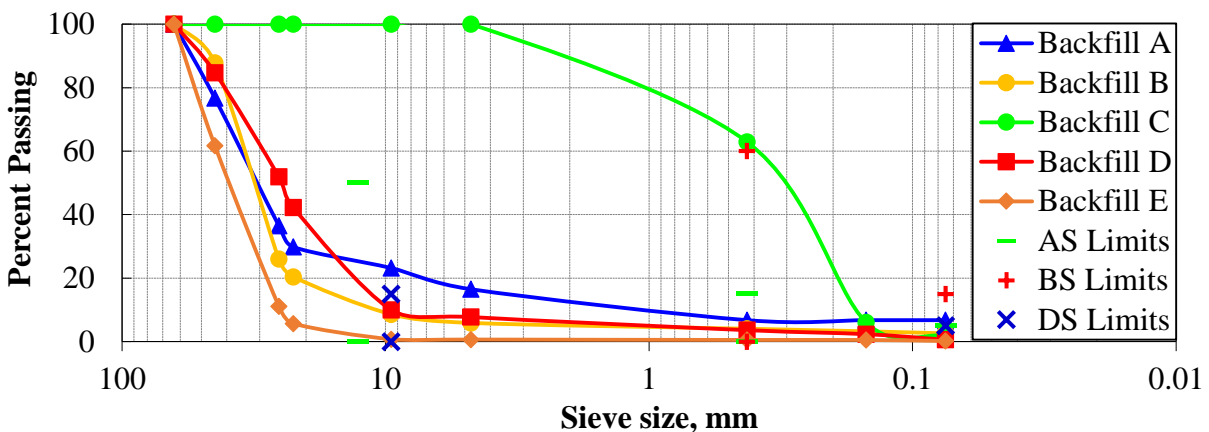


Figure 6.5: Grain Size Distribution of Texas Wall Backfills

Figure 6.6 compares the relationship between the measured and modeled resistivity values as a function of the degree of saturation when data for the degree of saturation of down to 20% (Figure 6.6a) and above 50% (Figure 6.6b) were used. In most cases, both models are reasonably accurate in capturing the relationship of resistivity with degree of saturation. For the case when the model with data up to 20% degree of saturation used, Backfills C and E show some divergence. The standard error of estimate across the five materials for this model is of 5888  $\Omega$ -cm. On the other hand, the model that used data up to a degree of saturation of 50%, the resistivity values of all five backfills are reasonably accurately estimated. The standard error of estimate across the five materials for this model is 3314  $\Omega$ -cm. Given that the average resistivity is greater than 20,000  $\Omega$ -cm, the uncertainty of these models may be acceptable. As such, the model that contained data up to 50% degree of saturation is more accurate.

The main advantage of this model is that it can provide a simple means for estimating the resistivity based on the minimum resistivity of the backfill material, its gradation, and field moisture conditions. This could eventually be useful for evaluating the corrosion potential of in-service walls under various climatic conditions, as it is done in the current mechanistic empirical pavement design. However, similar precautions described in Chapter 5 should be taken for this model. The model could also be refined further, through the inclusion of either more materials in the optimization of the model or the consideration of more soil parameters that could affect the resistivity-moisture relationship. The possibility of implementing both of these to eventually arrive at a single model that is independent of gradation could be explored in future studies.



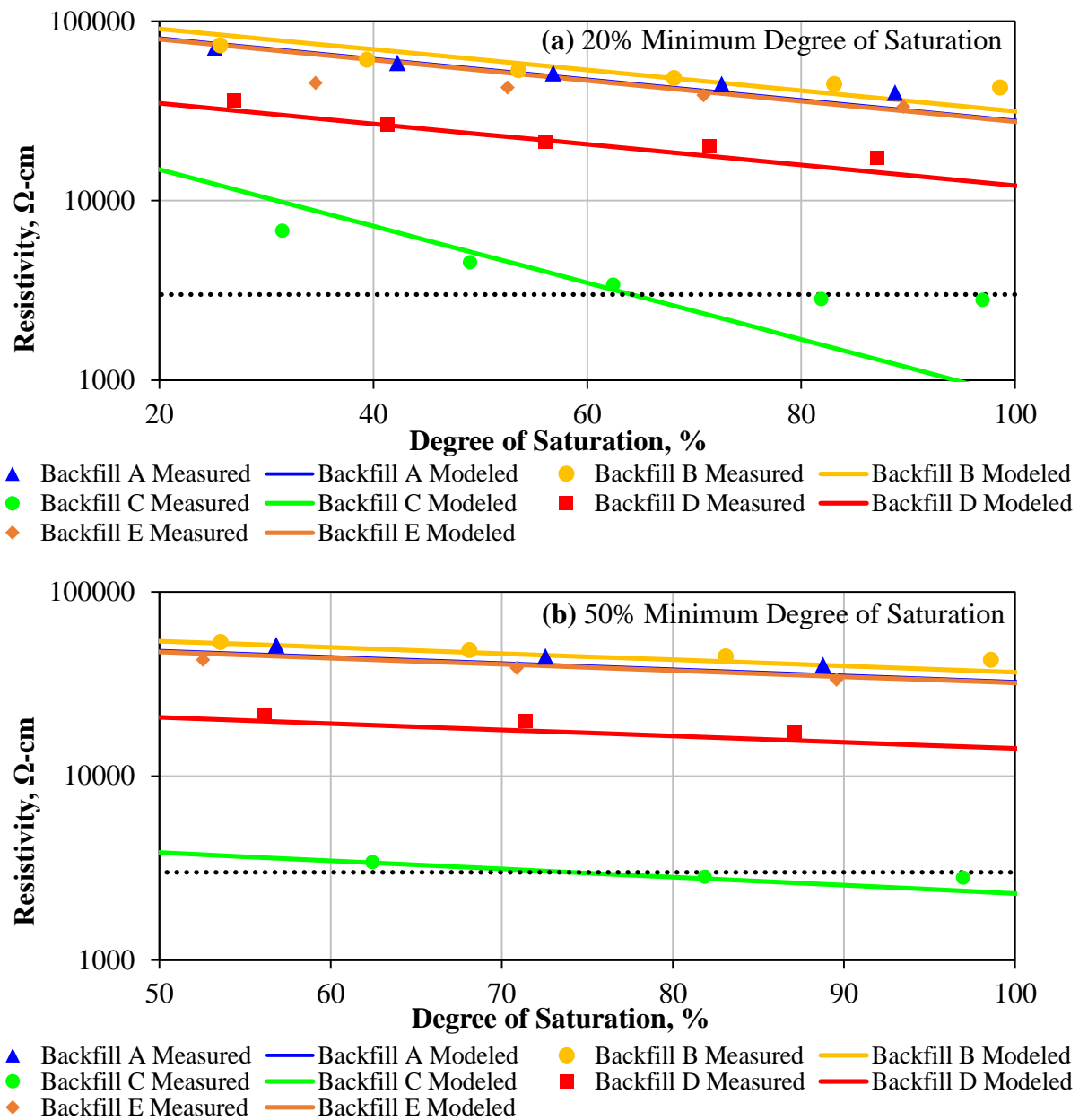


Figure 6.6: Resistivity vs Degree of Saturation for Measured and Modeled Values

## **Chapter 7: Conclusion**

### **7.1 New Specification**

The resistivity of MSE wall backfill materials and the moisture conditions in the field are important parameters in the estimation of the corrosion potential, which is in turn a critical factor for the service life of the walls. The concern that current testing procedures do not provide an accurate representation of the resistivity of coarse materials used as backfill has led to numerous studies looking for an alternative. Test procedure Tex-129-M was developed with the purpose of allowing the size fractions larger than the previously specified passing #8/10 sieve through the use of larger boxes. Through testing of 18 different materials with TxDOT Type AS, BS, and DS gradations and its constituent USCS size fractions (gravel, coarse sand, fine sand, and fines), several observations were made. Most importantly, the resistivity of a sample was observed to be correlated with its particle size distribution (*i.e.*, gradations with a greater weight fraction of fine sand and fines had lower resistivity). These trends suggest that the use of the new proposed specification could be greatly beneficial in the proper characterization of the corrosion potential of aggregate commonly used as backfill in MSE Walls.

### **7.2 Gradation Model**

Based on the hypothesis that the resistivity of a material can be approximated as a function of its composition as a weight fraction of the constituents, a model was developed to predict the aggregate resistivity based on the constituent size fractions acting as resistors in parallel. The model can be used as a tool to design the gradation of a material in a manner to achieve acceptable resistivity. Use of this model will be valuable as it can provide a starting point for the modification

of aggregate size distributions for use in MSE walls, avoiding a large amount of the laboratory trial and error that would otherwise be required. Further testing with a larger number of samples is recommended for further refining the model for a wide scale implementation. In the meantime, it is proposed to verify the results with laboratory testing.

### **7.3Moisture Model**

Relationships between the degree of saturation and resistivity as a function of the laboratory-measured minimum resistivity are proposed. The relationships equate the resistivity of a material to the resistivity of the pore water in the system. The resistivity of the pore water is considered to be a function of the porosity, the conductivity of the pore water (assumed to be equal to the minimum resistivity of the material at saturation), degree of saturation, and the tortuosity of the voids. Two models were developed: one for when the degree of saturation is greater than 20% and the second restricted to degrees of saturation greater than 50%. Both models proved promising in estimating the resistivity as a function of degree of saturation, with the second model being more accurate. When the models were validated with five materials that were not included in their development, the estimated resistivity values were reasonably accurate. The model can be used as a way to estimate resistivity (and corrosion potential) of in-service MSE walls knowing the minimum resistivity and moisture conditions. Future considerations for this model should include further refinement of the fitting parameters with more laboratory data, and the inclusion of more soil parameters and a more generalized model.

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## **Vita**

Jose Luis Arciniega was born in Tijuana, Mexico. He attended The University of Texas at El Paso obtained his Bachelor's Degree in Civil Engineering in December 2016 and immediately started pursuing his Master's Degree. In 2014, he started working as a volunteer in the Center for Transportation Infrastructure Systems (CTIS), and by 2015 he became involved in projects for the Texas Department of Transportation (TxDOT) and the National Cooperative Highway Research Program (NCHRP) focused in analyzing the corrosion potential of MSE Wall backfill materials. During his time working on these projects, he participated in the Transportation Research Board Minority Fellowship Program for the year of 2017. On the following year, he successfully published a paper in the Transportation Research Record.

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