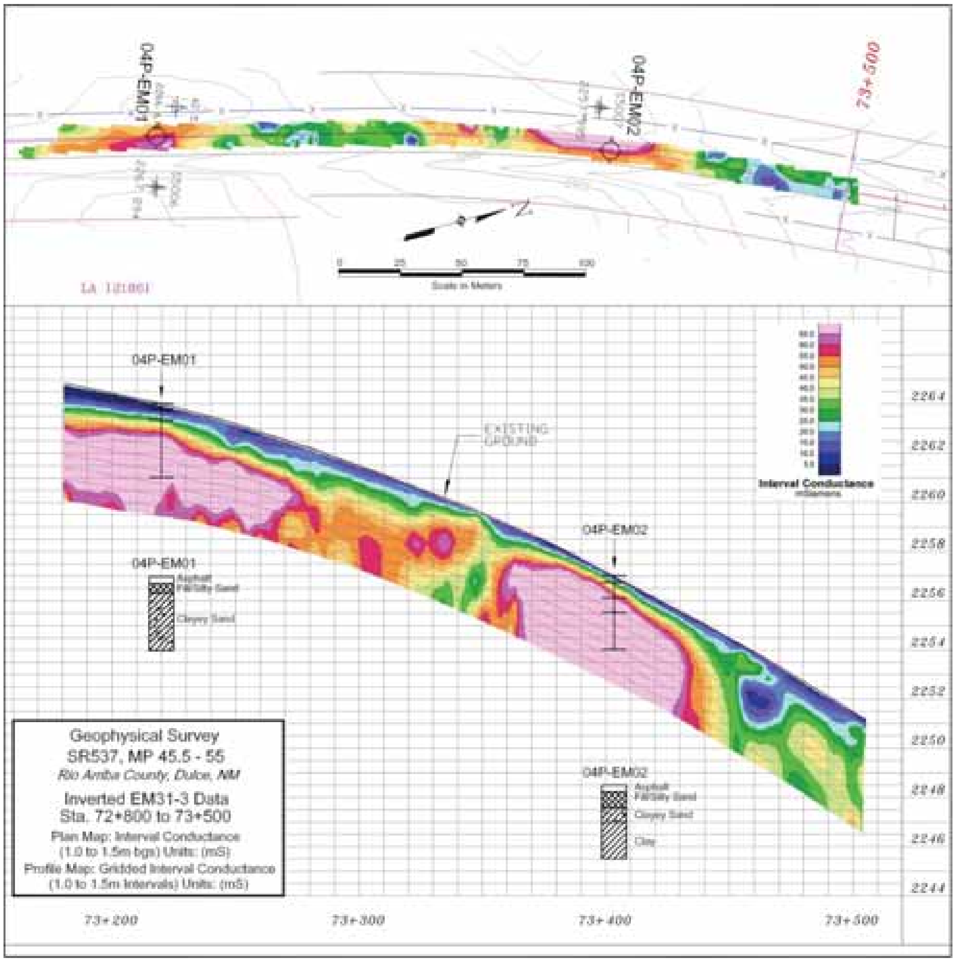
CLAY SEAM MAPPING

With Electromagnetic Induction

Publication No. FHWA-CFL/TD-05-010 **November 2005**



U.S. Department of Transportation
Federal Highway Administration

Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
12300 West Dakota Avenue
Lakewood, CO 80228

FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practice, and related information and knowledge sharing to Federal agencies, Tribal government, and other offices within the FHWA.

Oftentimes the FLH seeks outside services for studies where final reports or other documents are required. At many sites where road projects are planned by the FLH, unknown or undetected swelling-clay zones may be present. This report provides an engaged effort by the FLH and Blackhawk, a division of ZAPATA ENGINEERING, to accurately and economically locate clay rich zones that may affect highway stability.

F. David Zanetell, P.E., Director of Project Delivery
Federal Highway Administration
Central Federal Lands Highway Division

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.
FHWA-CFL/TD 05-003

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Clay Seam Mapping
With Electromagnetic Induction

5. Report Date
November 2005

6. Performing Organization Code

7. Author(s)
Jim Pfeiffer, Associate Geophysicist; Kanaan Hanna, Senior Engineer

8. Performing Organization Report No.
5008

9. Performing Organization Name and Address
Blackhawk, a division of ZAPATA ENGINEERING
301 Commercial Road, Suite B
Golden, CO 80401

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFH68-03-00180

12. Sponsoring Agency Name and Address
Federal Highway Administration
Central Federal Lands Highway Division
12300 W. Dakota Avenue, Suite 210
Lakewood, CO 80228

13. Type of Report and Period Covered
Technical Report, 2005

14. Sponsoring Agency Code
HFTS-16.4

15. Supplementary Notes
COTR: Khamis Haramy, FHWA-CFLHD. Advisory Panel Members: Roger Surdahl and Linden Snyder, FHWA-CFLHD, and Khalid Mohamed, FHWA-EFLHD. This project was funded under the FHWA Federal Lands Highway Technology Deployment Initiatives and Partnership Program (TDIPP).

16. Abstract
The presence of swelling clay beneath roadway poses a significant problem to road rehabilitation design and construction. Roads constructed over areas of clay are generally subjected to potential differential settlement due to volume changes caused by swell/shrink and low shear strength of the clay resulting from high moisture content. If roadways with clay seams are not properly designed, a premature subgrade failure may occur and will also pose difficulties during construction resulting in higher construction costs.

This report summarizes multi-phase geophysical demonstrations using various electromagnetic induction (EMI) methods on SR537 near Dulce, New Mexico. The road has had extensive surface rehabilitation due to the presence of swelling clay-rich zones in the road base. Using electromagnetic geophysical methods with rapid acquisition procedures provided a means of detecting the location of potential swelling clay-rich zones. This information was used to guide the soil boring program, thus greatly reducing the risk of missing a clay-rich zone during the site characterization planning stage and thus preventing or minimizing cost-overruns during the reconstruction phase. The results from the three-phase investigation prompted a production survey along Natchez Trace Parkway, Mississippi. The combined results from Dulce and Natchez have shown that the EMI method can provide qualitative correlations for evaluating the roadbase materials. A comparison between individual Atterberg Limits of soils obtained from the soil lab analysis and the EMI data suggests that no direct correlation can be established. However, the correlation between the bulk conductivity and the Casagrande Plasticity Classification may be used as a quick evaluation tool for predicting Casagrande soil type along the entire length of the roadway surveyed.

17. Key Words
CLAY, CLAY SEAMS, ELECTROMAGNETIC EMI, GEOPHYSICAL METHODS.

18. Distribution Statement
No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	106	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ACRONYMS

ATV	All-Terrain Vehicle
bgs	below ground surface
BIA	Bureau of Indian Affairs
CPC	Casagrande Plasticity Classification
DGPS	Differential Global Positioning System
EMI	Electromagnetic Induction
GPS	Global Positioning System
Hz	Hertz
LI	Liquidity Index
LL	Liquid Limit
MC	Moisture Content
MP	Mile Post
mS	milliSiemens
P&P	Plan and Profile
PI	Plasticity Index
PL	Plastic Limit
RTK	Real-Time Kinematic
Rx	Receiver
TSCI	Trimble Survey Controller
Tx	Transmitter
WGS	World Geodetic System
USCS	Unified Soil Classification System

EXECUTIVE SUMMARY

The presence of swelling clay beneath roadway poses problems to roadway rehabilitations design and construction. Roads constructed over clay areas are subject to potential deferential settlement and deformation due to: a) volume changes caused by swell or shrink; b) low shear strength; c) high moisture content; and d) clay structure including dipping or horizontal bedding. Soil borings are typically taken at 0.4 or 0.8 km (0.25 or 0.5 mi) interval for geotechnical verification. Although direct soil sampling provides the best information in terms of soil type and Atterberg Limits of Soils, it is limited: a) set boring intervals may miss critical clay-rich zones; b) geologic interpolation between borings may not be representative; and c) great potential to miss large expanses of clay.

Thus, there is a need to utilize geophysical technology such as the frequency domain electromagnetic induction (EMI) method to map clays beneath roadways, fill the gaps between the soil sampling locations, and assist in focusing the soil sampling program in areas with the greatest risk for clay problems.

Blackhawk, a division of ZAPATAENGINEERING, in coordination with the Federal Highway Administration (FHWA), Central Federal Lands Highway Division (CFLHD), conducted multi-phase surface geophysical investigations using various EMI instruments on SR537, Rio Arriba County, near Dulce, New Mexico. These investigations lead to a full scale EMI production survey, utilizing the new Geonics EM31-3 at Natchez Trace Parkway, Mississippi to rapidly and accurately locate clay-rich zones beneath long stretches of roadways.

The main purpose of this multi-phase program was to demonstrate the effectiveness of the EMI method as a state-of-practice geophysical imaging tool for mapping the presence of clay seams beneath roadways. More specifically, the overall objectives of this program were:

- To locate and map the spatial distribution of clay beneath the roadway.
- To determine the depth and thickness of the clay.
- To integrate the geo-electric sections into Plan and Profile (P&P) format.
- To evaluate the empirical relationships between measured geophysical parameters (e.g. bulk conductivity) and Atterberg Limits of Soils (e.g., plasticity index).
- To demonstrate the engineering benefits of the EMI method as a production tool to rapidly and accurately locate clay seams beneath roadways.

This report covers the results from the multi-phase geophysical investigations program at the Dulce site with emphasis on the Phase III study. A summary of the results obtained from the Natchez Trace Parkway survey is also discussed. Based on the results obtained from the multi-phase investigations and the Natchez case study, the following represents the conclusions and recommendations of the EMI method in mapping clay seams for roadway applications.

- Phase I investigation concluded that frequency-domain EMI profiling would be the only cost-effective, rapid method capable of mapping, in sufficient detail, the lateral extent of conductive soils in the roadbase over the 16 km (10 mi) of surveyed area. Modifications to the field techniques clearly indicated what additional data would be required to resolve clay materials beneath the roadway, in the engineering P & P drawings. Thus, a follow-up Phase II was conducted.

- Phase II investigation, using the EMI techniques measuring the bulk electrical conductivity of the subsurface, demonstrated that a useful geo-electric section could be developed and integrated into the P & P format. The P & P information provided an effective means of prioritizing areas of concern with clay-rich soils.
- Phase III investigation provided the opportunity to demonstrate the effectiveness of the new Geonics EM31-3 frequency domain EMI instrument as a viable state-of-practice geophysical tool for preliminary site assessment. The EMI P & P data, in terms of measured soil conductivity were evaluated to identify 20 boring locations using a prioritization scheme that classified areas along the 16 km (10 mi) roadway as low, moderate, or high potential clay content.
- Natchez case study demonstrated the efficiency of the EMI method as a production tool for mapping the spatial variation of soil conductivity within the road base. The EMI survey was conducted along 55 km (34 mi) of roadway and completed in four field days. Preliminary maps were produced within one to two days following data collection. The EMI P & P data were used to identify 41 boring locations with soil sample analysis.
- Soil conductivity information derived through EMI methods can provide valuable qualitative information for the evaluation of road base materials during the design phase.
- Soil conductivity information can be used to guide the soil-boring program by targeting the most likely locations with potential swelling clay problems.
- The correlation between bulk conductivity and Casagrande Plasticity Classification may be used as a quick evaluation tool for predicting Casagrande soil type along the entire length of roadway surveyed.
- It is critical for the geotechnical engineers to understand the in-situ behavior of soil. Current practice of soil classification is based on laboratory testing. These tests use disturbed soil samples may not represent real ground conditions. Implementation of geophysical techniques such as the EMI would provide better understanding of the overall soil behavior. This geophysical investigation has demonstrated the effectiveness of the EMI method, as a promising tool to support geotechnical engineering investigations.

Overall, the EMI method is a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways with non-metal reinforced pavement types. A strong correlation between soil conductivity and the Atterberg Limits of Soils were not established, however, a qualitative evaluation of areas with increased potential for high plasticity clay content can be estimated from the EMI data. The EMI method can be used to focus the drilling programs during project site investigations, road rehabilitation, and construction. The EMI method may provide significant cost savings by reducing construction cost overruns.

REPORT ORGANIZATION

The Executive Summary provides a summary of the geophysical study, results, and recommendations.

Chapter One provides a brief background on engineering problems related to the presence of clay and an overview of the three-phase geophysical program investigations.

Chapter Two details the geological background and the site setting of the survey area.

Chapter Three describes the geophysical methods and instruments used during the investigations.

Chapter Four describes data acquisition procedures.

Chapter Five details the data processing process and the EMI modeling.

Chapter Six summarizes the results of the geophysical surveys, the correlation of geophysical and geotechnical data, and the advantages of the EMI method.

Chapter Seven is a case study detailing the EMI Clay Seam Mapping on the Natchez Trace Parkway in Mississippi.

Chapter Eight states the conclusions and recommendations derived from this report.

The certification and disclaimer, the acknowledgement, and references are listed at the end of the text.

Appendix A presents Plan and Profile Electromagnetic Maps from Dulce, New Mexico.

Appendix B presents comparison plots of EMI data versus soil sample (0.9 - 1.5 m (3 – 5 ft)) analysis results, Dulce, New Mexico.

Appendix C presents comparison plots of EMI data versus soil sample (1.5 – 3.0 m (5 – 10 ft)) analysis results, Dulce, New Mexico.

Appendix D presents comparison plots of EMI data versus soil sample analysis results, Natchez, Mississippi.

CHAPTER 1 – INTRODUCTION

1.1 PROBLEM DESCRIPTION

The presence of swelling clay beneath roadways poses a significant problem to road rehabilitation design and construction. Clays may occur in various geological settings including dipping seams and within flat alluvium seams. Roads constructed over areas of clay are generally subjected to potential differential settlement due to volume changes caused by swell/shrink and low shear strength of the clay resulting from high moisture content. Current practice methods for locating clay seams and sampling typically involve the use of intrusive soil boring through the road pavement, and in some instances involve test pits. Although direct soil sampling provides the best information in terms of soil type and Atterberg Limits of Soils, it is limited. This limitation is that the analysis of the soil sample is only valid for that particular boring location. Due to the great distance between boring locations (typically at 0.8 or 0.4 km (0.5 or 0.25 mi intervals)), interpolation of the geology between borings may not be representative of actual subsurface conditions. More importantly, the potential is great for missing expanses of clay that may be present between borehole locations.

Thus, there is a need to map clays beneath roadways in order that accommodation may be made during the planning stage. The frequency domain EMI geophysical method may have economic potential to rapidly and accurately locate clay seams in various geologic settings. If the deployment of this method proves successful, then it can be used to fill the gaps between the soil sampling locations, and assist in focusing the soil sampling program in areas with the greatest risk for clay problems.

1.2 OBJECTIVES

The main purpose of this multi-phase program was to demonstrate the effectiveness of the EMI method as a state-of-practice geophysical imaging tool for mapping the presence of clay seams beneath roadways. Specifically, the purpose of Phase III was to acquire geophysical and geotechnical data along a 13-km (8-mi) stretch of SR537, Rio Arriba County near Dulce, New Mexico. The results obtained form the multi-phase demonstrations lead to a full scale deployment of the EMI method for mapping clay-rich zones along 55 km (34 mi) stretches of roadway at Natchez Trace Parkway, Mississippi. The overall objectives of this program were to:

- Evaluate the performance of various EMI instruments in locating and defining the presence of high plasticity clay seams by measuring the bulk electrical conductivity of the subsurface.
- Demonstrate the effectiveness of the EMI instruments in providing: a) continuous data collection; and b) complete coverage of the surveyed road area.
- Applying the geophysical data to traditional FHWA geotechnical exploration practices to facilitate the reduction of drilling and sampling locations.
- Evaluate empirical relationships between measured geophysical parameters (e.g., bulk conductivity) and Atterberg Limits of Soils (e.g., plasticity index).

- Demonstrate the usefulness of EMI method as an exploration tool to provide continuous plan and profile (P & P) images over the entire length of surveyed roadway.
- Demonstrate the engineering benefits of the EMI method as a production tool to rapidly and accurately identify and locate clay seams beneath long stretches of roadway.

1.3 GEOPHYSICAL PROGRAM OVERVIEW

Blackhawk, a division of Zapata Engineering, in coordination with the FHWA-CFLHD conducted multi-phase surface geophysical investigations using various EMI instruments on SR537, Rio Arriba County, near Dulce, New Mexico. Phases I and II of the subsurface imaging program, using EMI techniques measuring the bulk electrical conductivity of the subsurface, were completed under separate contracts in 2001 and 2002, respectively. Reconnaissance-level surveys along a 16-km (10-mi) stretch of SR537 comprised the Phase I investigation (figure 1). Phase I was performed between milepost (MP) 45 and 55. A more detailed set of geophysical data was acquired under Phase II from MP 47 to 50. Additionally, under Phase II, geotechnical data were obtained from CFLHD and correlated with the geophysical results. Phase III presents the deployment of the new Geonics EM31-3 instruments, field and analysis methods, and geotechnical correlation and presentation of the geophysical data in the P & P format.

The following sections provide a summary of the geophysical surveys, and the most significant results and conclusions obtained from Phases I and II using various EMI instruments and techniques. This report details Phase III and provides a summary of the full-scale production survey conducted over Natchez Trace Parkway in Mississippi.

1.3.1 Summary of Phase I

Phase I surveys were conducted between September 26 and 30, 2001. The Phase I geophysical survey covered a length of road of about 16 km (10 mi). Survey measurements were obtained on both north- and south-bound lanes from approximately mile marker MP 45.5 north to the intersection with U.S. 64, just north of MP 55 (figure 1).

Phase I survey results were presented in a Blackhawk GeoSciences report, dated November 2, 2001. Summarizing the Phase I investigation, the survey provided the following general results and conclusions:

- A rapid electrical resistivity profiling method using the Geometrics Ohm-mapper was not successful for mapping clay in the roadbase because of the generally conductive soils at this site and the type of capacitive electrode coupling this system employs.
- Field techniques were developed with existing EMI survey instruments to acquire data tied to GPS surveying using a towed array system. EMI terrain conductivity meters showed good resolution of the lateral variations in soil conductivity, which was relatively correlated to the presence of clay in the road base. Field activities must be coordinated with local construction activities to avoid dangerous traffic conditions and maintain crew safety.

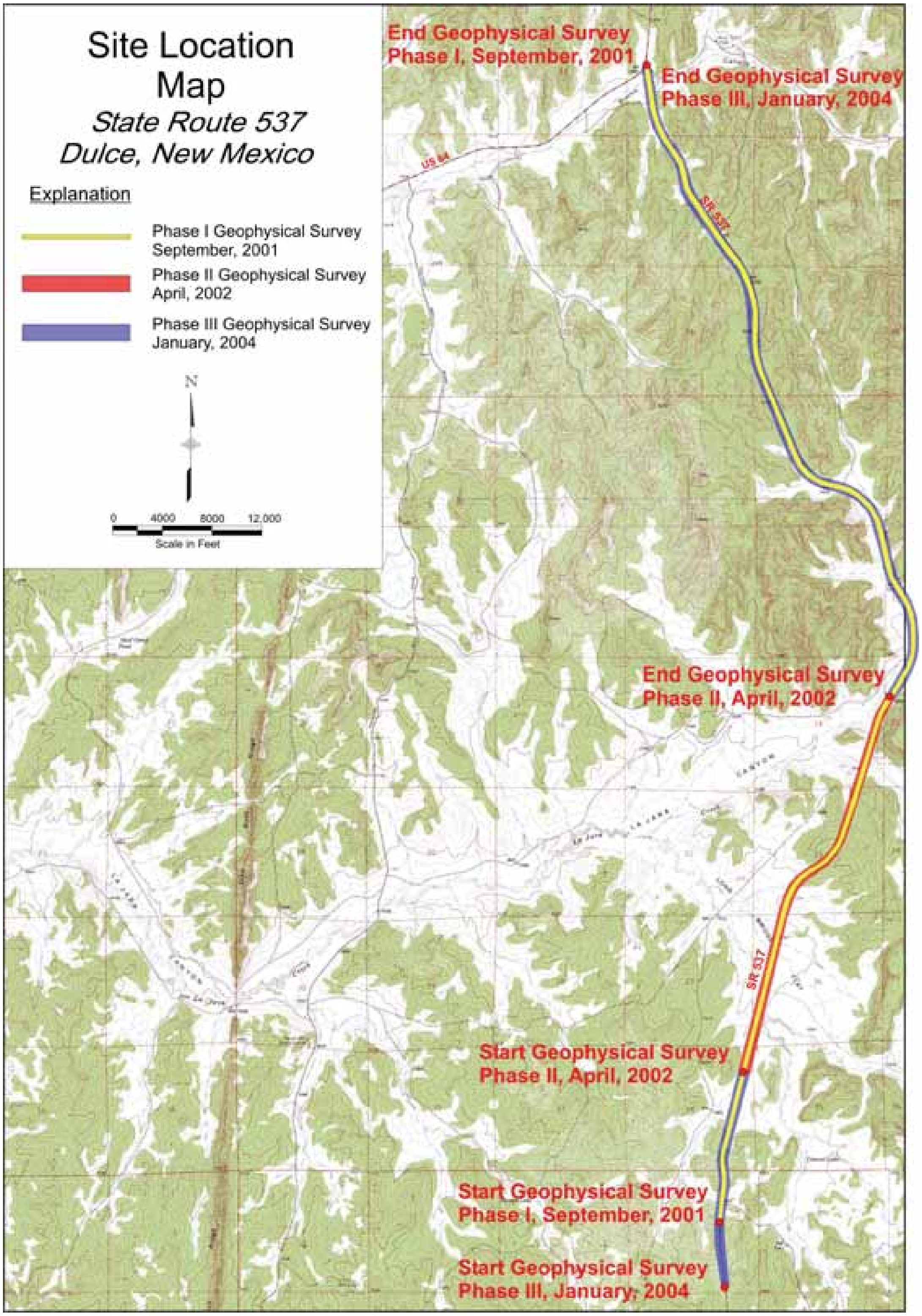


Figure 1. Map. Site Location Map.

- Close cooperation between the geotechnical engineers and our geophysicists is required to determine if any correlation exists between geophysical data and soil properties needed for highway design.
- Limited success was achieved to resolve the vertical section (profile) below the roadbase because of insufficient sampling directly caused by logistical problems and time constraints.

It was concluded from the Phase I investigation that frequency-domain EMI profiling would be the only cost-effective, rapid method capable of mapping, in sufficient detail, the lateral extent of conductive soils in the road base over the 16 km (10 mi) of survey area. Additionally, the conductive soils as defined by the EMI data were generally correlated spatially with the limited number of samples available from a 1989 geotechnical investigation along this 16-km (10-mi) stretch of roadway. However, defining the vertical profile of the upper 2 to 3 m (6.6 to 10 ft) of roadbase proved to be too difficult without additional terrain conductivity data from additional dipole (coil) orientations and coil heights and spacings above the road. The findings from Phase I clearly indicated what additional data would be required to resolve clay materials beneath the road, in plan as well as in profile; thus, a follow-up Phase II investigation was proposed.

1.3.2 Summary of Phase II

Phase II surveys were conducted between April 21 and April 23, 2002. The survey was purposely confined to a short section of SR537 between MP 47 and 50 (figure 1). This 5-km (3 mi) stretch was currently under design by FHWA-CFLHD; therefore the geophysical data were acquired to potentially assist with design. Also, if the objectives of the study could be met, it would provide support to the existing set of geotechnical data.

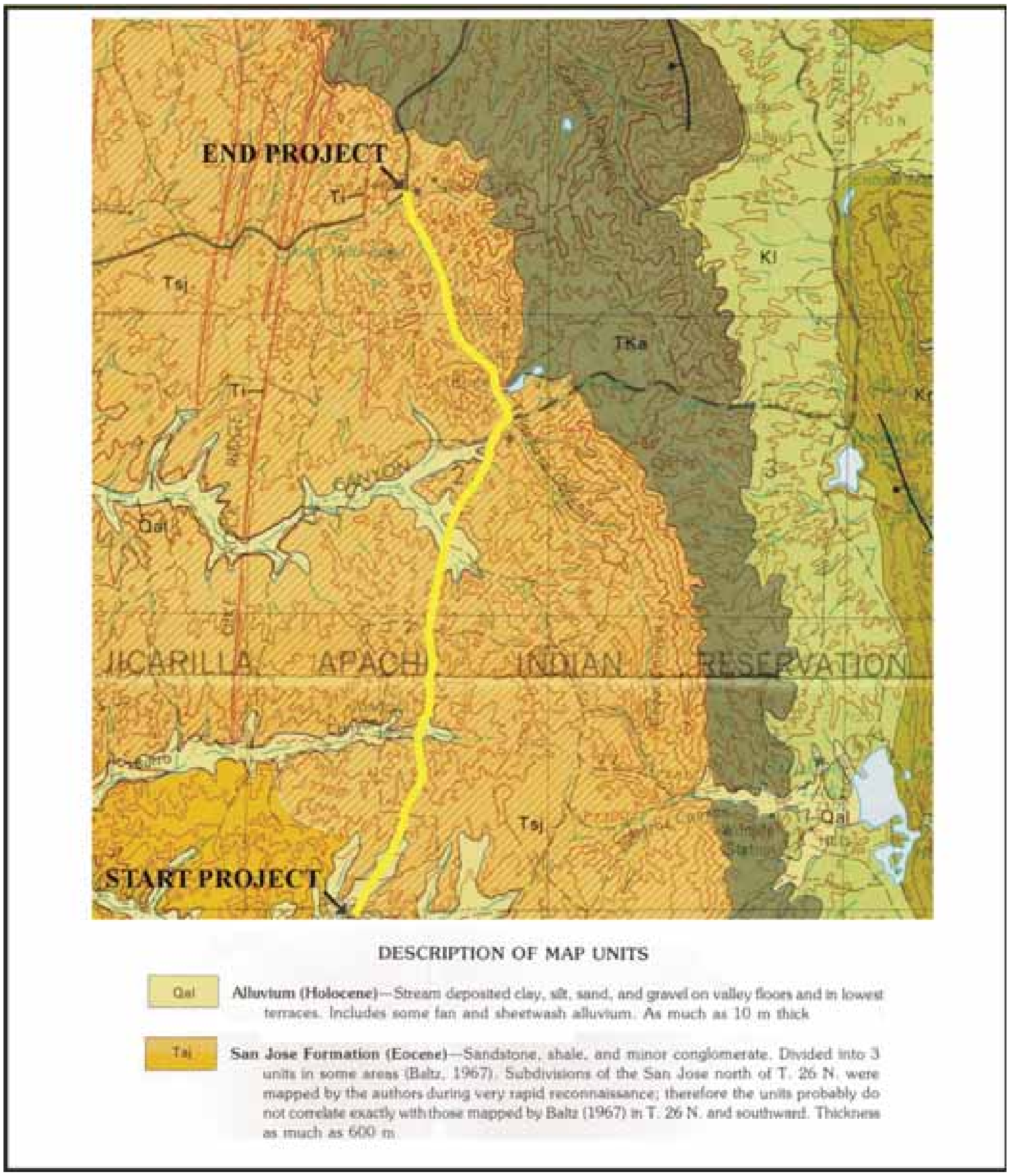
A well-defined set of objectives was established for Phase II.

- Acquire sufficient EMI geophysical data to provide more resolution in plan and section.
- Recommend geotechnical lab testing on specific samples, and potentially recommend areas where additional sampling should be conducted.
- Procure any and all surficial soil and geologic data (e.g., soil conservation service and USGS, respectively) that can be superimposed on the area of investigation.
- Establish empirical correlations between the EMI induction data and the Atterberg Limits of soils laboratory results – if practical.
- Create a manner to prioritize areas of interpreted clay-rich soils of concern for design and/or construction based on correlation of all the data.
- Produce the geophysical/geological results in P & P format.

Phase II demonstrated that a useful geo-electric section could be acquired and integrated into the P & P engineering drawings. Additionally, Phase II demonstrated evidence of a correlation between EMI measured conductivity and Atterberg Limits of soils laboratory results, such as PI. This correlation should provide an effective means of prioritizing areas of concern for clay-rich soils.

CHAPTER 2 – GEOLOGICAL SETTINGS AND SITE CONDITIONS

The geology under the roadbed in the surveyed area consists of two formations: the Eocene-age San Jose Formation and a Holocene-age Alluvium. The San Jose Formation consists of a sequence of interbedded sandstones, shales, and minor conglomerates. The Alluvium is predominantly composed of stream deposits ranging from clays, silts, sands, and gravels, generally positioned on valley floors and on the lowest terraces. The Alluvium includes some fan and colluvium (sheet wash) sediments. Figure 2 contains a windowed United States Geological Survey (USGS) geologic map of the area (1).



DESCRIPTION OF MAP UNITS

Qal	**Alluvium (Holocene)**—Stream deposited clay, silt, sand, and gravel on valley floors and in lowest terraces. Includes some fan and sheetwash alluvium. As much as 10 m thick
Tsj	**San Jose Formation (Eocene)**—Sandstone, shale, and minor conglomerate. Divided into 3 units in some areas (Baltz, 1967). Subdivisions of the San Jose north of T. 26 N. were mapped by the authors during very rapid reconnaissance; therefore the units probably do not correlate exactly with those mapped by Baltz (1967) in T. 26 N. and southward. Thickness as much as 600 m

Figure 2. Map. Geological map of the Dulce survey area.

Four major soil formations, according to a draft report from the Bureau of Indian Affairs (BIA), are present in the survey area. These include the Orlie-Cement Lake Complex, the Vosburg-Millpaw Complex, the Losindios-Escrito-Parkelei Complex, and the Rock Outcrop-Vessilla-Menefee Complex (2). The BIA is interested in our geophysical results in order to evaluate the potential for integration of geophysical measurements with their soil mapping activities in this area.

The site conditions can be generalized as open, relatively flat with some rolling hills for the majority of the survey area (e.g., between MP 45.5 and MP 53). Figure 3 is a representative picture of the open brush country in this area. Further north, steeper grades and heavily wooded areas were encountered (i.e., MP 53 to the intersection with U.S. 64). Figure 4 provides a picture that is representative of this terrain. Survey conditions during Phase III field effort were typically cold with snow and ice. Generally, the weather did not detract from the acquisition of quality conductivity data measured using the EMI methods.

Global positing system (GPS) survey control point was tied into a local USGS control point (WELLS, PID GN0531) located near the Wells lookout tower during the September 2001 Phase I survey. The local control point used for the GPS base location was FHWA control point PT3500 located near MP 49. The GPS system used for these surveys is described in Chapter 3.0.

Figure 3. Photo. Data collection in representative open area traveling north on SR537.

Figure 4. Photo. Representative wooded area traveling north on SR537.

CHAPTER 3 – GEOPHYSICAL METHODOLOGY AND INSTRUMENTATION

The Geonics EM31-3 is a frequency domain EMI instrument. This instrument is comprised of one transmitter (Tx) coil and three receiver (Rx) coils all operating at a frequency of 9.8 kHz. The three Rx-Tx coil spacings are 1 m, 2 m, and 3.66 m (3.3 ft, 6.6 ft, and 12 ft), as shown in figure 5. The maximum effective depth of investigation of this instrument is approximately 5 m (16.4 ft).

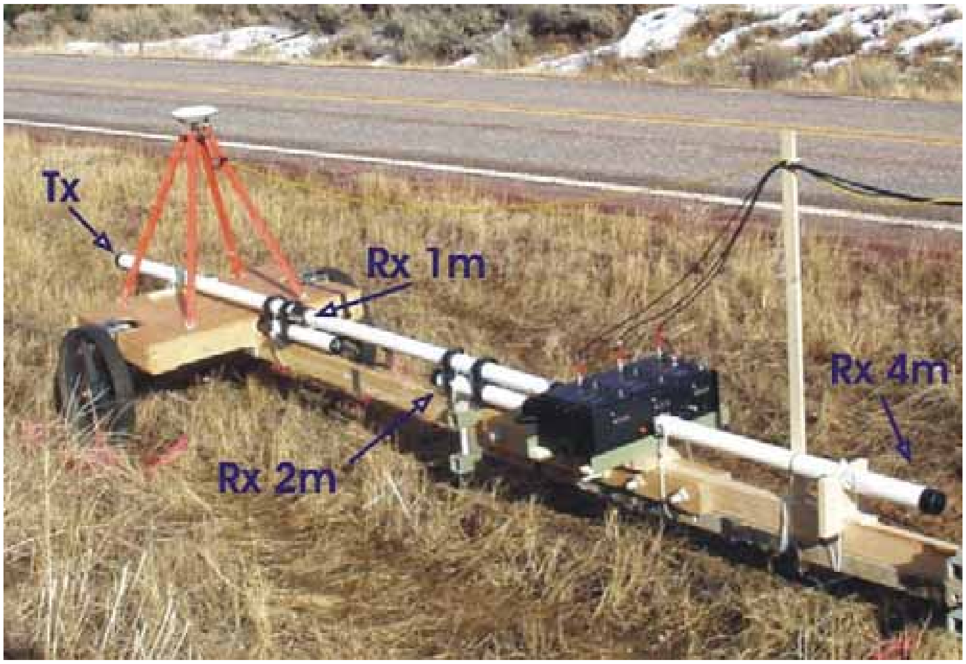


Figure 5. Photo. EM31-3 mounted on low metal content trailer.

Current is induced into the ground by the transmitter coil, while the receiver coils measure the secondary fields due to the decay of the induced (ground) current. The secondary electromagnetic field is not in phase with the primary electromagnetic field and therefore can be resolved into both a quadrature (out of phase) and an in-phase component. The amplitude of the quadrature component of the secondary electromagnetic field is proportional to the bulk conductivity (or apparent conductivity) of the ground down to the instrument depth of investigation. For this project the quadrature component is the only measurement used from the EM31-3 instrument. However, the in-phase data were recorded and used for identifying metallic structures under the roadway and to assist in determining the data lag correction parameters, which are related to the differential global positioning system (DGPS) positioning, used in data processing.

Positioning of the EMI data with the ATV-towed array was accomplished using a Trimble Real Time Kinematic (RTK) DGPS. The positional data were recorded in World Geodetic System 1984 (WGS 84) Longitude and Latitude and converted to FHWA local grid coordinates. The EMI and DGPS data were recorded simultaneously in the field.

CHAPTER 4 – DATA ACQUISITION

The fieldwork for Phase III was performed from January 17th through January 20th, 2004.

The GPS control point used for this survey was FHWA point PT3500 located west of SR537 near MP 49. The coordinates for this FHWA control point, established by field personnel during the Phase I survey, which is based on the WGS84 spheroid (no geoid model), are listed in table 1.

Table 1. Base Station Coordinates.

<table>
<tr><th rowspan="2">WGS84 Coordinates</th><th>Latitude</th><th>Longitude</th><th>Elevation</th></tr>
<tr><td>36° 42’ 50.22013” N</td><td>107° 00’ 32.01764” W</td><td>2235.99 m</td></tr>
<tr><th rowspan="2">FHWA PT3500*</th><th>Northing</th><th>Easting</th><th>Elevation</th></tr>
<tr><td>69956.42 m</td><td>37260.19 m</td><td>2236.00 m</td></tr>
<tr><td colspan="4">* - FHWA coordinates are measured in meters and based on a local grid system.</td></tr>
</table>

A GPS repeater station was also used. The repeater was located at the top of the road cut west of SR537 approximately halfway between MP 53 and MP 54. The repeater provided greatly improved GPS radio link coverage without changing control points.

4.1 DATA ACQUISITION METHODS

To facilitate a direct comparison of the Phase III data with the Phase I and Phase II data, the same basic data acquisition parameters, instrument calibration location, and initial data reduction procedures were used for the Phase III investigation.

To rapidly acquire data along profile lines, in one lane of SR537 at a time, the EM31-3 was mounted on a trailer constructed primarily from non-conductive materials (see figure 5). Due to the configuration change between the EM31-3 and the standard EM31, it was necessary to make some modifications to the original trailer used in the Phase I and Phase II surveys. The EM31-3 was securely mounted to the trailer and a GPS receiver was positioned directly above the center point between the Tx coil and the 1 m (3.28 ft) Rx coil. As previously described, different dipole orientations and instrument heights impact the effective depth of investigation, thus a variety of dipole orientations and instrument heights were used for each pass in each lane. Table 2 identifies the field setup for each pass made during Phase III data acquisition.

The instrument manufacturer recommended that the minimum distance between the All Terrain Vehicle (ATV) and the nearest coil should be greater than 2.3 m (7.6 ft) in order to minimize any potential interference from the ATV. A Trimble 5700 GPS rover system was mounted on the ATV with only the GPS receiver antenna, attached by the antenna cable, mounted on the instrument trailer.

Table 2. EM31-3 Instrument Height and Orientation

Instrument	Coil Separation	Coil Height*	Dipole Orientation
EM31-3	1m	49 cm	Vertical
	2m	47 cm	Vertical
	4m	47 cm	Vertical
EM31-3	1m	67 cm	Horizontal
	2m	67 cm	Horizontal
	4m	65 cm	Horizontal

* Nominal coil height above existing road surface.

The GPS data were both logged in RTK on the Trimble Survey Controller (TSC1) data logger and with post-processing data logging enabled on each GPS receiver. RTK data were collected continuously at 1 Hz (1 per second) on the TSC1 data logger mounted on the ATV. Data for post-processing were collected at 2 Hz in order to acquire a full day's data on the Trimble 4700 receivers without downloading data during the day. The post-processed data would only be used to improve GPS positioning during periods of low GPS satellite coverage or poor radio link with the GPS base station.

EM31-3 data were logged in automatic (time) mode at a sample rate of 5 Hz. Nominal data acquisition speed using the ATV was about 16 km/h (10 mph), yielding a data station interval of about 1 m (3.28 ft) along the EMI lines, and a GPS survey data station interval of about 4.5 m (14.8 ft) along the profile lines. Data were collected along two profile lines, one profile along the center of each lane.

Daily field instrument calibration checks were performed for the EM31-3 instrument. Instrument calibration was performed following the manufacturer's specifications. The calibration site is located at a pull-off along the west side of SR537 across the road from MP 49. In addition to instrument calibration checks, the quadrature and in-phase components were recorded at this location at the start and end of data collection for each instrument orientation to check and compensate for daily instrument drift, if any. The in-phase component is primarily a "metal detection component" for the EM31-3 instrument. The in-phase data were recorded along the roadway for this investigation, but were only used to assist in identifying metallic structures (e.g., metal culverts) beneath the roadway. Quadrature component data recorded near metallic features can be biased by the influence of the metal on the bulk conductivity readings.

4.2 SITE SPECIFIC CONSIDERATIONS AND LIMITATIONS

During the Phase I survey in September, 2001 several significant limitations were prevalent at the site. These included vehicular traffic concerns, surveying control and coordinate issues, and GPS coverage limitations. The main concern at the site during Phase I surveying was safety issues arising from heavy haul truck traffic, nearly continuous Monday through Friday and from dawn to dusk. During the Phase II and Phase III geophysical surveys, the gravel haul trucks were not operating and only limited heavy truck traffic was present during the survey, which did not significantly affect the safety of the crew or the data quality.

Since field personnel established GPS surveying control during the Phase I survey, no further GPS survey control points were needed for the Phase II or Phase III surveys. DGPS post-processing was not used for Phase II or Phase III.

CHAPTER 5 – DATA PROCESSING

The processing flow for the EM31-3 data involved fourteen steps, as follows:

1. Download EMI and GPS data from the handheld data logger to the laptop computer.
2. Import data into the Multi31 software package developed by GeoMar Software Inc.
3. Split the data for each coil separation, apply GPS positioning and export data in ASCII format.
4. Analyze latency test files to determine proper latency correction.
5. Apply latency correction to all data sets.
6. Check daily background test data to determine if instrument drift has occurred. (Shift baseline values if necessary.)
7. Reformat data for upload into the Emigma ™ software package developed by Petros Eikon Inc.
8. Once the best starting model has been determined, the EM31-3 data were inverted for each profile section; that is, each lane. The geo-electric section is then comprised of a series of 1-D depth soundings spaced about 1 m apart along the length of the road surveyed.
9. The output from the Emigma inversion program yields modeled layer thickness and resistivity (inverse of conductivity) values for each closely spaced 1-D sounding.
10. To improve the profile interpretation, interval conductance values (conductivity multiplied by thickness) were calculated for each 0.5 m depth interval.
11. Interval conductance values were imported into Geosoft Oasis and gridded to produce color cross-section (profile) plots.
12. The interval conductance from 1.0 to 1.5 m was stripped out of the profile and plotted on the plan with FHWA-CFLHD stationing, topography and cultural features.
13. The conductivity and interval conductance values were used to determine if any correlation exists between soil conductivity and other physical soil properties (e.g., plasticity index, liquid limit, plastic limit, etc.).
14. All output data were imported into AutoCAD for scaling and fitting to the FHWA P & P design drawings.

5.1 EMI MODELING

The EMI data were modeled using Emigma™ software, commercially available from Petros Eikon, Inc. Emigma is a profile data interpretation program for interpreting electromagnetic conductivity sounding data acquired using Geonics EM31, EM34, EM38 or similar instruments, in terms of layered earth (1-D) models.

Figure 6 shows a hypothetical example of the derivation of interval conductance from the raw (field) apparent conductivity data. Two cases are shown in the figure, a *conductive* and a *resistive* case. The first window box labeled "Raw Data, Multiple Configurations" represents the individual apparent (or terrain) conductivity values versus effective investigation depth for each instrument orientation. The effective investigation depth is a function of coil spacing, dipole orientation, frequency and instrument height above the ground surface. The apparent, or terrain, conductivity measured by each instrument is the average or “bulk” conductivity of all the material from the surface to the effective depth of investigation. The next window box labeled “Model from Inverted Data” shows the1-D model results from inversion of the raw apparent conductivity data. The next window box labeled “Total Conductance” shows the cumulative increase in total conductance with depth. The last window box labeled “Interval Conductance” shows the calculated conductance over 0.5 m (1.6 ft) intervals as determined from the layered model. In this last window box we attempted to match the color scheme with the color contouring used for all the final plots. The station-to-station variability in the inverted layered models (plotted in conductivity) can be relatively large due to the limited number of data points and the degrees of freedom in the 1-D modeler. The station-to-station variability in the total conductance is much less because the layer thickness is introduced. The calculation of interval conductance (layers shown in color) allows the gridding of vertical profiles and provides a means to smooth out the station-to-station variations inherent in the inverted data. In doing so, the dynamic range is slightly reduced in proportion to the thickness of the depth interval selected.

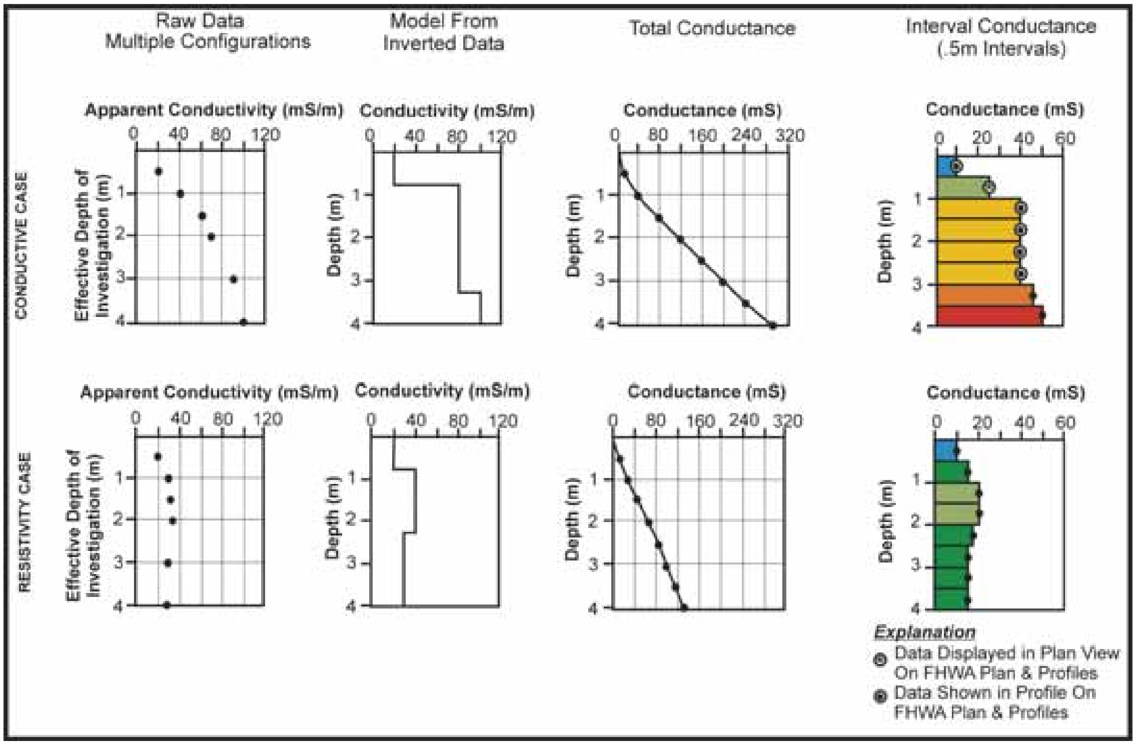


Figure 6. Charts. Hypothetical Example of Derivation of Interval Conductance.

EMI conductivity sounding curves were acquired along profiles using three different coil separations and two dipole orientations collected from two passes with the instrument down each profile lane (see table 2). The software can only invert data that is acquired at discrete station locations. Due to the necessity of acquiring large volumes of data over large areas rapidly, it is not possible to repeatedly occupy and record EMI measurements at discrete station locations; that is, at the exact same location for every instrument configuration for every pass in the lane.

To obtain data at discrete locations for entry into the inversion program, the following data preparation steps were followed using the Emigma™ software:

1. Merge common data sets into a single profile.
2. Divide the profile into approximately straight-line segments.
3. Sort on data locations.
4. Filter spatial positions to smooth profile locations.
5. Interpolate data to obtain common data positions.
6. Decimate data back to approximately 1 m spacing.

The data were then inverted using the Emigma™ inversion routine. The starting model used 8 layers. The layer thickness for layers 1 through 7 was fixed at 0.5 m (1.6 ft). Layer 8 was a half-space. The starting resistivity for layer 1 was 50 Ohm-m to approximate the pavement and the sub grade immediately below the pavement. The resistivity value assigned to layers 2 through 7 for the starting model was 10 Ohm-m representing clay-rich materials. Layer 8 was assigned a starting resistivity value of 20 Ohm-m representing the native materials. All of the inversion sets were subdivided to correspond to the individual P & P drawings provided by CFLHD

5.2 GROUND TRUTH

To provide ground truth information, 20 locations were selected for soil boring sampling and analysis. The boring locations were identified based on the EMI P&P data, in terms of measured soil conductivity using a prioritization scheme that classified areas along the 16 km (10 mi) roadway as low (4 borings), moderate (7 borings) or high (9 borings) potential clay content. Geotechnical drilling, sampling and lab analyses were performed in accordance with specifications used by CFLHD for similar highway investigations (i.e., geotechnical design needs). Enviro-Drill, Inc., performed the boring and sampling, and Western Technologies, Inc., performed lab analyses under ASTM standards C136, D4318, C566, and D2487. All the lab data were included in the unpublished Phase II Report. Table 3 lists the definitions of the Atterberg Limits of Soils properties samples tested during the analysis or calculated from results of the analysis. The locations of the borehole are shown on the P & P plots in appendix A and are listed in table 4.

Table 3. Definitions of Atterberg Limits of Soils Properties.

Sieve Analysis	Percentage of material finer than NO. 200.
Liquid Limit (LL)	The water content corresponding to an arbitrary limit between the liquid and plastic states of consistence of a soil (3).
Plastic Limit (PL)	The water content corresponding to an arbitrary limit between the plastic and the semisolid states of consistence of a soil (3).
Plasticity Index (PI)	The numerical difference between the liquid limit and the plastic limit, or, synonymously, between the lower plastic limit and the upper plastic limit (3).
Moisture Content (MC)	Percentage of water present by mass of a given soil sample (4).
Liquidity Index (LI)	Dependent on the water content with respect to the liquid limit and plastic limit (5).

Table 4. Dulce Borehole Locations.

Borehole ID	Approximate Meters North of Mile Marker	FHWA X	FHWA Y	Offset from Center Line (approx.)
04P-EM01	774.3 m N of MM45	35666	64697.9	1.8 m left
04P-EM02	959.1 m N of MM45	35656.5	64881.8	1.8 m right
04P-EM03	1253.6 m N of MM45	35684.9	65175.4	1.8 m right
04P-EM04	1481.9 m N of MM46	35707.6	65401.5	1.8 m left
04P-EM05	19.7 m N of MM46	35713.7	65547.5	1.8 m left
04P-EM06	361.6 m N of MM46	35715.7	65888.3	1.8 m left
04P-EM07	613.6 m N o MM46	35779	66132.4	1.8 m left
04P-EM08	858.2 m N of MM46	35841.1	66369	1.8 m left
04P-EM09	978.8 m N of MM46	35871.7	66485.6	1.8 m right
04P-EM10	1459.1 m N of MM50	35994	66950.1	1.8 m right
04P-EM11	596.6 m N of MM50	38068.5	72035.5	1.8 m right
04P-EM12	933.5 m N of MM50	38066	72372.4	1.8 m left
04P-EM13	1228.9 m N of MM50	38018.4	72661.3	1.8 m right
04P-EM14	461.9 m N of MM52	36662.6	74526.5	1.8 m left
04P-EM15	178.8 m N of MM53	36204.8	75767.6	1.8 m left
04P-EM16	713.8 m N of MM52	36192.6	76303	1.8 m left
04P-EM17	898.5 m N of MM53	36159.3	76483.9	1.8 m left
04P-EM18	1010.3 N of MM53	36127.1	76590.2	1.8 m left
04P-EM19	63.9 m N of MM54	35778.1	77159	1.8 m left
04P-EM20	1019.5 m N of MM54	35334.4	77995.2	1.8 m left

Borehole Identification Legend

04 - Year Drilling occurred
P - Pavement
EM - Electromagnetic Survey
01 - Borehole Number

CHAPTER 6 – RESULTS

6.1 ANALYSIS OF GEOPHYSICAL RESULTS

As stated earlier, the results from Phase I indicated that plan mapping for the lateral extent of clay is a readily available and interpretable result obtained directly from the bulk conductivity measurements. From the processing and interpretation of all the EMI data from Phase II, a prediction was made that the broad areas of high apparent conductivity are attributable to high clay content, particularly swelling clay content, in the subgrade at different effective depths. It should be noted however, that apparent conductivity values may be affected by increased salinity content in the interstitial water, changes in water content, or the presence of metallic debris buried in the road base material. Isolated EMI anomalies from most buried metallic objects (e.g., culverts) were readily identified as sharp negative spikes in the EMI profiles. Most of the buried culverts were surveyed and their approximate locations annotated on the appropriate figures.

6.2 CORRELATION OF GEOPHYSICAL AND ATTERBERG LIMITS OF SOILS DATA

In the Phase II survey, soil data from nine boreholes previously collected at the site were compared with the EMI data. Although the total number of comparison data points was very limited, an apparent correlation was shown to exist between the conductivity properties of the soil and the PI and the LL determined from the soil samples. To further test this correlation in Phase II, the lab soils analysis data from the 20 boreholes were compared with the EMI geophysical data. All 20 of the soil borings, which were drilled to 3 m (10 ft) below ground surface (bgs) to correlate with the 4 m (13 ft) coil spacing on the EM31-3, which has an effective depth of investigation of approximately 4 m (13 ft), were initially tested using grab samples from a depth range of 0.9 to 1.5 m (3 to 5 ft). Sixteen of the 20 soil borings were retested using grab samples at varying depths a year later. Table 5 lists the EMI properties at the borehole locations.

6.2.1 Grab Samples Collected Between 0.9 to 1.5 m (3 to 5 ft)

Initially, grab samples collected between 0.9 and 1.5 m (3 and 5 ft) bgs were analyzed in the lab. In addition to subgrade fill, three other soils were identified in the soil boring logs of the grab samples collected between 0.9 and 1.5 m (3 and 5 ft). These included the Unified Soil Classification System (USCS) classifications clayey sands, sand-clay mixtures (SC), inorganic clays of high plasticity (fat clays) (CH), and inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays (CL). The soil classified CH, if present, typically occurred at depths greater than 1.5 m (5 ft) bgs and therefore was not analyzed in the lab during the initial testing. The majority of the lab analyzed grab samples consisted of soil with USCS classification SC.

Table 6 lists the Atterberg Limits of Soils properties of the borehole grab samples (0.9 to 1.5 m (3 to 5 ft)). Comparison plots of the lab soil analysis data and the EMI geophysical data from the 0.9 to the 1.5 m grab sample range are provided in appendix B. The results from boring location 04P-EM11 have been omitted from the comparison plots since the location of the borehole appears to be in close proximity to an unmarked metallic feature noted by a small dipole on a few of the EMI data plots.

Table 5. Bulk Conductivity and Interval Conductance Values at Dulce Borehole

Borehole ID	Anticipated Clay Content	Bulk Conductivity (mS/m)			Conductance (mS)	Conductance (mS)
		1 m coil Separation	2 m coil Separation	3.66 m coil Separation	.5 to 1 m depth modeled interval conductance	1 to 1.5 m depth modeled interval conductance
04P-EM01	High	71.61	73.42	82.58	33.82	58.63
04P-EM02	High	76.61	83.12	91.83	36.92	67.14
04P-EM03	High	65.19	59.05	67.88	21.29	37.38
04P-EM04	High	67.32	65.43	76.65	22.56	41.91
04P-EM05	High	72.31	73.29	79.92	38.52	66.98
04P-EM06	Low	50.69	30.01	33.17	20.21	11.01
04P-EM07	Moderate	56.56	44.91	55.84	4.15	11.27
04P-EM08	High	66.42	67.25	85.06	13.68	35.27
04P-EM09	High	76.63	88.83	108.26	18.72	49.86
04P-EM10	Moderate	54.73	39.27	45.63	15.88	26.29
04P-EM11	High	137.62	198.2	204.64	98.77	173.9
04P-EM12	Moderate	52.14	36.58	44.06	12.4	19.37
04P-EM13	Moderate	53.73	36.69	41.79	15.12	19.52
04P-EM14	Low	49.51	22.63	21.46	14.15	11.98
04P-EM15	Low	47.88	20.93	21.85	10.47	8.17
04P-EM16	Moderate	65.5	49.1	46.67	43.51	56.58
04P-EM17	High	78.37	80.53	86.22	41.85	63.87
04P-EM18	Moderate	60.14	47.57	50.38	23.74	38.83
04P-EM19	Low	50.69	22.23	23.36	10.5	8.74
04P-EM20	Moderate	59.29	43.61	49.01	14.76	24.01

Figures 35, 36, 37, 38, and 39, in appendix B, compare the 2 m coil bulk conductivity to clay percentage, LL, PL, PI, and MC, respectively. In general, the correlation noted between soil conductivity vs. LL ($R^2 = 0.88$) and soil conductivity vs. PI ($R^2 = 0.83$) in the Phase II survey appears to be much weaker with greater data scatter than that found in the limited data points compared to the Phase III survey. Additionally, there does not appear to be a correlation between soil conductivity vs. clay %, soil conductivity vs. PL and soil conductivity vs. moisture content at this site. The PI of a soil is the numerical difference between the LL and the PL of the soil (PI=LL-PL) and indicates the magnitude of the range of moisture content over which the soil

Table 6. Atterberg Limits of Soils Properties of Dulce Borehole Grab Samples (0.9 to 1.5 m).

Borehole ID	Depth Range of Grab Sample	Casagrande Plasticity Chart	% Passing #200 sieve	USCS Soil Class.	Liquid Limit	Plastic Limit	Plasticity Index	Moisture Content	Liquidity Index	Swell Index
04P-EM01	.9 to 1.5 m	clay/medium plasticity	47	SC	38	17	21	7.7	-0.44	0.20
04P-EM02	9 to 1.5 m	clay/low plasticity	26	SC	28	20	8	8.2	-1.48	0.29
04P-EM03	9 to 1.5 m	clay/medium plasticity	38	SC	32	17	15	12.6	-0.29	0.39
04P-EM04	9 to 1.5 m	clay/low-med. plasticity	22	SC	30	19	11	7.4	-1.05	0.25
04P-EM05	9 to 1.5 m	clay/low plasticity	45	SC	29	15	14	11.2	-0.27	0.39
04P-EM06	9 to 1.5 m	clay/low plasticity	30	SC	29	18	11	7.8	-0.93	0.27
04P-EM07	9 to 1.5 m	clay/low plasticity	25	SC	28	19	9	5.8	-1.47	0.21
04P-EM08	9 to 1.5 m	clay/medium plasticity	37	SC	32	16	16	9.6	-0.40	0.30
04P-EM09	9 to 1.5 m	clay/medium plasticity	49	SC	35	16	19	11.1	-0.26	0.32
04P-EM10	9 to 1.5 m	clay/low plasticity	34	SC	28	16	12	7.4	-0.72	0.26
04P-EM11	9 to 1.5 m	N/A*	33	SC	25	16	9	8.6	-0.82	0.34
04P-EM12	9 to 1.5 m	silt/low-med. compressibility	45	SM-SC	30	25	5	9.8	-3.04	0.33
04P-EM13	9 to 1.5 m	clay/low plasticity	55	CL	29	16	13	12.3	-0.28	0.42
04P-EM14	9 to 1.5 m	clay/low plasticity	38	SC	26	15	11	8.1	-0.63	0.31
04P-EM15	9 to 1.5 m	clay/low plasticity	36	SC	24	16	8	4	-1.50	0.17
04P-EM16	9 to 1.5 m	clay/medium plasticity	55	CL	32	18	14	5.1	-0.92	0.16
04P-EM17	9 to 1.5 m	clay/medium plasticity	50	CL-SC	32	15	17	10.6	-0.26	0.33
04P-EM18	9 to 1.5 m	clay/medium plasticity	40	SC	34	17	17	8	-0.53	0.24
04P-EM19	9 to 1.5 m	clay/low plasticity	52	CL	28	17	11	9.3	-0.70	0.33
04P-EM20	9 to 1.5 m	clay/medium plasticity	79	CL	32	18	14	13.3	-0.34	0.42

*The soils lab did not analyze the Casagrande Plasticity for this sample.

is in a plastic condition. The PL of a soil is the moisture content, expressed as a percentage of the mass of the oven-dried soil, at the boundary between the plastic and semi-solid states. The LL of a soil represents the lower limit for viscous flow of a soil. Comparing the lab data from the 20 soil borings with the geophysical data, the following generalizations can be shown.

- Variation in PL is small over the areas covered, typically ranging between 15 and 20.
- The variation in moisture content is also small, typically ranging from about 4 to 13 percent.
- The LL generally increases with increasing soil conductivity and ranges from about 24 to 37.
- The PI varies from about 5 to 21, and PI values do generally increase with increasing conductivity.
- The PI values are all less than 30, which is considered the lower limit swelling clays (6).
- Grab samples from soil boring were over the interval from 0.9 to 1.5 m (3 to 5 ft), whereas the EMI data is measuring the bulk conductivity over a volume of soil approximately 4 m (13 ft) thick.

6.2.2 Grab Samples Collected at Depths Greater Than 1.5 m (5 ft)

Table 7 lists the Atterberg Limits of Soils properties of the borehole data using grab samples from a depth greater than 1.5 m (5 ft). Comparison plots of the lab soil analysis data and the EMI geophysical data are provided in appendix C. As shown in table 7, the lab did not analyze four of the 20 boreholes.

Although the samples were a year old, they had been properly stored and sealed by the lab. The moisture contents of these year old samples were compared with the moisture contents measured for the original samples. The moisture content measured for year old samples were in the same range and had a similar distribution to the originally tested samples. This provides support for the validity of the results of testing the year old samples.

6.2.3 Interpretation of Geophysical and Atterberg Limits of Soils Results

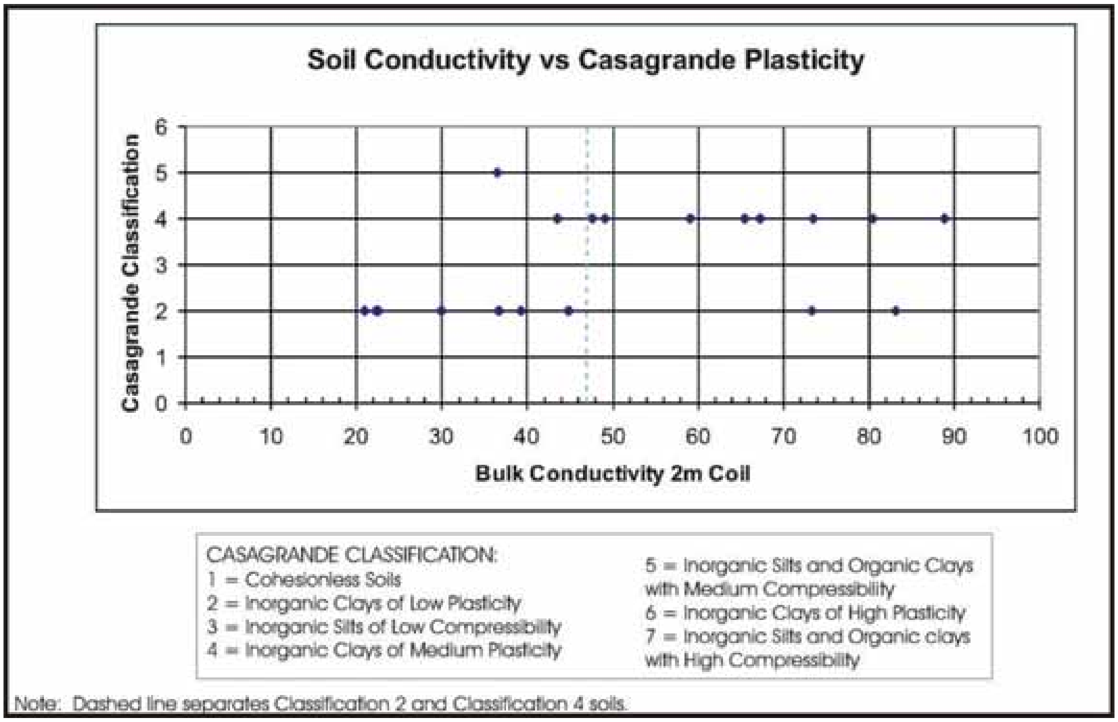
Interpretation of these results suggest that the primary correlation between soil conductivity and the soil properties typically measured for geotechnical analysis of a soil are related to the LL of the soil although there is only a weak direct correlation ($R^2 > 0.41$). A good correlation between soil conductivity and moisture content was not expected since soil conductivity is affected more by changes in the chemistry of the interstitial water rather than the volume percent of interstitial water. However, the poor correlation between soil conductivity and clay content (from the lab samples) was unexpected. This is most likely due to the depth of the clay noted in the soil boring logs, which was typically deeper than what was grab sampled and analyzed in the lab. A better correlation exists when comparing high apparent conductivity zones with the soil boring logs which list USCS soil classification and soil type for the entire 3 m (10 ft) depth of the soil boring.

Table 7. Atterberg Limits of Soils Properties of Dulce Borehole Grab Samples (1.5 to 3.0 m).

Borehole ID	Depth Range of Grab Sample	Casagrande Plasticity Chart	% Passing #200 Sieve	USCS Soil Class.	Liquid Limit	Plastic Limit	Plasticity Index	Moisture Content	Liquidity Index	Swell Index
04P-EM01	2.4 to 3.0 m	Clay/med plasticity	58	CL	35	16	19	4.6	-0.60	0.13
04P-EM02	2.4 to 3.0 m	Clay/med plasticity	73	CL	43	17	26	11.5	-0.21	0.27
04P-EM03	2.7 to 3.0 m	Clay/med plasticity	79	CL	42	17	25	14	-0.12	0.33
04P-EM04	2.4 to 3.0 m	Clay/med plasticity	67	CL	40	16	24	4.7	-0.47	0.12
04P-EM05	1.5 to 3.0 m	Clay/med plasticity	53	CL	35	13	22	5.6	-0.34	0.16
04P-EM06	2.4 to 3.0 m	Clay/med-high plasticity	82	CL/CH	50	18	32	10.8	-0.23	0.22
04P-EM07	2.4 to 3.0 m	Clay/med plasticity	65	CL	44	19	25	2.1	-0.68	0.05
04P-EM08	2.4 to 3.0 m	Clay/med plasticity	69	CL	39	19	20	7.7	-0.57	0.20
04P-EM09	1.8 to 3.0 m	Clay/med-high plasticity	76	CL/CH	50	19	31	11.1	-0.25	0.22
04P-EM10	1.8 to 3.0 m	Clay/med plasticity	80	CL	40	17	23	22.1	0.22	0.55
04P-EM11	Not Analyzed									
04P-EM12	2.4 to 3.0 m	Clay/med plasticity	82	CL	31	16	15	20.8	0.32	0.67
04P-EM13	1.5 to 3.0 m		67	ML				12.1		
04P-EM14	2.1 to 2.4 m	Clay/med plasticity	65	CL	33	10	23	12.6	0.11	0.38
04P-EM15	Not Analyzed									
04P-EM16	2.1 to 2.4 m	Clay/med plasticity	71	CL	37	18	19	11.7	-0.33	0.32
04P-EM17	1.8 to 3.0 m	Clay/low plasticity	46	CL	29	13	16	5.6	-0.46	0.19
04P-EM18	Not Analyzed									
04P-EM19	1.5 to 3.0 m	Silty clays	36	SC/SM	21	15	6	4	-1.83	0.19
04P-EM20	Not Analyzed									

Geophysicists have long used electrical and electromagnetic methods to successfully map clay materials in unconsolidated sediments. Quantitative laboratory analyses have shown that clay minerals typically have lower electrical resistivity (higher conductivity) than silt, sand or gravel. However, clay materials also exhibit a wide range in electrical resistivity. In particular, swelling clays have a higher capacity for ion exchange, which results in much lower measured resistivity than non-swelling clays. A qualitative comparison between the EMI data and the damaged and repaired pavement surfaces shows a good correlation between damaged pavement and high bulk conductivity values. Hence, from a pragmatic point of view, measurements of the electrical conductivity provide a reasonable predictor of potential roadbed subsurface problems.

Another comparison of soils properties and the EMI data is shown in figure 7. The soils at this site mostly fall into two categories, inorganic clays of low plasticity (#2) and inorganic clays of medium plasticity (#4). With the exception of a few outliers, the bulk conductivity of the 2 m (6.6 ft) coil separation data shows a good correlation between bulk conductivity and Casagrande soil classification. The Casagrande soil classification described as clays of low plasticity typically have bulk conductivity values less than 47 mS/m, while the Casagrande soils classification described as clays of medium plasticity typically have bulk conductivity values greater than 48 mS/m at this site. The comparison of the bulk conductivity data with the Casagrande soil classification is more consistent in this case than the comparison of the Casagrande soil classification with the USCS soils classification identified in the lab.



CASAGRANDE CLASSIFICATION:
1 = Cohesionless Soils
2 = Inorganic Clays of Low Plasticity
3 = Inorganic Silts of Low Compressibility
4 = Inorganic Clays of Medium Plasticity
5 = Inorganic Silts and Organic Clays with Medium Compressibility
6 = Inorganic Clays of High Plasticity
7 = Inorganic Silts and Organic clays with High Compressibility

Note: Dashed line separates Classification 2 and Classification 4 soils.

Figure 7. Chart. Soil Conductivity vs. Casagrande Plasticity.

6.3 ADVANTAGES OF EMI METHOD

EMI geophysical surveys provide advantages over the traditional soil sampling alone. EMI provides a fast and efficient means of continuous geophysical data coverage over the entire length of roadway to be surveyed. Soil conductivity is sensitive to bulk property changes, which directly or indirectly affect many different geotechnical soil properties. A weak correlation is shown between soil conductivity and LL even though the EMI data is measuring a larger volume of material than the soil boring grab sample. Therefore, EMI provides a useful precursor to soil boring programs because it offers complete data coverage between planned soil boring locations. EMI is sensitive to bulk changes and can be used to guide soil-boring locations to reduce overall cost. Overall costs can be reduced not only by reducing the number of soil boring necessary, but more importantly, by greatly reducing the risk of missing a swelling clay-rich zone that can significantly and unexpectedly increase reconstruction costs.

Table 8 outlines the advantages obtained with the EMI induction method versus soil boring analysis alone.

Table 8. Comparison of Soil Boring vs. EMI Surveying.

Soil Boring	**EMI Surveying**
Direct sampling	Inductive measurement
Detailed vertical sample	Bulk measurement
Limited sampling density	Continuous sampling plan/profile
Lab analysis extra expense	Survey all inclusive
Repeatable	Repeatable
Measurements valid for borehole annulus only	Volumetric measurement
Measures specific geotechnical properties	Measures summed effect of multiple geologic properties

CHAPTER 7 – CASE STUDY – NATCHEZ TRACE PARKWAY

7.1 INTRODUCTION

Blackhawk performed a production surface geophysical survey using the Frequency Domain EMI method from March 9 through March 12, 2004. The geophysical survey was conducted from MP8 to MP20 and from MP37 to MP59 along the Natchez Trace Parkway in Mississippi resulting in a total of 54.7 km (34 mi) of roadway surveyed (figure 8). Apparent conductivity maps were produced for the surveyed area. These maps were used by Eastern Federal Lands and Highway Division (EFLHD) to aid in the soil-boring program for locating clay-rich zones in the subgrade of the road that is planned for rehabilitation.

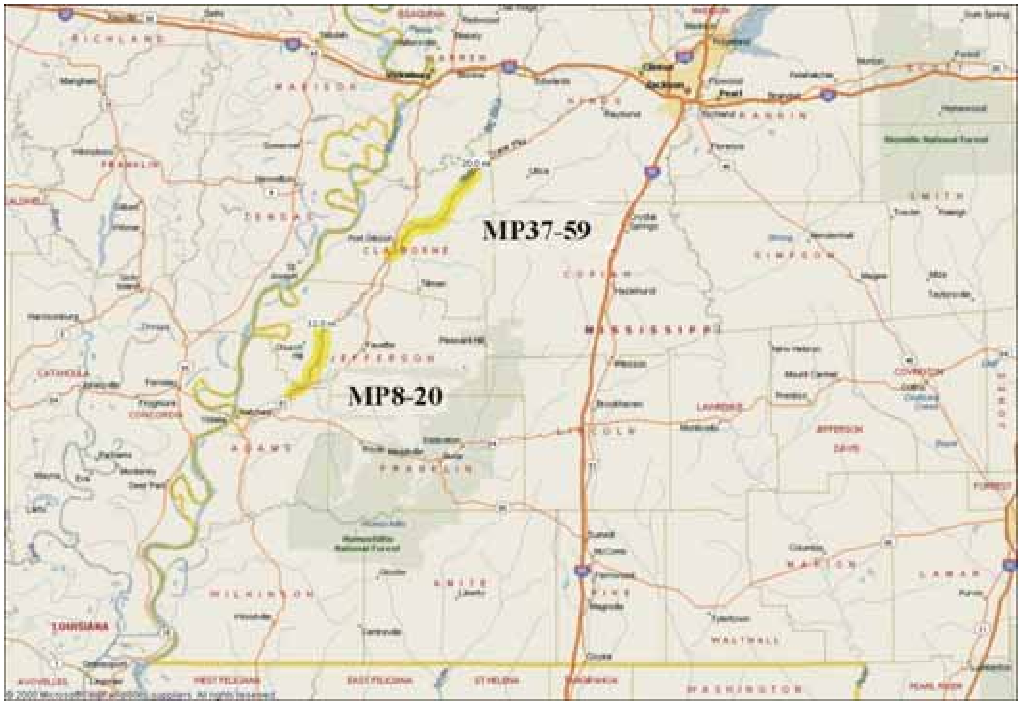


Figure 8. Map. Natchez Trace Parkway Site Map.

7.2 GEOPHYSICAL METHODOLOGY AND INSTRUMENTATION

The surface geophysical survey was performed using a state-of-the-practice instrument, the Geonics Limited EM31-3, a frequency domain electromagnetic induction data acquisition system. This instrument is an upgrade from the standard EM31 MK2. The EM31-3 has a transmitter coil in vertical dipole mode (with the plane of the coils parallel to the ground surface) operating at a frequency of 9.8 kHz. In addition to the standard EM31 MK2 single 3.66 m (12 ft) receiver coil spacing, the EM31-3 has two additional vertical dipole receiver coils spaced 1 m (3.28 ft) and 2 m (6.56 ft) from the transmitter coil. This allows for the acquisition of three separate data sets simultaneously, each measuring the apparent conductivity to a different effective depth below grade. The EM31-3 was mounted onto a specially built tow cart that was constructed with a minimal amount of conductive materials and no ferrous metal materials, thus minimizing its influence on the data. A GPS receiver was mounted above the midpoint between the transmitter coil and the 1 m (3.28 ft) receiver coil. The array is towed using a diesel powered Kawasaki Mule ATV. The EM31-3 mounted on the tow array attached to the ATV is shown in figure 9.

Figure 9. Photo. EM31-3 and ATV on Natchez Trace Parkway.

7.3 DATA ACQUISITION

Data from the EM31-3 and GPS were logged on a Juniper Systems Allegro data logger running the Multi31 acquisition software developed by GeoMar Software Inc. The array was towed at a nominal speed of 16 km/h (10 mph). The data logger recorded the EM31-3 data at 5 Hz and the GPS data at 1 Hz. This provided a nominal EMI data density of about 1 m (3.28 ft) and a nominal GPS data point spacing of about 4.5 m (14.8 ft). Two passes were recorded for each mile of road surveyed with one pass in each traffic lane in the same direction as the flow of traffic.

Data acquisition coverage averaged about 13.7 km (8.5 mi) of roadway per day (27.4 km (17 mi) of linear profile per day) and required four field days to complete the 54.7 km (34 mi) of roadway. At the end of each field day, the data were edited and uploaded to Blackhawk's FTP site along with the transcribed field notes for subsequent processing in the Golden, Colorado office. This was done to decrease the turnaround time necessary to produce preliminary draft maps to aid EFLHD's drilling program. The data was used to determine drilling locations. A small number of soil samples were obtained by EFLHD and the clay content of these samples compared well with the conductivity data.

7.4 DATA PROCESSING

The proprietary Multi-Sensor Towed Array Detection System Data Analysis Software (MTADS DAS) was modified to accept the EM31-3 data. This program has better capabilities than the standard processing programs (Oasis montaj) for editing and correcting GPS problems. After position corrections were applied, the data were exported as a file containing the conductivity data and associated spatial coordinates (XYZ grid file) and uploaded into Oasis montaj written by Geosoft Inc., to grid and display the data, and overlay the mapped cultural features (i.e. MPs and bridges). The data were then exported from Oasis montaj and imported in AutoCAD where the geophysical maps were integrated with the basemaps provided by EFLHD.

No interval conductance modeling was performed on the data.

7.5 GROUND TRUTH

To provide ground truth information, 41 locations (15 between MP8 and MP20 and 26 between MP37 and MP59) were selected from the geophysical data for soil boring sampling and analysis. An EFLHD geotechnical crew collected the soil borings. Laboratory tests, including gradation analysis, Atterberg limits, natural moisture content, and soil classification were performed on representative soil samples.

7.6 RESULTS

7.6.1 Analysis of Geophysical Results

Color contoured plan views of the apparent conductivity for all three coil separations were overlain on the roadway alignment maps provided by EFLHD. An example of this is shown in figure 10. The color-coded scale of the apparent conductivity, ranging from ≤ 20 milliSiemens/meter (mS/m) to ≥ 80 mS/m, is used to show the potential presence of clay zones under the road. For example, the apparent conductivity of 20 mS/m (in dark blue) is indicative of less clay potential, and the apparent conductivity of 80 mS/m (in pink) is indicative of greater clay potential.

The figure is divided into three plan views, one for each receiver coil separation. Coil 1 data are for the 1 m (3.28 ft) receiver-transmitter coil spacing. This spacing has an effective depth of investigation of approximately 1 m (3.28 ft) below ground surface in the configuration used in this survey. The plan view map for coil 1 represents a volumetric measure of the apparent conductivity of the material from 0 to 1 m (0 to 3.28 ft) below ground surface. Coil 2 data are for the 2 m (6.56 ft) receiver-transmitter coil spacing. This spacing has an effective depth of investigation of approximately 2.5 m (8.40 ft) below ground surface. The plan view map for coil 2 represents a volumetric measure of the apparent conductivity of the material from 0 to 2.5 m (0 to 6.56 ft) below ground surface. Coil 3 data are for the 3.66 m (12 ft) receiver-transmitter coil spacing. This spacing has an effective depth of investigation of approximately 5 m (16.4 ft) below ground surface. The plan view map for coil 3 represents a volumetric measure of the apparent conductivity of the material from 0 to 5 m (0 to 16.4 ft) below ground surface.

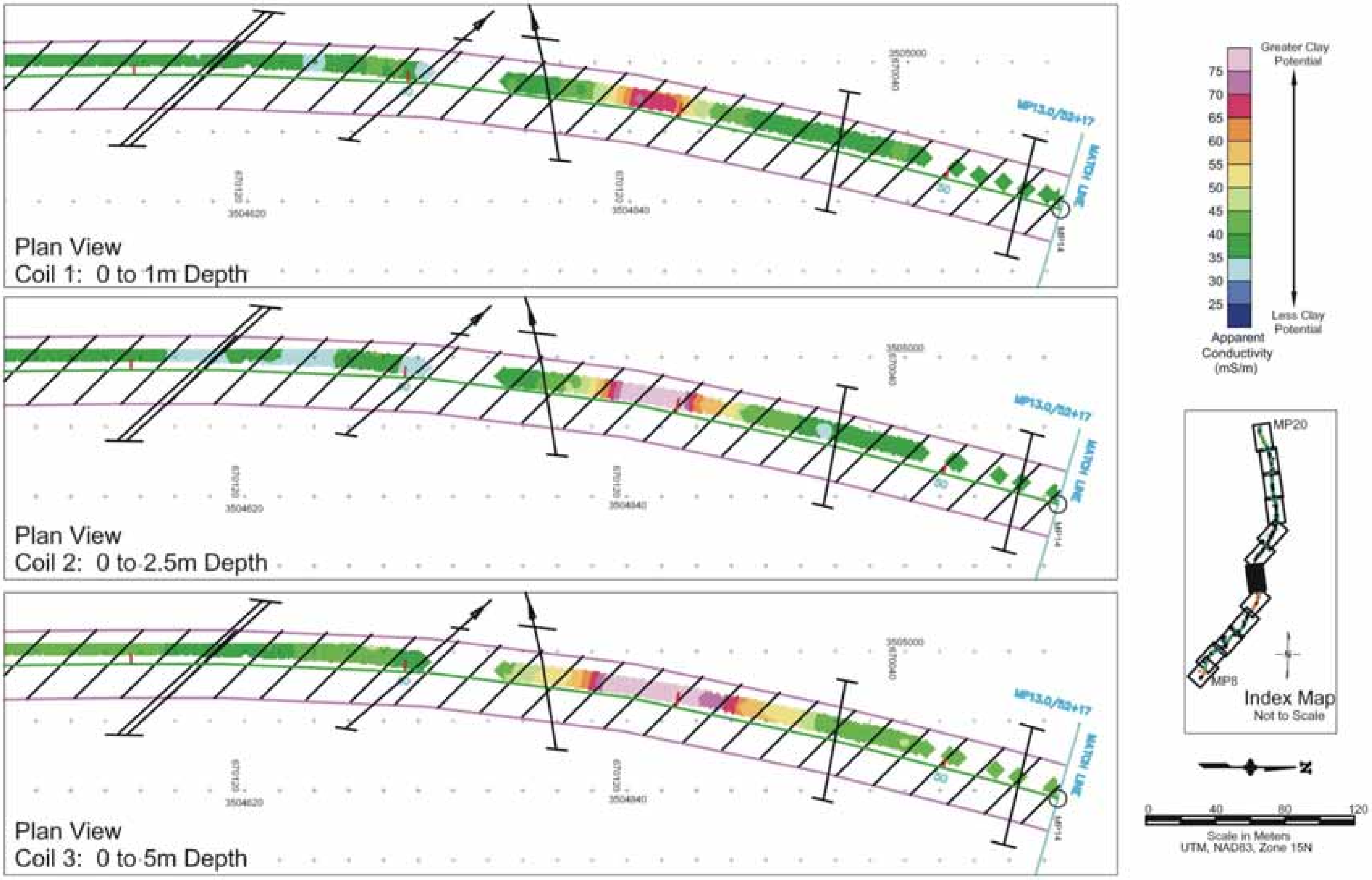


Figure 10. Plan View Map. EM31-3 EMI Apparent Conductivity Map from Natchez, Mississippi.

By comparing the apparent conductivity values for all three-coil spacings at a specific location, a rough estimate can be made on the vertical extent of the clay. For example, if the apparent conductivity for Coil 1< Coil 2< Coil 3, then it is likely that the clay extends from the near surface to the maximum depth of 5 m (16.4 ft) below ground surface. Conversely, if the apparent conductivity for Coil 1> Coil 2> Coil 3, then it is likely that the vertical extent of the clay is confined to the upper 1 m (3.28 ft) below the ground surface. Figure 10, between station 40 and station 50, displays a good example where the apparent conductivity increases with depth. This was the typical case for high-conductivity zones at this site.

7.6.2 Correlation of Geophysical and Atterberg Limits of Soils Properties Data

Table 9 lists the location of the boreholes and the EMI properties at the borehole locations. Table 10 lists the Atterberg Limits of Soils properties derived from samples from the boreholes. Appendix D contains plots comparing the EMI data results and the geotechnical results.

The correlation plots in appendix D show the comparison of bulk conductivity values for the 2 m (6.56 ft) and 3.66 m (12 ft) coil separation EMI data and the liquid limit, plastic limit, plasticity index, moisture content and liquidity index. The bulk soil conductivity does not appear to directly correlate with any of the soil properties data listed above. However, the variation in the values of the soil data is small which leads to a poor comparison.

The distribution of the soil data values for the Natchez data set falls within a narrow range. Table 11 lists the minimum, maximum, standard deviation and average values for each of the Atterberg Limits of Soils property.

In the correlation plots, this leads to a cloud of data points falling within a narrow range of values and may not include a sufficiently broad range of values to adequately determine if a correlation exists.

7.7 CONCLUSIONS

The field survey demonstrated the efficiency of EMI mapping by completing 54.7 km (34 mi) of roadway in four field days. The EMI survey is a fast, efficient, and cost effective geophysical method useful in the preliminary roadway surveys to plan and design road rehabilitation projects where clays in the road base materials are of concern. A soil-boring program, guided by EMI results, can greatly reduce the potential for missing areas of subgrade with potential construction problems in the design phase. Problem areas that are not detected prior to the construction phase can cause significant budget overruns during construction. Currently, this method is most effective as a reconnaissance tool to guide the soil-boring program. Further refinement in the application and data processing of this EMI method will also help realize further cost savings in performing the EMI survey and reduced turnaround time for the results.

Table 9. EMI Properties at Borehole Locations in Natchez, Mississippi.

Boring ID	Nad 83, UTM 15N		Bulk Conductivity (mS/m)		
	Easting (m)	Northing (m)	1 m Coil Separation	2 m Coil Separation	3.66 m Coil Separation
RW-01	665153.04	3498976.86	37.42	29.62	40.06
RW-03	665580.22	3499396.24	38.91	33.05	44.74
RW-04	665721.39	3499709.22	41.06	32.36	34.92
RW-05	666045.10	3500129.31	34.81	24.28	34.18
RW-09	667935.05	3500982.00	31.34	19.34	23.87
RW-10	668744.71	3501498.23	59.6	80.47	90.75
RW-15	670092.40	3503941.52	30.58	21.69	24.94
RW-17	670055.50	3504776.52	39.58	38.91	46.5
RW-18	670194.49	3505267.42	46.09	37.02	42.79
RW-21	671583.57	3506550.84	43.1	33.8	38.76
RW-26	672516.46	3508948.54	41.48	24.27	26.3
RW-27	672522.08	3509183.47	48.38	34.01	34.41
RW-28	672565.29	3509834.20	40.04	24.27	30.08
RW-30	672761.99	3510870.73	41.96	29.3	33.38
RW-33	672853.18	3512338.89	44.31	34.32	44.83
RT-01	689042.69	3534006.14	42.95	51.63	60.34
RT-02	689363.69	3534332.05	33.46	25.4	32.16
RT-06	691177.16	3535130.26	32.64	28.7	36.44
RT-07	691612.99	3535543.67	35.81	30.81	37.71
RT-09	692283.14	3536406.96	23.09	11.67	20.87
RT-10	692530.48	3536929.07	22.69	4.78	12.08
RT-12	692893.51	3538245.99	34.78	30.51	41.53
RT-15	693730.80	3539483.83	33.93	25.63	34.11
RT-19	694879.12	3541054.36	33.57	20.96	27.99
RT-21	695687.17	3541753.37	34.4	24.87	32.96
RT-22	696591.41	3541819.30	25.61	8.6	15.2
RT-23	696050.09	3541855.23	27.75	12.72	19.85
RT-32	701335.13	3542452.84	24.96	6.31	13.7
RT-33	701699.26	3542690.15	23.01	4.12	12.63
RT-36	703145.77	3544457.45	37.22	25.61	33.61
RT-38	703848.34	3545301.70	38.54	29.22	41.65
RT-43	704637.93	3547737.58	46.58	46.98	52.74
RT-44	704832.63	3548305.28	49.99	56.62	70.92
RT-46	705293.14	3549280.82	42.4	44.3	41.58
RT-48	706247.54	3550145.92	46.64	56.63	75.55
RT-50	706819.13	3550710.40	34.75	29.7	39.8
RT-55	708478.82	3552627.55	65.67	84.04	94.26
RT-56	708964.79	3553112.72	37.47	28.73	37.56
RT-60	710293.52	3554780.97	46.02	47.03	59.15
RT-62	710971.48	3555896.22	31.45	20.12	31.13
RT-63	711122.91	3556037.21	29.29	14.74	22.42

Table 10. Atterberg Limits of Soil Properties from Boreholes in Natchez, Mississippi.

Boring ID	Moisture Content (%) (MC)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	Liquidity Index (LI)
RW-01	19	30	17	13	0.15
RW-03	14.9	28	21	7	-0.87
RW-04	18.2	28	19	9	-0.09
RW-05	16.9	24	18	6	-0.18
RW-09	21.2	30	16	14	0.37
RW-10	11.1	29	12	17	-0.05
RW-15	19.6	26	16	10	0.36
RW-17	23.9	25	20	5	0.78
RW-18	14.6	25	14	11	0.05
RW-21	16	26	16	10	0.00
RW-26	18.2	28	18	10	0.02
RW-27	15.3	25	20	5	-0.94
RW-28	17.7	32	17	15	0.05
RW-30	18.7	25	19	6	-0.05
RW-33	15.6	25	19	6	-0.57
RT-01	11.7	27	27	na	na
RT-02	12.8	18	9	9	0.42
RT-06	12.7	19	13	6	-0.05
RT-07	18.6	22	10	12	0.72
RT-09	11.6	16	15	na	-3.40
RT-10	8.1	13	12	na	-3.90
RT-12	15	14	14	na	na
RT-15	14.5	19	11	8	0.44
RT-19	17.8	18	13	5	0.96
RT-21	12.1	14	11	3	0.37
RT-22	18.7	29	18	11	0.06
RT-23	13.2	16	12	4	0.30
RT-32	8.3	na	na	na	na
RT-33	5.9	na	na	na	na
RT-36	11.1	24	15	9	-0.43
RT-38	10.2	18	13	5	-0.56
RT-43	9.2	15	12	3	-0.93
RT-44	10.1	20	8	12	0.18
RT-46	8.2	20	9	11	-0.07
RT-48	7.4	14	13		-5.60
RT-50	16.6	29	17	12	-0.03
RT-55	18.1	30	15	15	0.21
RT-56	20	31	19	12	0.08
RT-60	16.4	29	15	14	0.10
RT-62	13.8	24	15	9	-0.13
RT-63	13.9	21	13	8	0.11

Note: not analyzed = na.

Table 11. Statistical Analysis of the Atterberg Limits of Soils Results from Natchez, Mississippi.

	Moisture Content (%)	Liquid Limit	Plastic Limit	Plasticity Index	Liquidity Index
Minimum	5.9	13	8	3	-5.6
Maximum	23.9	32	27	17	1
Standard Deviation	4.2	5.6	3.9	3.7	1.3
Average	14.6	23.2	15.2	9.2	-0.3

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CHAPTER 8 – CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

EMI ground conductivity instruments when integrated with GPS provide a fast, efficient and cost-effective means for providing continuous mapping of the spatial distribution of the bulk conductivity of the roadbase over long distances. The new Geonics EM31-3 provides a more efficient means of collecting EMI data by reducing the number of data collection passes required along each profile, thus greatly reducing the field effort.

Currently, the available EMI modeling software, as with the earlier phases of this study, is still not easily capable of processing EMI data from this type of EMI survey. With the Emigma software, the primary limitation was in the preprocessing of the data prior to the inversion process. The preprocessing steps included sorting, positioning, and combining the data sets for each profile. Once the data was in the proper sorted and data subsets format, the inversion process proceeded more efficiently.

Through a comparison of the soil lab data from the 20 soil borings from Dulce, a weak correlation is shown to exist between LL and soil conductivity. Similar trends and prediction line fits are evident not only in the plot of Interval Conductance (1 to 1.5 m (3.28 to 4.92 ft)) vs. LL, but also in the plot of bulk conductivity (2 m (6.56 ft) coil separation, vertical dipole) vs. LL and in the plot of bulk conductivity (3.66 m (12 ft) coil separation, vertical dipole) vs. LL. An even weaker correlation is shown between soil conductivity and PI; however, this appears to be primarily related to the effect of LL. Bulk soil conductivity appears to be insensitive to moisture content and the samples clay percent at this site.

In general, the use of this EMI method will provide FHWA with two major advantages: 1) a geotechnical investigation could possibly be tailored to sample specific areas defined by either interval conductance or bulk conductivity; and 2) a potential reduction in the cost of soil borings and laboratory tests could be realized by providing a direct approximation of LL and PI values across long stretches of roadway. As noted in the Pavement and Subgrade Investigation Report 02-02 (7), "*From milepost 45 to 50, the pavement distresses were significantly more severe than from milepost 55 to 50. Although this trend is not supported from the soil classification data, it is supported when evaluating the PI data of the soil*." This statement suggests that soil boring alone is not enough to evaluate the subgrade at this site, and that laboratory analysis of soil samples is necessary to accurately identify problem areas. EMI surveys could provide an efficient means to map the spatial distribution (laterally and vertically) of soil conductivity. The conductivity data collected at this site shows the overall trend stated in the quoted statement above with overall relatively high conductivity values from MP 45 to 50 and overall relatively low conductivity values from MP 55 to 50. In addition, the data can be used to provide a prediction of the approximate LL and PI values along this entire length of roadway with much greater data density and spatial resolution than using soil boring data alone.

This project has been in part a demonstration of various EMI instruments and deployment of the new Geonics EM31-3 study. Although using EMI soil conductivity meters to map the spatial distribution of apparent ground conductivity is common, applying multiple instrument configurations to produce 2-D vertical profiles over large areas is rarely attempted. In addition, the integration of the interpreted EMI data in P & P drawings has been an iterative process between CFLHD and Blackhawk personnel in order to determine the most appropriate information to overlay on the P & P and the best way to display these data.

Large amount of time and effort have been expended in order to accomplish the program objectives and to derive an appropriate processing scheme to best meet the objectives. Through the efforts of all phases of this study, most of the difficulties have been overcome and future work could precede in a much more time- and cost-effective manner.

The deployment of the new Geonics EM31-3 instruments has provided several advantages over the other EMI (EM38 and EM31) instruments used during the Phase I and Phase II investigations:

- Three EM31 receiver coils separated at three different coil spacings all recorded simultaneously.
- Digital data acquisition with faster sampling rates allow for a faster rate of data collection.
- Capability to log both GPS and EMI data on the same data logger.

Table 12 presents a summary of the correlation of coefficients comparing Atterberg Limits of soils with conductive properties. As shown in the table, none of the attributes correlate strongly. The highest correlation was for the LL at the 0.9 to 1.5 m (3 and 5 ft) grab sample depth. This probably was due to the wide range of LL measured from the samples. The lower correlation for the 1.5 to 3.0 m (5 to 9.8 ft) grab sample depth and Natchez are due to the consistent LL values with no variation.

Based on the results obtained from this study, and the correlation coefficient shown in Table 12, the following conclusions can be made:

- Soil conductivity information derived through EMI methods can provide valuable information for the evaluation of road base materials in the design and redesign process.
- Soil conductivity information can be used to guide the soil-boring program by targeting the most likely locations with potential swelling clay problems.
- The weak correlation between bulk conductivity and LL can provide a first pass approximation of the predicted LL values along the entire length of the roadway surveyed.
- The correlation between bulk conductivity and Casagrande Plasticity Classification may be used as a quick evaluation tool for predicting Casagrande soil type along the entire length of roadway surveyed.

Overall, the EMI method is a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways with non-metal reinforced pavement types. A strong correlation between soil conductivity and the Atterberg Limits of Soils were not established, however, a qualitative evaluation of areas with increased potential for high plasticity clay content can be estimated from the EMI data. The EMI method can be used to focus the drilling programs during project site investigations, road rehabilitation, and construction. The EMI method may provide significant cost savings by reducing construction cost overruns.

Table 12. Correlation of Coefficients Summary

Attribute	**Location**	**R^2**		
		1 - 1.5 m Interval Conductance	**2 m Bulk Conductivity**	**3.66 m Bulk Conductivity**
% 200 Sieve	Dulce, 0.9 - 1.5 m	0.0026	0.0034	0.0091
	Dulce, 1.5 - 3.0 m	0.0210	0.0019	0.0003
	Natchez	*1	*2	*2
Liquid Limit	Dulce, 0.9 - 1.5 m	0.4127	0.4270	0.4133
	Dulce, 1.5 - 3.0 m	0.0169	0.0057	0.1476
	Natchez	*1	0.0667	0.0334
Plastic Limit	Dulce, 0.9 - 1.5 m	0.0161	0.0083	0.0036
	Dulce, 1.5 - 3.0 m	0.0016	0.0377	0.0806
	Natchez	*1	0.0009	0.002
Plasticity Index	Dulce, 0.9 - 1.5 m	0.3228	0.2968	0.2579
	Dulce, 1.5 - 3.0 m	0.0188	0.0885	0.1005
	Natchez	*1	0.0923	0.0942
% Moisture	Dulce, 0.9 - 1.5 m	0.0695	0.0975	0.1126
	Dulce, 1.5 - 3.0 m	0.0044	0.0601	0.0509
	Natchez	*1	0.041	0.0058
Liquidity Index	Dulce, 0.9 - 1.5 m	0.1045	0.0844	0.0611
	Dulce, 1.5 - 3.0 m	0.0477	0.0139	0.0139
	Natchez	*1	0.0307	0.0021
*1 - Interval conductance values were not calculated for the Natchez data.				
*2 - Lab did not test % 200 Sieve.				

8.2 RECOMMENDATIONS

Recommendations for future work include the following:

- The EM31-3 should be used in vertical dipole mode with only a single pass down each lane of the roadway to produce three different plan maps, each with a different effective depth of investigation.
- Although a good correlation with Atterberg Limits of Soils has not been shown, a reasonable qualitative correlation between high soil conductivity and areas with buckling or problematic roadbase appears to exist. This would make the EMI method a useful reconnaissance tool for mapping bulk soil conductivity prior to the soil-boring program.
- Inversion of the EMI data to produce vertical interval conductance profiles, while extremely time intensive using the currently available EM inversion software, appears to

provide only a small benefit over plan mapping alone. In particular, with the new EM31-3 instrument, the data from the three separate coil separations, recorded simultaneously, can be plotted side-by-side as three separate plan maps, each with a different effective depth of investigation. Inversion of the EMI data is unnecessary as it currently provides little additional benefit, yet greatly increases the time and cost required to process the data using currently available commercial EMI inversion software.

- EMI surveys should be conducted at suitable sites prior to the soil-boring program, such that the results of the EMI survey can be used to identify potential problem areas that can then be investigated through soil borings and other geotechnical investigations. This will significantly reduce the risk of missing a potential problem area when compared to conventional random soil boring programs alone.
- The EMI method should be utilized as a tool to complement the drilling program during preliminary site investigations, and for road rehabilitation design and construction highway projects, when the presence of clay in the road subgrade is of concern.
- Making a direct correlation between measured conductivity and Atterberg Limits of Soils properties data has proven difficult at this time. Furthermore, the development of empirical relationships between the geo-electric and soil properties are complex, site-specific and not readily quantified into individual soil properties.
- Various methods, such as laboratory testing, computational modeling, and limited geophysical techniques are currently being used for soil investigations. This study has demonstrated that a combination of these methods can provide better information to understand the soil behavior. Although finding a direct correlation between EMI results and laboratory geotechnical classification has proven difficult, EMI surveys should be implemented in geotechnical engineering projects independently of the current classification methods. Further developments in geophysical testing may produce a new classification scheme that can compliment current geotechnical classification practice. EMI methods can be used for investigating in-situ soil behavior rather than depending on the laboratory classification only.

8.3 ELECTROMAGNETIC INDUCTION BENEFITS

The EMI method is a fast, efficient, and cost effective geophysical tool for mapping spatial variations in soil conductivity beneath roadways with non-metal reinforced pavement types. While a direct correlation between soil conductivity and Atterberg Limits of Soils measurements may not be possible, a qualitative evaluation of potential problems areas can be determined from the EMI data.

- The EMI method will complement and focus soil sampling programs during preliminary site investigations, and for road rehabilitation design and construction projects.
- The EMI method will create significant cost savings by reducing construction cost overruns.

CERTIFICATION AND DISCLAIMER

All geophysical data analysis, interpretations, conclusions, and recommendations in this document have been prepared under the supervision of and reviewed by Blackhawk senior geophysicists.

This geophysical investigation was conducted using sound scientific principles and state-of-the-art technology. A high degree of professionalism was maintained during all aspects of the project from the field investigation and data acquisition, through data processing, interpretation, and reporting. The results and interpretations were limited by the data obtained in the field and from the client. All original field data files, field notes, observations, and other pertinent information are maintained in the project files at Blackhawk's Golden office, and are available to the client for a minimum of five years.

A geophysicist's certification of interpreted geophysical conditions comprises a declaration of his/her professional judgment. It does not constitute a warranty or guarantee, expressed or implied, nor does it relieve any other party of its responsibility to abide by contract documents, applicable codes, standards, regulations, or ordinances.

In order to ensure the highest quality geophysical data, a multi-layer approach to Quality Assurance and Quality Control (QA/QC) was implemented. Before shipping equipment to job sites, rigorous tests were conducted to ensure all equipment is functioning properly.

Quality control is obtained in the field by highly trained geophysicists. Survey parameters and acquisition procedures are agreed to by at least two geophysicists, who are then responsible for conducting the surveys. When time allows, survey data is recorded a second time, either in the same or opposite directions, to ensure repeatability. Data were then compared during the data processing and interpretation steps. Data are also returned to the home office for analysis by senior geophysicists within the QA/QC department.

During data processing and interpretation, the geophysicists discuss results and interpretations with the internal QA/QC department on a daily basis. Ideas and alternate techniques are discussed and implemented to provide clients with the most accurate data possible.

The processing geophysicists generally handle report writing. Draft reports are generated and circulated within the QA/QC department as well as given to at least one additional senior geophysicist. These different layers of the QA/QC approach ensure that a high-quality product is produced for each and every client.

ACKNOWLEDGEMENTS

The authors would like to express their sincere appreciation to Mr. Khamis Y. Haramy, COTR of the FHWA-CFLHD, for his guidance, valuable technical assistance, and review during the course of this investigation. The authors would also like to thank Mr. Roger Surdahl and Mr. Linden Snyder of the FHWA-CFLHD for their technical advice and review of this report.

The authors would also like to express their appreciation to Mr. Khalid Mohamed of the FHWA-EFLHD for guiding, directing, and providing valuable technical assistance and review during the course of the Natchez, Mississippi EMI investigation of clay seams.

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APPENDIX A – PLAN AND PROFILE MAPS FROM DULCE, NEW MEXICO.

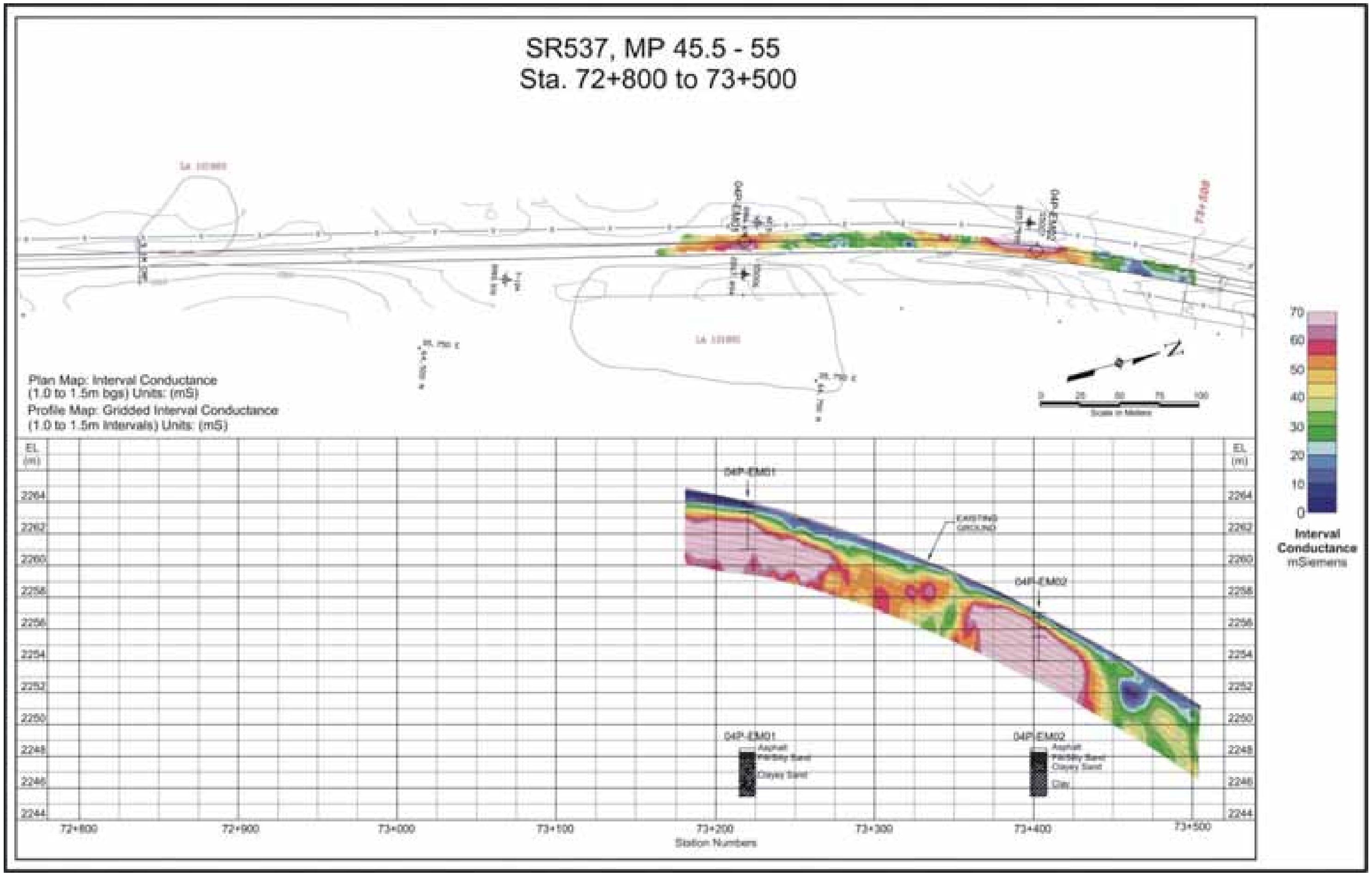

Figure 11. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 72+800 to 73+500).

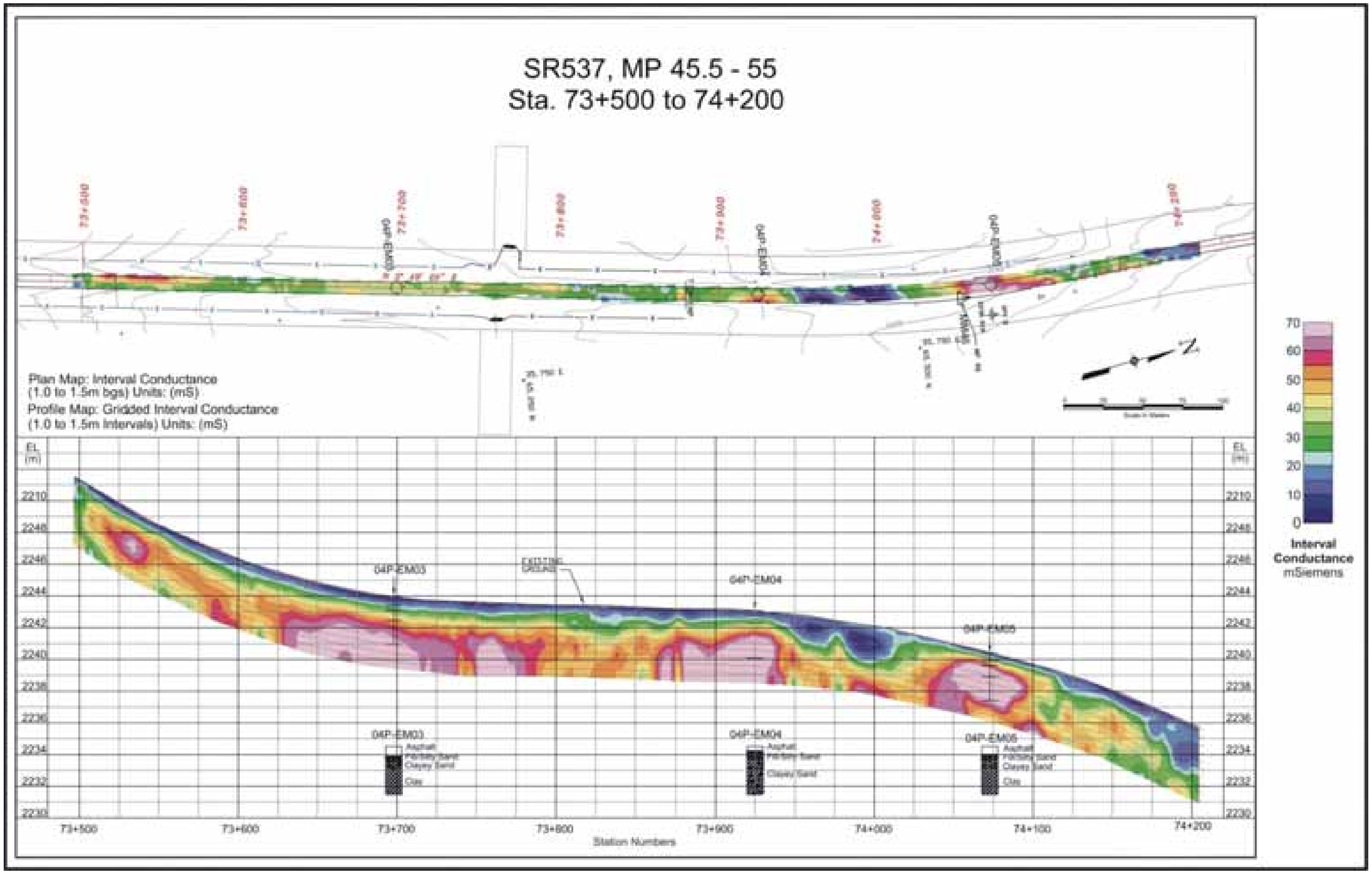

Figure 12. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 73+500 to 74+200).

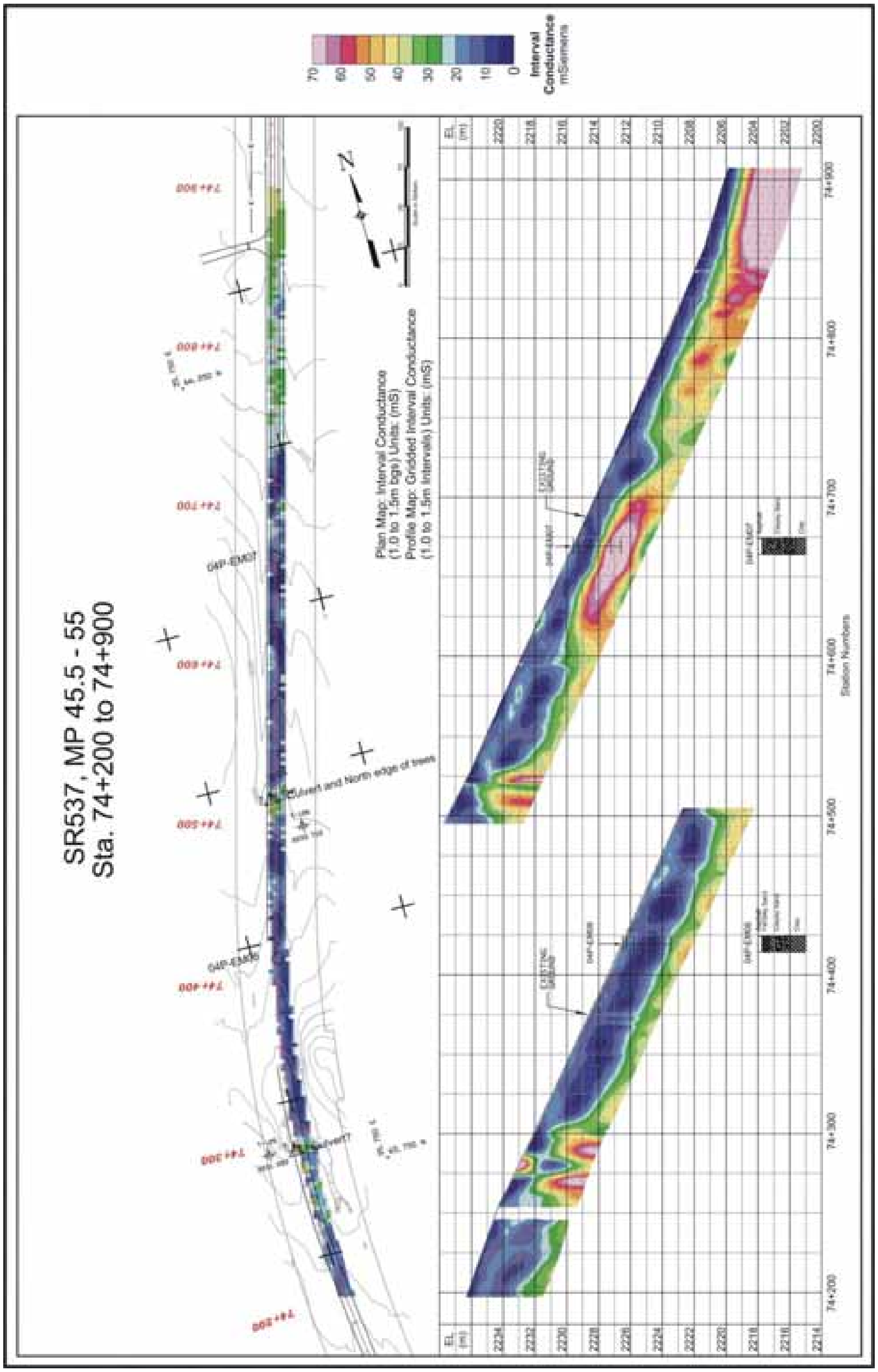

Figure 13. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 74+200 to 74+900).

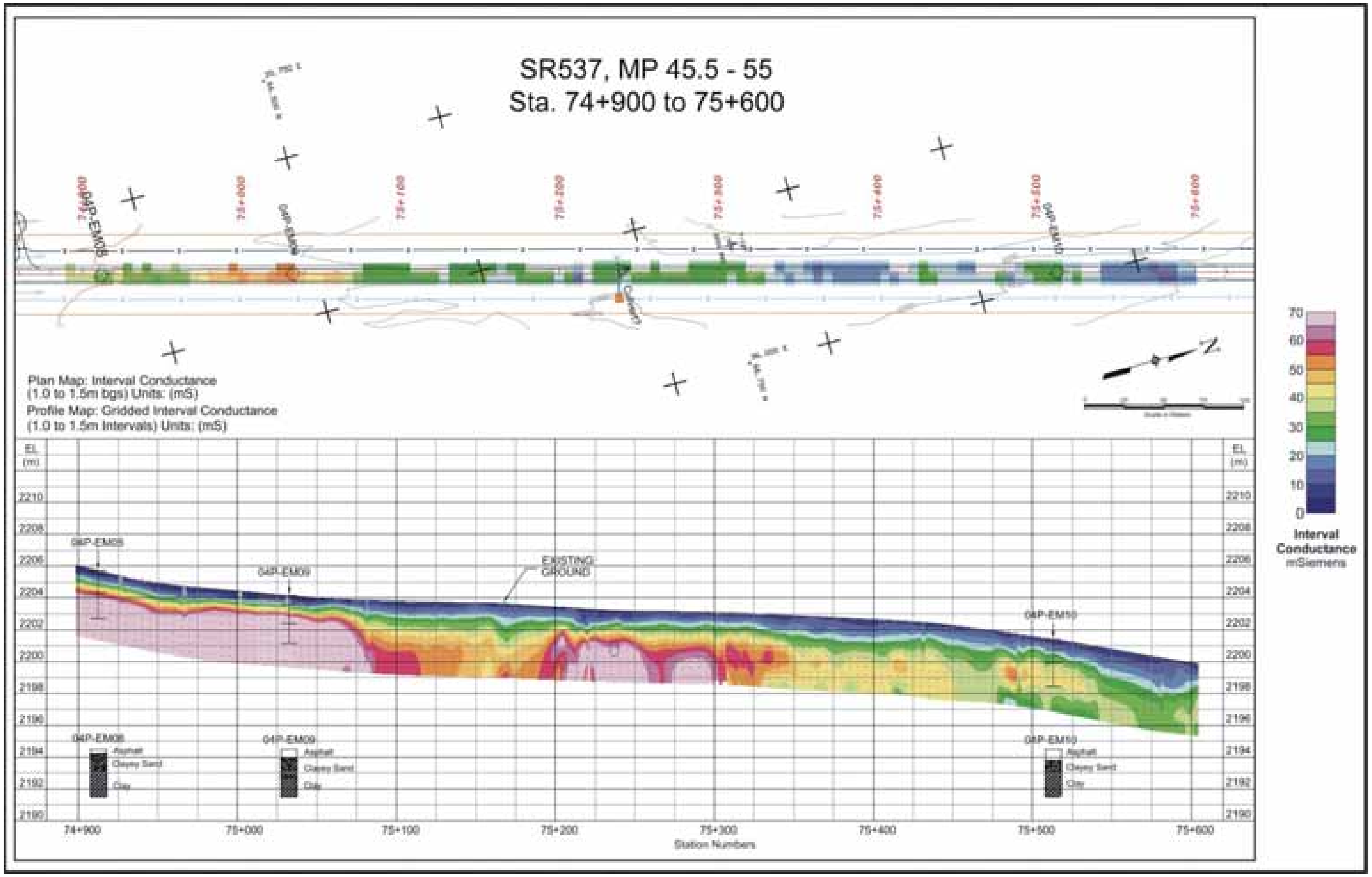

Figure 14. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 74+900 to 75+600).

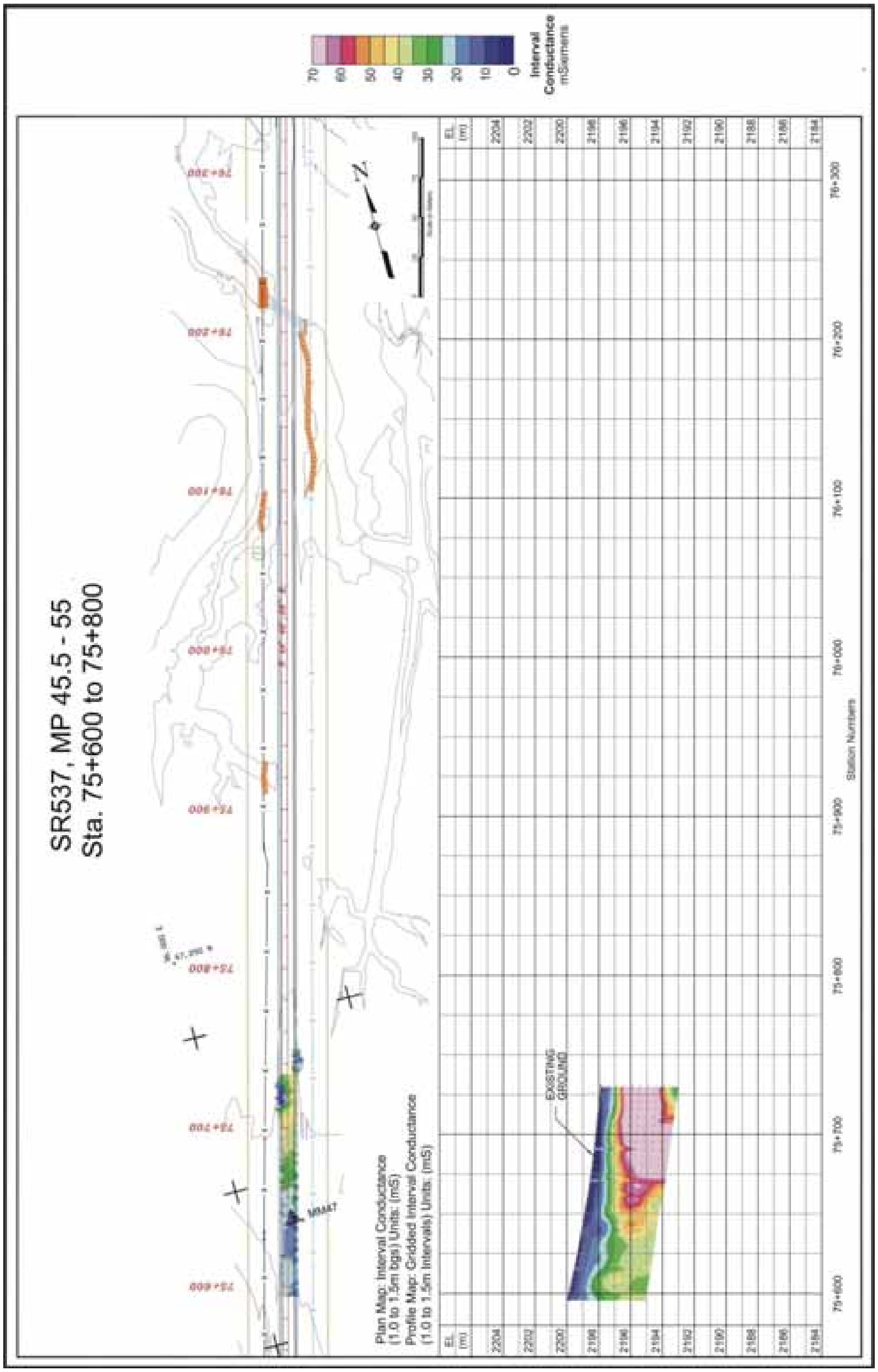

Figure 15. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 75+600 to 75+800).

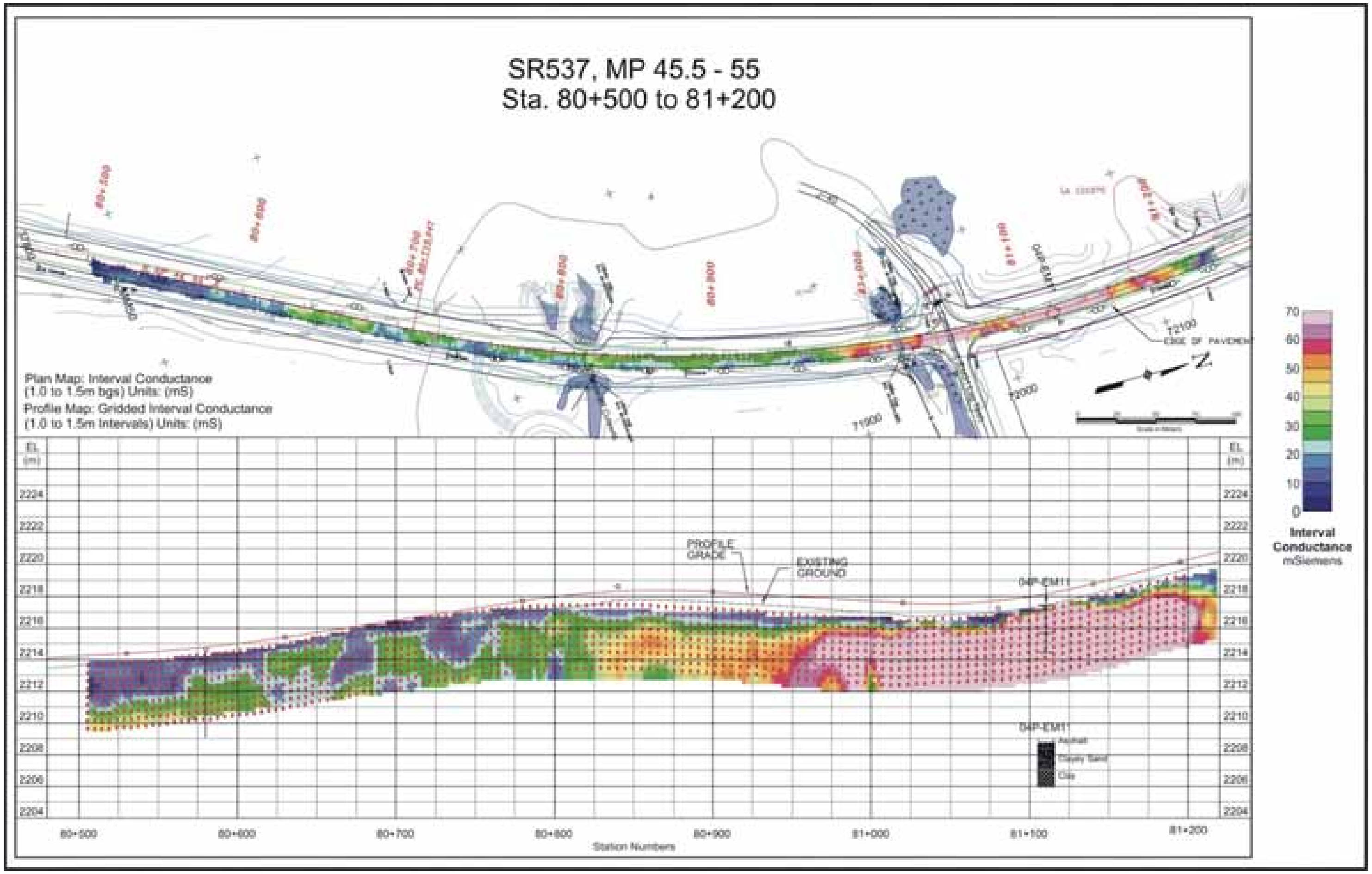

Figure 16. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 80+500 to 81+200).

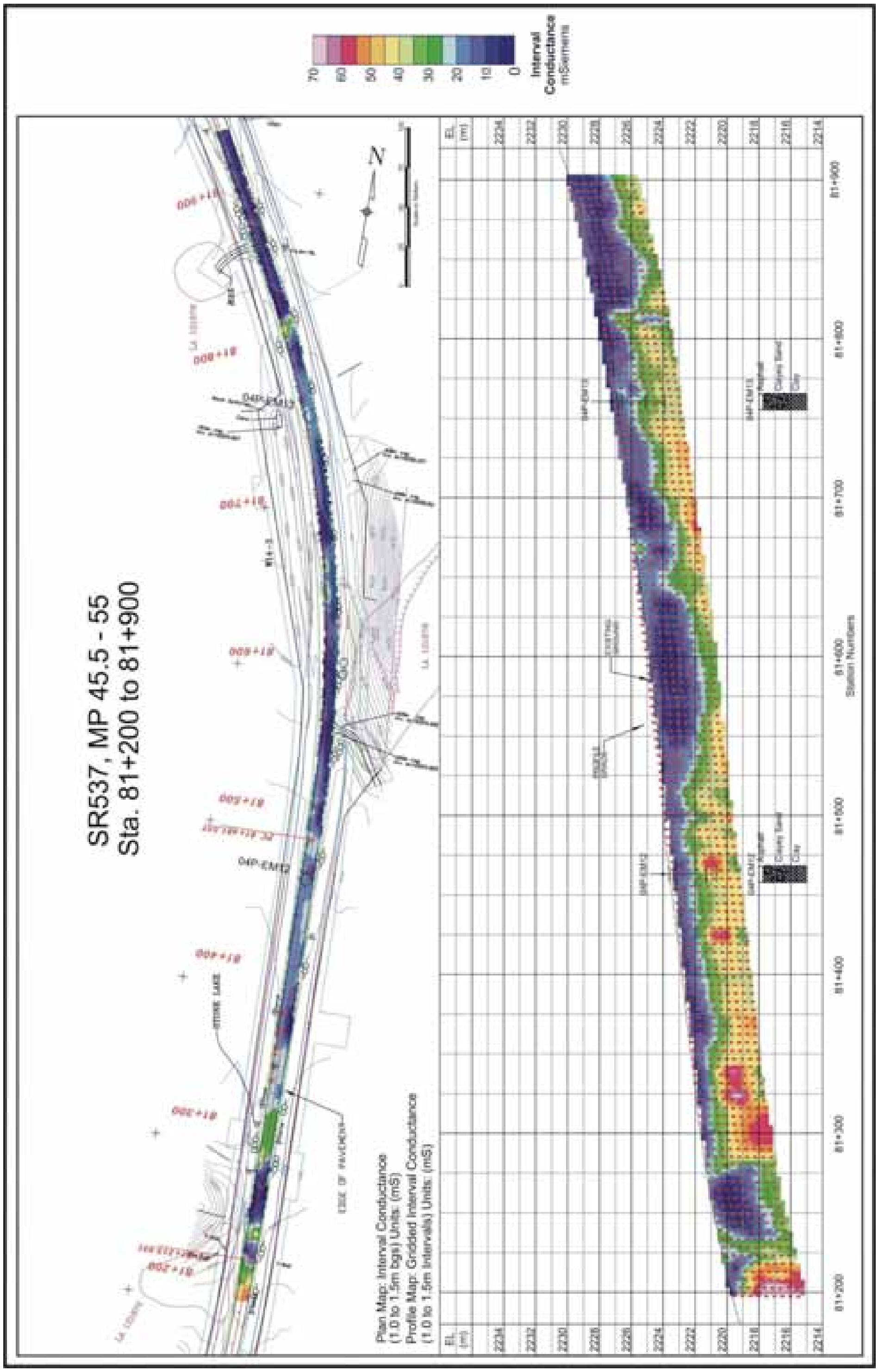

Figure 17. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 81+200 to 81+900).

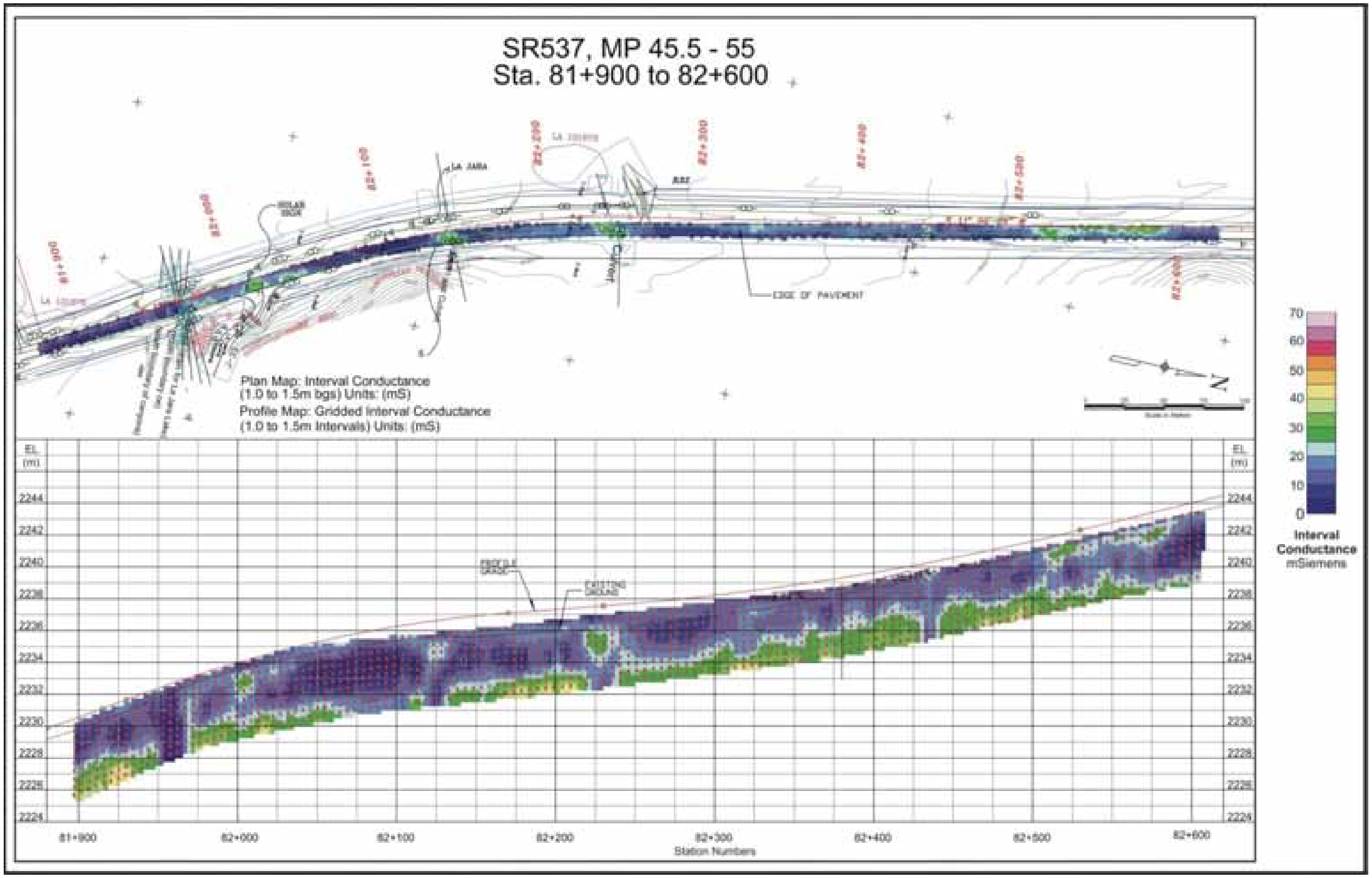

Figure 18. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 81+900 to 82+600).

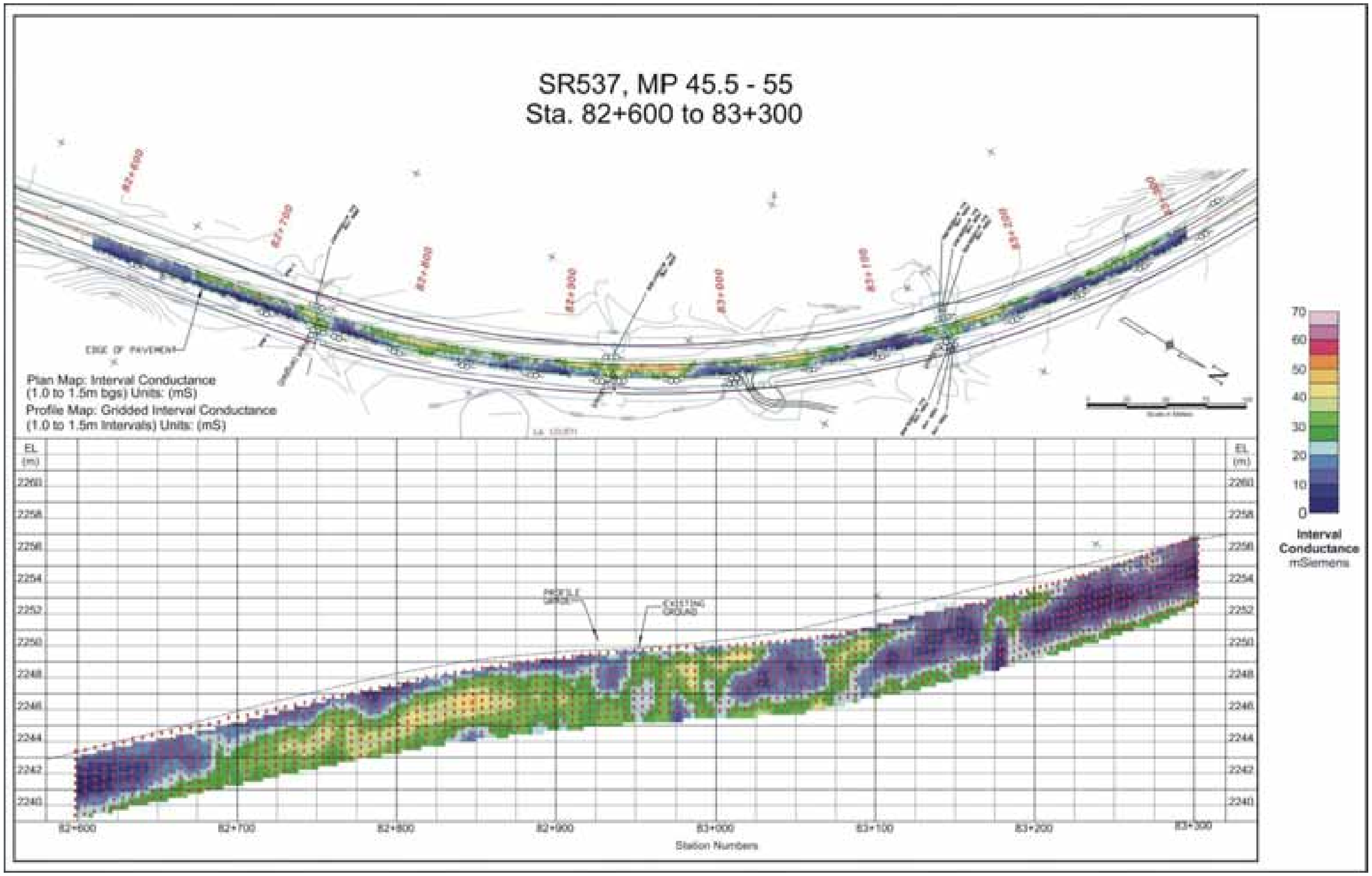

Figure 19. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 82+600 to 83+300).

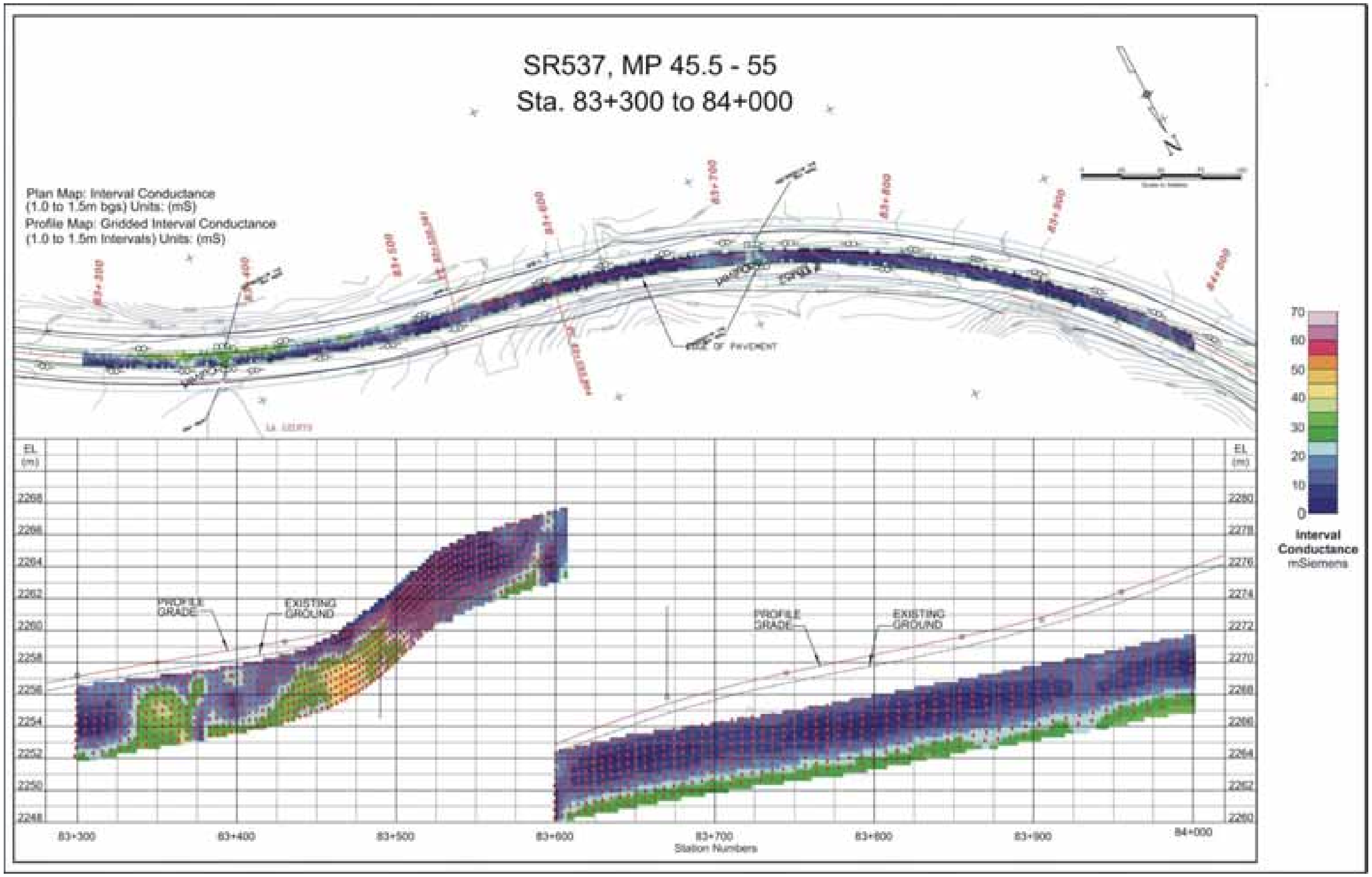

Figure 20. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 83+300 to 84+000).

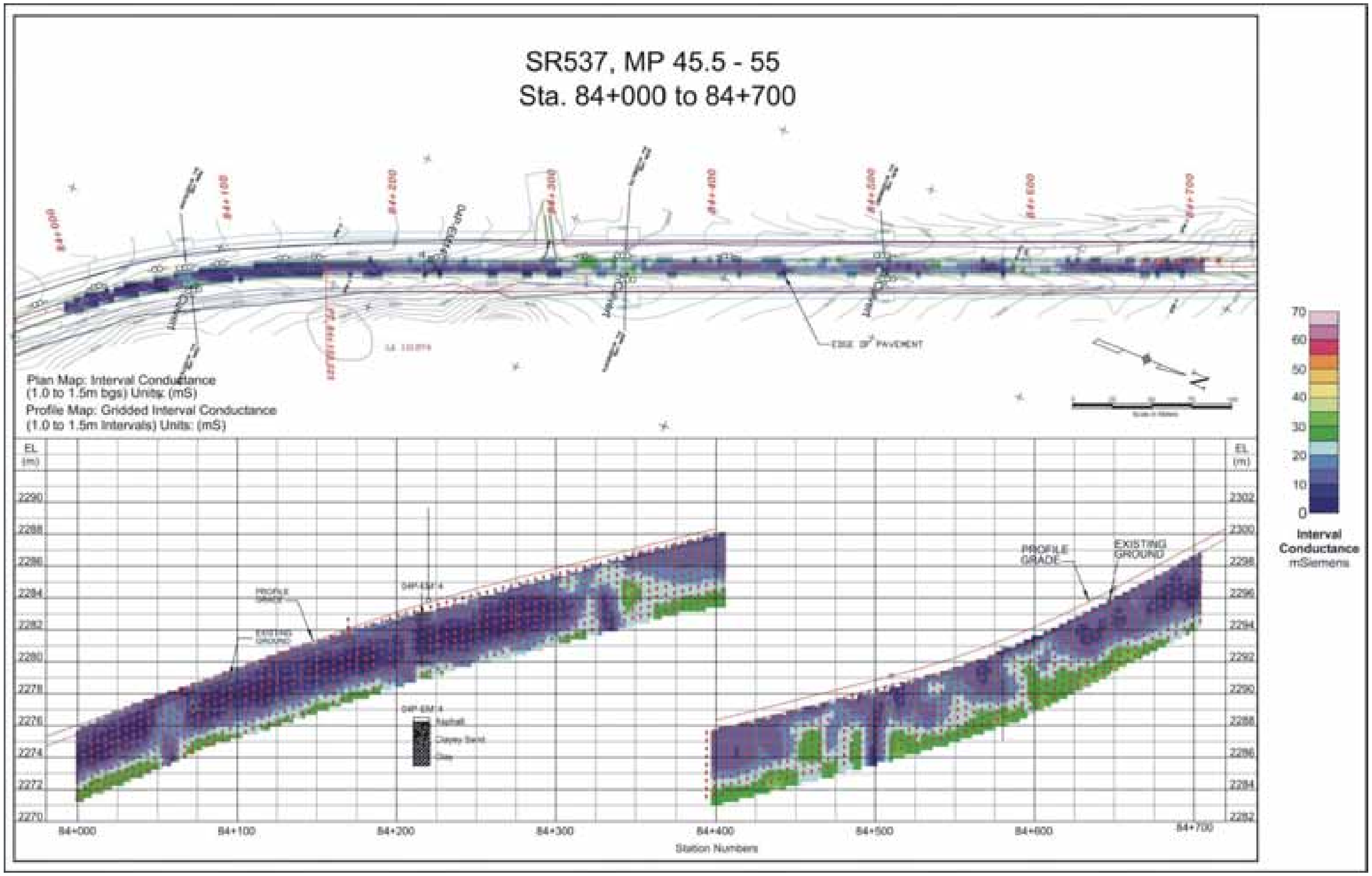

Figure 21. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 84+000 to 84+700).

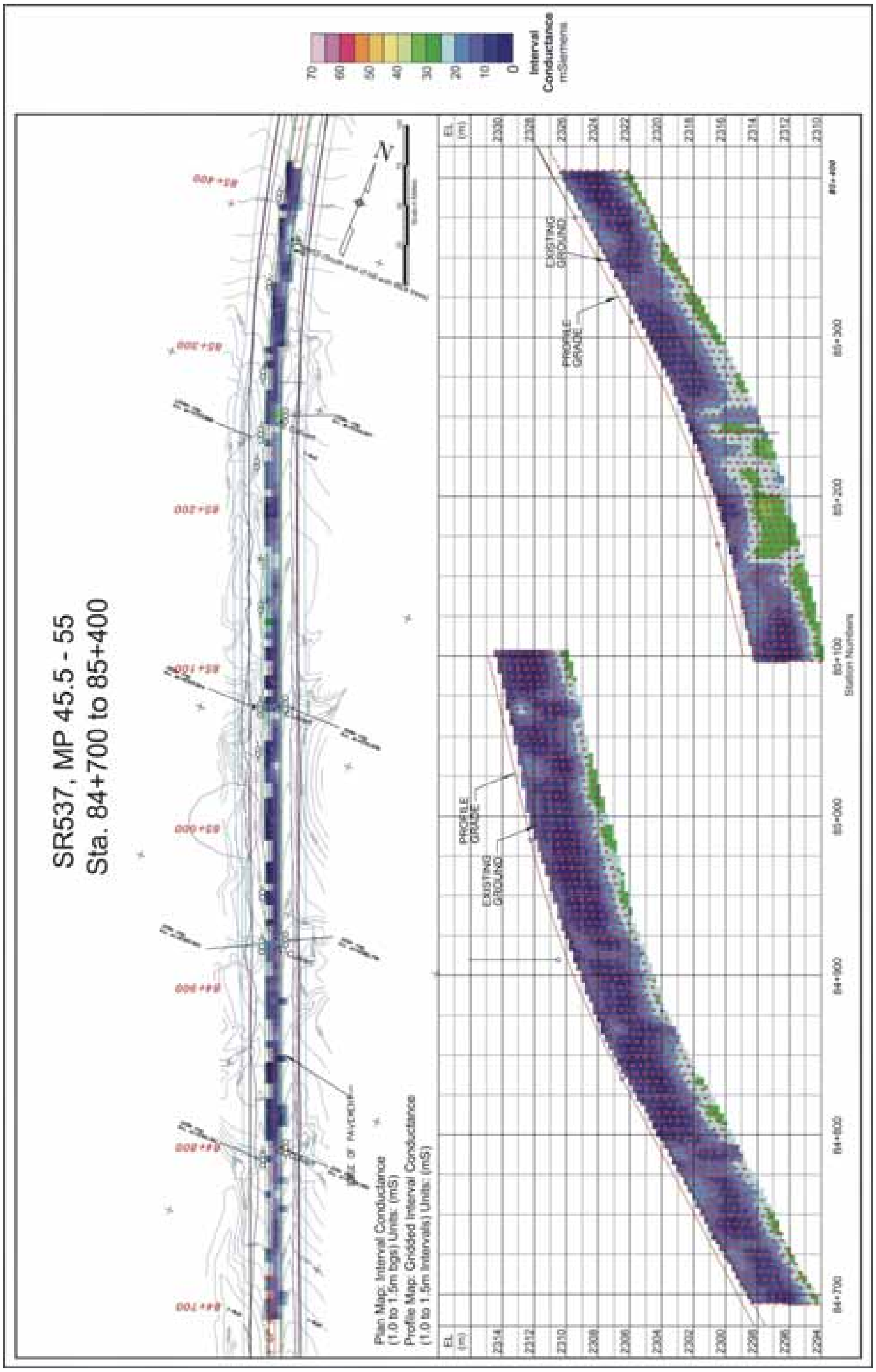

Figure 22. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 84+700 to 85+400).

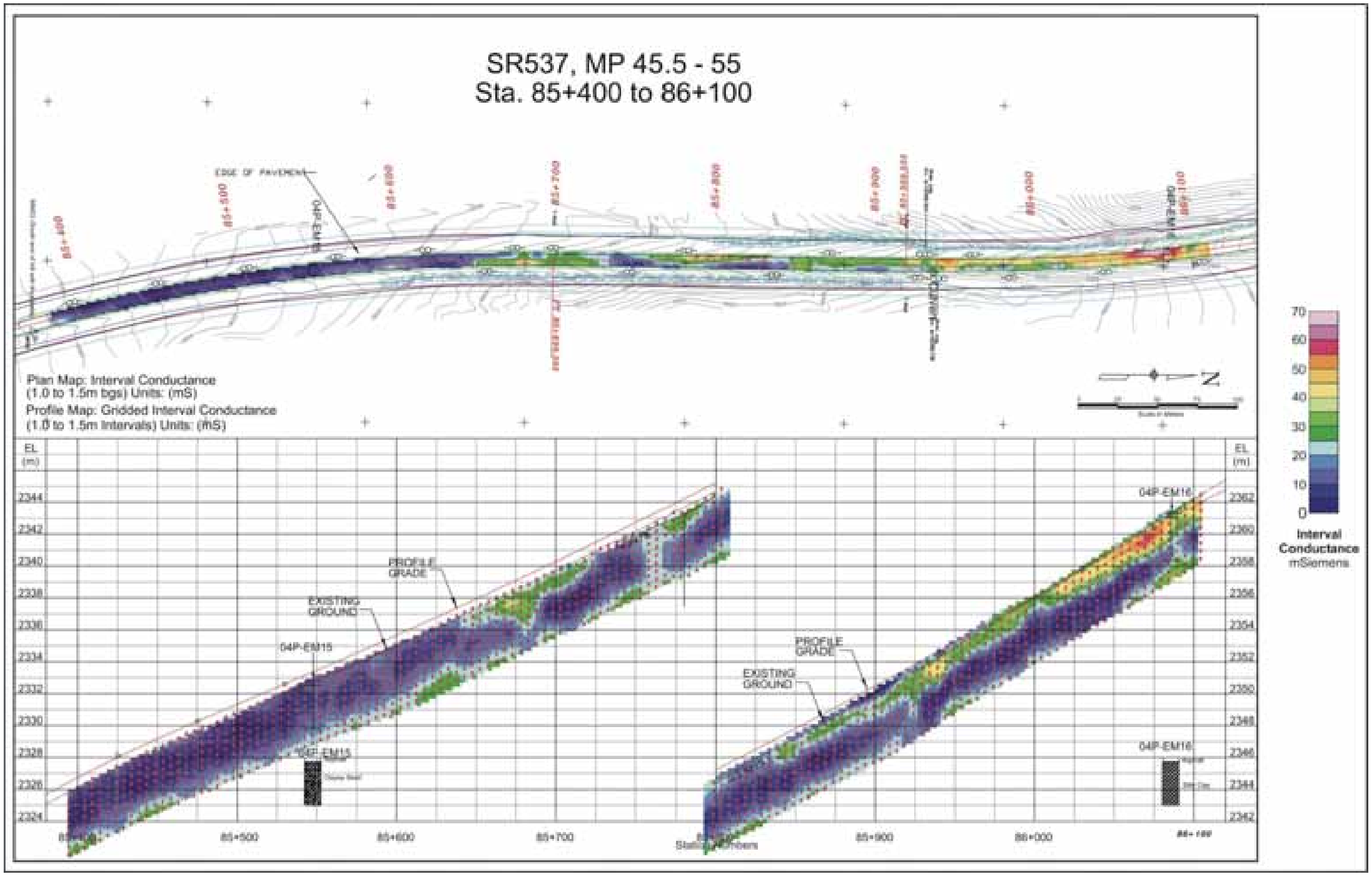

Figure 23. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 85+400 to 86+100).

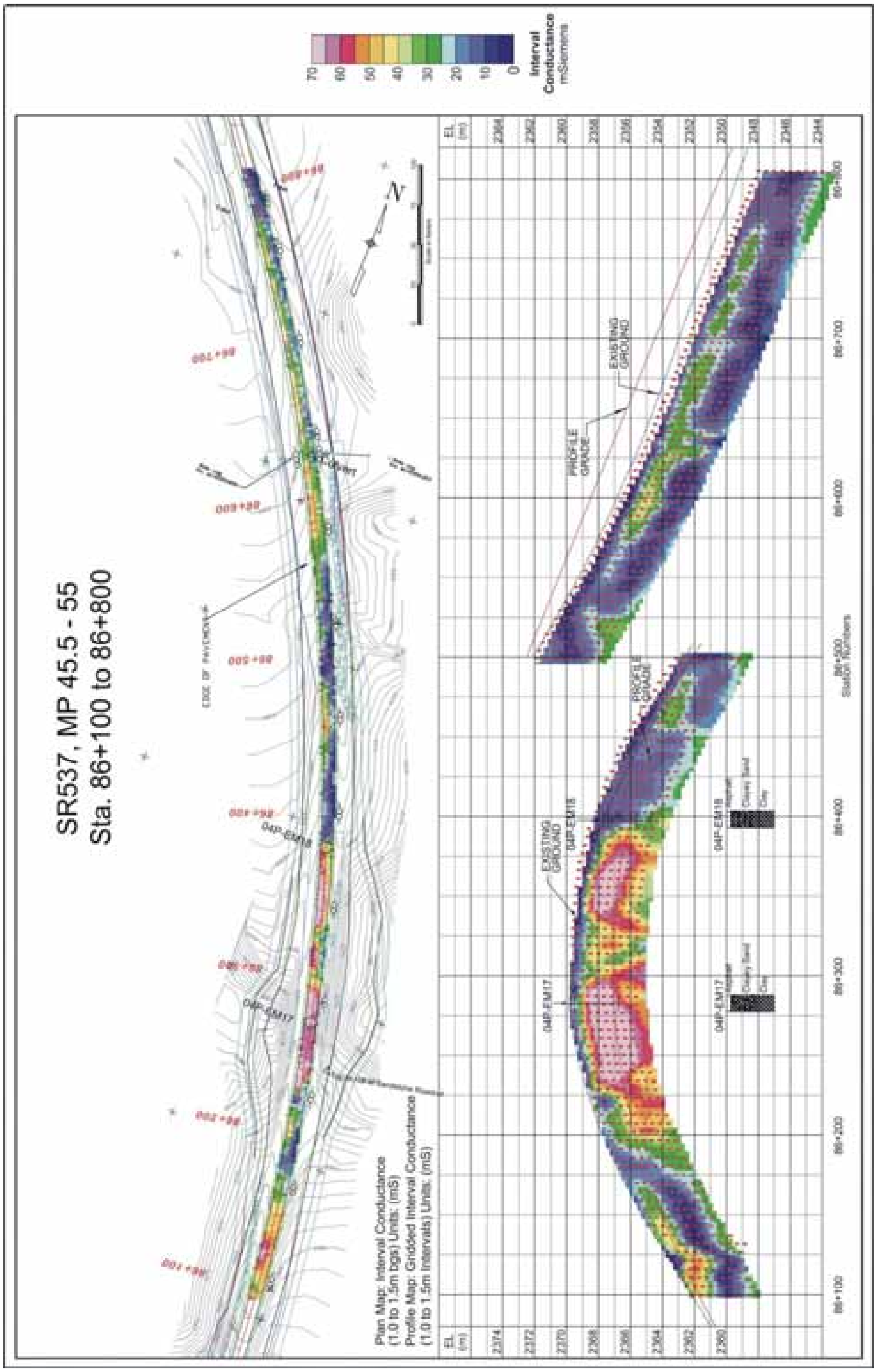

Figure 24. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 86+100 to 86+800).

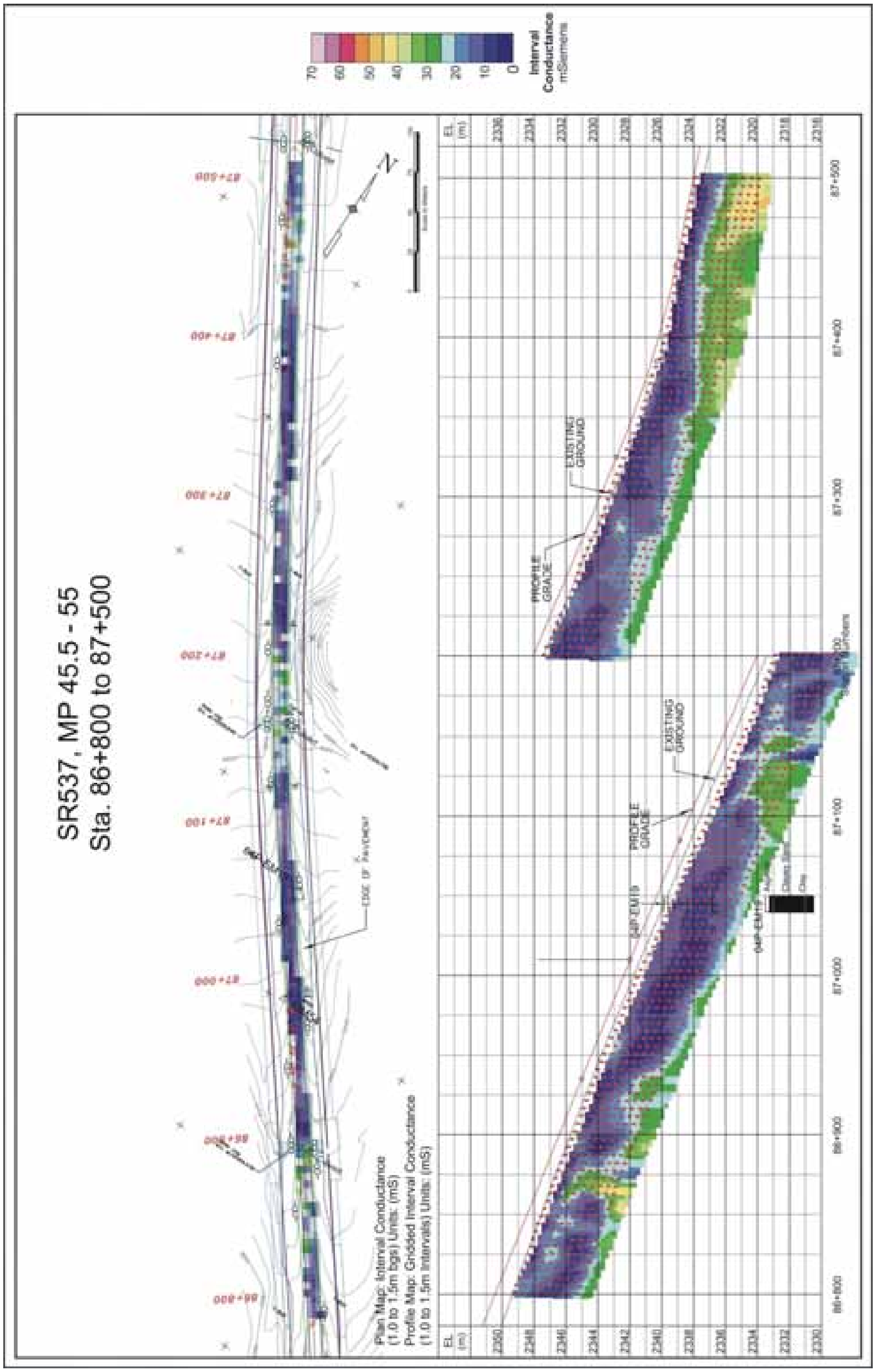

Figure 25. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 86+800 to 87+500).

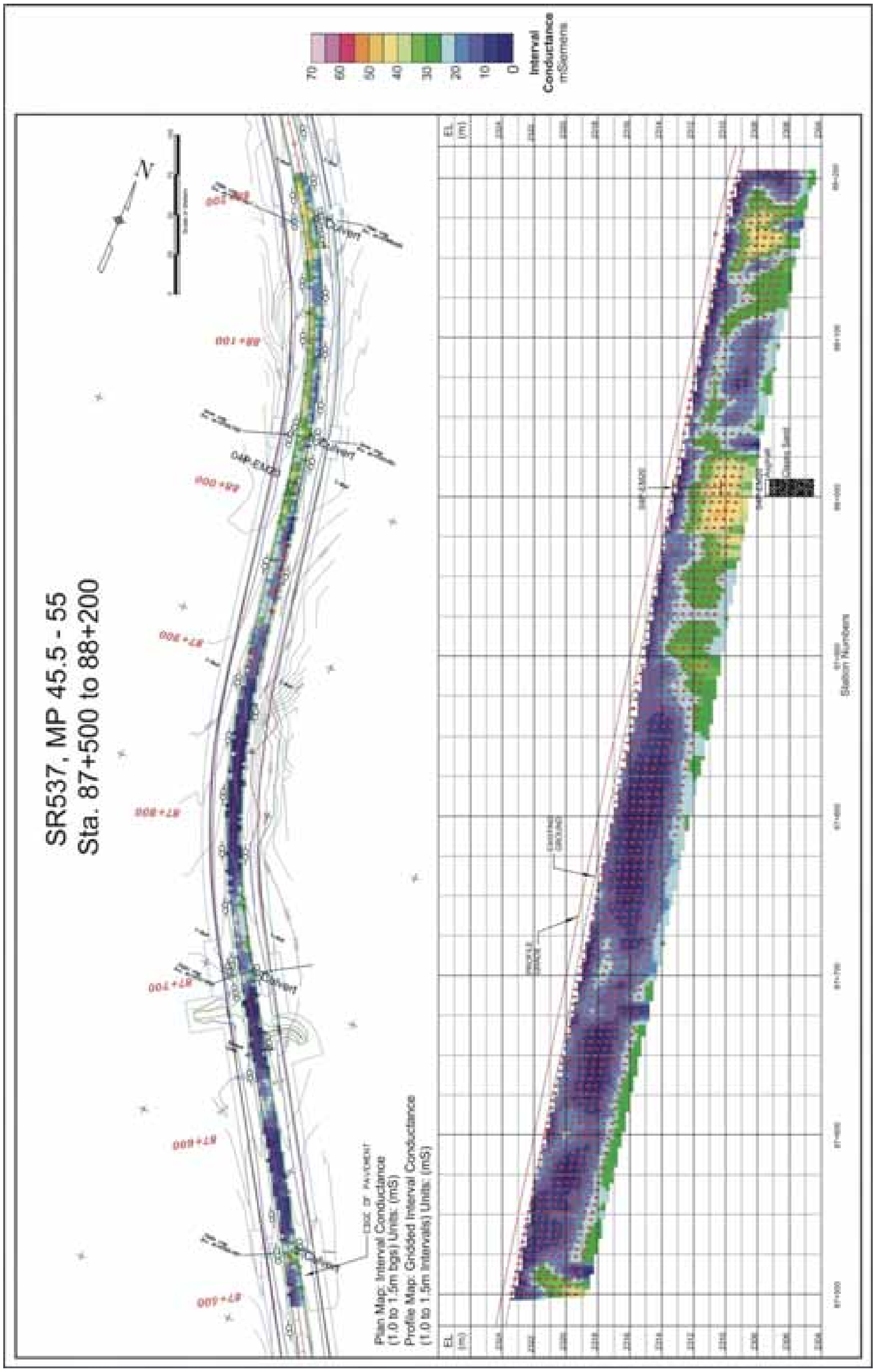

Figure 26. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 87+500 to 88+200).

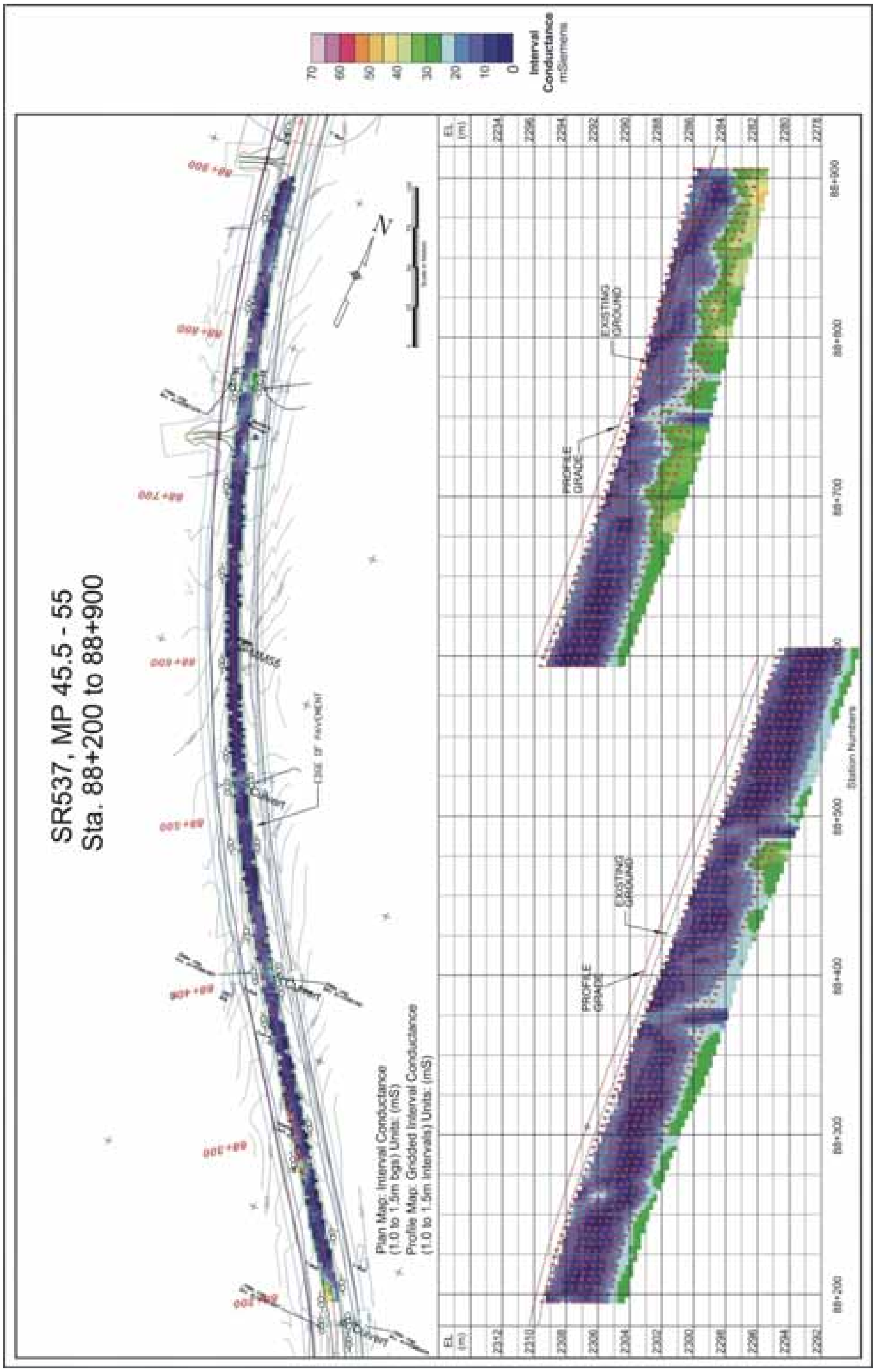

Figure 27. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 88+200 to 88+900).

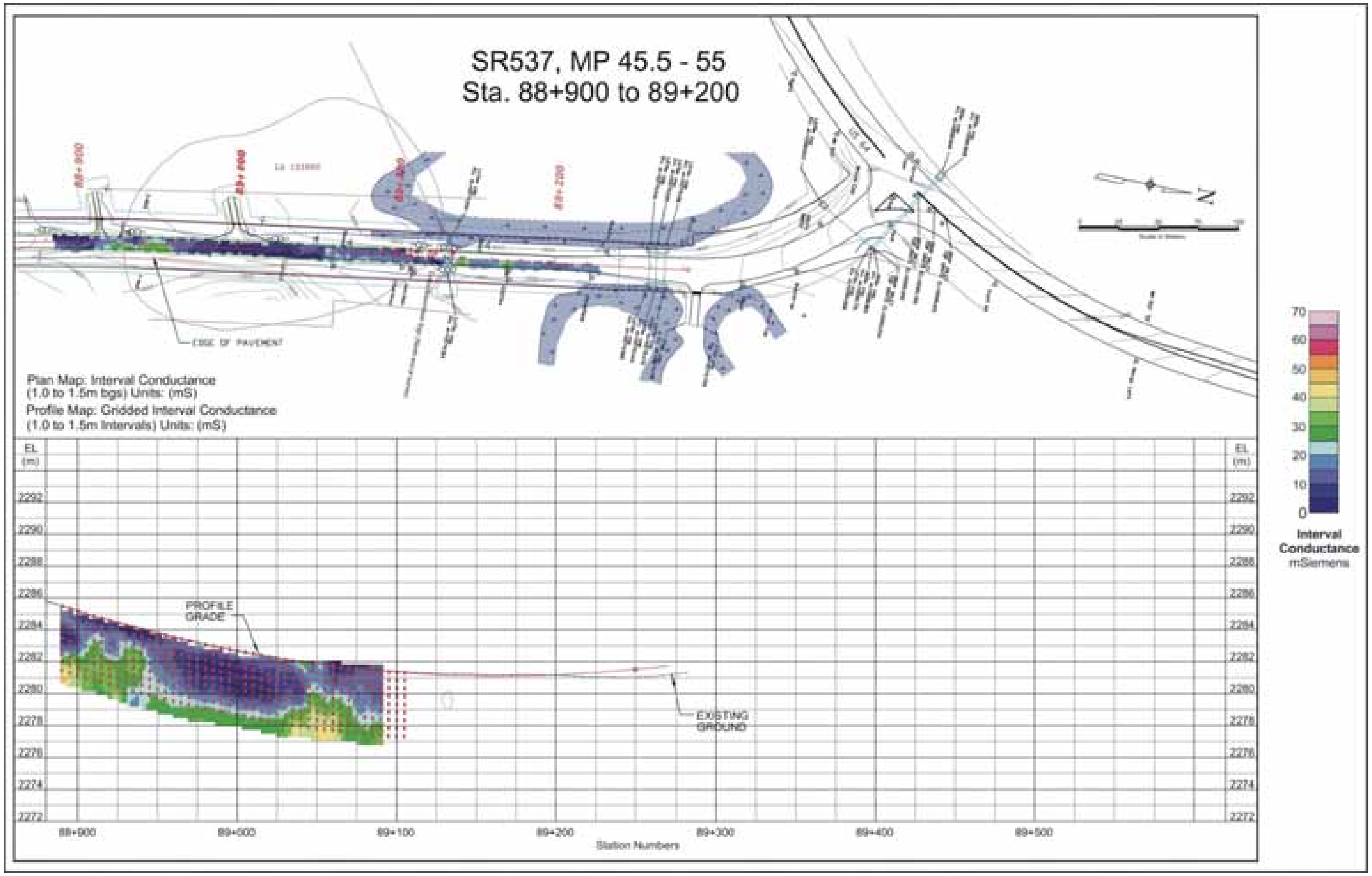

Figure 28. Plan and Profile Maps. Inverted EM31 –3 Data (Stat. 88+900 to 89+200).

APPENDIX B – COMPARISON PLOTS OF THE LAB SOIL ANALYSIS DATA AND THE EMI GEOPHYSICAL DATA FROM THE 0.9 TO 1.5 m GRAB SAMPLE, DULCE, NEW MEXICO.

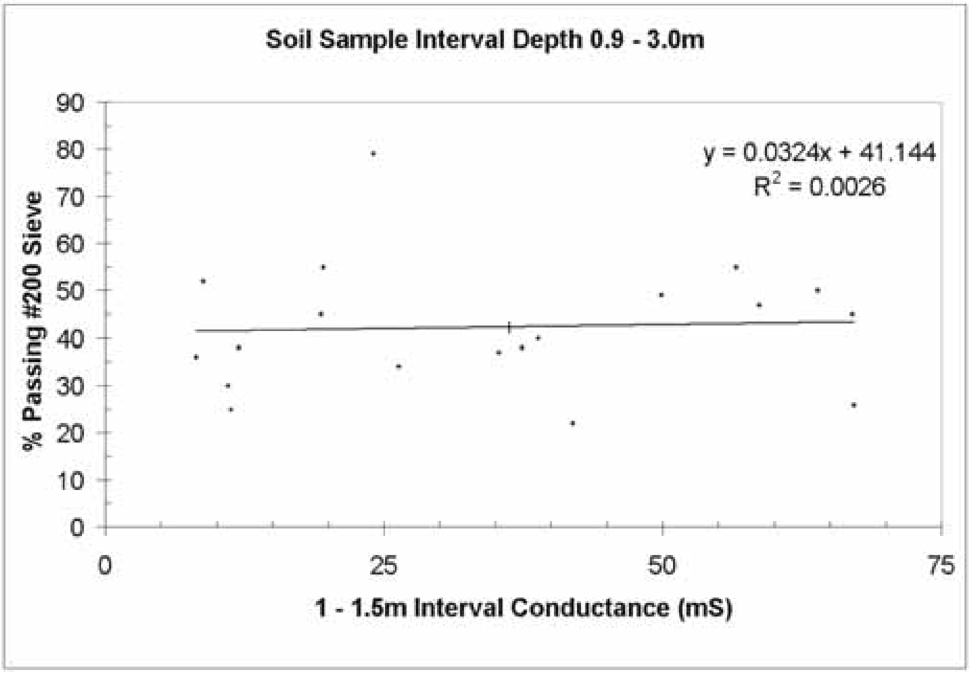

Figure 29. Graph. Dulce. 1-1.5 m Interval Conductance vs. Fines Percentage.

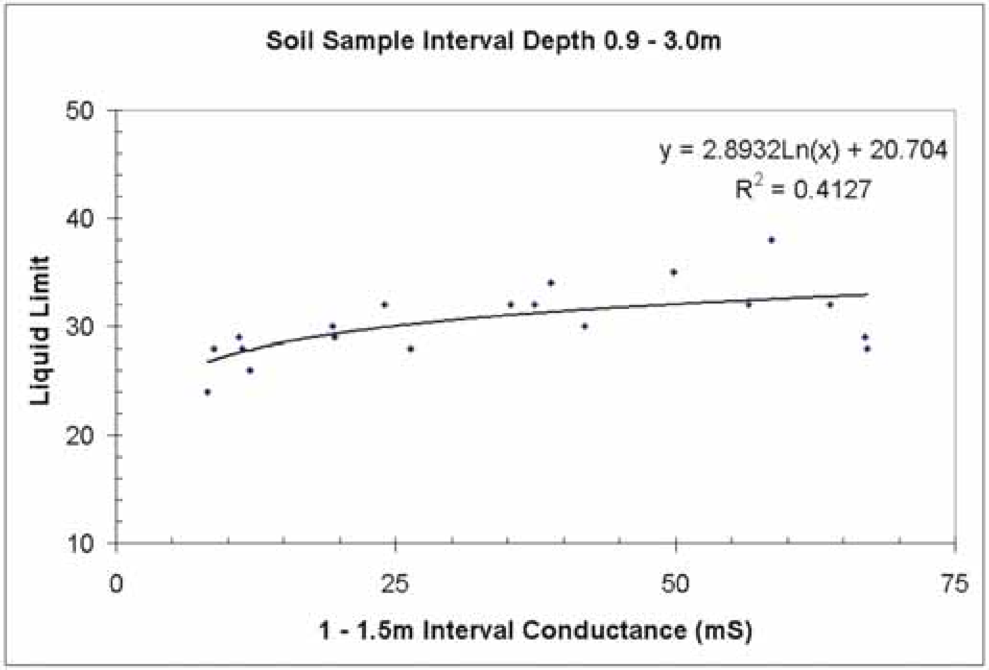

Figure 30. Graph. Dulce. 1-1.5 m Interval Conductance vs. Liquid Limit.

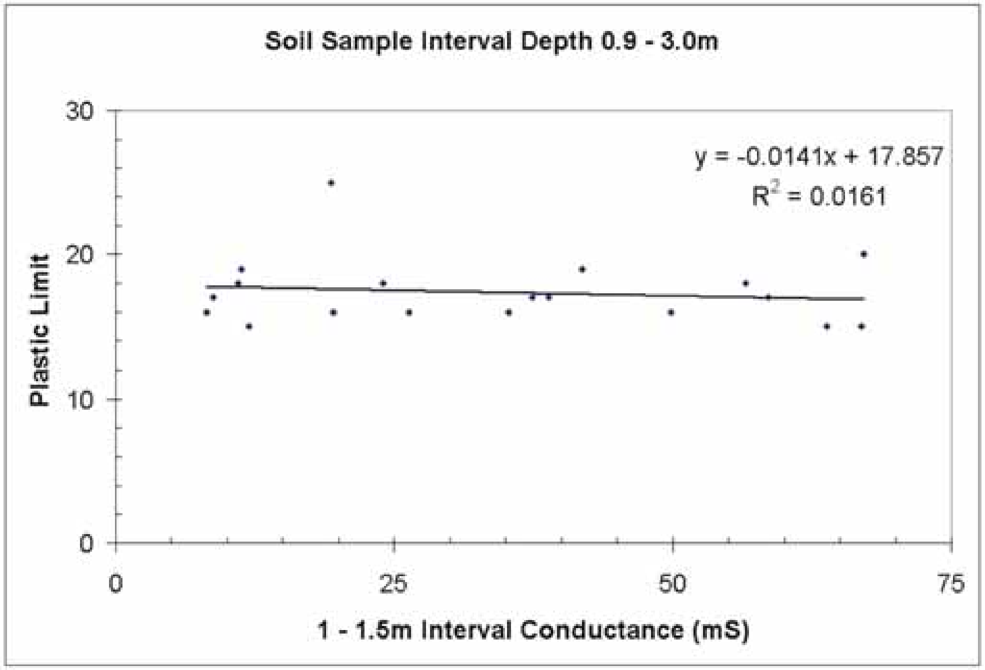

Figure 31. Graph. Dulce. 1-1.5 m Interval Conductance vs. Plastic Limit.

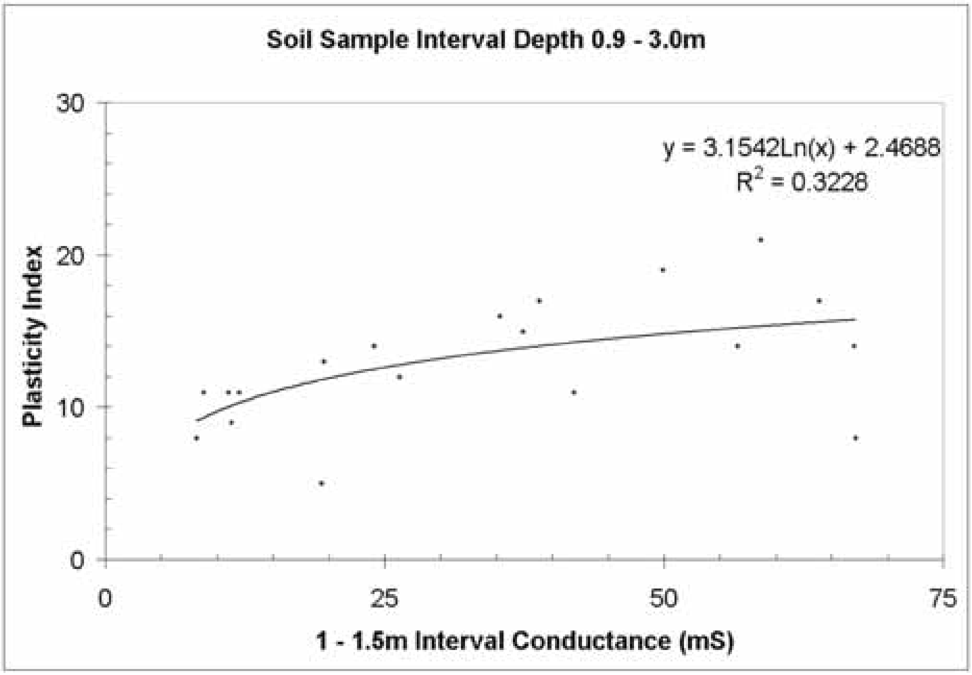

Figure 32. Graph. Dulce. 1-1.5 m Interval Conductance vs. Plasticity Index.

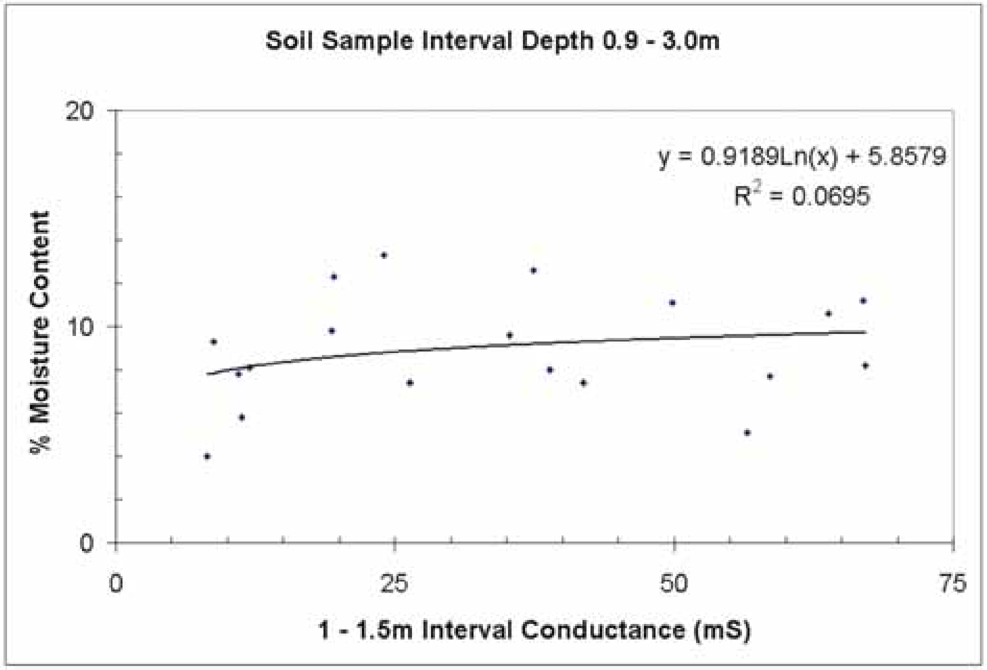

Figure 33. Graph. Dulce. 1-1.5 m Interval Conductance vs. Moisture Content.

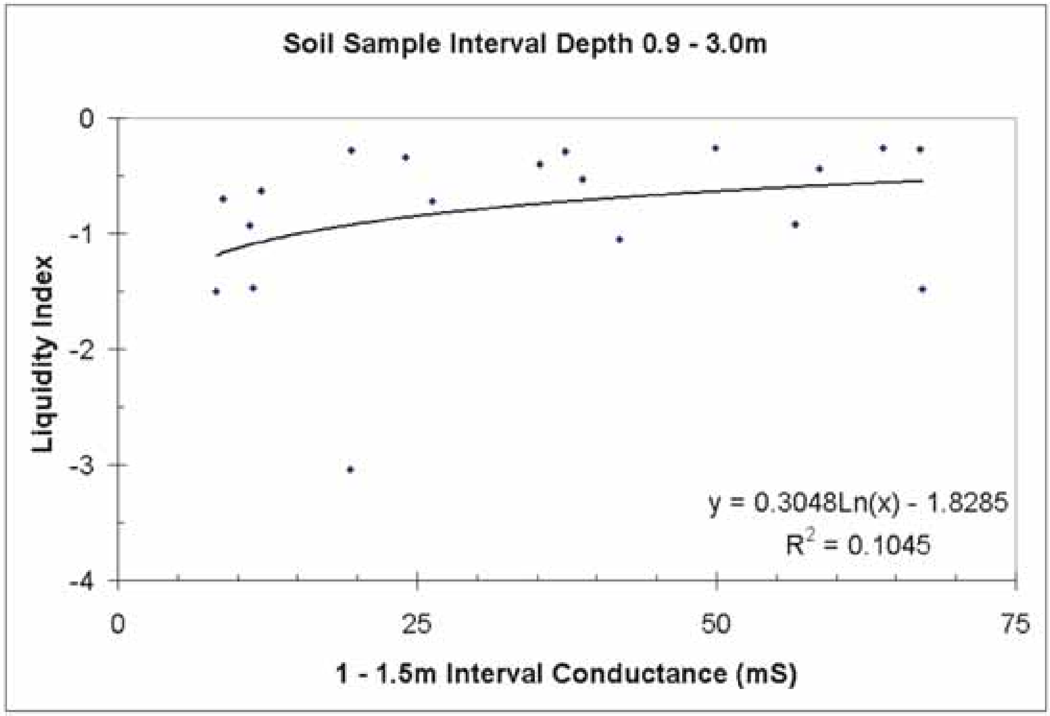

Figure 34. Graph. Dulce. 1-1.5 m Interval Conductance vs. Liquidity Index.

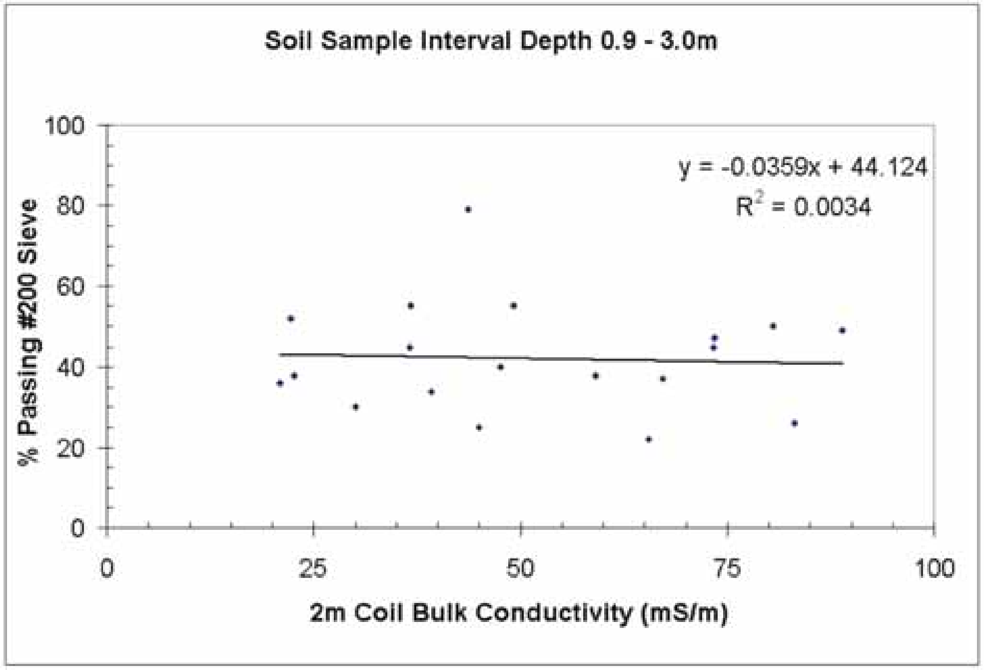

Figure 35. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Fines Percentage.

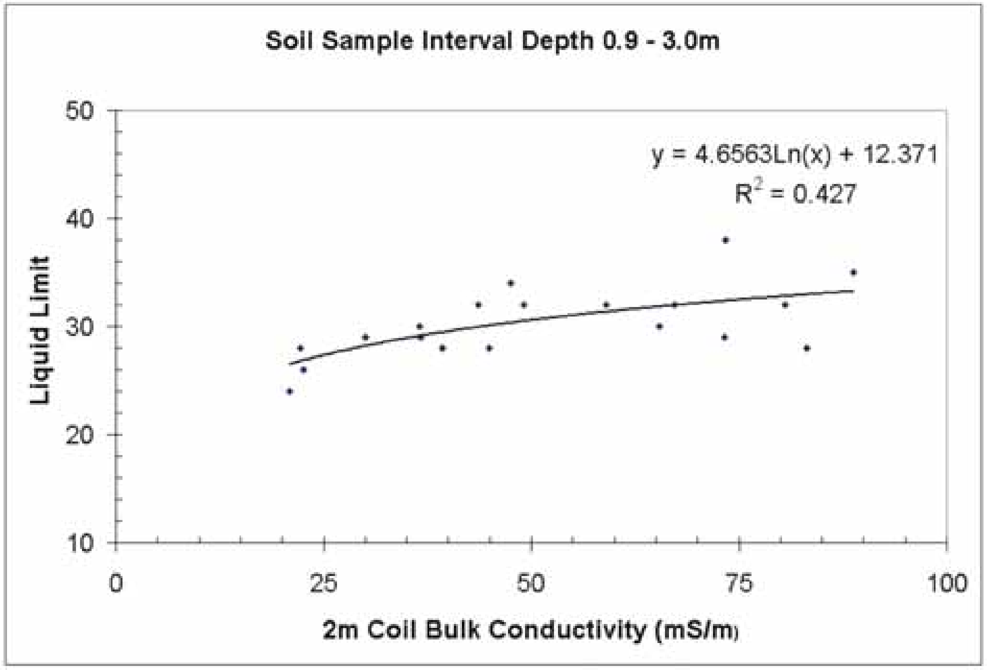

Figure 36. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Liquid Limit.

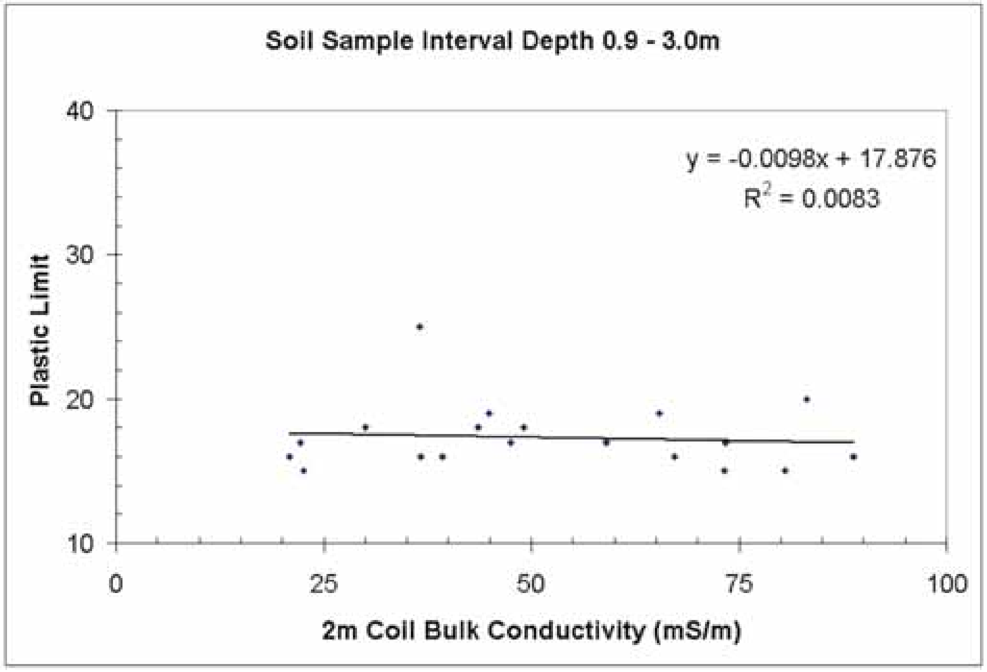

Figure 37. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Plastic Limit.

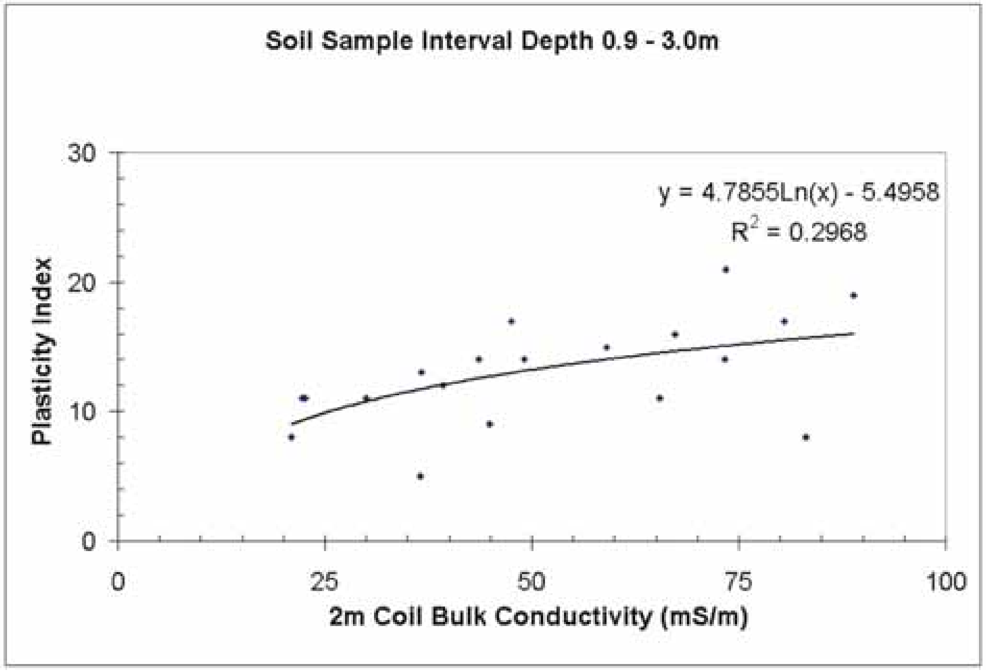

Figure 38. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Plasticity Index.

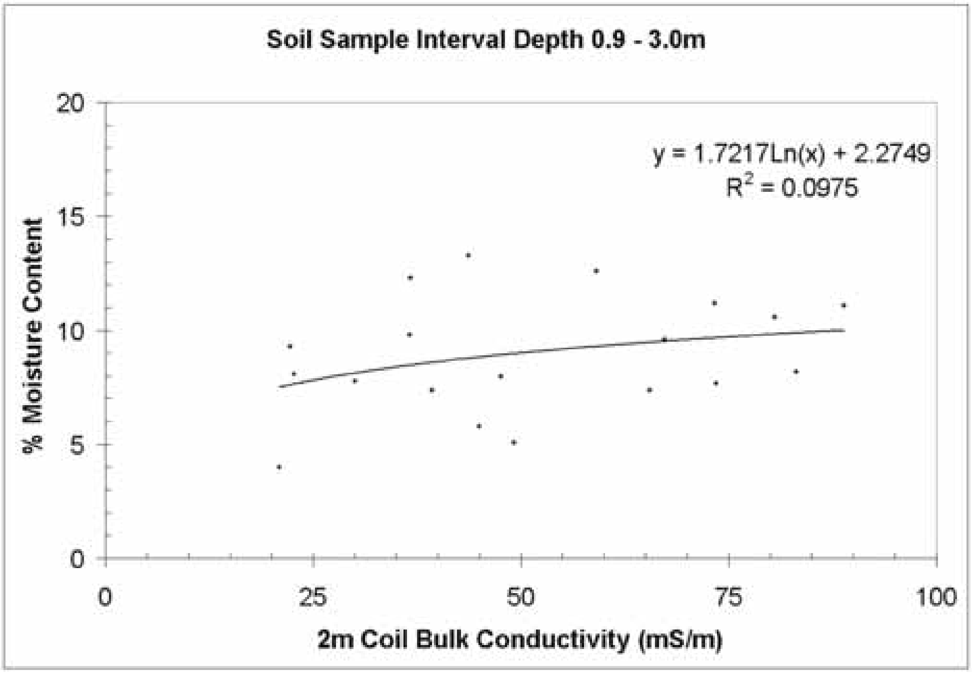

Figure 39. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Moisture Content.

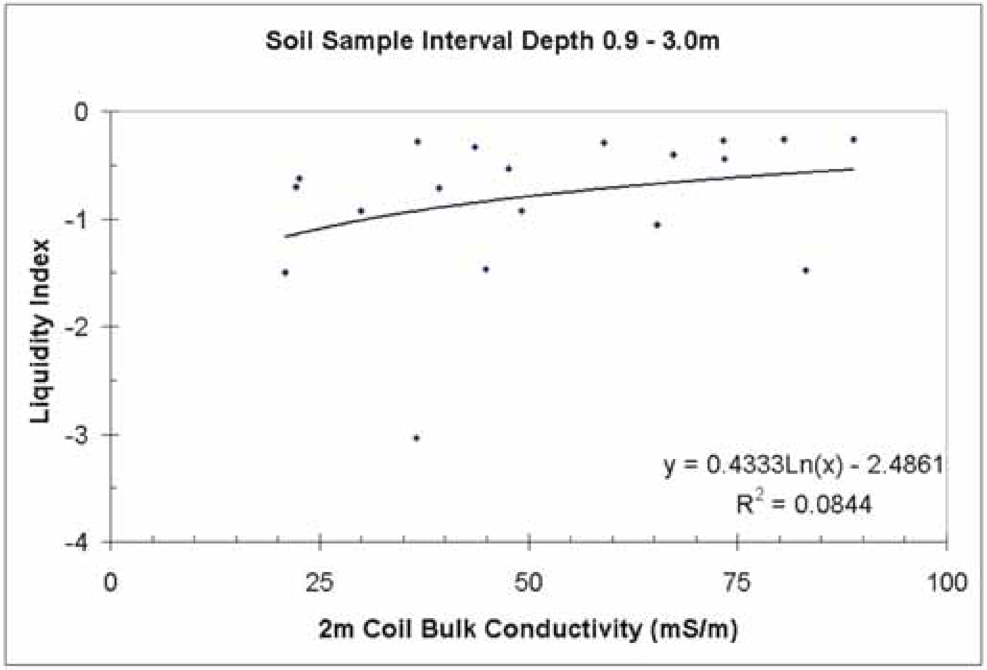

Figure 40. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Liquidity Index.

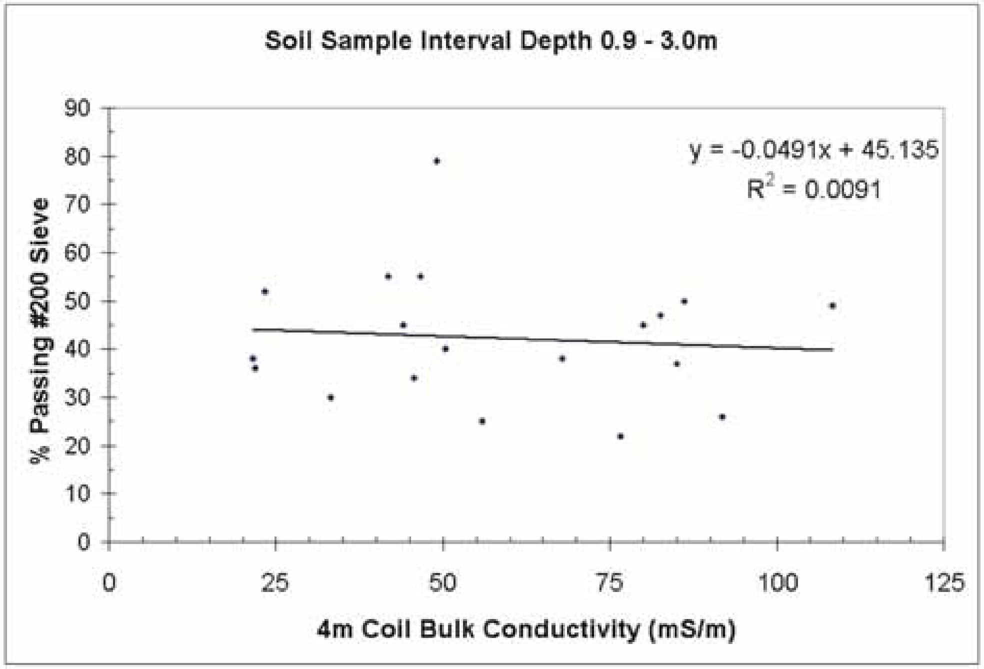

Figure 41. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Fines Percentage.

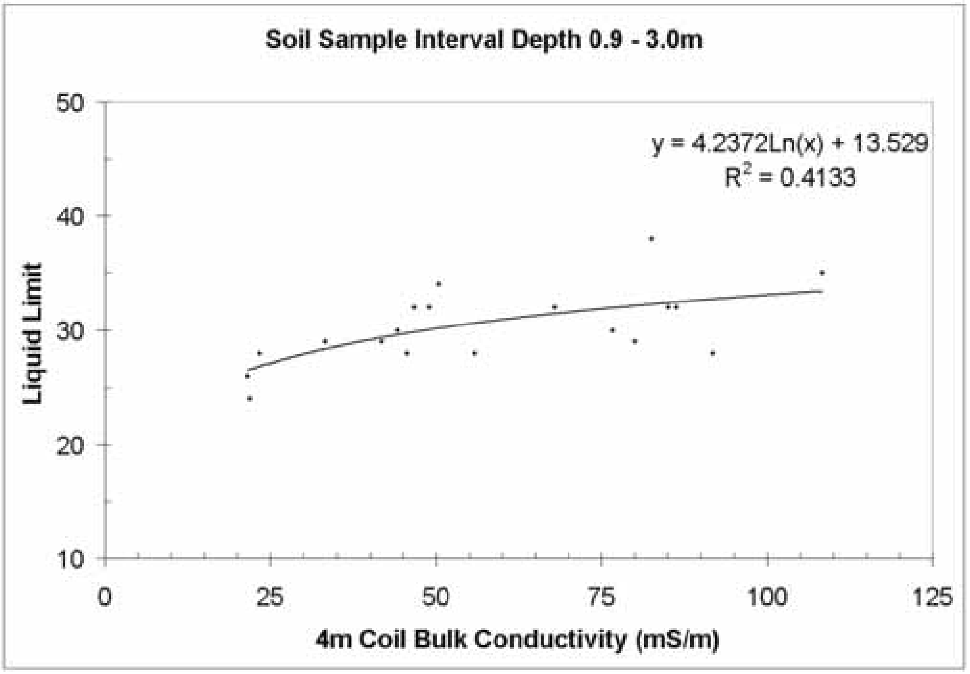

Figure 42. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Liquid Limit.

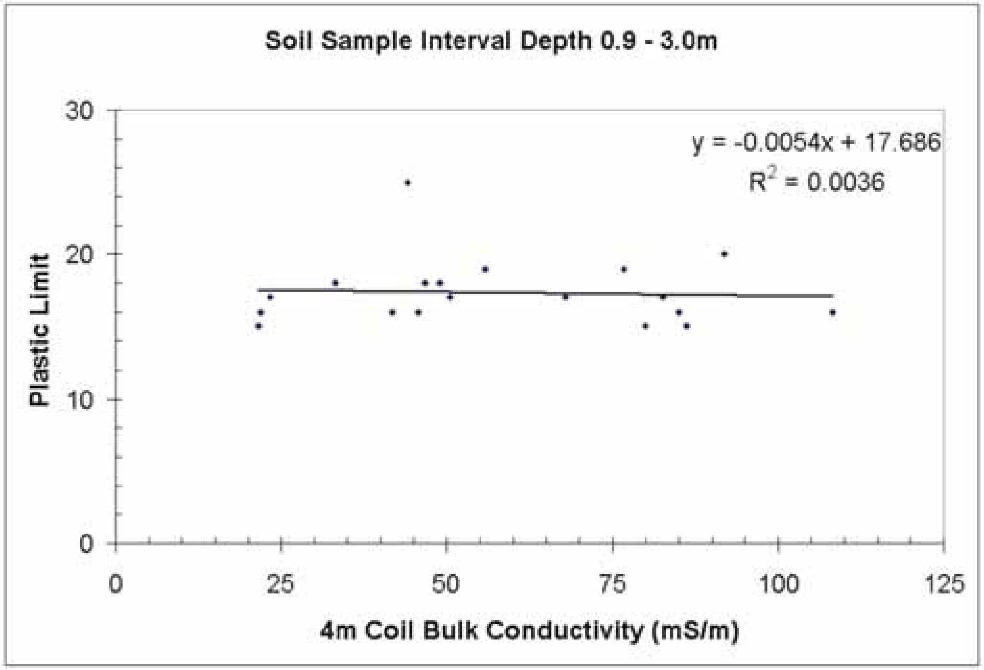

Figure 43. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Plastic Limit.

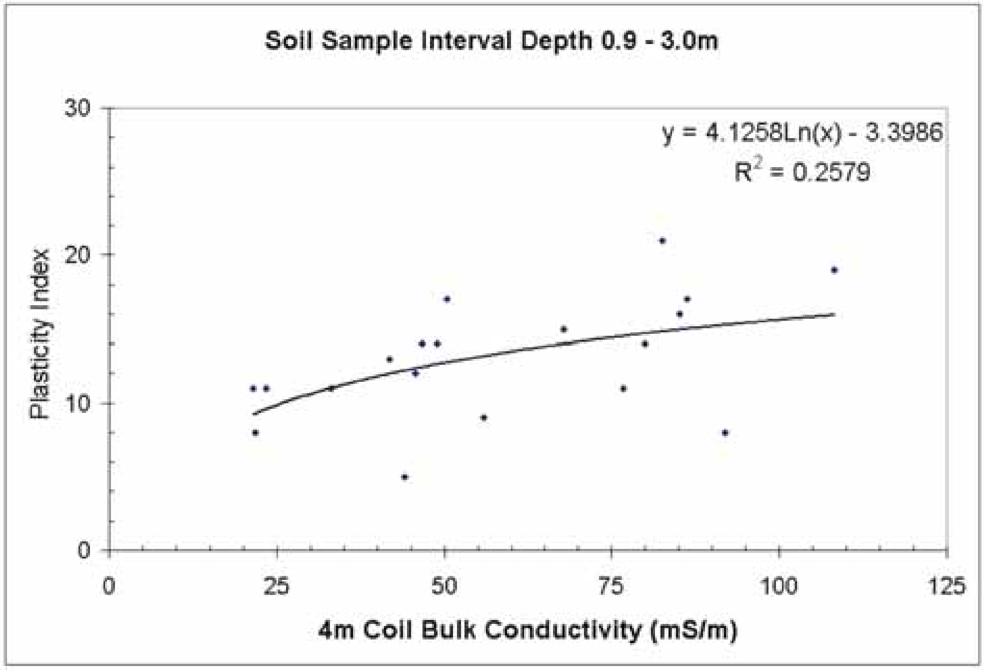

Figure 44. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Plasticity Index.

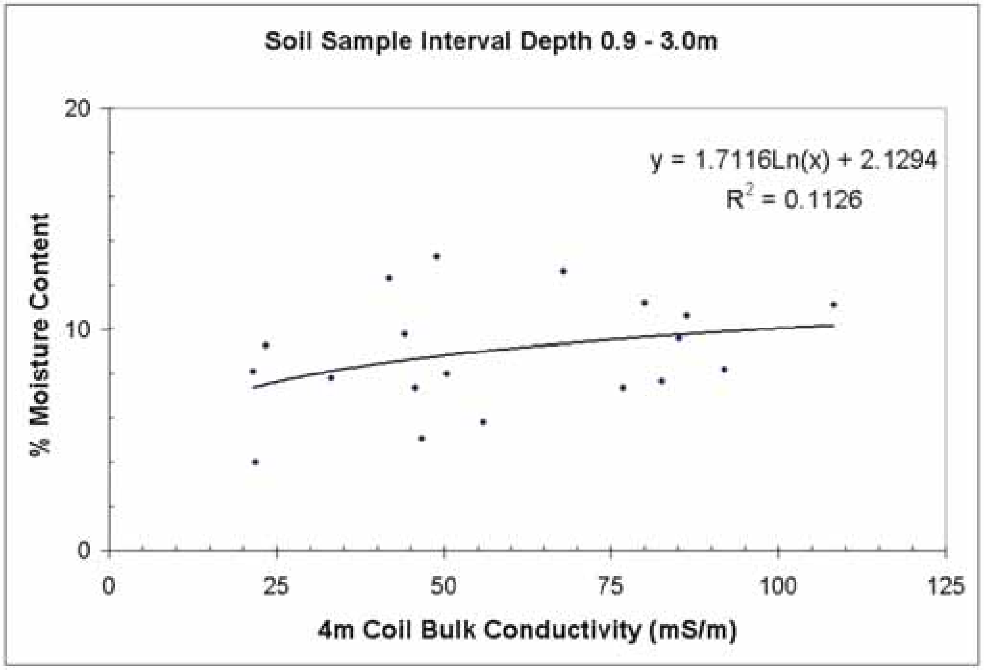

Figure 45. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Moisture Content.

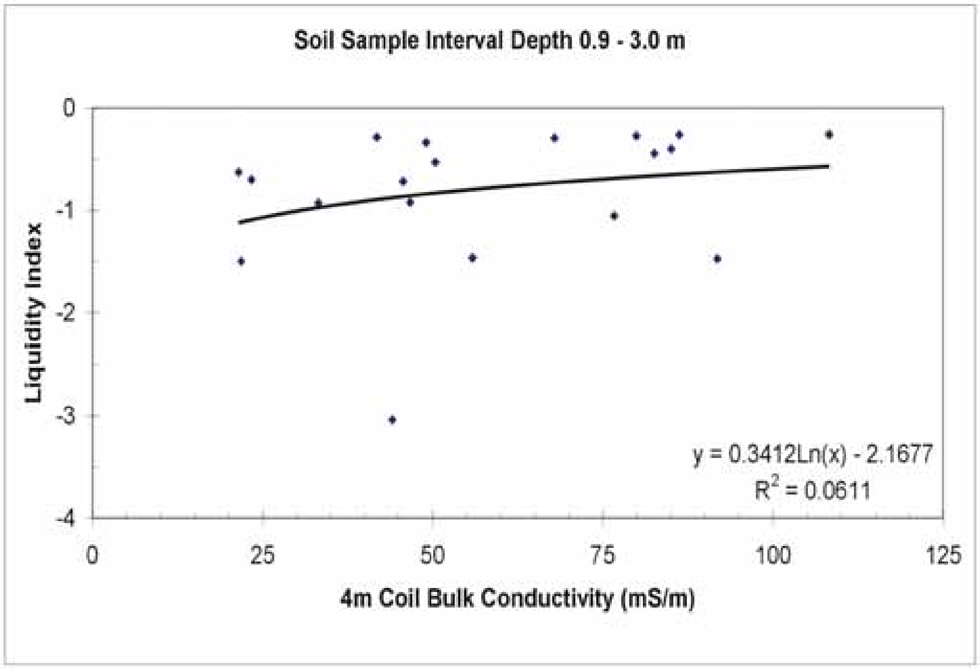

Figure 46. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Liquidity Index.

APPENDIX C – COMPARISON PLOTS OF THE LAB SOIL ANALYSIS DATA AND THE EMI GEOPHYSICAL DATA FROM THE 1.5 TO 3 m GRAB SAMPLE, DULCE, NEW MEXICO.

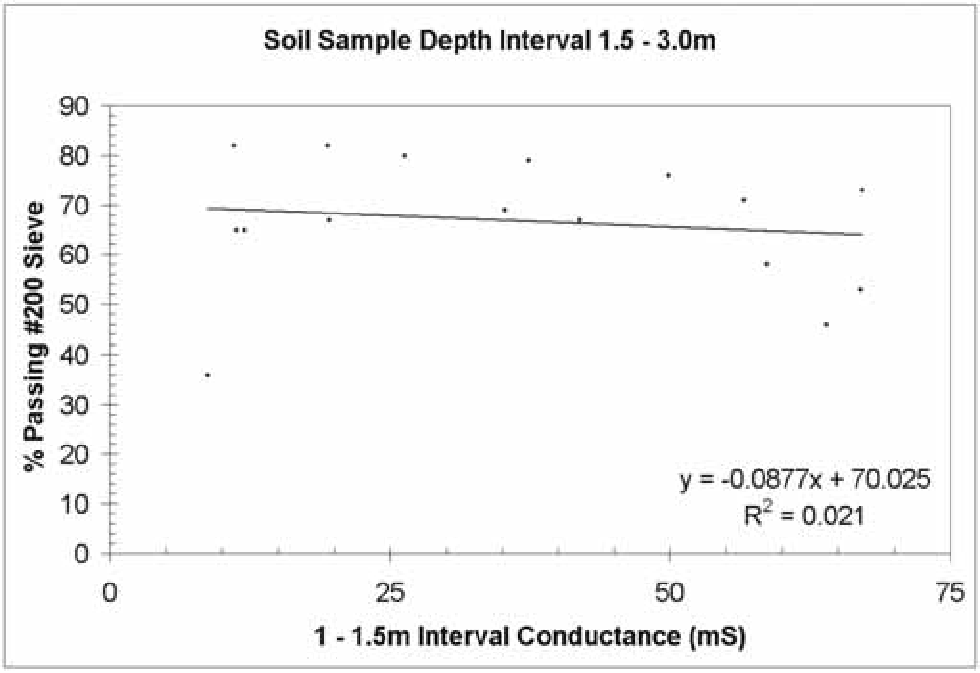

Figure 47. Graph. Dulce. 1-1.5 m Interval Conductance vs. Fines Percentage.

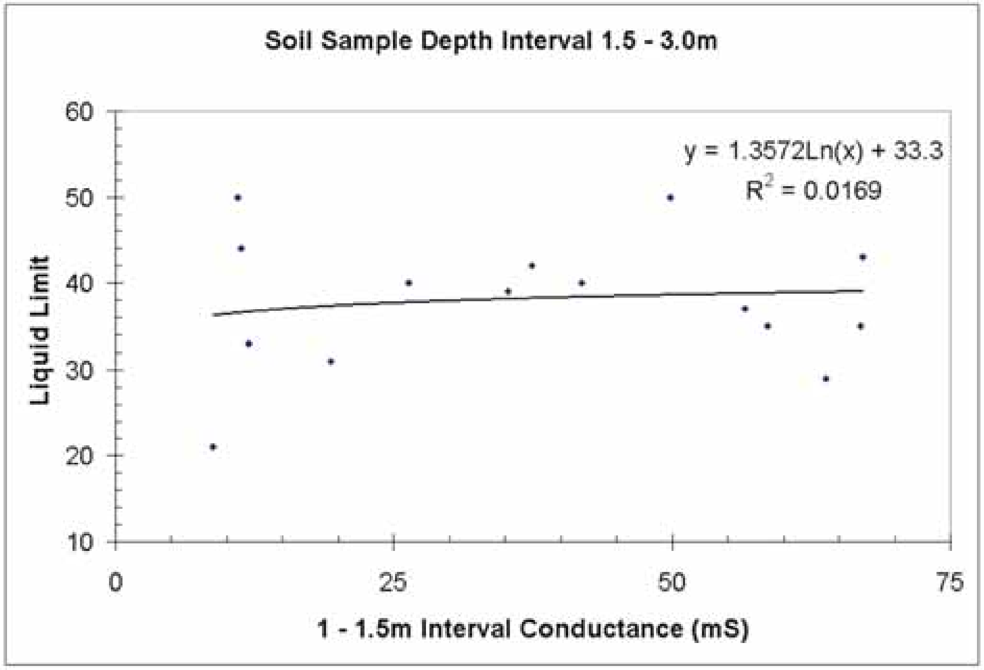

Figure 48. Graph. Dulce. 1-1.5 m Interval Conductance vs. Liquid Limit.

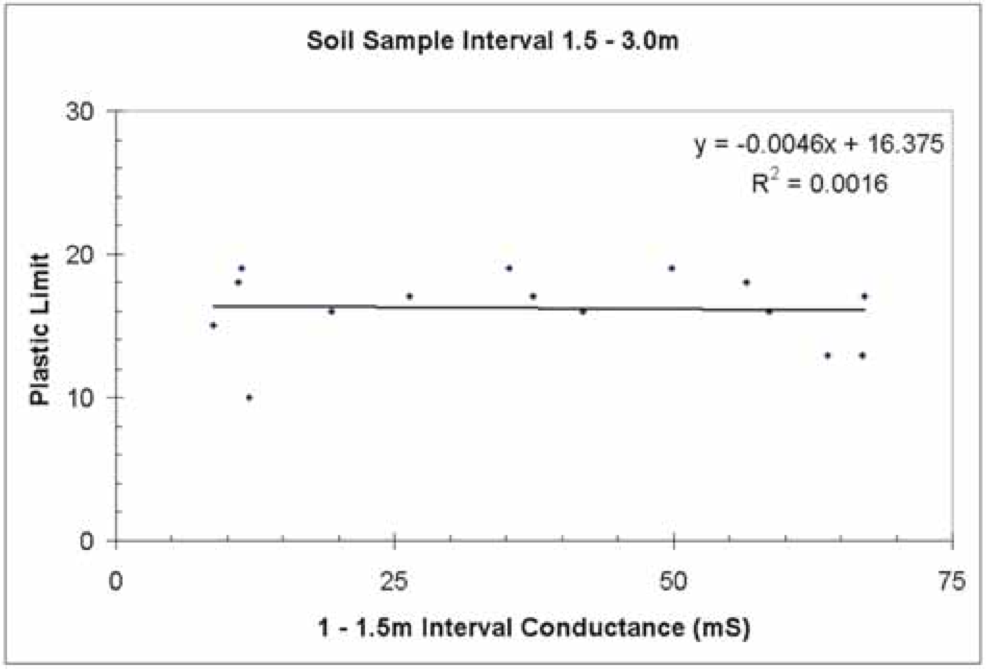

Figure 49. Graph. Dulce. 1-1.5 m Interval Conductance vs. Plastic Limit.

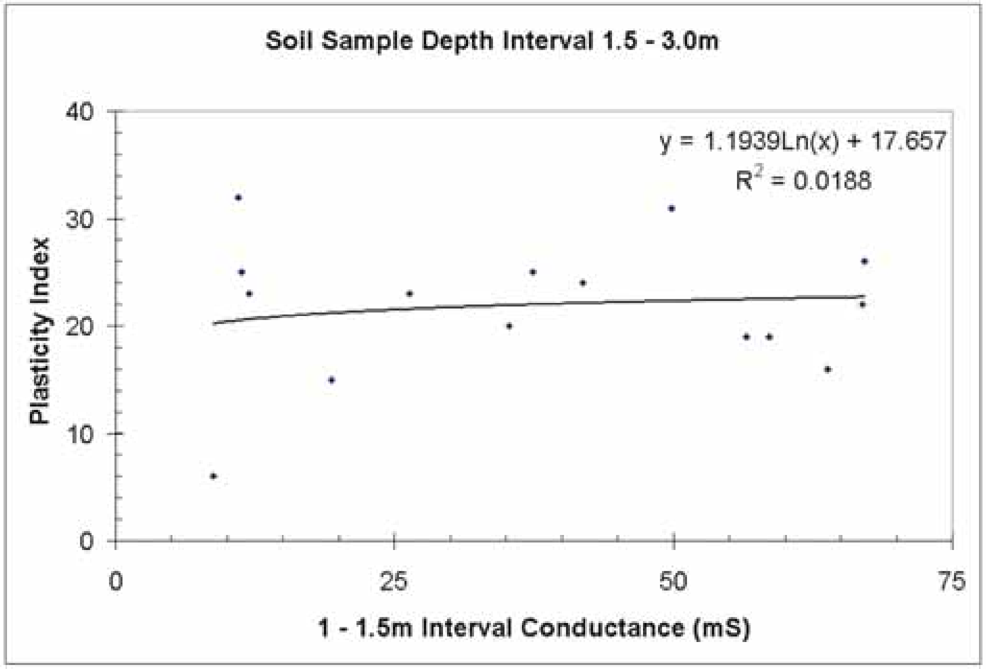

Figure 50. Graph. Dulce. 1-1.5 m Interval Conductance vs. Plasticity Index.

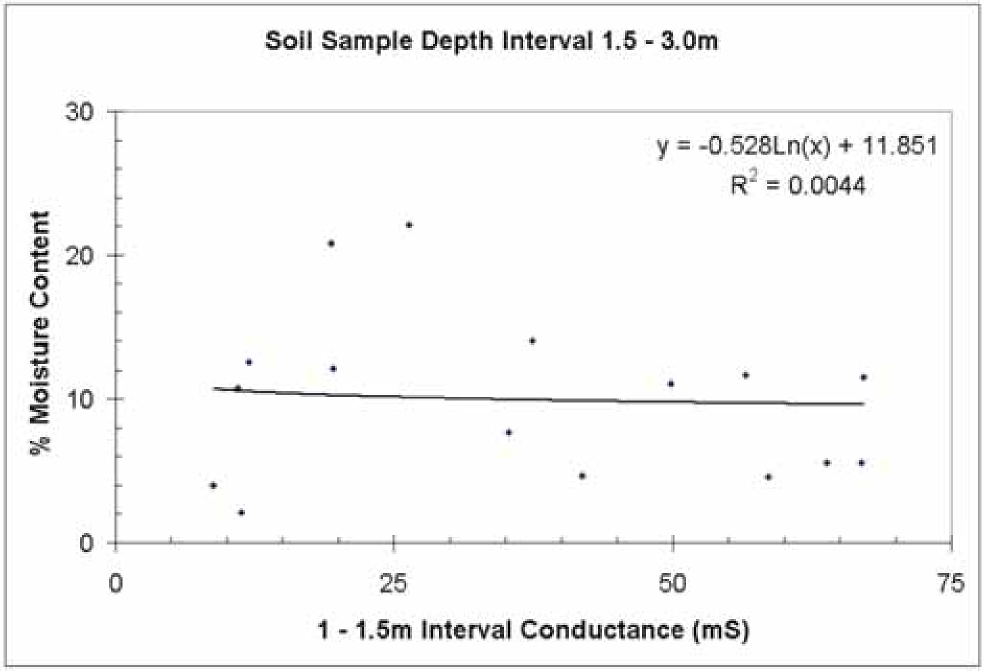

Figure 51. Graph. Dulce. 1-1.5 m Interval Conductance vs. Moisture Content.

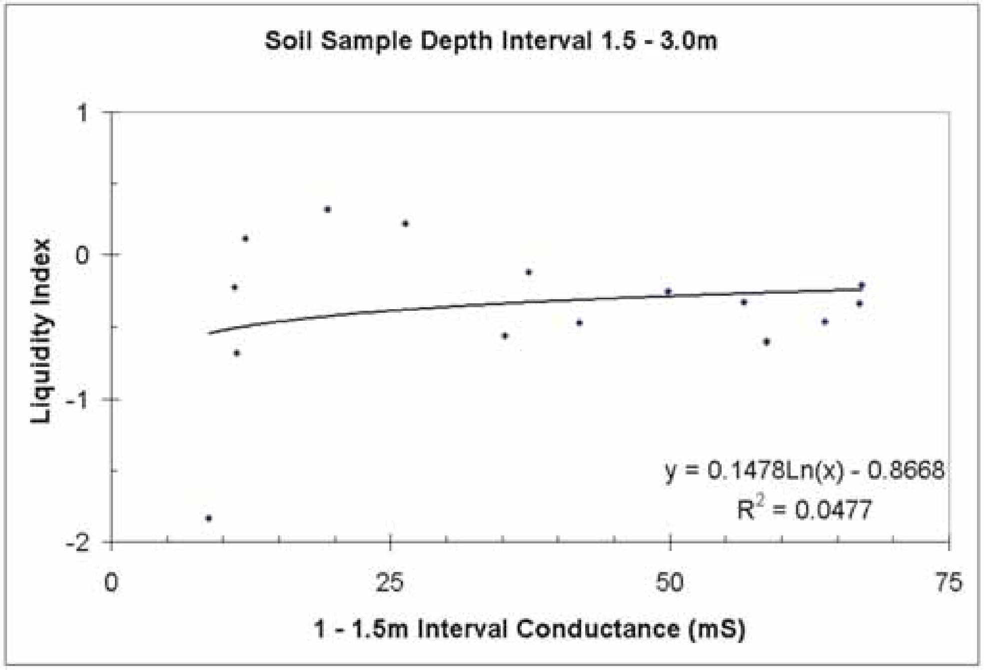

Figure 52. Graph. Dulce. 1-1.5 m Interval Conductance vs. Liquidity Index.

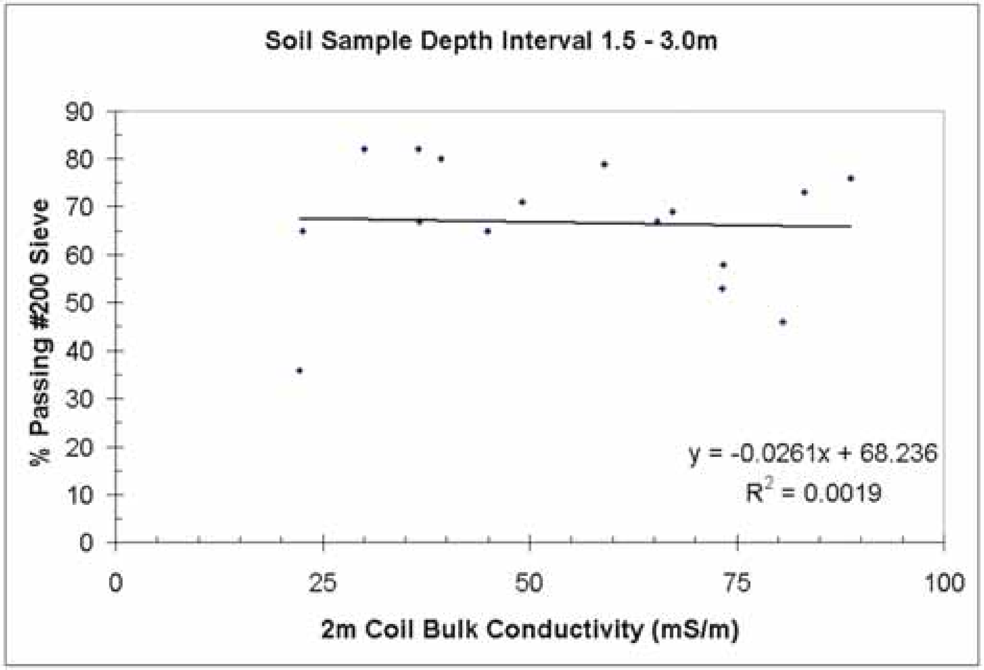

Figure 53. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Fines Percentage.

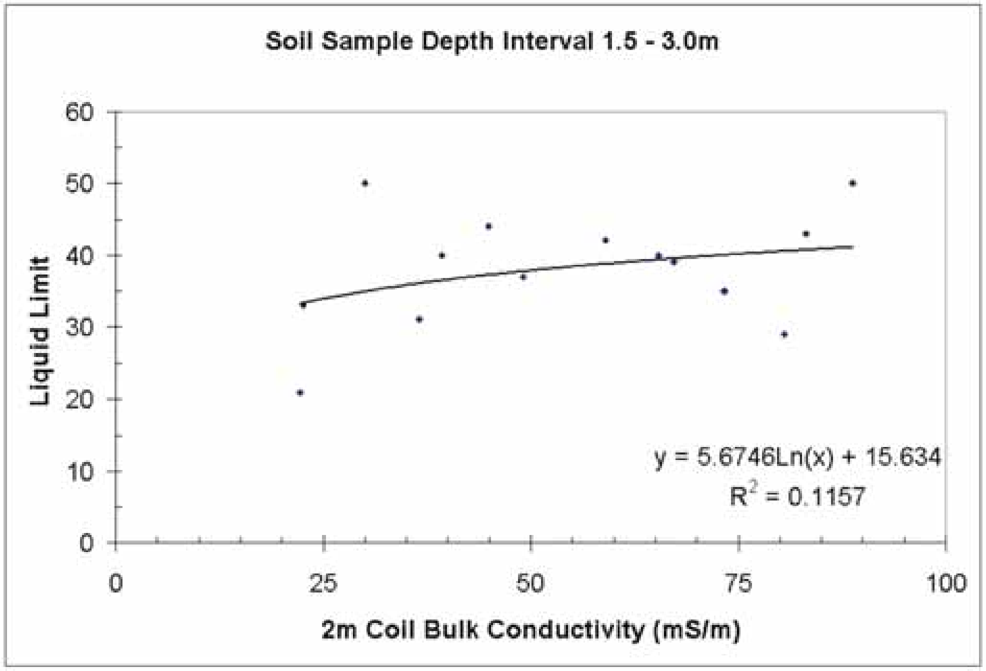

Figure 54. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Liquid Limit.

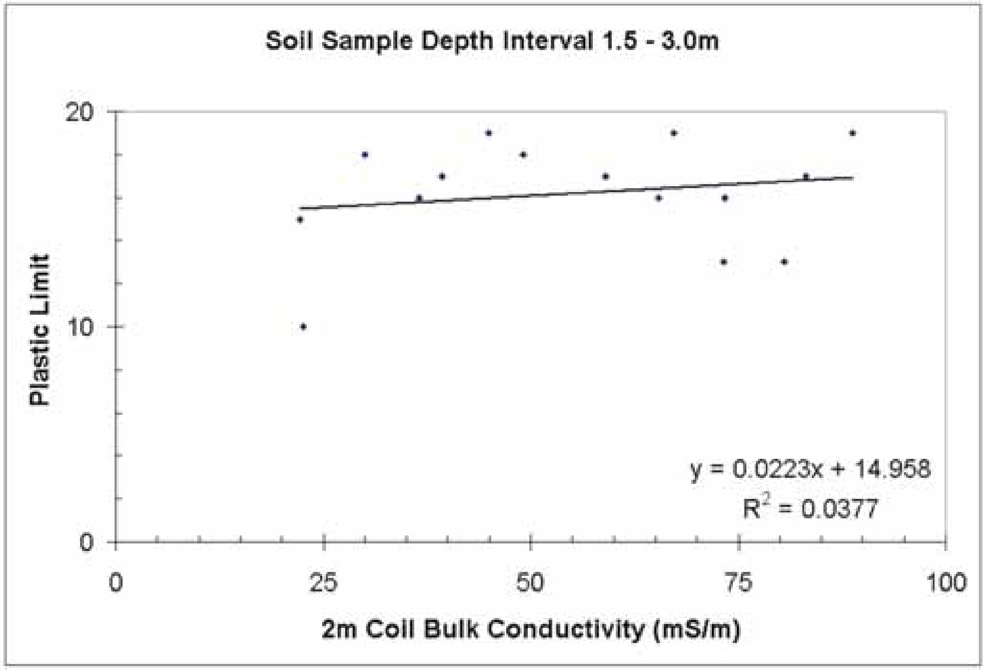

Figure 55. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Plastic Limit.

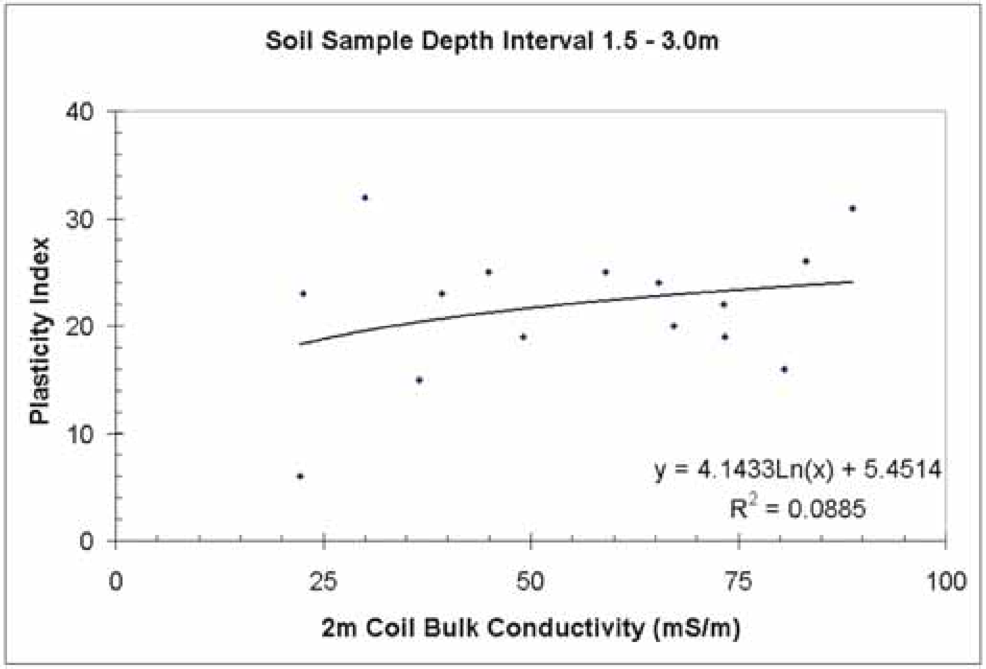

Figure 56. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Plasticity Index.

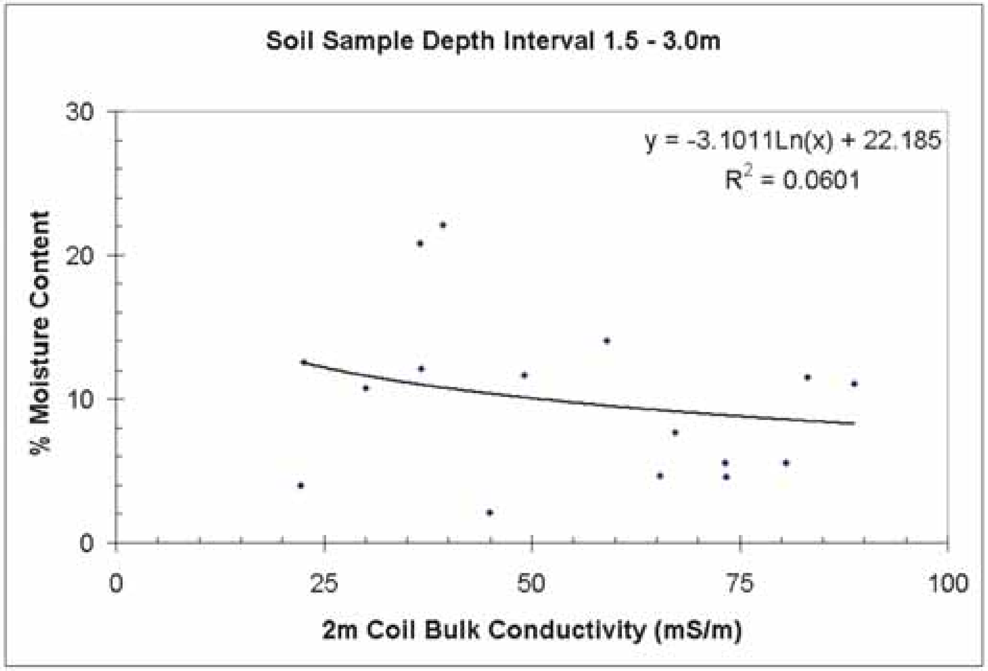

Figure 57. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Moisture Content.

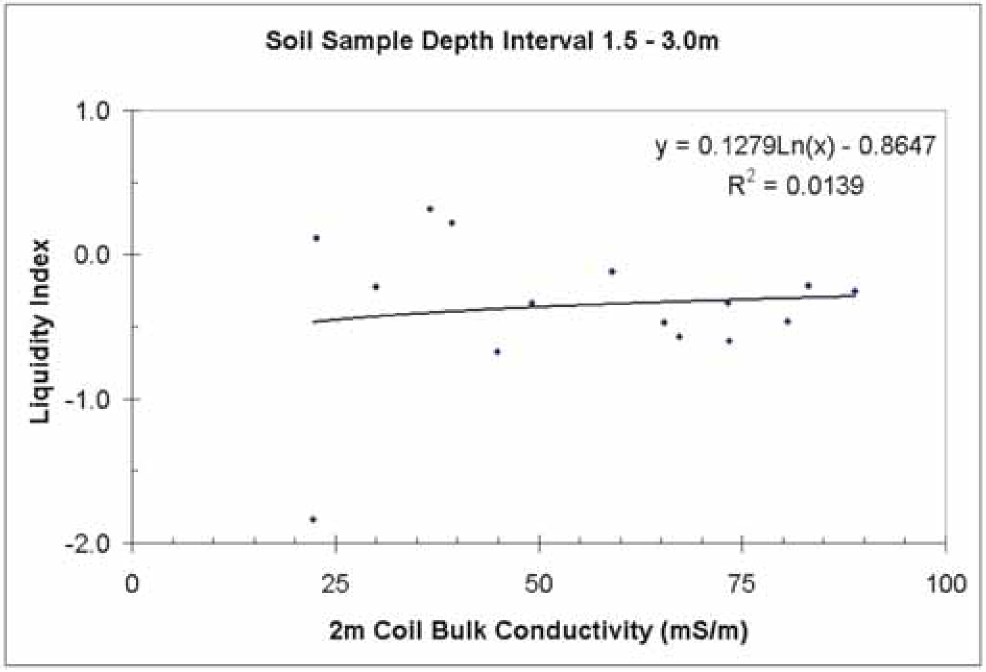

Figure 58. Graph. Dulce. 2 m Coil Bulk Conductivity vs. Liquidity Index.

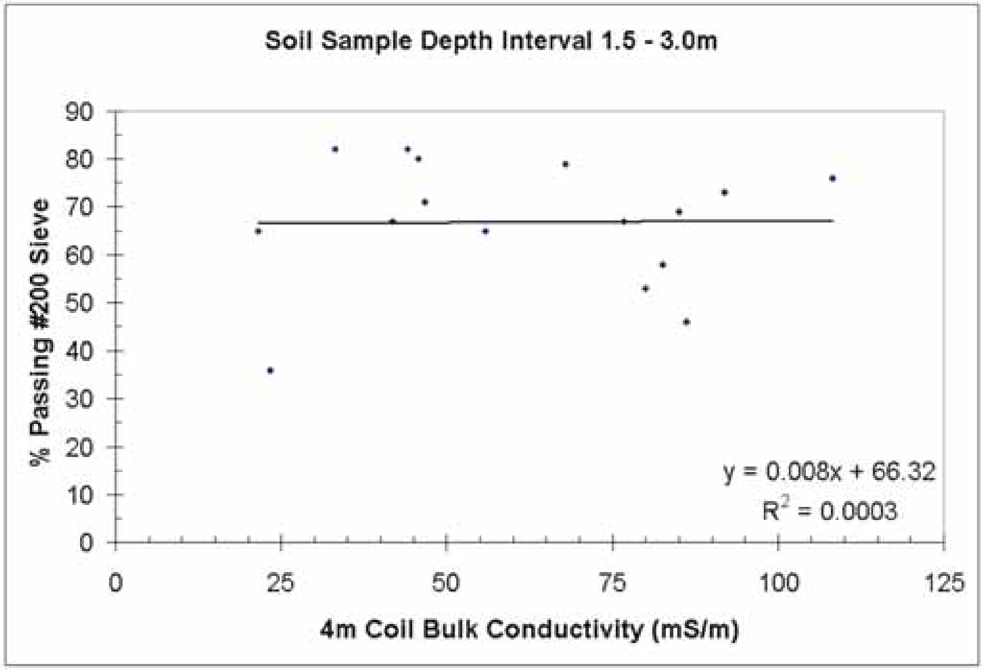

Figure 59. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Fines Percentage.

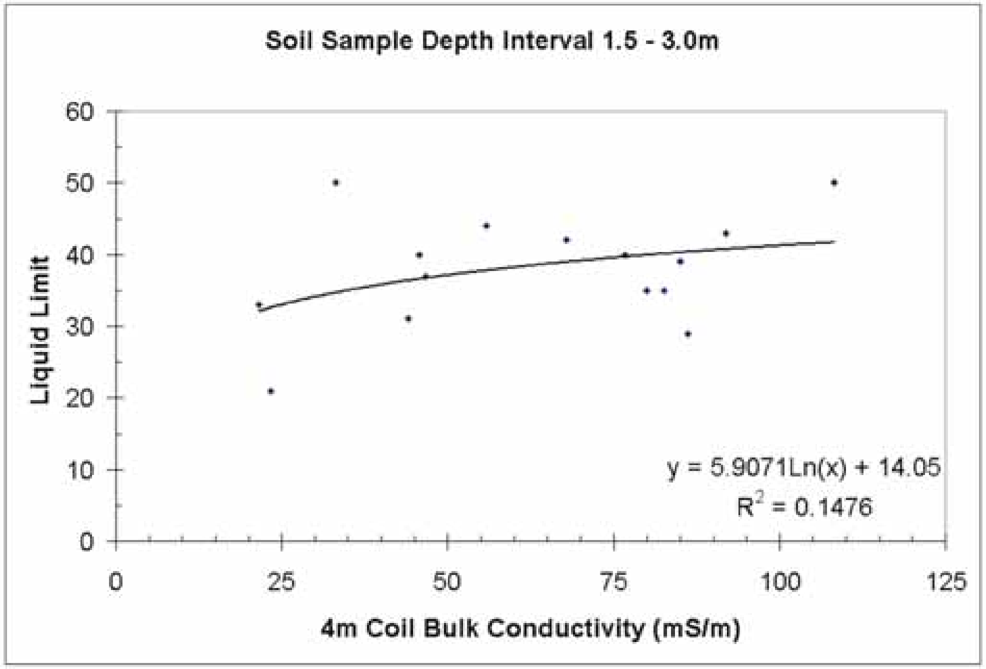

Figure 60. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Liquid Limit.

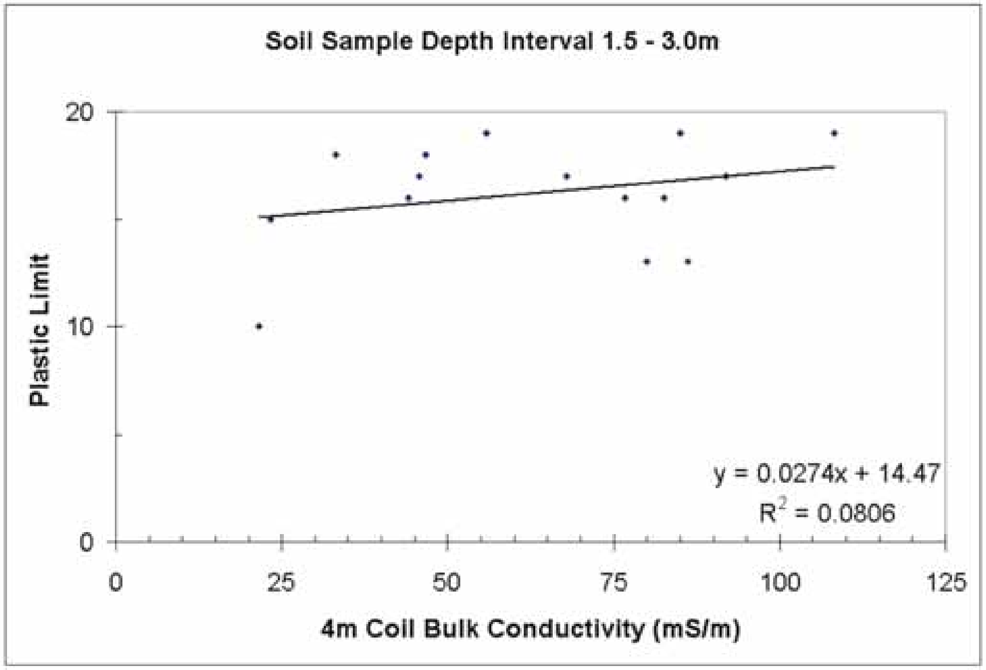

Figure 61. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Plastic Limit.

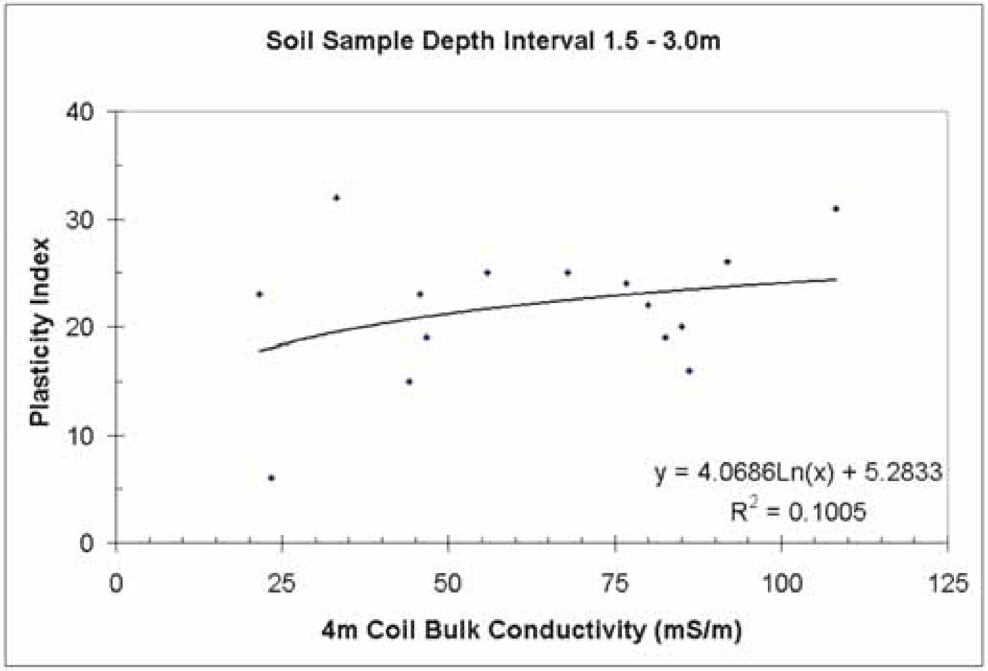

Figure 62. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Plasticity Index.

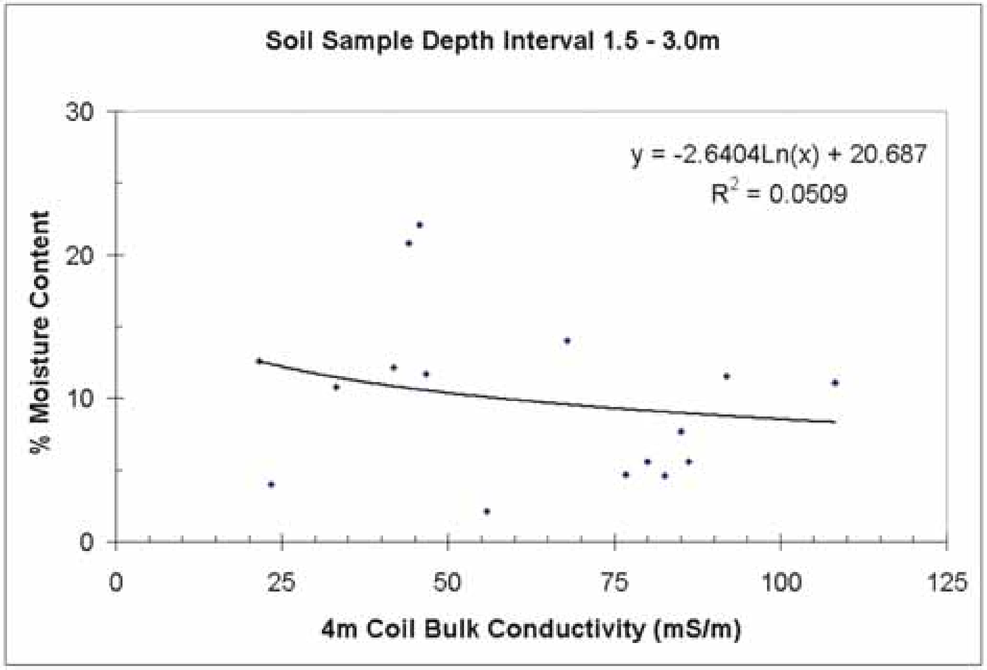

Figure 63. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Moisture Content.

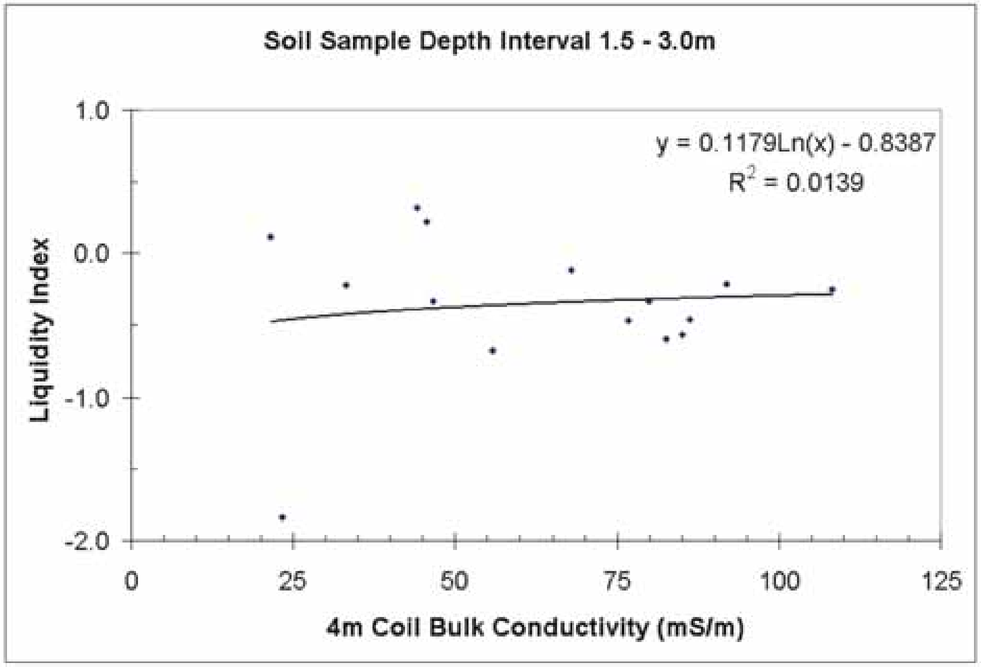

Figure 64. Graph. Dulce. 4 m Coil Bulk Conductivity vs. Liquidity Index.

APPENDIX D – COMPARISON PLOTS OF THE LAB SOIL ANALYSIS DATA AND THE EMI GEOPHYSICAL DATA, NATCHEZ, MISSISSIPPI.

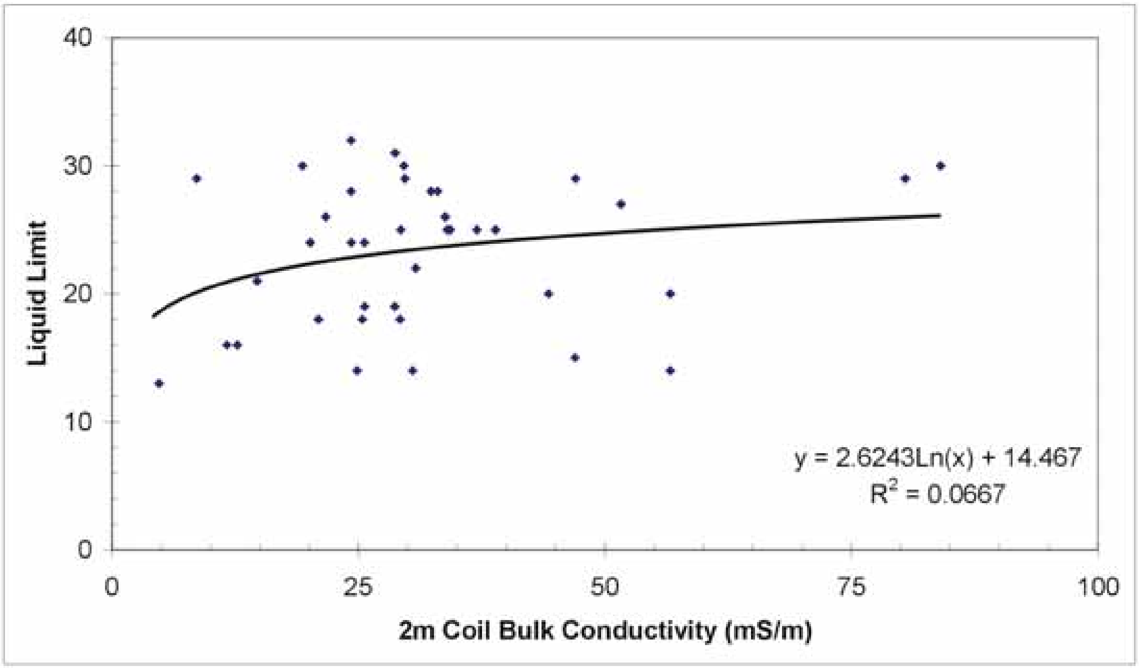

Figure 65. Graph. Natchez. 2 m Coil Bulk Conductivity vs. Liquid Limit.

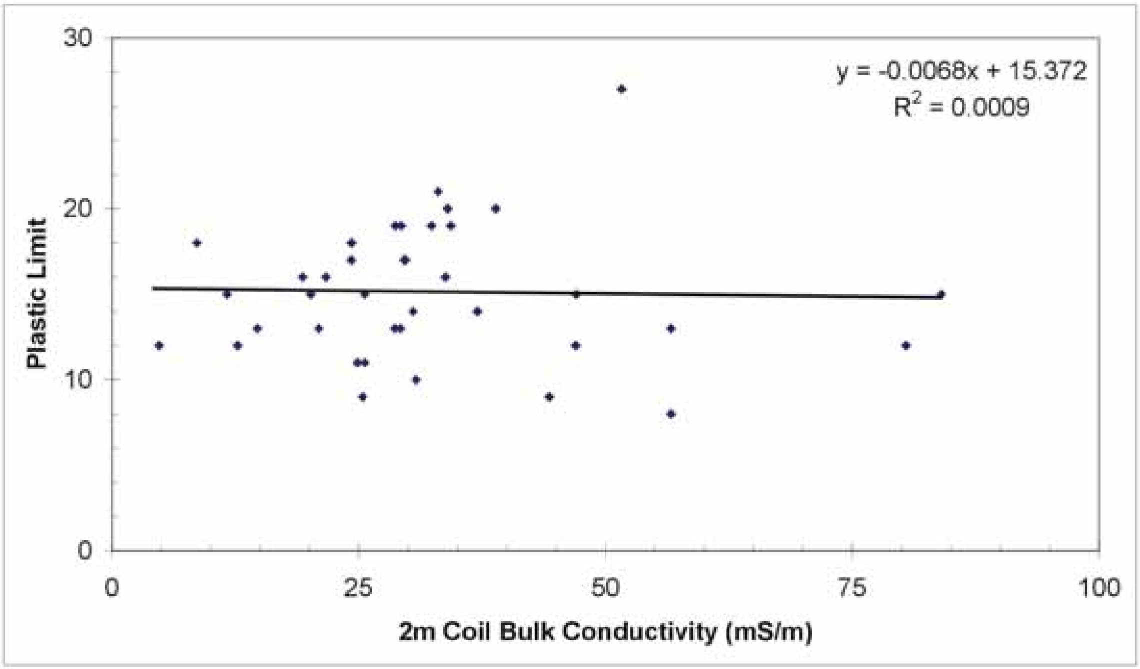

Figure 66. Graph. Natchez. 2 m Coil Bulk Conductivity vs. Plastic Limit.

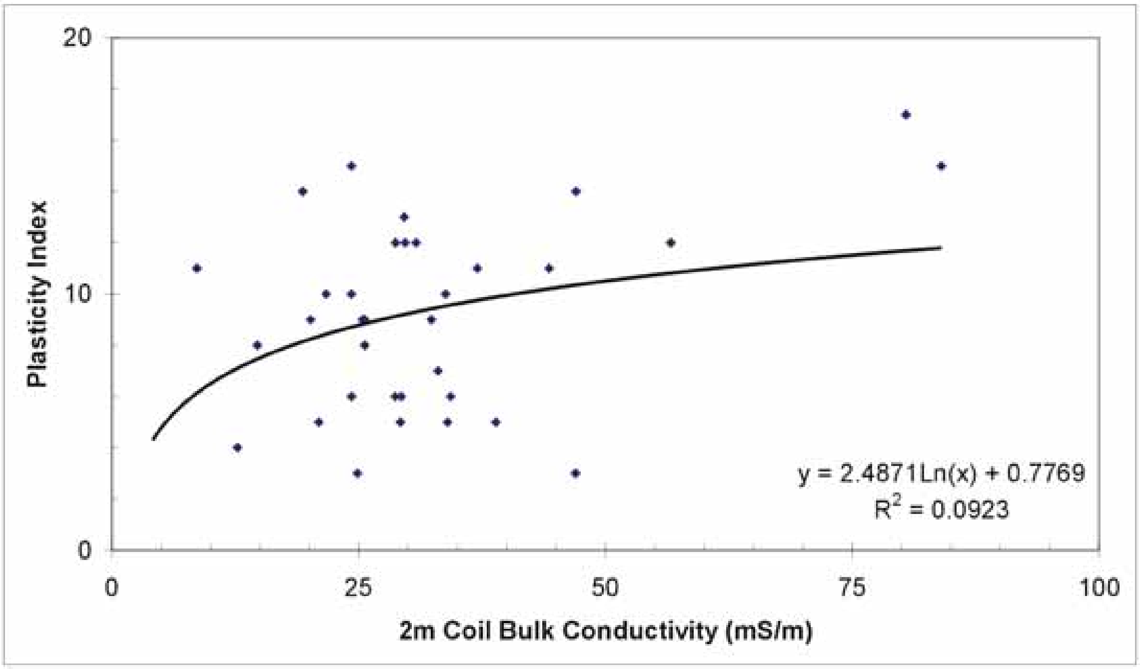

Figure 67. Graph. Natchez. 2 m Coil Bulk Conductivity vs. Plasticity Index.

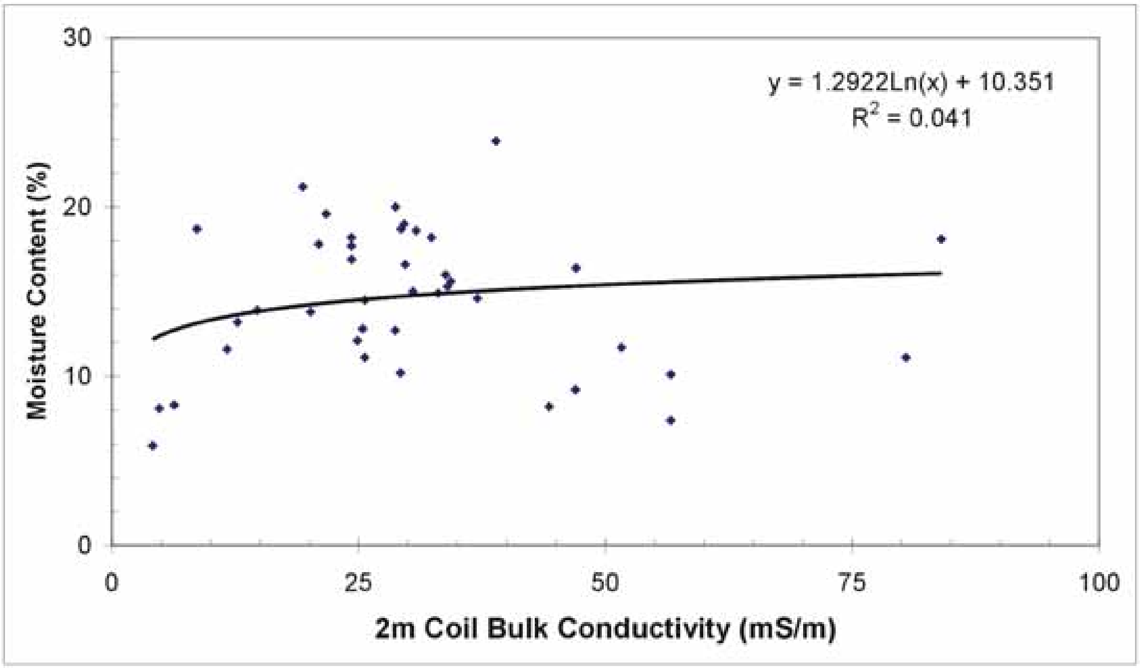

Figure 68. Graph. Natchez. 2 m Coil Bulk Conductivity vs. Moisture Content.

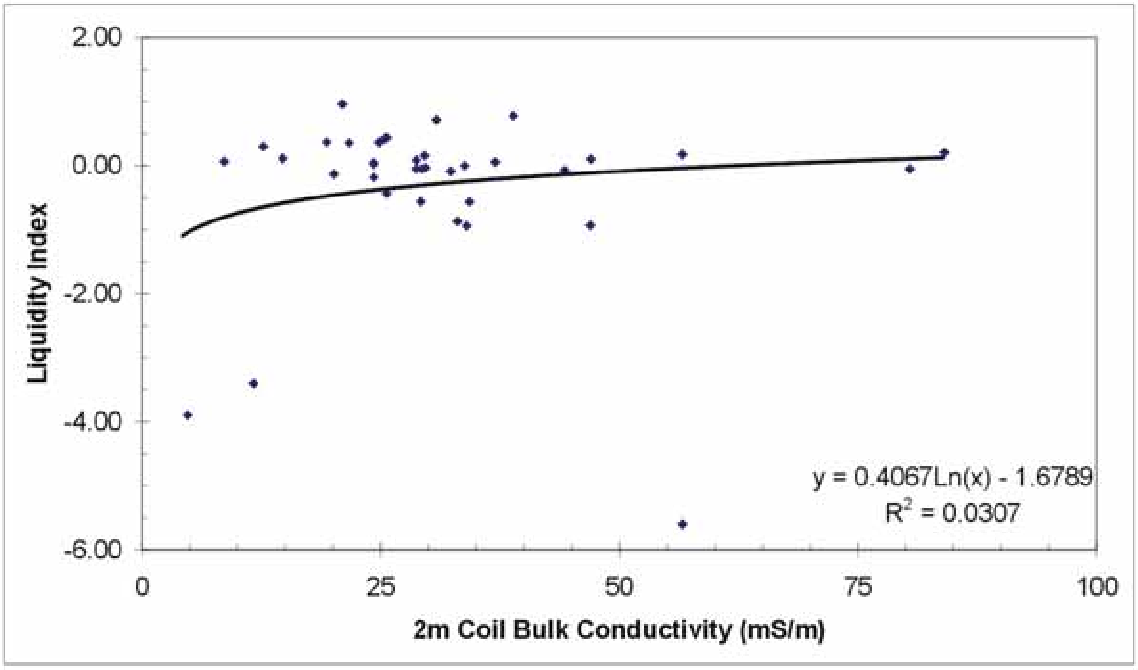

Figure 69. Graph. Natchez. 2 m Coil Bulk Conductivity vs. Liquidity Index.

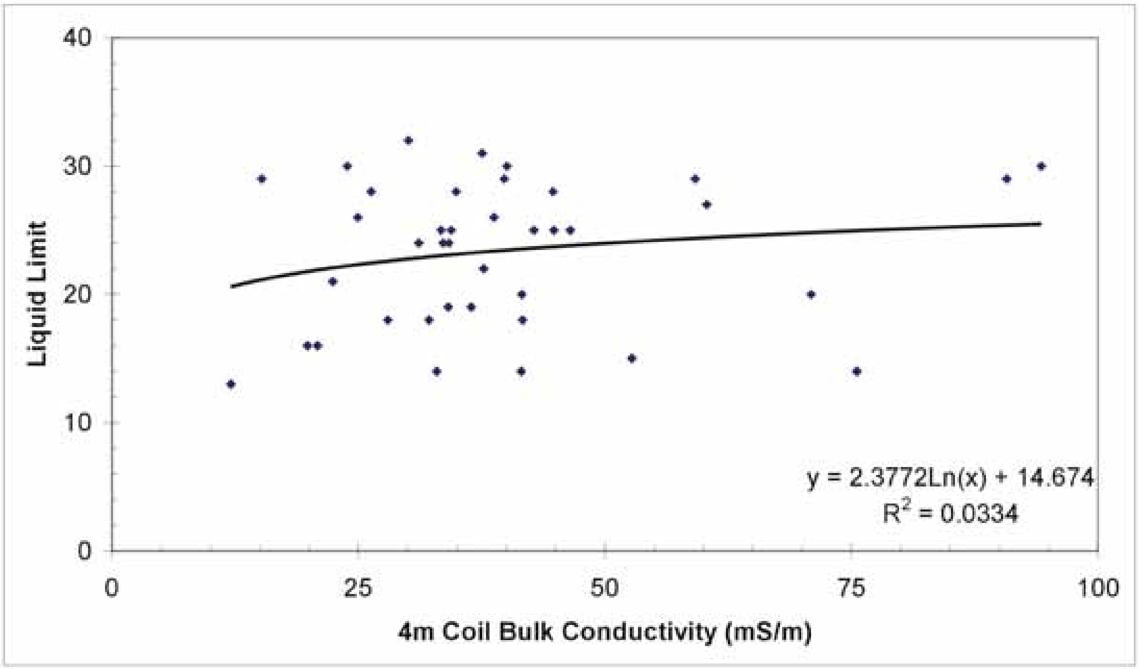

Figure 70. Graph. Natchez. 4 m Coil Bulk Conductivity vs. Liquid Limit.

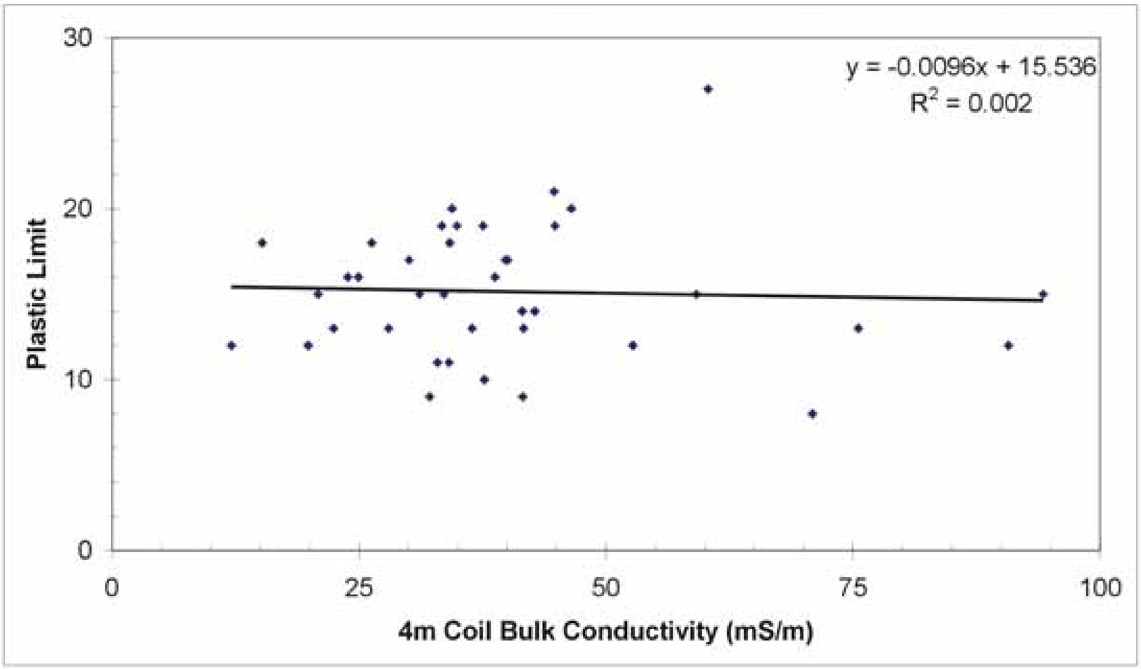

Figure 71. Graph. Natchez. 4 m Coil Bulk Conductivity vs. Plastic Limit.

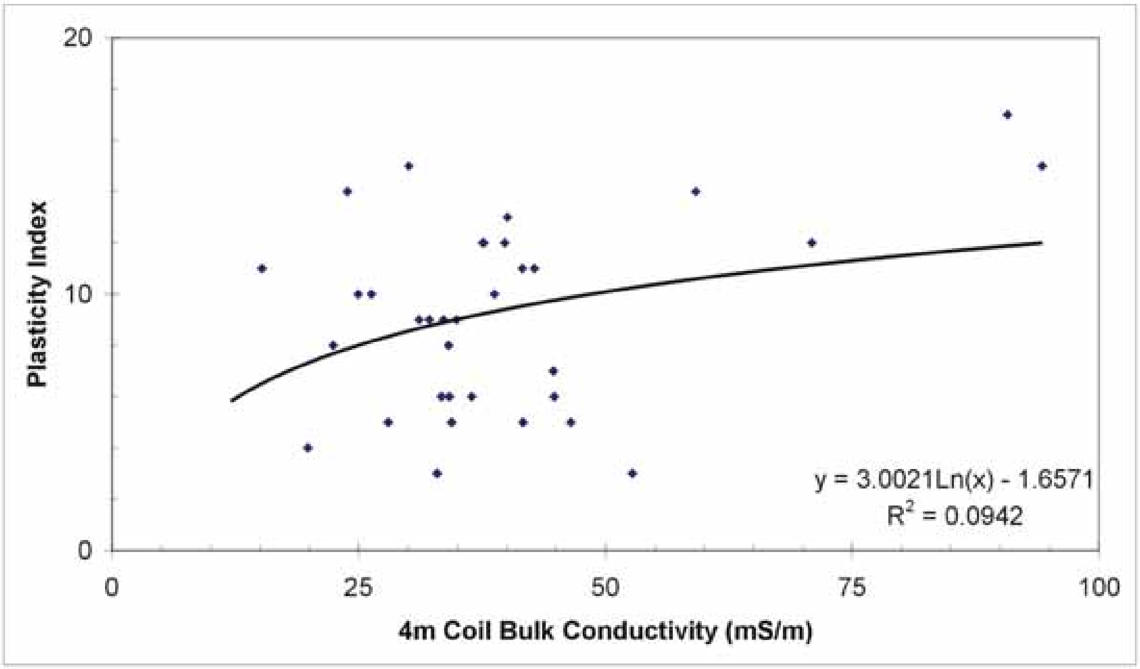

Figure 72. Graph. Natchez. 4 m Coil Bulk Conductivity vs. Plasticity Index.

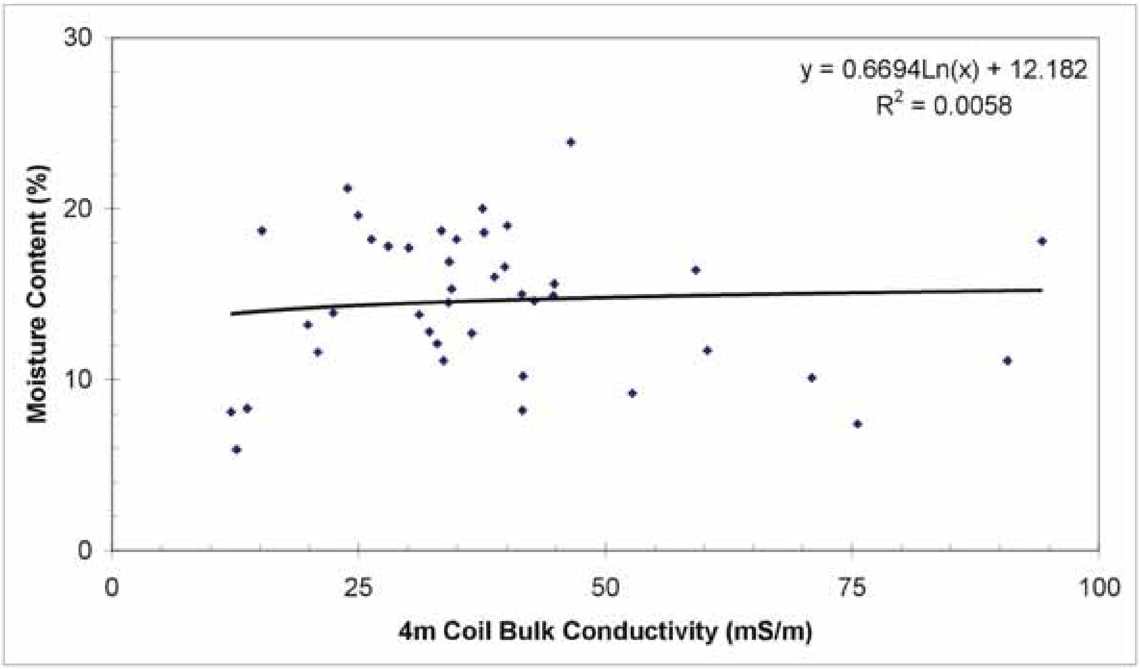

Figure 73. Graph. Natchez. 4 m Coil Bulk Conductivity vs. Moisture Content.

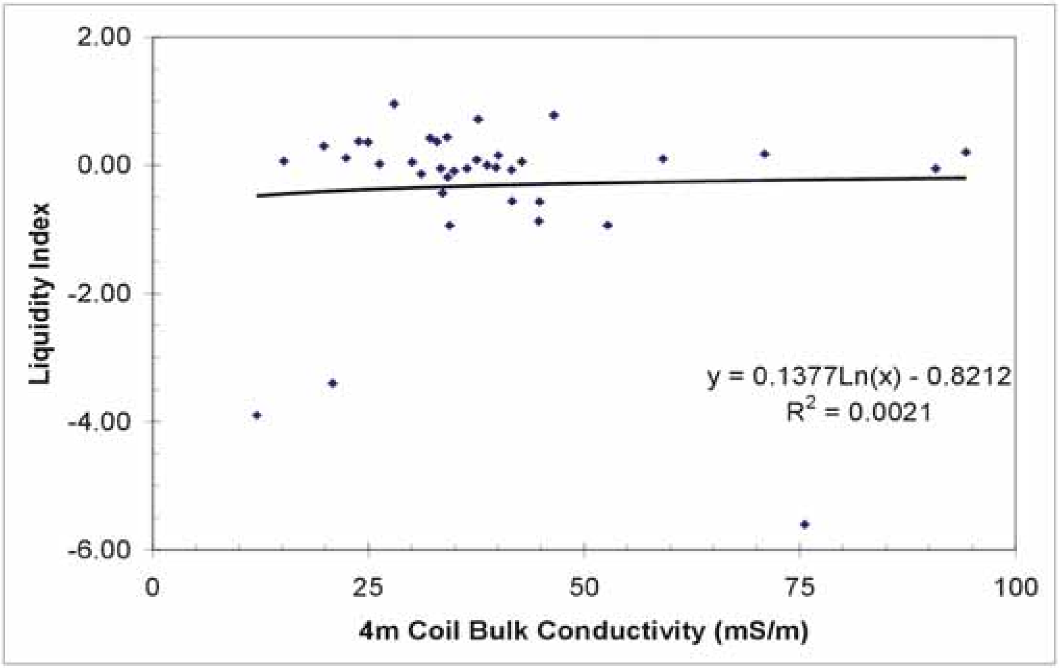

Figure 74. Graph. Natchez. 4 m Coil Bulk Conductivity vs. Liquidity Index.