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.

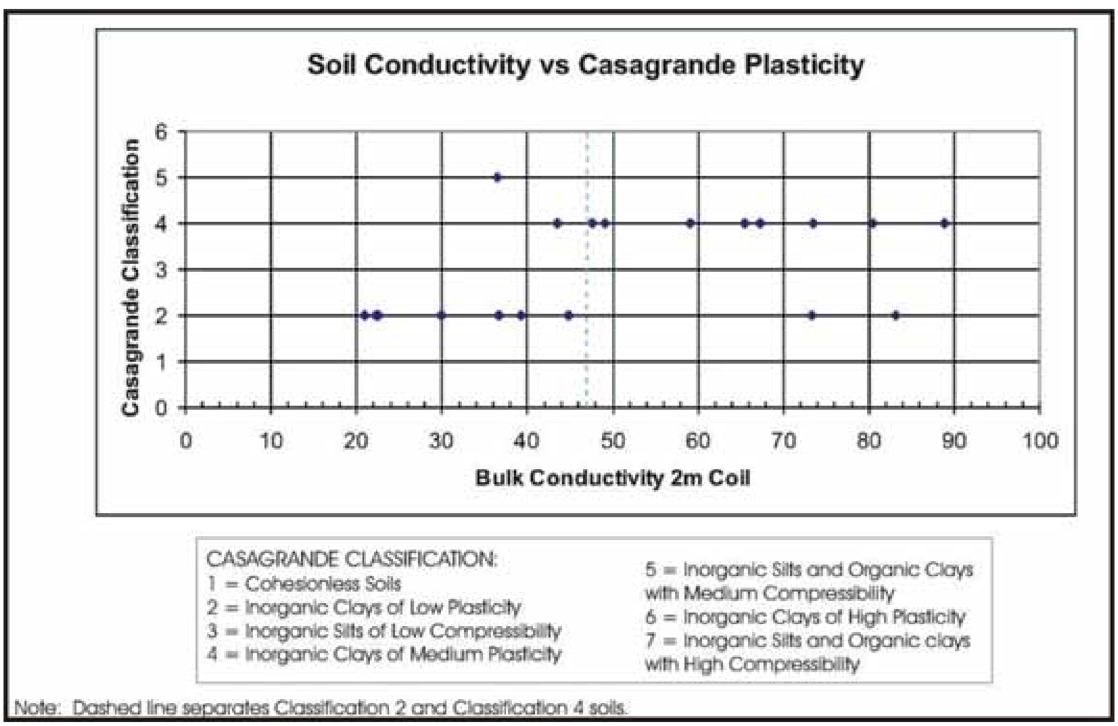

Figure 7. Chart. Soil Conductivity vs. Casagrande Plasticity.

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