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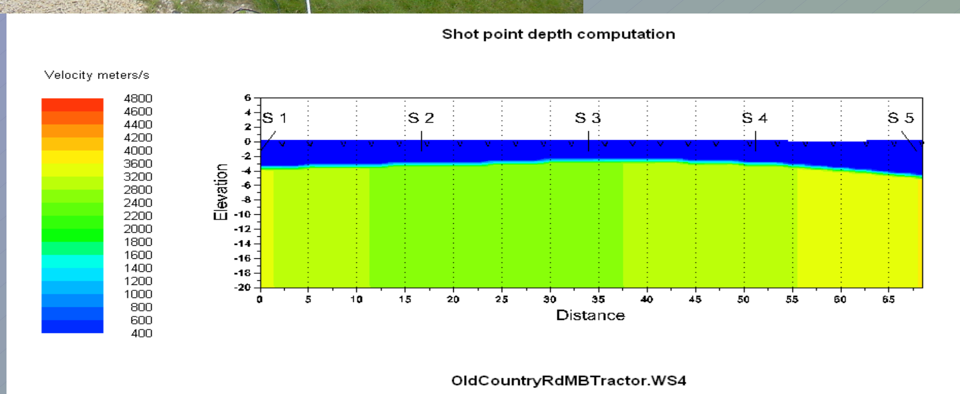

Integrated Geophysical Methods for Geotechnical Subsurface Investigations

Final Report

Prepared by the New Hampshire Department of Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration

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This report summarizes the New Hampshire Department of Transportation's (NHDOT's) investigation of geophysical techniques to supplement conventional test borings and other explorations on transportation projects. The Department's geotechnical investigations often encounter bedrock or unstable soils at variable depths over short lateral distances. Test borings are point specific and may miss sudden depth changes and variations in the soil and rock properties. Additional borings can be expensive and time consuming and may even result in a more puzzling subsurface interpretation. Site conditions and/or highly conductive soil properties can sometimes limit the use of the NHDOT's ground penetrating radar equipment, but through the implementation of additional geophysical techniques the Department has enhanced its capabilities and helped alleviate some of the uncertainties that arise when making subsurface interpretations based solely on conventional exploration methods.

This report presents both successful and less successful case histories utilizing resistivity imaging and seismic refraction in conjunction with test borings and ground penetrating radar to characterize a transportation project's subsurface conditions. The methods employed in using these geophysical techniques, the results of the geophysical investigations, and how these results were calibrated and verified are presented.

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INTEGRATED GEOPHYSICAL METHODS FOR GEOTECHNICAL SUBSURFACE INVESTIGATIONS

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ACKNOWLEDGEMENTS

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ABSTRACT

This report summarizes the New Hampshire Department of Transportation's (NHDOT's) investigation of geophysical techniques to supplement conventional test borings and other explorations on transportation projects. The Department's geotechnical investigations often encounter bedrock or unstable soils at variable depths over short lateral distances. Test borings are point specific and may miss sudden depth changes and variations in the soil and rock properties. Additional borings can be expensive and time consuming and may even result in a more puzzling subsurface interpretation. Site conditions and/or highly conductive soil properties can sometimes limit the use of the NHDOT's ground penetrating radar equipment, but through the implementation of additional geophysical techniques the Department has enhanced its capabilities and helped alleviate some of the uncertainties that arise when making subsurface interpretations based solely on conventional exploration methods.

This report presents both successful and less successful case histories utilizing resistivity imaging and seismic refraction in conjunction with test borings and ground penetrating radar to characterize a transportation project's subsurface conditions. The methods employed in using these geophysical techniques, the results of the geophysical investigations, and how these results were calibrated and verified are presented.

INTRODUCTION

The NHDOT is interested in investigative techniques to supplement its conventional geotechnical test boring program. Such techniques can be used to help determine where test borings should be located or to help fill in gaps in information between borings that have already been conducted. Additional objectives are to reduce costs, reduce investigation time, and improve capabilities in areas with environmental, utility, or access constraints.

Other state DOTs have used geophysics to supplement their test boring activities and have found that this technology helps in interpreting subsurface conditions; however, its effectiveness is dependent upon the local geology. Ground penetrating radar has been used successfully by NHDOT. While this technique has worked well on many projects, its use is sometimes hindered by site conditions or the characteristics of the underlying soils. To determine if other geophysical techniques could help interpret subsurface conditions, the NHDOT evaluated resistivity imaging and seismic refraction as supplements to its existing testing program. This report documents geophysical exploration activities conducted on projects within the state of New Hampshire in 2004 and 2005. It highlights several case histories and includes a description of the techniques employed, the geophysical results, and how the results were calibrated and verified. It is hoped that these case histories will help others recognize the benefits that geophysics can bring to geotechnical investigation programs.

A literature search conducted prior to the start of the project found several related studies. A study in 2003, by Wolfe *et al*, discussed the use of seismic refraction and resistivity imaging in Ohio as a reconnaissance method for locating areas of a highway that could collapse because of underground coal mines. Another study in Ohio (Sheets, 2002) found that electrical resistivity imaging was an important tool for detecting subsurface depressions associated with a ground surface collapse. A study in California discussed the advantages of using seismic refraction to determine bedrock rippability for the calculation of earthwork factors (Leeds, 2002). Another study, also in California, discussed the advantages of using seismic refraction as a geophysical tool to investigate landslides (Narwold and Owen, 2002). In 2003, Anderson and Cardimona studied the use of seismic reflection, ground penetrating radar, electromagnetics, and electrical resistivity, and evaluated their utility on transportation projects for the Missouri Department of Transportation.

These studies have demonstrated that geophysics can effectively be used within the transportation industry for geotechnical evaluations in various areas of the country. Since the successful application of geophysical techniques is highly dependent upon local geology, it would be difficult to extend the specific results from these states to the local conditions in New Hampshire or to the operational procedures utilized by NHDOT.

METHODOLOGY

Geotechnical case studies were used as the method to evaluate the effectiveness of seismic refraction and electrical resistivity imaging in determining the depth to bedrock or in locating changes in the subsurface soil properties on NHDOT projects. The geological and engineering staff at the NHDOT, Bureau of Materials & Research, conducted this research. A 24-channel Seistronix exploration seismograph and a 48-node Iris resistivity imaging system were utilized for the study. The geophysical data were analyzed using RES2DINV by Geotomo Software and WinSism 9.0 by W_GeoSoft.

The criteria for selecting test sites included the following factors: the existence of a current geotechnical project, the local geology, and the ability to ground truth, mobilize, setup, and acquire the geophysical data. The geophysical explorations were conducted as either preliminary exploration techniques or as methods to fill in the gaps between existing test boring locations. Ground truthing consisted of drilling test borings, digging test pits, or conducting hand auger probes. These projects represent typical applications of the use of geophysics on transportation projects within New Hampshire.

CASE STUDIES

Rochester: Spaulding Turnpike Exit 12 Southbound On-ramp

Resistivity imaging was conducted as part of the geotechnical investigation for the Spaulding Turnpike expansion project. The proposed project involved constructing an additional travel lane in both the northbound and southbound directions for approximately 15 miles. It also included new bridges and the reconstruction of several interchanges. The proposed work would consist of cut and fill sections making accurate subsurface information essential. The local geology consists of sands, silts, and clays over glacial till and bedrock. The sands, silts, and clays were deposited as either recent alluvial deposits, or in a glacial-marine environment as a deltaic-type deposit. Previous explorations in the area of the proposed Exit 12 southbound on-ramp had indicated that there is a presence of soft glacial-marine clays in the area. It was thought that resistivity imaging could provide subsurface information helping to define the limits of the glacial marine clays in the areas where test boring data were absent.

To map the subsurface, a path was cleared along the centerline of the new on-ramp (Figure 1). Forty-eight nodes at five-meter spacing were set up as a Wenner-Schlumberger array with 520 quadrapoles capable of obtaining an exploration depth of 38 meters. The multi-electrode unit automatically switched on and off two sets of current and potential electrodes throughout the length of the array until all 520 quadrapoles were read over a period of approximately one hour. The readings were then downloaded from the resistivity imaging unit onto a desktop computer where the results could be analyzed using the RES2DINV software.

Figure 1: Path along alignment of proposed Exit 12 southbound on-ramp.

Using the analysis software and a least squares type of inversion, the resistivity data were inverted and the results displayed as shown in Figure 2. A large portion of the profile consists of material with resistivity values below 100 ohmmeters, which according to Table 1 are typical of silts and clays. To ground truth the results of the resistivity imaging a second round of test borings was conducted along the same line as the resistivity profile. By comparing the resistivity values to a fence diagram created from the test boring data (Figure 3), a strong correlation can be observed.

The resistivity profile shows the glacial marine clays (blues) to a depth of 20 to 28 meters below ground surface with an area towards the middle of the profile showing slighter higher resistivity values (green). It is possible that these higher values indicate the presence of an old river channel that had previously cut through the glacial marine sediments as the river meandered over time. A fence diagram was created from the test boring data showing the glacial-marine clays (zero blow count material) to a depth of 21 to 23 meters below ground surface. By using the known depths of the glacial-marine clays, a bedrock surface could be interpreted on the resistivity profile as somewhere close to the top of the light blue color.

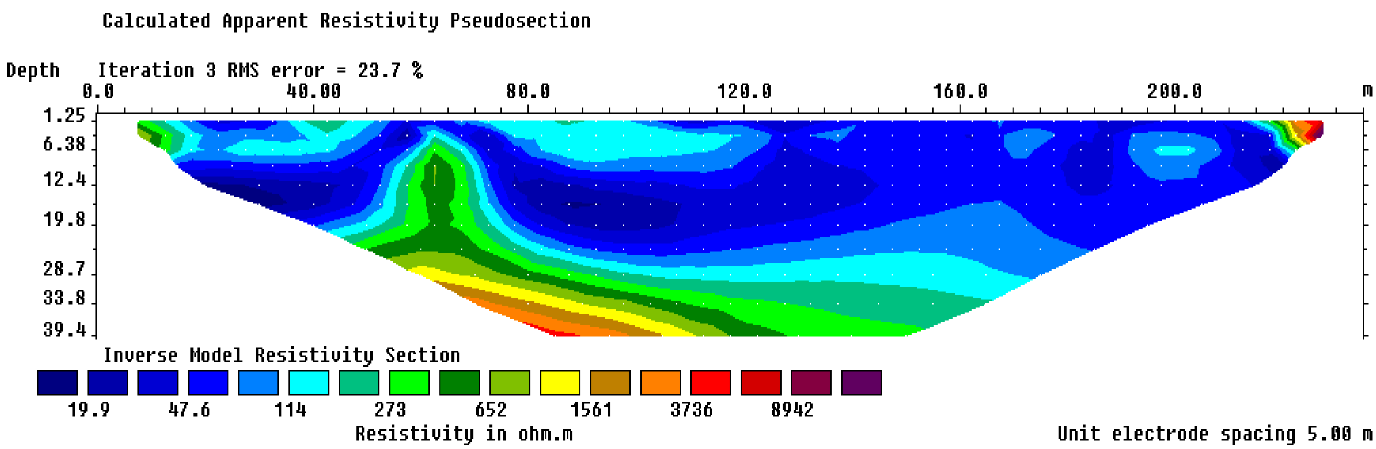

Figure 2: Wenner-Schlumberger resistivity array

Type of Soil or Water	Typical Resistivity Ωm	Usual Limit Ωm
Sea Water	2	0.1 to 10
Clay	40	8 to 70
Ground well and spring water	50	10 to 150
Clay and sand mixtures	100	4 to 300
Shale, slates, sandstone, etc.	120	10 to 1000
Peat, loam and mud	150	5 to 250
Lake and brook water	250	100 to 400
Sand	2000	200 to 3000
Moraine gravel	3000	40 to 10000
Ridge gravel	15000	3000 to 30000
Solid granite	25000	10000 to 50000
Ice	100000	10000 to 100000

Table 1: Resistivity values for several types of soils and waters, ref. Earthing RFI Industries website.

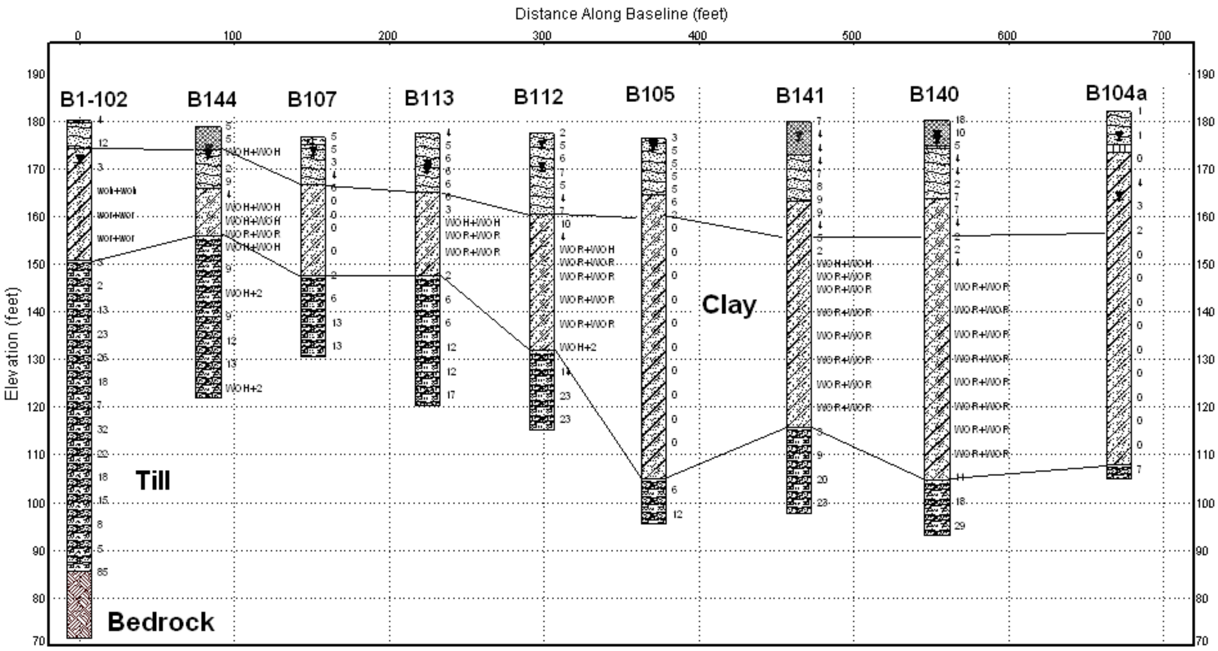

Figure 3: Fence diagram of test boring logs from Exit 12 southbound on-ramp

The subsurface conditions beneath the proposed Exit 12 southbound on-ramp were accurately mapped and analyzed by a combination of resistivity imaging and a series of test borings. The data were used to design a large embankment fill over the soft soils encountered directly beneath the alignment.

Salem-Manchester: I-93 Exit 3 Southbound On-ramp

The expansion of I-93 is currently the largest highway project in New Hampshire. Two additional travel lanes are proposed in both the northbound and southbound directions for a distance of 34 kilometers (21 miles). New bridges, reconstruction of the interchanges, reconstruction and realignment of sections of state and town roads, construction of sound walls, a variety of retaining structures, and a new alignment for portions of the interstate highway are all included in the scope of work. The new alignments will be traveling through shallow bedrock resulting in high rock slopes and over areas of soft soils with large embankment fills. Resistivity imaging was conducted as part of the geotechnical investigation for the proposed I-93, Exit 3 southbound on-ramp.

The local geology along this stretch of highway is characterized by shallow gneissic and schistose bedrock overlain by a sandy glacial till with a perched water table that generally sits on top of the bedrock surface. Organic deposits in low-lying wetlands are scattered throughout the area. Topographic features recognized during a field reconnaissance and a review of existing as-built plans have indicated that soft organic soils could be present along the proposed alignment for the Exit 3 southbound on-ramp. Conventional explorations would be planned at this location if the results of the resistivity imaging show areas of low resistivity values.

To facilitate the geophysical investigation, a path was cleared through tall cattails (Figure 4) near the proposed centerline of the new southbound on ramp. Forty-eight stainless steel electrodes were placed at five-meter intervals and a Wenner-Schlumberger array with 360 quadrapoles capable of obtaining an investigation depth of 20 meters was created. The water table was near the ground surface in the area where the electrodes were placed. The data were collected, readings were downloaded onto a desktop computer, and the RES2DINV analysis software was used to analyze the data. Using a least squares type of inversion, the data were inverted and a resistivity profile was created (Figure 5).

Figure 4: Photo of area with suspected organic deposits.

The inversion results indicated that a large portion of the profile is characterized by a material with low resistivity values (less than 90 ohm-meters). As indicated by Table 1, low resistivity values are typical of wet organic and clayey soils. Based upon the results indicated by the resistivity survey, a series of hand auger probes was conducted to collect soil samples for laboratory analysis and to further map the extent of the deposit. Figure 6 displays the on-ramp alignment, the resistivity line, and the locations of the hand auger probes. Table 2 displays the laboratory results of the soil samples collected through the hand auger probes. This deposit is characterized by soils with high moisture and organic contents to a maximum depth of 35 feet below ground surface.

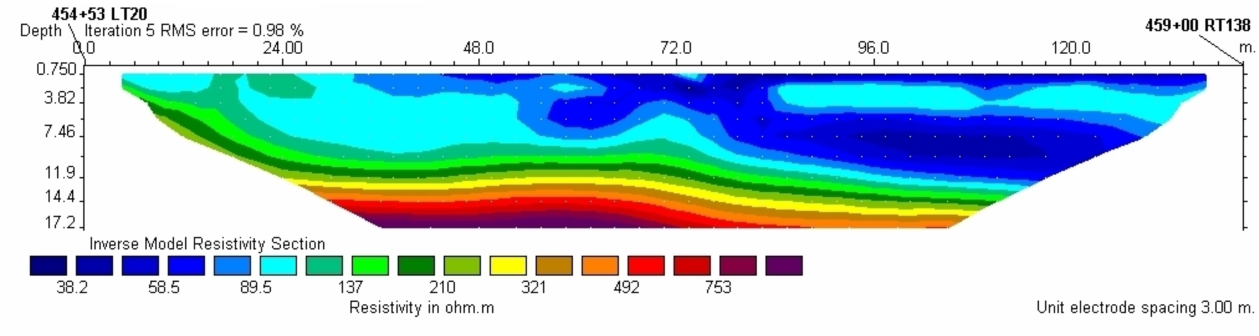

Figure 5: Wenner-Schlumberger array

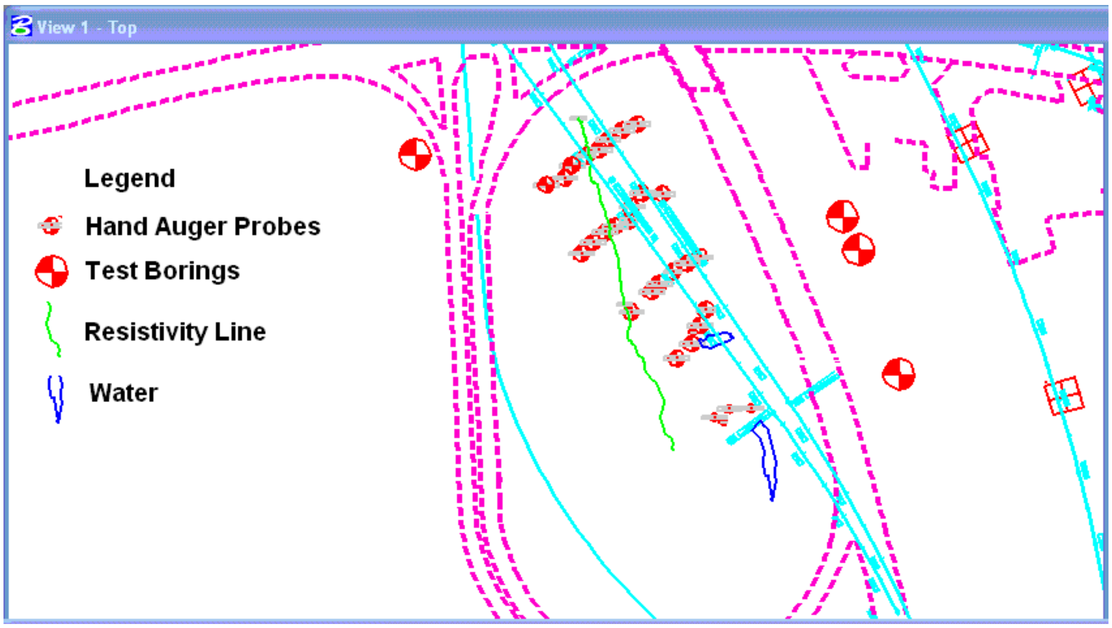

Figure 6: Exit 3 ramp alignments, location of hand auger probes & resistivity line.

Sta & Offset	Description	Depth (ft)	Sample	Moisture	Organics
456+03, RT 61	Organic silt	5.4-8.5	1	119.3%	14.9%
456+01, RT 41	Organic silt	4.0-8.5	2	114.8%	17.0%
456+02, RT 24	Organic silt	3.5-7.4	3	172.0%	21.0%
457+00, LT 24	Muck	2.4-5.5	4	89.4%	13.7%
456+98, LT 1.8	Muck with peat	1.8-6.8	5	188.3%	22.9%
456+00, RT 23	Muck & peat	2.0-11.4	6	28.9%	25.9%
457+03, RT 37	Peat	3.0-14.0	7	224.6%	22.6%
457+09, RT 75	Peat	0-24.4	8	670%	73%
457+96, RT 62	Peat	0-35.0	9	597.9%	68.1%
457+91, RT 34	Peat	0-23.6	10	505.9%	36.7%
457+91, RT 34	Peat	27.2-28.2	11	487.1%	55.2%
457+78, RT 10	Peat	8.5-17.0	12	490.7%	48.3%
457+78, RT 10	Organic silt	17.0-24.7	13	168.6%	11.9%
457+78, RT 10	Peat & Muck	5.4-17.0	15	175.5%	18.7%

Table 2: Laboratory results of samples collected through hand auger probes, proposed I-93, Exit 3 SB on-ramp.

The resistivity imaging results will be used in conjunction with the laboratory test data and the hand auger probes to design a large embankment fill over soft organic soils for the proposed Exit 3 southbound on-ramp.

Plaistow: NH Route 125/Old Country Road Intersection

This project involved the signalizing, re-grading, and expansion of an existing intersection on a busy state highway with poor sight distance. The first phase of the project included the drilling of test borings to help characterize the soils and to determine if bedrock would be encountered within the project limits. It was important to accurately map the depth to bedrock throughout the entire area of the intersection because the grade was to be dropped and subsurface drainage was to be installed. The test borings encountered shallow bedrock. Seismic refraction was employed to increase the exploration coverage and to locate any areas where the bedrock surface might suddenly change between the test boring locations.

Figure 7 is a photograph looking away from the intersection and down Old Country Road. A seismic line containing 24 geophones was set up at a three-meter spacing over a distance of 69 meters along the roadway shoulder. A Betsy Gun with a 400-grain charge was used as an energy source. Two end shots, two quarter shots, and one middle shot were fired. For each shot, the first arrivals were picked at each geophone and the velocities were calculated for a two-surface model. Figure 8 displays the velocity profile for the seismic line that was run along this section of Old Country Road.

Figure 7: Photograph of Old Country Road, which intersects NH Route 125.

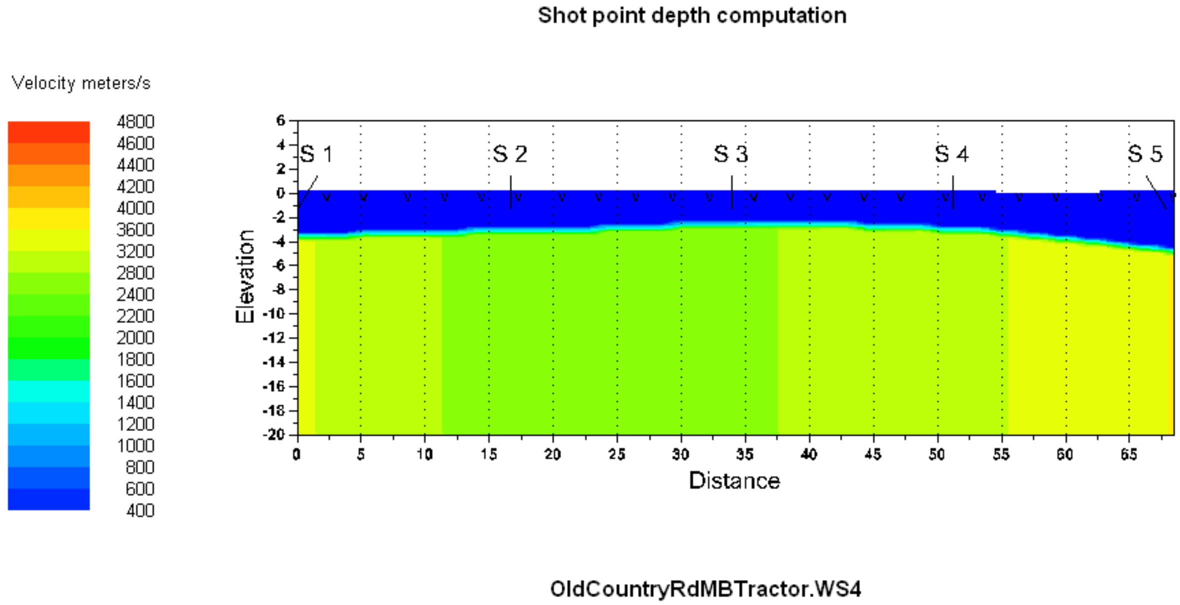

Figure 8: Seismic velocity profile along 1 section of Old Country Road.

Figure 9 is a plan view of the intersection displaying the locations of the test borings and the seismic lines. For the seismic profile displayed in Figure 8, seismic shot S1 was closest to test boring B131 and seismic shot S5 was closest to test boring B118. The yellow and green velocities represent the bedrock while the blue velocities are the overburden soils. The test borings were used to ground truth the seismic profiles.

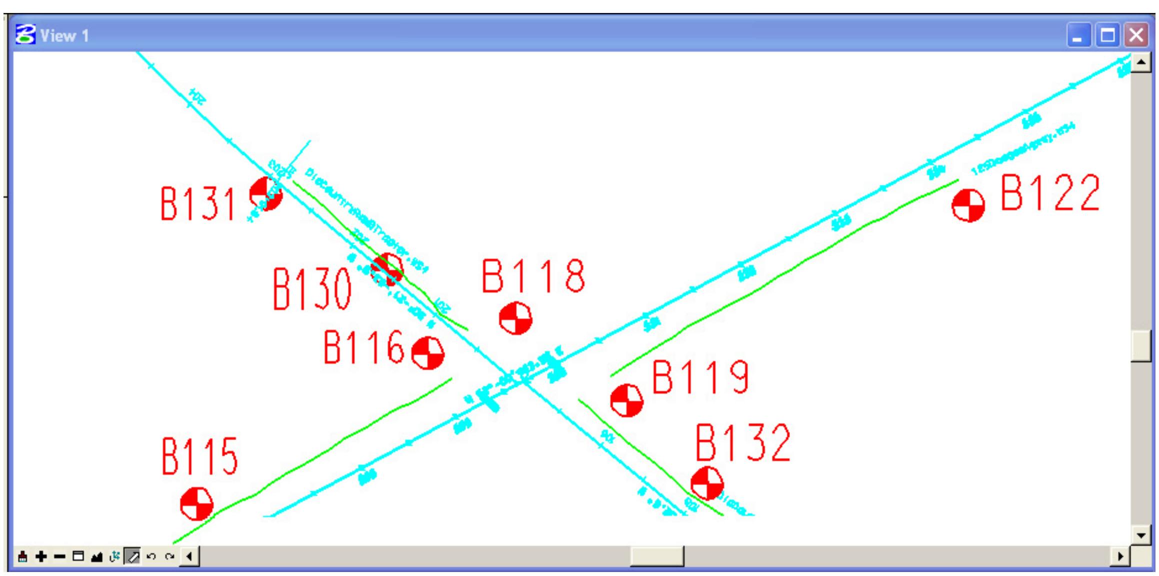

Figure 9: Plan of Old Country Rd & NH Route 125 showing test borings & seismic lines.

Displayed in Figure 10 is a fence diagram of the test boring data moving away from the intersection. The ground surface can be seen dropping in elevation by approximately one meter (4 ft) as the bedrock surface increases in elevation by approximately one-and-a-half meters (5 ft). Similar depths to bedrock are displayed on the seismic profile in Figure 8.

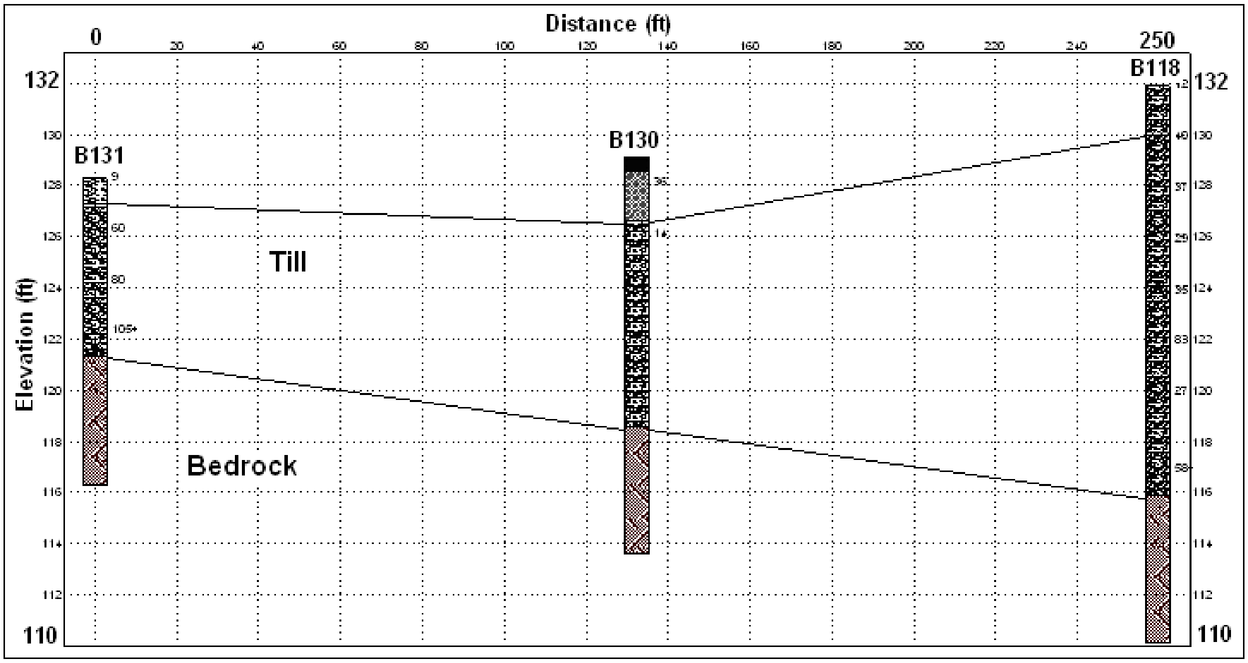

Figure 10: Fence diagram of test borings along a section of Old Country Road.

Walpole: NH Route 12A

This project involved the use of resistivity imaging and ground penetrating radar (GPR) to investigate possible voids beneath NH Route 12A in the vicinity of a failed 1.5 meter diameter metal pipe located under approximately 18 meters of roadway fill and asphalt (Figure 11). A project was scheduled to slip-line the failed pipe to stop settlement of the southbound travel lane caused by fine-grained soil moving through a break in the existing pipe. NHDOT maintenance forces planned to place new fill beneath the failed section of roadway but needed to accurately identify the location and extent of the voids to avoid a large open cut in the pavement.

NH Route 12A is located in the western part of the state and travels along the eastern shore of the Connecticut River. The geophysical investigation encountered primarily roadway fill material with possible natural deposits of sand and silt. Figure 12 is a Global Positioning System (GPS) survey showing the locations of the GPR and resistivity profiles, cracks in the pavement, the failed section of roadway, and the location of catch basins and pipes. Also shown is an area of concern based upon the geophysical results.

Figure 11: 1.5 meter metal pipe buried beneath 18 meters of roadway fill.

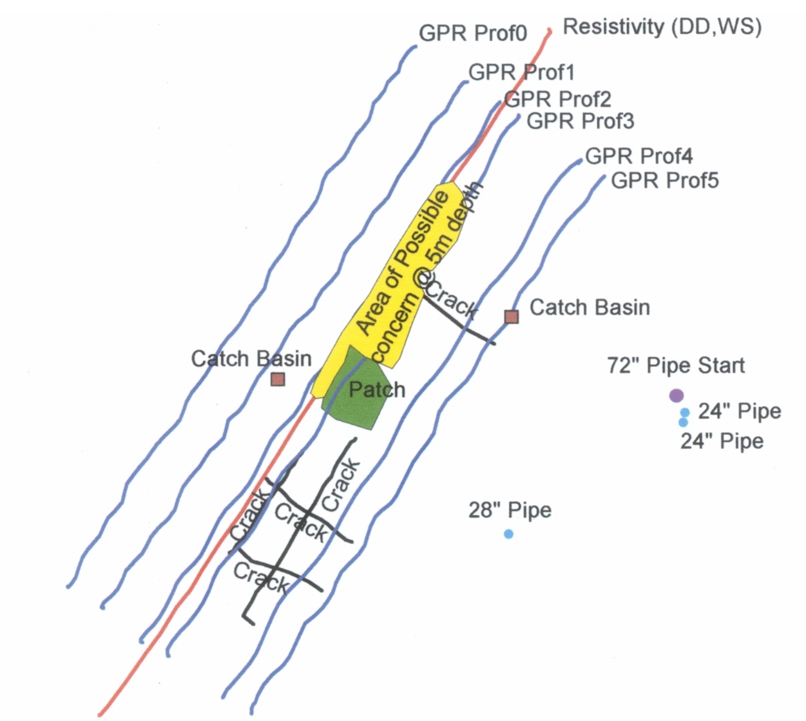

Figure 12: Geophysical and GPS survey of project.

Figure 13 is one of six GPR profiles that were collected at the site. This profile was collected near one of the catch basins just south of the failed roadway section. A 100 MHz shielded antenna was used to collect data displayed in this profile. As shown in

Figure 13, the maximum depth of penetration was approximately six meters, which was about a third of the depth needed to reach the buried (1.5 meter diameter) metal pipe. A reflection from the catch basin pipe is observed in the profile, but voids or other subsidence are not observed. The remaining GPR profiles were similar to that of Figure 13, voids were not detected and the 1.5-meter diameter buried pipe was not observed.

Figure 14 is a resistivity profile that was collected on the southbound shoulder of the roadway adjacent to where the failed surface is located. Twenty-four electrodes were placed at four-meter spacing and a Dipole-Dipole array was set up. The metal pipe buried at 18 meters was not encountered even though the array was designed to reach a depth of 21.5 meters. However, an area with low resistivity values (less than 20 ohm-meters) possibly composed of loose silty fine material (i.e. area of concern in Figure 12) was located and could be a contributing factor to failure of the roadway.

A second resistivity profile was collected in the same location using a Wenner-Schlumberger array with the same number of electrodes and spacing as the previous array. The results from this array were similar to that of the first, and neither the buried pipe nor any other voids were observed in the resistivity profile. As a result of the geophysical investigation, the project was designed to include a large open cut in the pavement for the placement of new material.

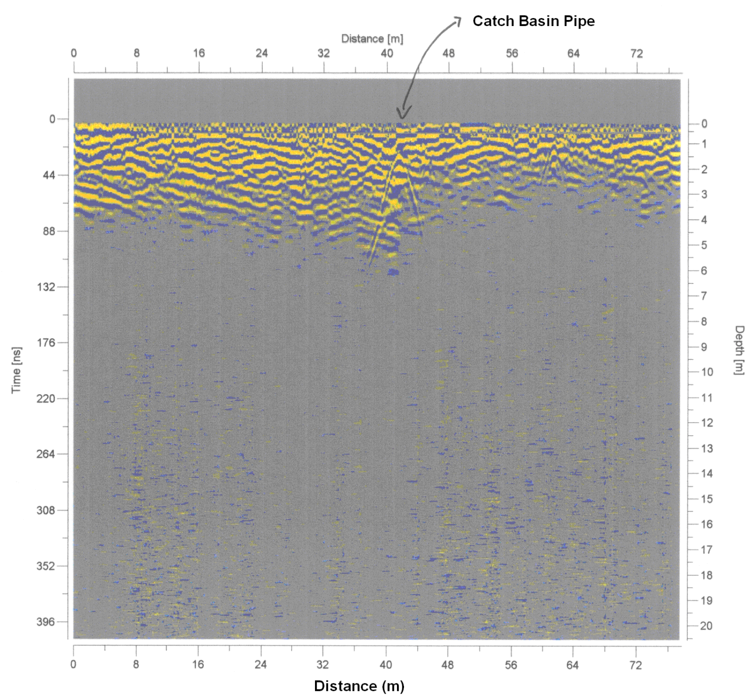

Figure 13: GPR profile showing catch basin pipe.

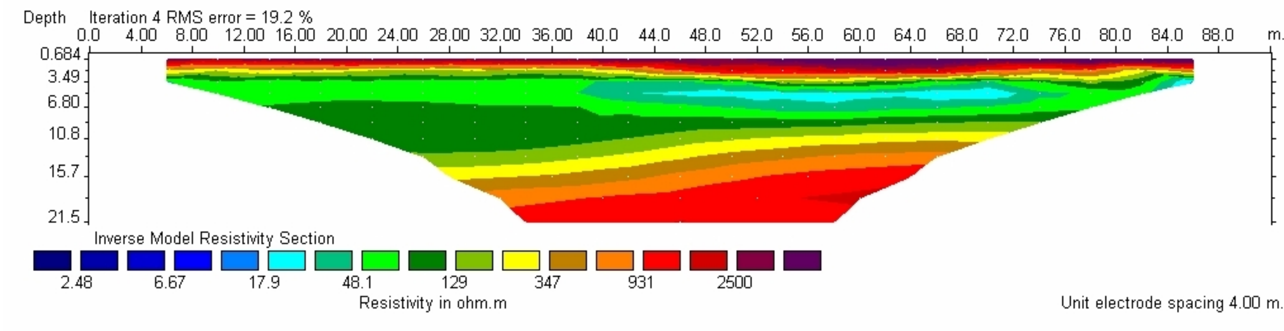

Figure 14: Dipole-Dipole array looking for 1.5-meter metal pipe at a depth of 18 meters.

Warren-Benton: NH Route 25

This project is located on NH Route 25, beginning at the Warren/Benton town line and continuing east approximately two miles. Plans called for a section of the roadway to be straightened to eliminate S-curves and to improve sight distance. The project consisted of full roadway reconstruction and minor realignment for portions of the existing roadway, and reclamation and repaving for the remaining sections of roadway. The geotechnical investigation involved the use of ground penetrating radar, resistivity imaging, and seismic refraction in conjunction with test borings and test pits to locate soft soils, shallow bedrock, and a suspected, buried corduroy road built above logs that float over a wetland.

On this project, the geophysical investigation was conducted prior to drilling the test borings and excavating the test pits. This was done to locate areas where the test borings and the test pits should be taken to confirm the presence and location of the corduroy road, soft soils and shallow bedrock. After the geophysical investigation was completed, the test borings and test pits were conducted to serve as ground truth and confirmation of the corduroy road.

Seismic refraction was conducted along the southern side of N.H. Route 25 covering 460 meters of roadway. Figure 15 is a typical seismic profile for the project area. 24 geophones were placed at five-meter spacing intervals and five shots at locations S1 through S5 were fired. The shallow bedrock displayed in the profile agreed well with the test borings and test pits that were conducted along this side of the roadway.

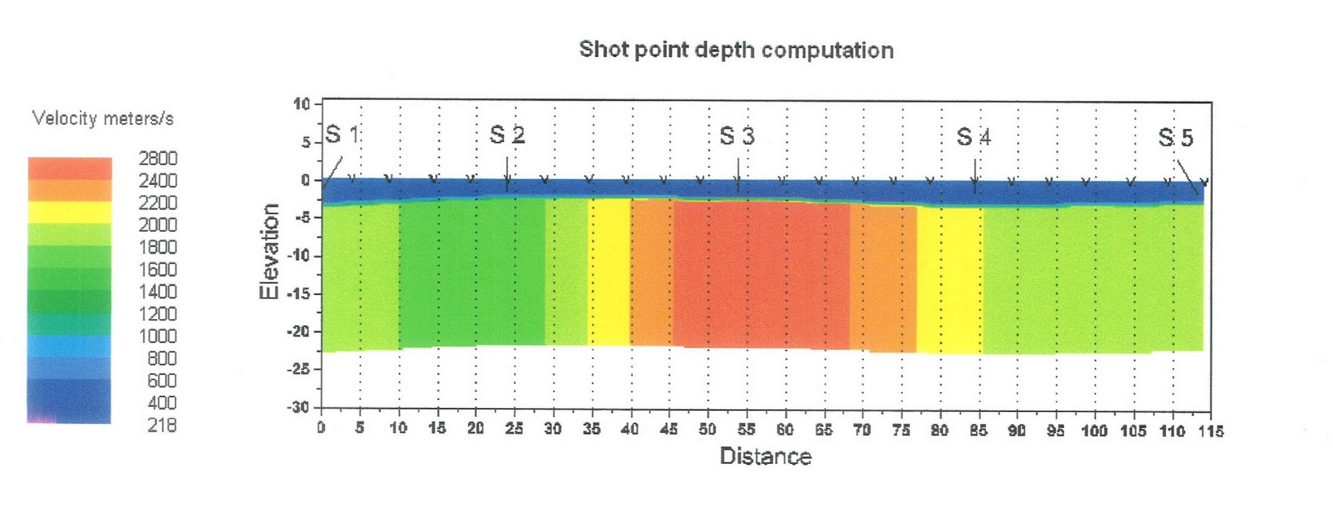

Figure 15: Typical seismic refraction profile along southern side of roadway

Resistivity profiles were collected along the southern side of the road for 470 meters (Figure 16) and along the northern side of the road for 23.5 meters. Figure 17 displays two resistivity profiles collected along the southern side of the road with five-meter electrode spacing. These profiles display soils with relatively low resistivity values over shallow bedrock with higher resistivity values. Figure 18 is similar to Figure 17 except that the bottom profile has an electrode spacing of one half meter. This profile is different from the others in that it displays data only to a depth of 1.2 meters but is at a much higher resolution.

Figure 19 is a shallow test pit that was dug to a depth of two meters along the northern section of the roadway where resistivity imaging and GPR were conducted. The test pit helped to ground truth these profiles and confirmed the presence of the corduroy road. The logs that compose the corduroy road were smaller in diameter than expected and are placed parallel to the roadway alignment instead of perpendicular. In addition, small branches were found along with the logs.

Ground penetrating radar (GPR) was conducted along the southern side of the road for 460 meters, along the northern side of the road for 250 meters, and over the central part of the road for 240 meters. A shielded 100 MHz antenna was used to collect the data for the southern and northern sides of the road, and a 500 MHz shielded antenna was used to collect the data from the central part of the road. Figure 20 displays GPR profiles taken along the section of roadway where the corduroy road was expected. These profiles were collected with the 500 MHz antenna with a depth penetration of approximately two meters.

Figure 16: Resistivity line set up along the southern side of the roadway.

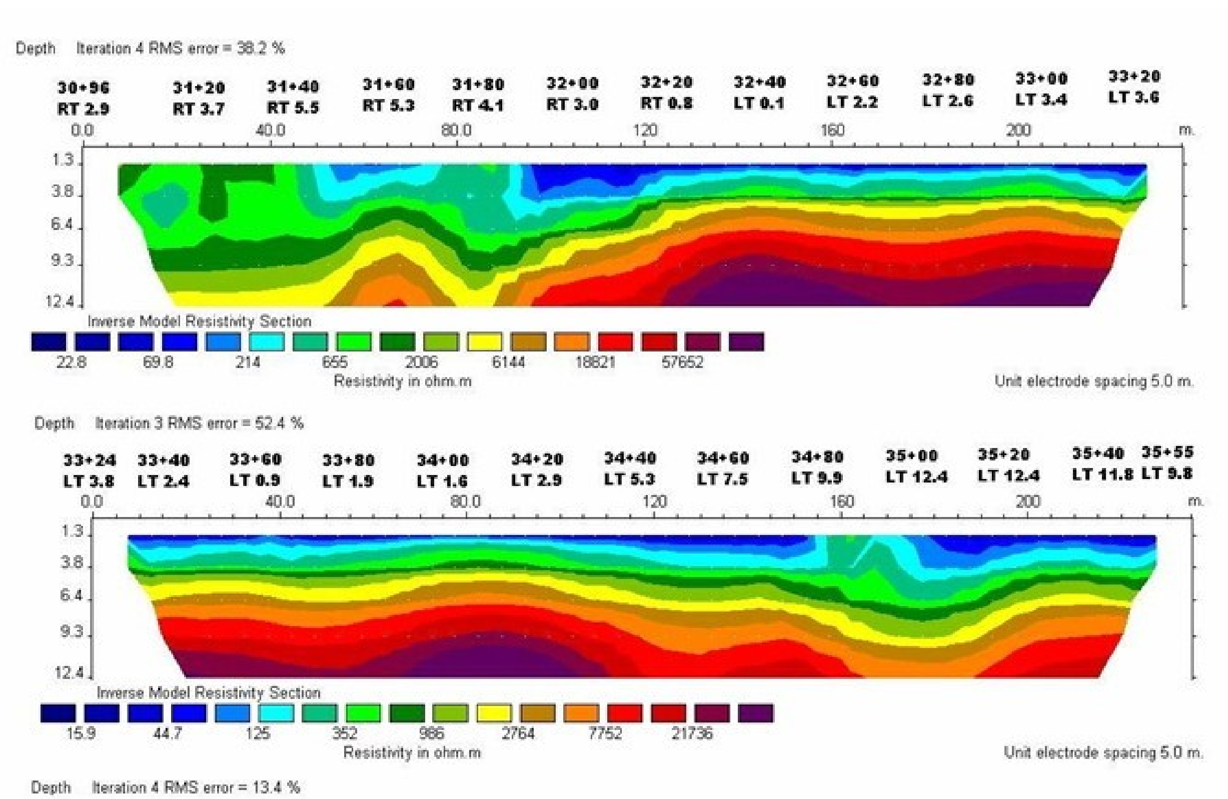

Figure 17: Resistivity profiles along the southern side of the road.

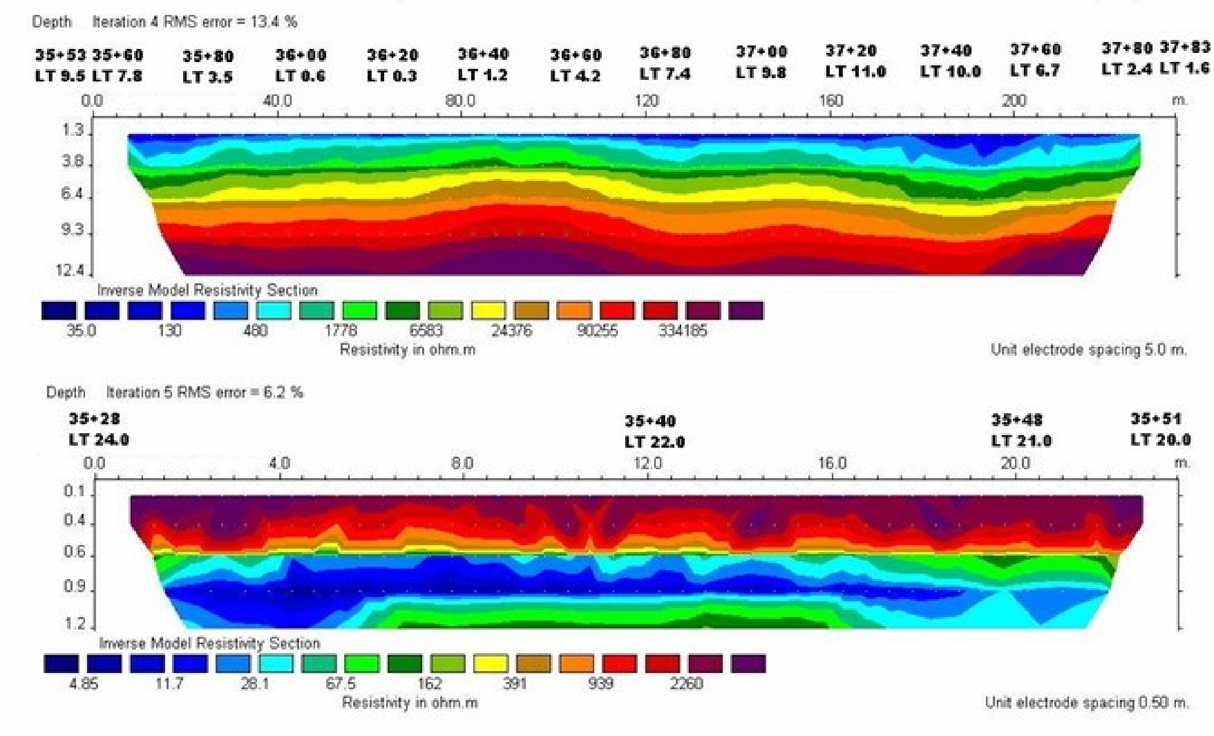

Figure 18: Resistivity profiles along the southern & northern sides of the road.

Figure 19: Test pit showing corduroy road.

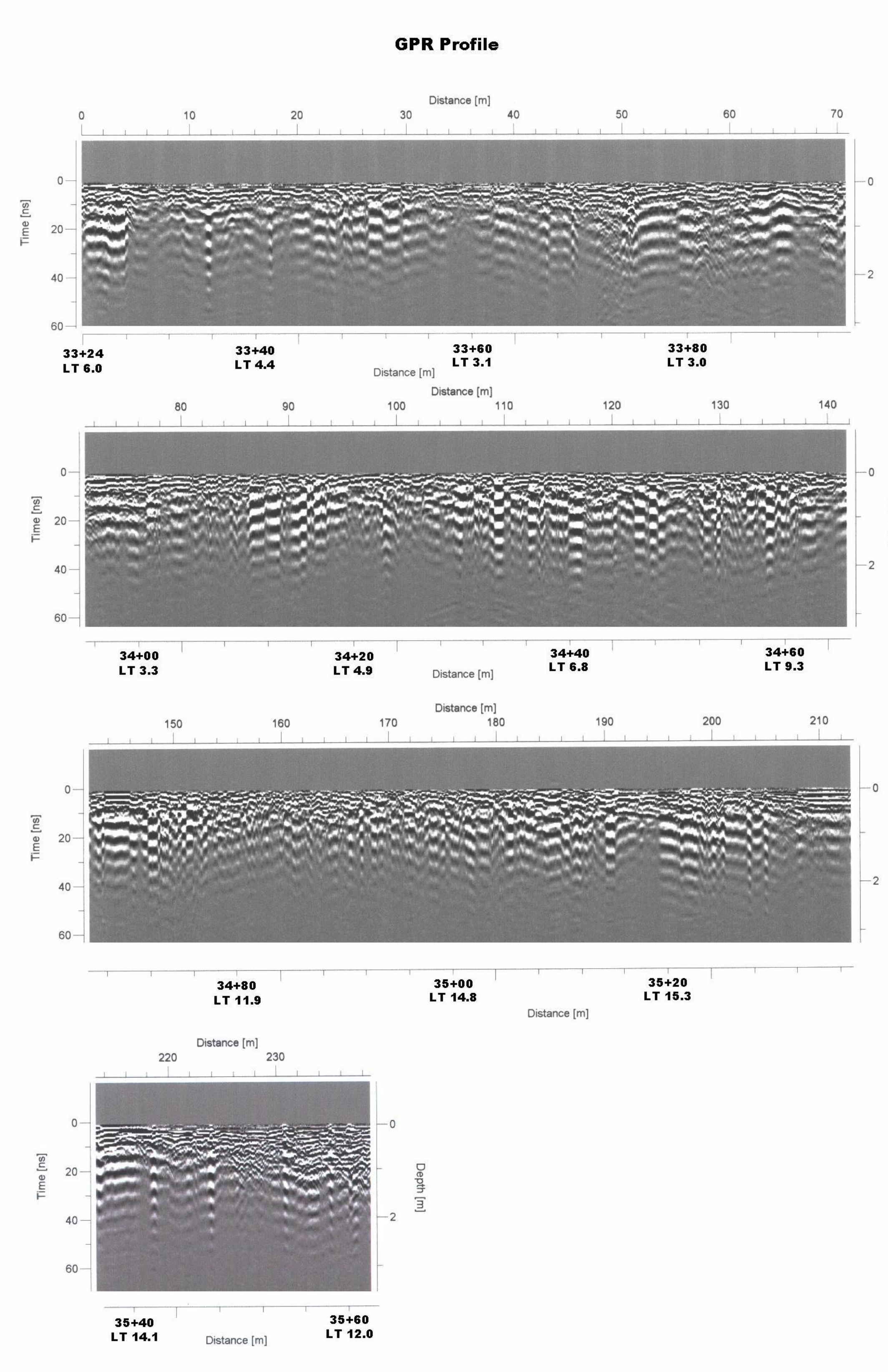

Figure 20: GPR profiles using 500 MHz antenna.

DISCUSSION

The case histories reported here have demonstrated that geophysics can be used for subsurface investigations on geotechnical projects in New Hampshire. Both resistivity imaging and seismic refraction worked well in characterizing the subsurface conditions when used in conjunction with other types of explorations (i.e. test borings, test pits, hand auger probes and GPR).

The sites selected for this study were associated with ongoing geotechnical work where ground truthing could be accomplished and where the mobilization, setup, and acquisition of geophysical data could be completed without difficulty. This report contains five case histories selected from 17 project sites where resistivity imaging and/or seismic refraction were used as part of geotechnical investigations in New Hampshire. The I-93 ramp in Salem and the Warren/Benton corduroy road projects collected geophysical data as a preliminary exploration technique. The Spaulding Turnpike on-ramp and the Old Country Road intersection projects collected geophysical data as a supplement to conventional explorations. Geophysical data were collected at the Walpole pipe project in an attempt to locate areas where the underlying material had settled and fill was needed. These five projects represent typical applications showing that seismic refraction, resistivity imaging, and GPR can be implemented on transportation projects in New Hampshire.

The resistivity results from the Spaulding Turnpike on-ramp project ground truthed well with the test borings. A section of the profile revealed an area of higher resistivity values close to the ground surface. This area could represent an abandoned river channel within the Cocheco River flood plain. This demonstrates that test borings alone can miss areas that could be significant to the geotechnical aspects of a project. For this site, an important question is: Where would you interpret the bottom of the marine clay deposit if test boring data could not be used as a ground truth? On the right side of the resistivity profile, the blues (20–114 ohm-meters) transition into the greens (200-650 ohm-meters) over a depth range of 20 to 28 meters below ground surface. Without test boring data it would be difficult to accurately determine the bottom of the marine clay deposit.

The hand auger results compared well with the resistivity profile collected for the proposed I-93 Exit 3 southbound on-ramp. The resistivity data was able to confirm suspicions that deep soils with high moisture and organic content were most likely present beneath the area of the proposed high embankment fill. The difficulty was how to confirm the results of the resistivity imaging. The ground was too soft for drilling conventional test borings, so hand auger probes were used to confirm the extent of the deposit and to collect soil samples for laboratory analysis. The use of geophysics on this project was different from that of the other case histories. Resistivity imaging was used as a preliminary type of investigation in an attempt to locate problem soils within the limits of the project. By using resistivity imaging to locate soft soils prior to developing an exploration plan, test borings, test pits, or hand auger probes can then be taken at locations where they will best collect subsurface data key to the design of the project.

The seismic refraction results from the Old Country Road project also ground truthed well with the test borings. This demonstrates that in areas of shallow bedrock, seismic refraction works well at filling in the gaps between test boring locations. The bedrock surface mapped by seismic refraction did not reveal any sudden changes in the elevation. If the seismic refraction results had indicated sudden changes additional test borings would have been conducted to confirm the refraction results. For this project, the seismic refraction results provided confidence to the geotechnical engineer that the bedrock surface depth encountered through the test borings remained relatively constant over the entire project area.

The geophysical investigation that was conducted to locate the buried 1.5-meter diameter pipe in Walpole was considered to be less successful. It was known ahead of time that trying to obtain a depth of 18 meters with GPR would be difficult. The Maintenance Engineer was informed that GPR would probably only be able to locate near-surface voids and not voids that surrounded the pipe buried at a depth of 18 meters. This proved to be partially correct because GPR was only able to reach a depth of approximately six meters before the signal attenuated. It did not detect any near-surface voids. In order to detect voids, there must be a difference in the dielectric constants between the material surrounding a void and the material filling a void. In this case, either the near-surface voids did not exist, the material that filled these voids and the material that surrounded these voids had similar dielectric constants, or the voids were beyond the resolution of the antennas. The resistivity results also could not locate the buried pipe at a depth of 18 meters. Both the Wenner-Schlumberger and the Dipole-Dipole arrays were centered on the pipe and should have been able to reach a depth of 18 meters. Although the pipe was not detected, the results were somewhat useful because a near-surface area with low resistivity values was observed. Unfortunately, this area of low resistivity did not correlate well with the area of roadway subsidence. To obtain the maximum depth penetration and a higher resolution, a pair of additional arrays should have been designed using all 48 nodes. These arrays should have set the electrode spacing at two-and-a-half meters and at five meters. The combination of these additional arrays would have increased the near-surface resolution as well as the depth penetration of the profiles. With these additional arrays, the buried pipe and any near-surface voids might have been detected.

The geophysical investigation in Warren easily detected the soft soils, shallow bedrock, and water table, but it is questionable whether it detected the corduroy road. The logs used to construct the road had a relatively small diameter and were placed parallel with the roadway as observed in some of the 1.5 to 2 meter deep test pits (Figure 19). The direction of the geophysical investigation was parallel with the roadway which made it difficult for the ground penetrating radar unit to obtain cross-sectional reflections of the small logs buried to a depth of approximately 1.5 meters. The GPR profiles collected using the 500 MHz antenna (Figure 20) display some shallow reflections that could be from the logs, but it would be difficult to confirm the presence of the corduroy road solely based upon these GPR profiles. The resistivity profile collected along the northern side of the road with half-meter electrode spacing (Figure 18) clearly displays the water table beneath the roadway sands. This profile was taken very near the test pit displayed in Figure 19, but the buried logs cannot be detected within the water-saturated soils.

CONCLUSIONS AND RECOMMENDATIONS

These case histories have summarized typical applications of the use of geophysics to supplement conventional subsurface exploration techniques within the NHDOT. The results of this study may be difficult to compare to the use of geophysics in other states because of New Hampshire's unique geological conditions. These case studies have demonstrated that through the addition of geophysical techniques, subsurface conditions on NHDOT projects are better characterized when compared to conventional explorations alone. Time and money are saved because the number of test borings and test pits required for the same level of confidence has been reduced. By implementing these additional geophysical techniques, the NHDOT has enhanced its capability to characterize subsurface conditions on geotechnical projects.

There are a few limitations when using seismic refraction and resistivity imaging. There is a decrease in the resolution and reliability of the data with depth. Another limitation of seismic refraction occurs when a higher velocity layer is located above a lower velocity layer. In this instance, pertinent information below the higher velocity layer could be missed. Examples of situations that can occur on geotechnical projects when a denser material is encountered over a less dense material include perched water tables, highly compacted soils within a roadway embankment, or an asphalt layer over roadway soils.

It is recommended that the NHDOT continue to use its geophysical capabilities whenever possible. By using geophysics as a supplement to conventional test borings and as a preliminary tool to locate problem soils, more accurate subsurface characterizations can be provided for less time and money. The researchers realize that some applications of the current seismic and resistivity techniques might be beyond the limits of the Department's equipment and capabilities. It is the responsibility of the geophysicist to inform the geotechnical project manager of the limitations of the geophysical equipment and techniques as they relate to the geological conditions at each site. To insure that these new capabilities do not become obsolete, the geophysical instrumentation and the analysis software need to be maintained and should be updated as improvements are made. In addition, the geophysicist needs to continue to be trained on new geophysical techniques and applications as they become available.

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