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Highway IDEA Program

Mobile Geophysical Technology: A Subsurface Scoping Tool for Reducing Unforeseen Roadblocks in Project Delivery

Final Report for Highway IDEA Project 107

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Mobile Geophysical Technology: A Subsurface Scoping Tool for Reducing Unforeseen Roadblocks in Project Delivery

IDEA Program Draft Final Report

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EXECUTIVE SUMMARY

This IDEA project assessed a specialized application of a mobile geophysical technology (known as the EM^3), for conducting non-destructive preliminary surveys for highway construction. The EM^3 provides fundamental information regarding the consistency or variability of subsurface materials, the presence or absence of buried objects, and lateral trends in soils and rock. This information is important because unknown subsurface factors such as relict or current transportation infrastructure, underground storage tanks or utilities, and unpredicted changes in soils or geologic strata complicate excavation work and trigger highway construction delays. Mobility and continuous data acquisition make total project area coverage technically and economically feasible. They also make possible the evaluation of existing road and roadbed conditions, providing greater assurance that buried objects and environmental concerns are adequately characterized and addressed prior to construction.

As with all electromagnetic induction methods, the EM^3 transmits an electromagnetic current to induce a bulk response from materials in the earth, without direct contact with the ground. Geophysical methods, including electromagnetic induction, depend on the presence of contrasting physical properties between subsurface features and their surroundings. With sufficient contrast, features described as anomalies manifest as discrete variations from the typical background signal on a qualitative basis. Anomalies can be associated with cultural and natural features. Strongly patterned anomalies are readily recognized and identified (e.g., long narrow linear anomalies are likely to be underground utilities). Focal and/or areal anomalies may be associated with human influences (e.g., buried objects, contaminant plumes) and geological features (e.g. landscape-level soil and bedrock variation and buried channel deposits). The actual cause of an anomaly is confirmed by conducting some level of invasive exploration (probing, drilling, or excavation), which also allows for data to be calibrated with known ground conditions and geology.

Applications of the EM^3 as a "broad scoping tool" were evaluated for two Caltrans projects at different stages of the planning/development process, the Donner Summit Rehabilitation Project along Interstate 80 and the Cherry Avenue Four-Lane Project along State Route 119. The two projects are situated in contrasting settings, high rocky mountainous terrain and low desert valley terrain. These elevational/geological/environmental contrasts and differing stages of project development are advantageous, allowing demonstration of both the broad scoping and focused capabilities of the technology. Primary advantages of using an instrument such as the EM^3 include non-destructive data collection, high-density sampling intervals collected at a rapid rate, delineation of landscape-level changes in physical properties of the subsurface, and identification of anomalous subsurface conditions and buried objects. Following the survey and data display, areas are readily identified for further testing by other methods or for validation by boring or excavation.

1.0 IDEA PRODUCT

This IDEA product is a specialized application of a mobile geophysical technology (known as the EM^3), tailored to non-destructive preliminary surveys for highway construction. The EM^3 provides fundamental information regarding the consistency or variability of subsurface materials, the presence or absence of buried objects, and lateral trends in soils and rock. This information is important because unknown subsurface factors such as relict or current transportation infrastructure, underground storage tanks or utilities, and unpredicted changes in soils or geologic strata complicate excavation work and trigger highway construction delays. In fact, one of the top five root causes of delay to highway construction is "differing site conditions" (*1*). Thus, efforts to identify potential problems during the planning and design phase, rather than during construction are strongly recommended, to not only avoid untimely project completion but also to reduce design errors and change orders. Finally, furnishing EM^3 data to technical specialists managing various aspects of a project (e.g. storm drains, right of way, hazardous waste, etc.) in the planning stages of project delivery allows engineers to identify potential obstacles to construction before they become problems. Designers and planners may carry out subsequent work such as site assessment, constructability reviews, and design engineering with greater confidence and accuracy. With advanced knowledge of subsurface conditions, projects should be more easily completed, have fewer change orders and construction claims, and thus less schedule slippage, scope creep, and fewer cost overruns.

2.0 CONCEPT AND INNOVATION

2.1 EM^3 INNOVATIONS

Argus Technologies (a TREMAINE Company) has developed the EM^3 to perform mobile, non-destructive underground surveys. Depending upon the speed and terrain, up to 45 line miles may be surveyed per day. Argus' EM^3 technology is an innovative adaptation of conventional hand-held electromagnetic instrumentation. Such instruments have been used successfully in near surface geophysics and soil studies for over 20 years. Our advancements to this base technology include: 1) mobilizing or placing the instrument on wheels; 2) combining three receivers into one instrument for a nested view of subsurface conditions in successive depths; 3) speeding up data acquisition rates, 4) simultaneously tagging incoming data with real time kinematic (RTK) GPS X, Y, and Z coordinates with centimeter-level accuracy; and 5) developing proprietary data collection and processing software. The current instrument design records three to six volumes of soil, to a maximum depth of 10 meters (about 30 feet) and an effective depth of 6 meters (about 20 feet), as it is towed behind an ATV traveling at 5-10 miles per hour. Future developments include 6-18 receivers and depth to 25 meters. Typically three to four readings are recorded per meter using an Allegro Field PC (Juniper Systems, Inc., Logan UT). Multi31 (Geomar Software Inc., Mississauga, Ontario, Canada), ArcGIS ArcView 9.1 (ESRI, Redlands, CA), IDL 6.2 (Research Systems Inc., Boulder, Co), EMIGMA 7.8 (Petros Eikon, Inc., Concord, Ontario, Canada), and proprietary software packages are used to process and display raw data, generate contour plots, produce 2-dimensional (2-D) profiles, and display 3-dimensional (3-D) visualizations of the data through inversion modeling.

2.2 PRINCIPLES OF OPERATION AND ANALYSIS TECHNIQUES

As with all electromagnetic induction methods, the EM^3 transmits an electromagnetic current to induce a bulk response from materials in the earth, without direct contact with the ground. The instrument, at an operating frequency of 9.8 kHz, passes a current through the transmitter coil generating a time-varying (sinusoidal) magnetic field (*2*). The primary field induces electrical currents in conductive subsurface materials that in turn generate secondary magnetic fields, which are detected by three receiver coils spaced at 1, 2, and 3.6 meters from the transmitter. The secondary field consists of two components, the quadrature and in-phase. The EM^3 measures both for each receiver/depth, providing data to distinguish between conductive targets that are metallic versus non-metallic, for example. The American Society for Testing and Materials lists electromagnetic induction as an appropriate technique for detecting and mapping lateral changes in geologic and hydrogeologic conditions, delineating contaminant plumes, and identifying buried metal objects (*3*). Accepted limitations of all electromagnetic induction technologies include interference or noise from cultural objects including overhead and underground power cables, radio transmitters, electrified transportation systems, metal-containing fences, moving and parked vehicles, buildings, underground public utilities, and interference from natural atmospheric sources such as solar activity (*15*).

2.2.1 Apparent Conductivity

The quadrature response indicates the apparent conductivity of subsurface materials, measured in milliSiemens per meter (mS/m). This response is primarily governed by soil moisture and the concentration of dissolved electrolytes in soil pores, grain size, temperature, compaction (porosity), and surface chemistry of the clay fraction (*4*). Generally sands and gravels tend to be poor conductors, with conductivities ranging from 0.1 to 5 mS/m while clays are highly conductive (10-250 mS/m) (*5*). Additional moisture and hence the mobilization of dissolved electrolytes causes apparent conductivity values to increase. Finally, buried metal objects are highly conductive in contrast to most types of surrounding material. In terms of constructability, the apparent conductivity of subsurface materials theoretically ranges from very low for competent bedrock, low for sands and gravels or buried channels, medium for silts and moist, highly weathered bedrock, high for clays, to very high for buried metallic objects.

2.2.2 Magnetic Susceptibility

The in-phase response indicates magnetic susceptibility, measured in parts per thousand (ppt). Magnetic susceptibility essentially gauges the degree to which soil components become magnetized by induction. Variations in magnetic susceptibility are primarily dependent on the types, oxidation state, and stability of magnetic iron minerals in soil, on the presence and mobility of magnetic ions in solution, or on the presence of ferromagnetic alloys (e.g. iron and steel). In practice, the in-phase response detects changes in the oxidation states and distributions of iron compounds (predominantly magnetite and maghemite) resulting from weathering processes that include wet-dry cycles (*6*) and/or as a result of historic and prehistoric burning (*7*). High-temperature heating that is associated with igneous rocks (a natural process) or with baked clay or pottery (an artificial process) contributes to the phenomenon known as remnant magnetism, which also contributes a high in-phase response (*8*). The in-phase response is particularly sensitive to buried metal objects (e.g. pipelines, underground storage tanks, and some ordnance) (*9*) that are magnetically susceptible.

2.2.3 Anomalies

Geophysical methods depend on the presence of contrasting physical properties between subsurface features and their surroundings. With sufficient contrast, features described as anomalies manifest as discrete variations from the typical background signal on a qualitative basis. Anomalies can be associated with cultural and natural features. Strongly patterned anomalies are readily identified (e.g., long narrow linear anomalies are likely to be underground pipes; rectangular anomalies are likely to be associated with building foundations). Focal and/or areal anomalies may be associated with human influences (e.g. buried objects, contaminant plumes) and geological features (e.g. landscape-level soil and bedrock variation and buried channel deposits). The actual cause of an anomaly is verified by conducting some level of invasive exploration (probing, drilling, or excavation), which also allows for data to be calibrated with known ground conditions and geology. High voltage overhead transmission and distribution lines, fences, and commercial or residential buildings may also cause anomalies (or noise).

2.2.4 Data Processing

The first step in data processing is to combine the individual data files into data sets with other sets of information, such as aerial photographs, topographic maps, and/or CAD files showing utilities and infrastructure. Generally, electromagnetic induction will detect a typical (or background) signal for a given location or landscape. Anomalies (areas that diverge from the background signal) will register either higher or lower than background readings. Usually the data form a bell-shaped curve, approximating a normal distribution. The mean of the data set and the values closely surrounding it represent the most frequently recorded values, or background. The values within one standard deviation from the mean are background. The values greater or less than one standard deviation from the mean are anomalous high and low values, respectively. Alternatively, the scale may be set at equal interval increments (e.g. 5 mS/m or 0.5 ppt).

To observe variation relative to natural landscape elements it is sometimes necessary to remove the effects of extraneous cultural objects from the data set in the data processing phase. To achieve this, spuriously high and low values (e.g., those associated with fences, buildings or specific utilities) are removed from the data set where there is a known source of interference. Following this masking process, geophysical anomalies are expressed in color using either individual data points or contour plots. The map color scale indicates relative values ranging from negative to positive for low and high apparent conductivity or magnetic susceptibility.

2.2.5 First Order 1-D Analysis

First Order analysis is the broadest scale of analysis for a data set, and is used to qualitatively locate obvious anomalies. Data are plotted using a scale that encompasses the entire range of values in a given data set using either individual data points or contour plots. The data are then inspected to locate anomalies. Anomalies that can be explained by known or previously mapped features (electric lines, pipes, building foundations) are accounted for or explained. These anomalies are termed "Identified Features." Those that cannot be explained by known or previously mapped features (Unidentified Features) are noted and analyzed to determine their possible cause.

First Order analysis is most appropriate for landscape-level studies and for high-contrast targets, where the geophysical properties of a feature register as gradual or abrupt changes in apparent conductivity and/or magnetic susceptibility within a relatively wide range of values.

2.2.6 Second Order 1-D Analysis

Second Order Analysis is targeted analysis of a subset of the data, and is used to identify smaller-scale and subtle anomalies. This level of analysis is undertaken when additional resolution is required for a focus area. The area could be an anomalous area identified in First Order analysis that requires further research to determine the properties and extent of the feature. Data again are plotted on maps, but using a scale that includes only the values recorded in a specific location. That is, the data range tends to be narrower, which expands the color range, revealing subtle variations in the data values. As with First Order analysis, data are presented using either individual data points or contour plots and inspected to locate anomalies and delineate subsurface features of interest.

Second Order analysis is appropriate for study areas where features with very high (large metal objects) and very low (bedrock, non-metal pipes, and voids) apparent conductivity values are present. In this case, depiction of the data is skewed toward the high and low data values above and below the mean or background. Thus, without Second Order analysis, middle-range anomalies and subtle changes in the data may be missed. Second Order analysis can be carried out on successively smaller areas of the survey; the lower limit depends upon the geophysical nature of the survey area and density of data points.

2.2.7 Multi-Dimensional Visualization

Multi-dimensional analyses are more intensive and costly to perform. Thus, multi-dimensional analyses target only subsets of the data revealed to be of interest from First and Second Order analyses. To accomplish this level of analysis, data are processed again and modeled using inversion algorithms. The inversion models present data from all three receivers on the same plot, forming a profile view. Thus changes in conductivity both laterally and with depth may be assessed (2-Dimensional visualization). When surveys have multiple passes or transects, profiles may be interpolated and displayed using 3-Dimensional visualization. This format more readily reveals the presence, origin, and extent of subsurface processes such as the point of origin, direction and extent of contaminants or seepage.

2.2.8 Ground Truth

Different subsurface features can produce similar geophysical signatures (e.g., high conductivity may be caused by conductive clay *or* conductive brackish saturated sand), making interpretation difficult without some level of ground truth, verifying the cause of anomalies in geophysical data. Ground truth methods range from inexpensive and non-invasive (visual inspection for surface indicators), to moderately invasive (small diameter hand augers and hand-digging), to costly and invasive (drilling and excavating with a backhoe).

2.3 APPLICATIONS TO PRACTICE

Studies of the near surface using older hand-held or invasive geophysical instruments are generally cumbersome (requiring grid setup), time consuming (data acquired at a walking pace or slower), and consequently expensive, not to mention data-sparse. Thus, such studies, despite their advantages, are often overlooked in site reconnaissance in favor of an extensive drilling effort. Their application to civil engineering and environmental problems however, is becoming more widely accepted with developments of digital methods for recording, processing, and presenting data, along with significant technological advancements in geophysical instrumentation (*10*). In addition, mobilization of instruments creates a new kind of technology with wider applications than possible with hand-held devices. Surface surveys may be carried out rapidly, generating dense data sets. These data can be used as "an intelligent guide to drilling" by enabling targeted, data-based subsurface exploration. Mobility and continuous data acquisition make total project area coverage technically and economically feasible, providing greater assurance that buried objects and environmental concerns are adequately characterized and addressed prior to construction.

3.0 INVESTIGATION

Applications of the EM^3 as a "broad scoping tool" were evaluated for two projects at different stages of the planning process. The Donner Summit Rehabilitation Project along Interstate 80 was already planned and at the specification/bid preparation stage. The Cherry Avenue Four-Lane Project along State Route 119, in contrast, was at the early design stage of development, ideal for the broad scoping approach. The two projects are situated in contrasting settings, high rocky mountainous terrain and low desert valley terrain. These elevational/geological/environmental contrasts and differing stages of project development are advantageous, allowing demonstration of both the broad scoping and focused capabilities of the technology as well as technological limitations. Findings from pre-construction site characterization can be considered when developing Project Specifications and Estimates (PS&Es) thus resulting in fewer change orders and claims for conditions differing from those indicated in contract specifications, particularly for tasks that require excavation. Primary advantages of using an instrument such as the EM^3 include non-destructive data collection, high-density sampling intervals collected at a rapid rate, delineation of landscape-level changes in physical properties of the subsurface, and identification of anomalous subsurface conditions and buried objects. Following the survey and data display, areas are readily identified for further testing by other methods or for validation by boring or excavation.

3.1 CALTRANS INTERSTATE 80 DONNER SUMMIT REHABILITATION PROJECT: PHASE 1

3.1.1 Background

The Donner Summit Rehabilitation Project is located in Nevada County, California along Interstate 80 (I-80) between the Soda Springs Overcrossing and the Trout Creek Undercrossing in Caltrans District 3 (P.M. R2.5/15.5). Phase One of the construction is a four-mile segment which starts at the Donner Lake Undercrossing on the west side, and continues to the Trout Creek Crossing on the east side (PM 9.1/15.5)(Figure 1). As the project area is steep, mountainous, and situated up to 7200 feet above sea level, severe weather constrains the construction window to as few as three months per year. In addition high levels of trucking and recreational traffic constrain the construction window to about 4 days a week. Thus avoiding construction delays is of paramount importance.

The constructability concerns for the project include the difficulty level of subsurface excavations that will be required for the installation of retaining walls, infiltration basins, and drainage improvements, including approximately 30 cross culverts and over 2 miles of longitudinal pipe at depths of 4-6 feet. For example, glacial till or boulder fill excavations are typically accomplished with conventional excavation techniques. However, oversized boulders (up to approximately 8 tons in weight, 1.5 meter diameter) may be encountered in these materials, triggering over-excavation or other practices Caltrans has performed in the past, including use of hydraulic splitters, hoe-rams, expansive chemicals, and/or blasting. The resulting decrease in progress and increase in cost may be severe enough to prompt project re-design. Roughly mapping geologic units to delineate possible boundaries between reaches of glacial till, near-surface bedrock, and fill with or without boulders, could provide increased confidence for estimating excavation difficulty.

As a reconnaissance investigation tool, the EM^3 was used to survey Phase 1 of the project with intent of evaluating whether the dataset could provide information that would be useful to Caltrans before PS&Es were released. First Order analysis would be used to confirm the locations of existing drainage installations and identify relict or undocumented drainage installations. Second Order analysis would be used to delineate lateral landscape-scale changes into potential geologic units. Targeted Multi-Dimensional Visualization would be used to investigate the excavation difficulty of planned lateral drainage installations.

3.1.2 Pre-Survey Planning Meetings with Functional Managers

In April and May 2005, several pre-survey planning meetings were held with Project Manager, Dave Lopez, and his staff in Sacramento, California. Participants included Bill Webster (Engineering Geologist), Ali Kiani, (Project Design Engineer for Drainage), Ali Kiani and Jerry Cagle (Project Design Engineer for Roadways), and Momoh Mallah (Geophysics Division/Branch representative for Chief Bill Owen). Issues concerning constructability of drainage culverts and infiltration basins were specifically discussed, and construction details and maps were provided. In April 2005, the geophysical survey strategy and plans to close lanes on westbound I-80 during the survey were complete.

3.1.3 Fieldwork

The geophysical survey was completed in two phases due to rain. The overall strategy was to cover the westbound traffic lanes and the inner and outer shoulders with transects on four-foot (1.2 meter) intervals, parallel with the roadway. The first phase of the survey was completed May 16-17, 2005 and consisted of two transects on the outer shoulder and two transects in Lane Two (slow lane). The second phase of the survey was completed May 23-25, 2005 and consisted of two transects in Lane One (fast lane) and two transects on the inner shoulder (Figure 2). Approximately 32 line miles were covered in the two-day survey period.

3.1.4 Data Processing and Analysis

Data processing included combining aerial images of the project area with Caltrans CAD files showing existing and planned construction details, EM^3 transect data on a scale of 5 mS/m, and surface features (such as metal objects and overhead electrical lines) observed in the field which were tagged with GPS coordinates.

First Order analysis consisted of correlating EM^3 data with the existing utilities, including electrical and drainage, indicated on the CAD files. This step focused on transverse linear anomalies, which are defined as aligned anomalies present in multiple survey lines, oriented more or less perpendicular to the roadway. Transverse linear anomalies coinciding with known utilities are termed "Identified Features" (IF). "Unidentified Features" (UF) are transverse linear anomalies with a signature similar to those of known utilities, but are not demarcated in the CAD files. There are a number of focal and longitudinal (aligning parallel with the roadway) linear anomalies that may be of interest in another type of construction project. For example, animal crossings will be installed in the course of the Donnner Summit Rehabilitation Project. If the locations for the crossings were known, data could be examined to determine if anomalies are present in potential excavation areas.

Second Order analysis consisted of correlating EM^3 data with bore logs for 31 locations, which were completed as part of the Draft Geotechnical Design Report (*11*). Bore logs were located at the potential sites of light posts, sand vaults, and drainage structures. Although the geotechnical data were not collected to verify EM^3 data, they could be used to generate an understanding of the range of EM^3 readings that correlated with specific subsurface conditions (e.g. bedrock versus silty-sandy fill). Anchored with bore log data, interpolations between and extrapolations away from known subsurface materials were made by noting gross changes depicted in EM^3 data. In this case, data were scaled with 1/4 standard deviation increments and then all values below –2.42 mS/m were grouped in the lowest color value (dark blue) and all values above 93 mS/m were grouped in the highest color value (red). This procedure minimized the effect of the extreme values in the data set (which were associated with the strong signal from the metallic culverts) and enhanced the display of the natural subsurface materials.

Multi-dimensional analysis consisted of inversion modeling (Occam's method) using all three receivers to generate 2-dimensional profile contour diagrams for the outside shoulder data line.

3.1.5 Results and Discussion

Caltrans CAD Files and Transverse Linear Identified/Unidentified Features

A total of 58 transverse linear features were identified in First Order analysis, based on Caltrans CAD files and anomalous readings from each of the three receivers for apparent conductivity and magnetic susceptibility. Forty are associated with Identified Features (IF) and 18 are associated with Unidentified Features (UF). The results for Receiver 3, apparent conductivity are shown in Figure 3 and Unidentified Features are summarized in Table 1.

TABLE 1 Summary of Unidentified Transverse Linear Features, Donner Summit Rehabilitation Project, Phase 1.

Feature	Station (Approx.)	Figure Number	Easting	Northing
UF1	232+80	3d	735084	4356698
UF2	245+95	3h	736280	4357199
UF3	251+15	3i	736801	4357181
UF4	251+35	3i	736821	4357180
UF5	1029+45	3k	737557	4357047
UF6	1033+50	3o	737897	4356821
UF7	1034+95	3m	738000	4356728
UF8	1037+20	3n	738197	4356619
UF9	1038+00	3n	738266	4356599
UF10	1040+00	3o	738461	4356545
UF11	1040+40	3o	738504	4356535
UF12	1042+20	3o	738698	4356497
UF13	1044+10	3p	738860	4356476
UF14	1044+20	3p	738875	4356478
UF15	1044+60	3p	738914	4356465
UF16	1044+75	3p	738926	4356464
UF17	1045+65	3p	739018	4356451
UF18	1045+95	3p	739045	4356448

Data for Receiver 3, apparent conductivity reveal the majority of the transverse linear anomalies. Data for the other receivers and for magnetic susceptibility are not included due to the page limit of the report, but all data were cross-checked with Receiver 3 data. If an Identified Feature is not present in Receiver 3 apparent conductivity, it is present in data for another receiver or response. If an Identified Feature is not evident in any receiver or response, it is noted as "not identifiable in First Order analysis." A review of the Caltrans CAD files showed that most of the Identified Features align with transverse culverts, and several align with transverse electric utilities. The transverse culverts are predominantly corrugated steel pipe (CSP) with some reinforced concrete pipe (RCP), ranging from 600 mm (about 2 feet) to 1500 mm (about 5 feet) in diameter. The transverse culverts are shallowest on the outside shoulder (0.5 meter) and drop to varied depths on the inside shoulder, with a maximum depth of 12 meters. The outside shoulder side of the culverts and the shallowest culverts generated prominent anomalies in all three receivers while the position of sharply angled culverts on the inside shoulder side may be so deep that an anomaly could not be visualized in First Order Analysis, even for Receiver 3.

Figure 3i contains three IFs and two UFs, and includes examples of typical electromagnetic responses, demonstrating the application of electromagnetic (EM) data. Based on the CAD files and Drainage Profiles, anomaly IF 19 aligns with a 600 mm RCP at a depth of 1.0 meters on the outside shoulder and a depth of 4.5 meters below the inside lane. In this instance, the signal becomes attenuated with increasing depth. This could be due to changes in the base material across the roadway, or to a lower EM response from the concrete in a RCP compared with a higher response from exposed ferromagnetic material in a CSP. Identified Feature 20 aligns with a 600 mm CSP at a depth of 2.5 meters on the shoulder and a depth of 7.5 meters below the inside lane. As with the RCP, there is an attenuation of the signal with depth. In both cases, a continuation of the signal may be visible with narrowly focused, higher orders of analysis. In addition, there is a discrepancy between the location of the culvert on the CAD drawings and the location of the anomaly IF 20 in the EM data. As the EM anomalies align with the majority of culverts in the CAD drawings, it is likely that the actual location of the culvert aligns with the EM anomaly (i.e., it is inaccurately plotted in the CAD drawings). Identified feature 21, which aligns with a 750 mm CSP at a depth of 1.0 meter on the shoulder and a depth of 2.0 meters below the inside lane, does not show attenuation of signal. This is likely due to the shallow depth it maintains across the roadway. Finally, UF 3 and UF 4 are linear features with anomaly signatures typical for culverts, but in these locations, transverse culverts are not indicated on the construction plans. These may be relict, abandoned utilities or serviceable culverts, which may be true for the other Unidentified Features.

Several Identified Features, including drainage and electric utilities were not detected with Receiver 3 apparent conductivity data in First Order analysis. Transverse culvert IF 13 was identified in Receiver 3 in-phase data while transverse culverts IF 4 (203 mm CSP), IF 11 (1372 mm CSP), IF 12 (762 mm CSP), IF 13 (762 mm CSP), and IF 16 (1219 mm CSP) were not identified in First Order analysis for any receiver or response. Electric utilities IF 27, IF 29, IF 37, and IF 39 were also not identified. Potential explanations for the lack of an induced response include insufficient electromagnetic contrast between the targets and their surrounding materials, inexact locations of utilities in the CAD drawings, a utility is indicated but no utility exists, or in the case of the electric utilities, the line may be overhead rather than buried or is heavily insulated and/or not conducting electricity.

Geotechnical Drilling and Electromagnetic Data

URS, contractor for Caltrans, conducted geotechnical drilling along the study segment, producing thirty-three bore logs that coincided with the EM^3 survey area. Bore log information was used to interpolate between and extrapolate from bore locations by establishing correlations with EM data. In a Second Order analysis, Receiver 3 EM^3 signatures were compared with the general lithologic character of the represented strata primarily in terms of particle size and secondarily in terms of depth to bedrock and degree of weathering. Thus, high conductivity was correlated with clay, silt and moist or water-saturated fine-grained silty sand, sand, and gravel. Medium-ranged response in conductivity was correlated with sand, gravel, cobbles, and weathered bedrock. Low and very low conductivity was correlated with cobbles, boulders, and unweathered bedrock. With these guidelings, the EM data were used to preliminarily delineate segments of like-composition, potentially representing differences in geology, landform, or roadbed materials.

The associations between bore logs and EM^3 apparent conductivity data for Receiver 3 are shown in Figure 4 and are summarized in Table 2.

TABLE 2 Proposed Classification Scheme for Geologic Units, Donner Summit Rehabilitation Project, Phase 1.

Particle Size	Conductivity (mS/m)	Color Code (Figure 4)	Color Code (Figure 5)	Numerical Classification
Water-saturated fine-grained material or metal	Highest (>90)			
Fine-grained, silty sand, gravel (moist)	High (~50)			1
Tills - with silty sand, gravel	Medium (~30)			2
- with sand, gravel, and cobbles	Medium to Low (~20)			3
- with cobbles and boulders	Low (~10)			4
Boulders and unweathered bedrock	Low to Very Low(~1-0.1)			5

Note: Boulders could be found in any of the classifications, although in smaller numbers with lower probability.

Because the entire set of bore logs would not fit on the figure, representative logs are shown. Bore logs indicate the shoulder of the inside lane between bore logs B222-3 and B225-1 is predominantly fill/till with bedrock, with recorded EM^3 data in the range of 27-35 mS/m (yellowish green). Fill/till with boulders predominates between B225-2 and B225-6 with recorded EM^3 values slightly lower, in the range of 25-28 mS/m (green). Bores B225-7 through B230-2 show fill/till with underlying bedrock, and recorded EM^3 values in the range of 17 to 22 mS/m (dark green to light blue). Based on the color scale, this range of data continues to suggesting that subsurface materials may continue to be till with underlying bedrock on the shoulder of the inside lane. Fill/till with boulders is indicated on the outside shoulder from bore logs B236-1 to B236-4, with data ranging from slightly negative to 2 mS/m (dark blue). The decrease in conductivity may correlate with a trend toward increased presence of boulders. In contrast, in the vicinity of BSV–18, taken on the outside shoulder, have consistently recorded values of 16 mS/m, increased apparent conductivity relative to the outside shoulder which correlates bore log data of fill material consisting of silty sand and gravel with increased moisture. The EM^3 data for bore logs BSV1-19 through B243-2, which were taken on the outside shoulder, range from minus 5 to 5 mS/m. In this general area, trenching may be more difficult as the bore logs indicate the presence of shallower bedrock and till containing boulders. In the same area on the outside shoulder, bore logs BSV1-21 through BSV1-25 indicate the presence of till, with relatively higher apparent conductivity (12-20 mS/m)(light green), particularly in areas of higher moisture where conductivity reaches 50 mS/m (yellow-orange). Bore logs for BSV1-26 and BSV1-27, with even higher apparent conductivity (18-64 mS/m), indicate a transition to till with increased moisture, including highly weathered bedrock on the inside shoulder. A section of lower apparent conductivity (10 mS/m) was recorded for the inside shoulder in the area of BSV1-28 and BSV1-29 which corresponds with drier till. While bore logs are not available for the remainder of the survey area, based upon the existing information, it may be inferred that a series of alternating areas of possible moist fill/till (yellow-orange), boulder till with bedrock (dark blue) and till (green) are present. The easternmost portion of the survey area appears to have unusually high apparent conductivity values, possibly associated with a concentration of above- and below-ground utilities. Thus, potential designations of subsurface materials were not suggested for this area.

Inversion Models of Electromagnetic Data

Data from Receivers 1, 2, and 3 for the northernmost line (collected on the outside shoulder) were integrated into a profile view using Occam's method of inversion with EMIGMA Software (Figure 5a-j), and are accompanied by a proposed classification scheme (Table 2). The table was produced with the assumptions that fine-grained material (highest apparent conductivity) is most easily excavated while shallow boulders and unweathered bedrock (lowest apparent conductivity) are excavated with greatest difficulty. Thus, numerical classification 1 (color code red) may represent areas relatively free of boulders and bedrock. In contrast, numerical classifications 4 and 5 (color codes dark green and aqua), particularly when extending into top of the profile, may represent areas more likely to contain boulders or shallower unweathered bedrock. An initial verification of this interpretation is possible using bore logs taken on the northern side of the roadway. Figure 5c shows a transition from high conductivity (color code red) to low conductivity (color codes dark green and aqua) at approximately 735390 Easting and continuing to approximately 735600 Easting (Figure 5c and d, Segment 1). Segment 1 corresponds to the area in Figure 4b designated as Fill/Till with Boulders, based on bore logs B236-1 through B236-4. Along with Segment 1, Segment 2 is initially verified as Bedrock/Bouldery Till, based on bore logs BSV-19, BSV-20, B243-1 and B243-2 (Figure 5d and 5e). These are areas of potentially increased excavation difficulty. From these results, Segments 3 and 4 (Figure 5g) along with Segment 5 (Figure 5h) are projected to be areas of increased excavation difficulty.

3.1.6 Advancements and Technological Limitations

Several significant advancements toward a greater understanding of subsurface conditions in the Phase 1 area of the Interstate 80 Donner Summit Rehabilitation Project were gained using EM^3 data. First, the opportunity to update and improve the accuracy of the construction plans. There were nine linear features, consistent with transverse culverts, which were not noted in the construction plans. If longitudinal or transverse trenching were to take place in these locations, it is likely that construction delays and change orders would result. In addition, several transverse culverts appear to be offset from their positions in the construction plans. While it is likely that field observation would allow a contractor to locate the position of the culverts, the locations would ideally be mapped accurately.

A second advancement is the opportunity to infer the difficulty level of trenching in areas beyond the known, discrete positions obtained from bore logs. Drilling operations are exponentially more expensive than a geophysical survey. In a combinative approach, geophysical surveys complement drilling operations by enabling interpolations between bore logs and extrapolations from bore logs. Anchored by a conventional approach, EM signatures provide tentative designations of types of materials that may be encountered during trenching that extend beyond bore locations. With this, predictions of estimated excavation difficulty are possible on a project-wide scale. Increased knowledge of where and the extent to which materials are easily ripped versus requiring blasting would contribute to more accurate cost estimates for highway construction and decrease the potential of encountering unexpected conditions.

One technological limitation resulted from the timing of the drilling operations and geophysical survey. Optimally the geophysical survey would precede drilling. Then, geotechnical engineering could plan for a comprehensive evaluation of the project area with several bores in each area indicated by geophysical data. This would also provide verification of EM^3 data. As it was, the drilling plan focused on locations of infiltration basin locations with considerations for accessibility and safety. Thus, they were of limited utility for confirming findings as bore logs tended to be clustered in particular locations with expansive stretches between. As the project proceeds, actual trenching will be performed and Argus staff will be available to correlate results of the geophysical survey with actual trenching difficulty, enabling verification of results and refinement of theoretical models. The other technological limitations included spurious noise for the line taken closest to the metallic guardrail and a shift in the data values on the second day of the survey due to a period of rainfall between survey events.

3.2 CHERRY AVENUE FOUR-LANE PROJECT

3.2.1 Background

This project lies between Taft & Bakersfield, along State Route 119 P.M. 5.4/13.29) in Buena Vista Valley, Western Kern County (Figure 6), and is proposed to provide a bypass to the towns of Dustin Acres and Valley Acres. Of ten possible alternatives suggested in the scoping phase the most likely alternatives (9A and 9B), which bypass Dustin Acres and Valley Acres to the south, were the focus of the study. It is a 5-mile long 400-foot wide corridor, which splits on the northern portion, and ranges in elevation from about 400 to 320 feet above sea level. Electromagnetic data may provide valuable information to design engineers in several areas. These include discrimination of soil texture/density differences across the corridor for assessing suitability of road sub-base, identifying buried arroyos that would be of use for planning storm drainage layout, using EM^3 data to more judiciously select geotechnical boring locations, identifying anomalous areas or plumes that might indicate soil contamination, as well as identifying anomalous areas that might be suggestive of buried archaeological sites.

3.2.2 Pre-Survey Planning Meetings with Functional Managers

On April 9, 2005, pre-survey planning meetings were held with Mehran Akhavan (Project Manager), and his staff in Fresno, California. Staff and functional managers in attendance included Warren Lum (Traffic Operations), Hayinder Dhillon (Design), Jose Medrano (Construction), Bob Voss (Materials), Paul Varney (Storm Water), Glenn Medina (Surveys), Cliff Raley and Sarah Gassner (Environment), and John Liu (Traffic Engineering). It was noted that certain portions of the proposed route currently support dense scrub brush and may hinder EM^3 access while other portions are open fields. By the end of April 2005, the appropriate maps, rights-of-entry papers, and background information were reviewed to develop the geophysical survey plan.

3.2.3 Field Work

The geophysical reconnaissance survey was completed May 6-10, 2005. The overall goal was to cover the two-mile long portion of the project segment (those parcels with rights-of-entry) in 5 passes or transects. Two transects were to follow the upper and lower boundaries of the project with three transects between them on 100 foot (30 meter) intervals, all running northeast and southwest, parallel with the project section. Most of the survey was completed as planned. However, straight transect lines were not possible when large shrubs were necessarily avoided, and one portion of the project was inaccessible to the survey equipment. Transect lines are shown in Figure 7, with a photograph of the project area and data collection conditions.

3.2.4 Data Processing and Analysis

Data processing included combining the project area, aerial images and USGS topographic maps with EM^3 transect data, and surface features observed in the field, which were tagged with GPS coordinates.

First Order analysis consisted of correlating EM^3 data with the features depicted on the topographic maps and observed in the field. Linear anomalies coinciding with known utilities are termed "Identified Features" (IF). "Unidentified Features" (UF) are linear anomalies with a signature similar to those of known utilities, but are not demarcated on the topographic map. In addition, areal anomalies were included in "Unidentified Features." Second Order analysis was conducted by reducing the data set to individual files with file-specific color scales, but additional anomalies were not revealed.

Data processing commenced in the field, after the first day of data collection in the southern section. Preliminary data analysis involved screening raw data to identify data points above and below the average range and log their GPS coordinates. With this information staff returned to the location, noted if an object that could explain the high or low reading was present, and completed photo and video documentation.

3.2.5 Results and Discussion

Cherry Avenue Four Lane Project Identified and Unidentified Features

Three Identified Linear Features (IF) and seven Unidentified Features (UF) were noted in First Order Analysis, based on anomalous readings from each of the three receivers for apparent conductivity and magnetic susceptibility. Metallic anomalies are defined as high in magnetic susceptibility, usually accompanied by high apparent conductivity. Non-metallic anomalies are defined as high in apparent conductivity only. The results for Receiver 3, apparent conductivity and magnetic susceptibility, are shown in Figures 8 and 9, and are summarized in Table 3.

TABLE 3 Summary of Unidentified Features, Cherry Avenue Four-Lane Project, Alternatives 9A and 9B.

Unidentified Feature	R3-AC[1]	R3-MS[2]	Data Description	Possible Interpretation
UF1	High	High	Metallic Linear Feature	Unmarked Utility
UF2	Low	Low	Non-Metallic Linear Feature	Unimproved Road
UF3	High	High	Metallic Linear Feature	Unmarked Utility
UF4	High	High	Metallic Linear Feature	Unmarked Utility
UF5	Low	Low	Focal Feature	Unknown
UF6	Low	Low	Focal Feature	Unknown
UF7	High	High	Large-Scale Feature	Unknown

[1] Receiver 3 Apparent Conductivity Anomaly
[2] Receiver 3 Magnetic Susceptibility Anomaly

Identified Features are linear and metallic (IF1, IF3, and IF4), or linear and non-metallic (IF2). Linear metallic features are pipelines, confirmed with observation of US Geographical Survey topographic maps. Identified Feature 2 is an unpaved road, based on observation in the field.

Unidentified Features include possible unmarked pipes (UF1 and UF3), an unmarked, unpaved road (UF2, based on observation of aerial photograph), an unknown metallic linear feature (UF4), two focal areas of unusually low conductivity (UF5 and UF6), and one large area of unusually high conductivity (UF7). The two focal areas of unusually low conductivity, along with focal areas of high conductivity (unmarked) that are scattered throughout the survey area are likely associated with historic (not prehistoric) materials. A remarkable variety and amount of human refuse, including appliances, automobile parts, drums, pipes, and other materials were observed on the surface particularly in the northern portion of the survey area; these, along with buried refuse may cause the focal anomalies. Several of the high conductivity areas appeared to be recently disturbed by heavy equipment.

Unidentified Feature 7 appears to be contained within a property boundary and is noteworthy for apparent conductivity readings above the maximum capability of the instrument as it was set. Most of the area reached the maximum reading of 205 mS/m. As the region historically and currently is heavily geared toward heavy crude oil exploration and production, it seems plausible that the anomalous area could harbor crude oil tank bottoms, oily debris, or other by-products such as high salinity discharge water. Heavy metals (chromium and lead), sulfur compounds, and chloride are typical constituents crude oil production waste (*12*), and could contribute to the very high apparent conductivity and magnetic susceptibility readings. The United States Environmental Protection agency also notes that typical waste management strategies include on-site burial, on-site pits, roadspreading and landspreading; any or all of these techniques may have been utilized in the survey area, contributing substances potentially associated with geophysical anomalies. For example, ground conductivity measurements conducted near Petronila Creek (Nueces County, Texas) which is surrounded by relict and active oil gas wells, typically exceeded 400 mS/m at the site of a former saltwater separation pond (*13*). The Caltrans District 6 Division of Environmental Analysis is preparing to perform soil testing to rule out the possibility that highly saline or hazardous materials are present.

Contained within Unidentified Feature 7 are a number of generally west to east trending linear anomalies. These features have relatively low apparent conductivity and magnetic susceptibility responses, in contrast to the high background readings of the area. Concentrations of vegetation evident on an aerial photograph (Figure 10) coincide with the low conductivity areas. Assuming an increased density of vegetation is associated with additional water availability, it appears that the anomalies indicate the positions of buried arroyos or natural drainages. The results of soil testing will reveal if the materials that contribute to the high readings in the area are soluble, allowing their dissolution and movement out of these discrete locations (arroyos).

Geoarchaeological Trenching and Electromagnetic Data

Trenching was completed in conjunction with a geoarchaeological investigation (*14*), which was to provide the means to ground truth the EM data. However, the trenching occurred before the geophysical survey and the maximum depth of the trenches was 1.5 meters, and the trenching was oriented toward archaeology, not data anomalies, which limited the utility of the trenches for verifying the EM data as the instrument measures apparent conductivity to at least 6 meters.

3.2.6 Advancements and Technological Limitations

Several significant advancements toward a greater understanding of subsurface conditions in the Cherry Avenue Four Lane Project area, Alternatives 9A and 9B, were gained using the EM^3 instrument. First, based on the data, it appears that the soils in Alternative 9A contain less of the materials responsible for the unusually high recordings of apparent conductivity and magnetic susceptibility, an aid in site assessment. A primary finding from this use of the EM^3 as a reconnaissance survey method is that soil testing should be performed in the northern portion of the survey area. Ruling out the possibility that hazardous contamination exists before construction has obvious benefits, including avoidance of stop orders during construction and pre-planned worker protections. If design plans call for trenching in the locations of the focal anomalies, it would be well to perform drilling to verify subsurface conditions. There may be relict petroleum tanks or recently buried unknown materials to contend with during construction. Finally, the locations of active natural drainages will contribute to strategies for storm drainage layout.

There were several technological limitations. Due to the extreme disturbances of the landscape from oil production and waste dumping, it was difficult to discern subtle changes in subsurface materials such as soil texture and density, which would have aided in assessing the suitability of road sub-base. The presence of large shrubs impeded the progress of the ATV and instrument in some locations and precluded data collection in one area. Because the sensitivity of the instrument was set to record data in a range typical of natural conditions, the data readings from the northern section were predominantly at their maximum and lacked definition. Increasing the range setting would provide the means to determine if discrete areas were particularly high, or if plume(s) with specific origin(s) were present.

4.0 PLANS FOR IMPLEMENTATION

Applications of EM^3 data have been demonstrated for two projects, one on an existing Interstate Freeway and the other in native desert scrub, highlighting the versatility of the technology as a transportation innovation. Implementation is possible in a range of terrains and under a variety of conditions. As construction for the Donner Summit Rehabilitation project commences, and as the results of the hazardous materials testing become available from Segment 9 of the Cherry

Avenue Four-Lane project, additional confirmation of the utility of the technology will be achieved. In the mean time, specific plans to implement the technology include a Nomination of Technology Ready for Implementation to AASHTO's Technology Implementation Group. On the state level, a relationship with appropriate staff in the Division of Research and Innovation will be initiated to determine if criteria for the Concept and Laboratory Prototype Stages of the Caltrans 5 Stages of Research Deployment have been met, and if so, a Controlled Field Demonstration of the technology will be conducted. On the Federal level, The Highways for Life Program would be an appropriate venue for further test applications. Eventually the technology may be fully deployed as a tool to improve delivery of projects throughout California. If successful in California, the technology may eventually be commercially produced and become a candidate for implementation nationwide using the Technology Transfer Toolbox. Finally, during the project study and design phase, the technology will be useful for addressing issues of constructability in Value Analysis/Value Engineering on the state and national levels.

5.0 CONCLUSIONS

Non-destructive, rapid reconnaissance or scoping surveys provide information to make a preliminary assessment of site suitability and refine complementary boring or trenching studies. The principal advantage of using the EM^3 is that mobilizes an accepted electromagnetic induction technology, allowing continuously-collected data from three receivers that are GPS-tagged. Two independent yet complementary sets of data (apparent conductivity and magnetic susceptibility) are produced for each of the three receivers, providing a rich data set that may be analyzed by simple display over aerial photographs or topographic maps or by advanced methods such as inversion modeling. Thus the EM^3 measures a variety of useful parameters pertinent to engineering planning on the landscape level, or on a site-specific basis.

With the technology comes an opportunity to improve the accuracy of CAD drawings and as-built plans, reducing ambiguity during design and construction. Estimates of the extents of geologic units with differing levels of excavation difficulty improve the utility of bore logs, and if consulted during the planning stages of the drilling operation, could substantially reduce costs. This is achieved by core-testing to confirm the composition and boundaries of units defined with data, rather than on an equidistantly spaced basis. Establishing the locations of relict buried objects and utilities before trenching enables allows designers and contractors to anticipate subsurface obstacles and anticipate the issues inherent with their presence on the construction site. Soil testing should be performed in the northern portion of the Cherry Avenue survey area. Ruling out the possibility that hazardous contamination exists before construction has obvious benefits, including avoidance of stop orders during construction and pre-planned worker protections. Finally, the locations of active natural drainages will contribute to strategies for storm drainage layout.

In sum, EM^3 technology contributes valuable data to the following decision making arenas: geotechnical (e.g., decisions regarding judicious placement of boreholes, interpolation between boreholes, and extrapolation into areas where no borehole information is available, thereby reducing the number of boreholes required); ROW/subsurface utility engineering (e.g., providing "B-level" data or "designating" data for verification of utility as-built conditions, detecting previously unknown utilities and other obstructions such as underground storage tanks, improving identification of conflicts, and generally helping to guide relocation plans by focusing on clear corridors); environmental management (e.g., detecting contaminated plumes & buried archaeological sites, as well as identifying appropriate wetland banking sites, buried drainage systems, shallow water tables, etc.); and, ultimately, overall route appraisal (e.g., lateral variations in ground conditions) and selection of feasible and/or preferred alternatives.

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