USE OF GROUND PENETRATING RADAR FOR SITE INVESTIGATION OF LOW-VOLUME ROADWAYS AND DESIGN RECOMMENDATIONS

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16. Abstract

This report will present several case studies describing the use of ground penetrating radar (GPR) technology for site investigations. Two types of GPR will be described–the air-launched and ground-coupled systems. The use of air-launched radar is well established within the Texas Department of Transportation (TxDOT). The limitation of this technology is its depth of penetration. While providing very useful information on the surface and base layers, it provides little information on the subgrade soils. The use of low-frequency ground-coupled radar systems will provide little useful near-surface information but it can provide data on subgrade properties and how they vary along a project. Combining both radar types can potentially provide a comprehensive subsurface investigative tool for both new pavement construction and for major pavement rehabilitation projects.

In this report a brief description will be provided of the different systems together with the software used to process the GPR signals. Air-launched data are processed with the COLORMAP system developed by the Texas Transportation Institute. The ground-coupled data are processed using the Road Doctor™ system developed by Roadscanners, Inc. of Finland. The case studies presented were collected on actual TxDOT evaluation projects mainly in the Bryan District. They range from near-surface applications where the goal was to identify changes in pavement structure which were not available in construction records to identifying the areas beneath the pavement subsidence associated with strip mining activities.

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CHAPTER 1. INTRODUCTION

The major task in Project 7-4906 was to investigate improved methods of evaluating subsurface pavement conditions prior to pavement design. In particular how can nondestructive testing be incorporated into the pavement design process, and what changes should be made to the sampling procedures? The importance of indentifying subsurface subgrade conditions was evident in a recently completed Project 7-3903 where the performance of rehabilitated low-volume roadways clearly depended on the soil type (Syed and Scullion 1999). In that project the sections under evaluation had all been recycled, where the existing structure was stabilized to form a subbase layer. The major problem found in these pavements was in areas where the stabilized layers were placed directly over highly plastic subgrade soils. In the dry summer months longitudinal cracks developed in these areas. In some instances the cracking became severe. In other cases a short section of distress would be found in a long project. Upon site investigation, it was determined that this was a short section over high plastic materials. Based on these findings the Bryan District now conducts a complete site investigation of every upcoming low-volume road rehabilitation project. Subsequent field trials have found that "grid type" fabrics successfully mitigate the longitudinal cracking problem. However, pinpointing the areas where these fabrics should be used remains a problem. Currently, this is achieved by using United States Department of Agriculture (USDA) soil series maps (where available) and by selective field borings, typically at 1-mile intervals. One key question posed by Project 7-4906 is "Is the existing Nondestructive Testing (NDT) technology sufficiently advanced that it will permit a scan of any upcoming project and identify major changes in subsurface soil type?"

The research team recommended using ground penetrating radar (GPR) technology for this application. Therefore to complete this evaluation project, the Texas Transportation Institute subcontracted with the Finnish company Roadscanners, Inc. This company is comprised of former employees of the Finnish National Road Administration (FinnRA), who have spent almost 15 years evaluating the use of deep penetrating ground-coupled radar for site evaluation. Roadscanners, Inc. has developed an innovative software package called Road Doctor™ (Saarenketo 1999) which was made available for use on this project.

This project therefore comprises an evaluation of how both air-launched and ground-coupled GPR can be used in project evaluation. The air-launched evaluation technology is well established in Texas. The goal of this project is to integrate both the air-launched and ground-coupled radar into a single comprehensive subsurface evaluation. In conducting this project, researchers investigated a range of upcoming pavement projects. In some the information of major concern to TxDOT was obtained from the air-launched GPR survey, in others the ground-coupled systems provided the key information. In one project on SH 47, it was necessary to combine information from both air-launched and ground-coupled systems to diagnose the cause of premature pavement problems.

CHAPTER 2. BASICS OF GROUND PENETRATING RADAR

AIR-LAUNCHED GPR SYSTEMS

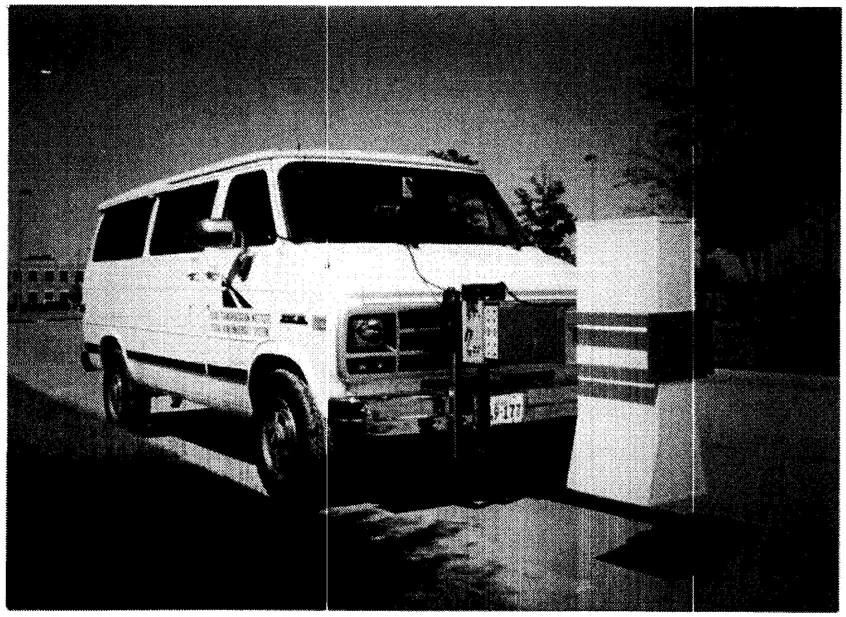
The Texas Transportation Institute's (TTI's) 1 Gigahertz (1 GHz) air-launched ground penetrating radar unit is shown in Figure 1. This system sends discrete pulses of radar energy into the pavement system and captures the reflections from each layer interface within the structure. Radar is an electro-magnetic wave and therefore obeys the laws governing reflection and transmission of e-m waves in layered media. This particular GPR unit can operate at highway speeds (60 mph), transmit and receive 50 pulses per second, and can effectively penetrate to a depth of 24 inches. A typical plot of captured reflected energy versus time for one pulse is shown in Figure 1(b), as a graph of volts versus arrival time in nanoseconds.

The reflection A_1 is the energy reflected from the surface of the pavement, and A_2 and A_3 are reflections from the top of the base and subgrade, respectively. These are all classified as positive reflections, which indicate an interface with a transition from a low to a high dielectric material. As described in the next section of this paper these amplitudes of reflection and the time delays between reflections are used to calculate both layer dielectrics and thickness. The dielectric constant of a material is an electrical property which is most influenced by moisture content and density. An increase in moisture will cause an increase in layer dielectric; in contrast an increase in air void content will cause a decrease in layer dielectric.

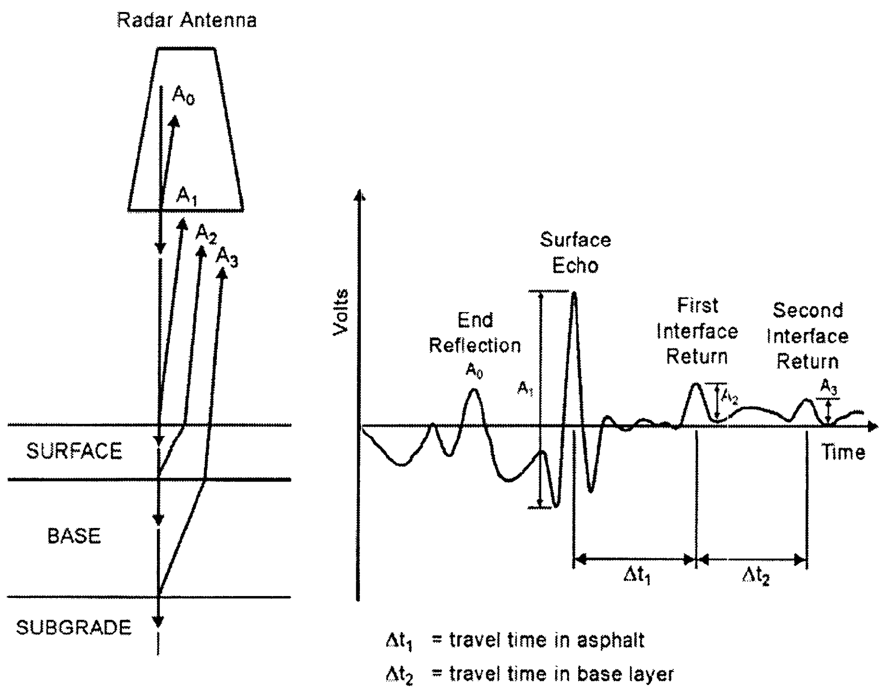
A range of typical dielectrics has been established for most paving materials. Hot mix asphalt (HMA) layers normally have a dielectric value between 4.5 and 6.5, depending on the coarse aggregate type. Measured values significantly higher than this would indicate the presence of excessive moisture. Lower values could indicate a density problem or indicate use of an unusual material, such as lightweight aggregate.

The examples below illustrate how changes in the pavement's engineering properties would influence the typical GPR trace shown in Figure 1:

1) If the thickness of the surface layer increases, then the time interval between A_1 and A_2 would increase.



(a) TTI GPR Equipment



(b) Principles of GPR. The incident wave is reflected at each layer interface and plotted as return voltage against time of arrival in nanoseconds.

Figure 1. GPR Equipment and Principles of Operation.

2) If the base layer becomes wetter, then the amplitude of reflection from the top of the base A_2 would increase.

3) If there is a significant defect within the surface layer, then an additional reflection will be observed between A_1 and A_2.

4) Large changes in the surface reflection A_1 would indicate changes in either the density or moisture content along the section.

GROUND-COUPLED GPR SYSTEMS

Figure 2 shows the ground-coupled systems available within TTI. The two units in the center of the figure are the data acquisition and control system. The remaining units are the different antennas, that can be used. The large units are the low-frequency antenna units. The low-frequency systems operate at 100 or 200 MHz. These units are the deep penetrating units. With favorable soil conditions, these units can provide subsurface information to a depth of 20 ft or greater; however, they do not provide any useful near-surface information. The smaller units are 500 and 900 MHz antennas. The higher frequency causes a shallower depth of penetration. However, the higher frequency units (500, 900, and 1500 MHz) also have better resolution and are capable of providing information from near-surface objects. When using these systems it is necessary to carefully select the antenna for each application balancing the depth of penetration and the resolution required.

Unlike the air-launched systems these units must stay in contact with the surface under test. When testing existing highways the arrangement shown in Figure 3 is often used. The speed of data collection is typically around 5 mph. When used to test new right-of-way, the unit is pulled by hand over the test area. In the area of subgrade evaluation GPR techniques have been used in Scandinavia to nondestructively identify soil type, to estimate thickness of overburden, and to evaluate the compressibility and frost susceptibility of subgrade soils. A detailed description of use of ground-coupled radar for highway evaluation is given elsewhere (Saarenketo and Scullion 2000).

The systems available within TTI were manufactured by Geophysical Survey Systems Inc. (GSSI) of North Salem, New Hampshire. The data acquisition system is the SIR 10B system manufactured by GSSI. With this system it is possible to simultaneously collect data with two ground-coupled systems.

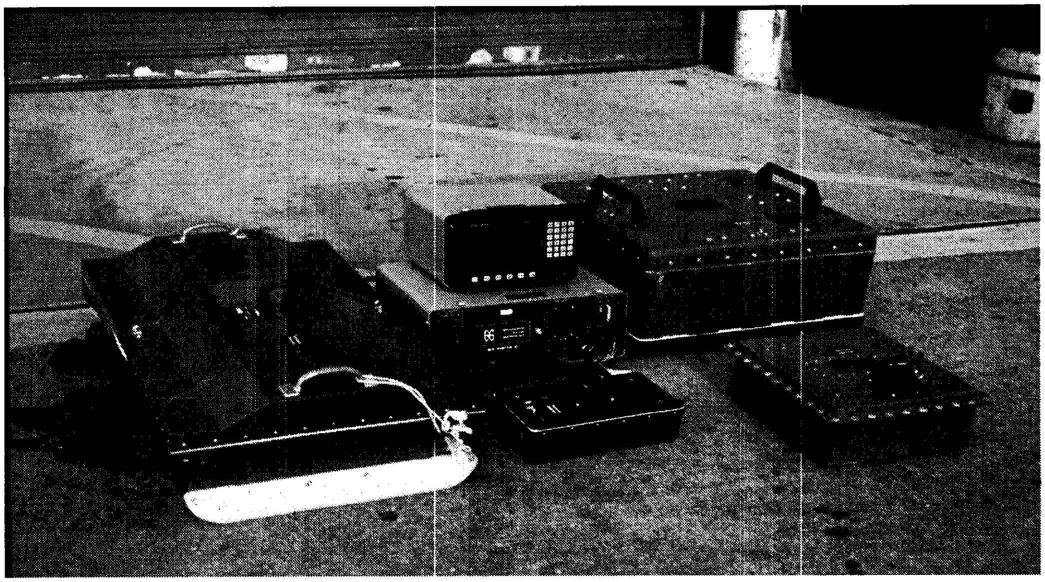


Figure 2. TTI's Ground-Coupled Equipment.

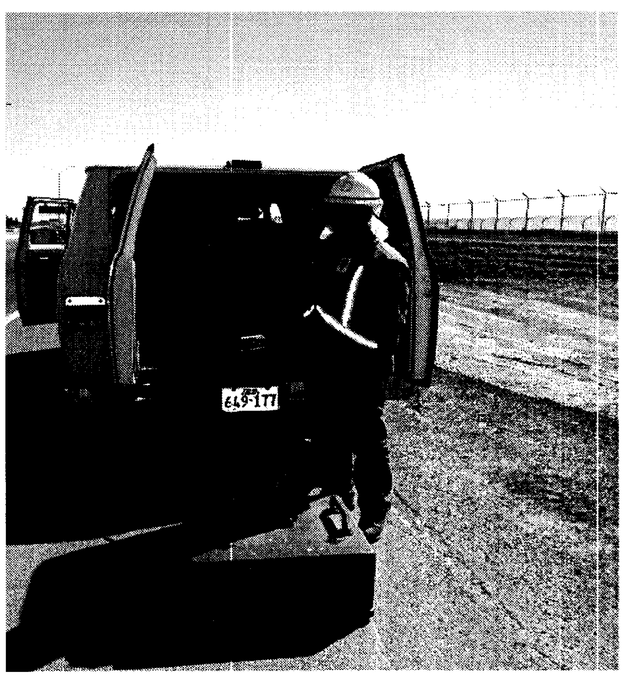


Figure 3. Data Collection with a 200 MHz Ground-Coupled System.

COMBINED AIR-LAUNCHED AND GROUND-COUPLED SYSTEMS

For Project 7-4906 it was necessary to simultaneously collect both air-launched and ground-coupled data on the same project. To accomplish this the arrangement shown in Figure 4 was developed. The air-launched antenna is positioned in front of the vehicle. The rear-mounted trailer accommodates two different ground-coupled antennas. The system shown in Figure 4 has both a 200 and 500 MHz ground-coupled antenna. Data acquisition speeds are limited to around 8 mph with this system.

Figure 4. Simultaneously Collecting Air-Launched and Ground-Coupled GPR Data.

CHAPTER 3. PROCESSING GPR DATA

AIR-LAUNCHED DATA (COLORMAP)

The Texas Transportation Institute has developed the COLORMAP system for processing air-launched GPR data. Full details of this system are referenced elsewhere (Scullion and Chen 1999). This system converts the GPR signals into information of use to pavement engineers. As described below, this system provides a color-coded output of the GPR data analogous to an "x-ray" of subsurface conditions. It also provides computation tools to compute layer thicknesses and dielectrics both of which are very significant in evaluating subsurface conditions. The significance of layer dielectrics is discussed in Chapter 4.

In most GPR projects, several thousand GPR traces are collected. In order to conveniently display this information, color-coding schemes are used to convert the traces into line scans and stack them side-by-side so that a subsurface image of the pavement structure can be obtained. This approach is used extensively in both Texas and Finland. A typical display from the Texas system for a thick hot mix pavement is shown in Figure 5. This display is taken from a section of newly constructed thick asphalt pavement over a thin granular base. The labels

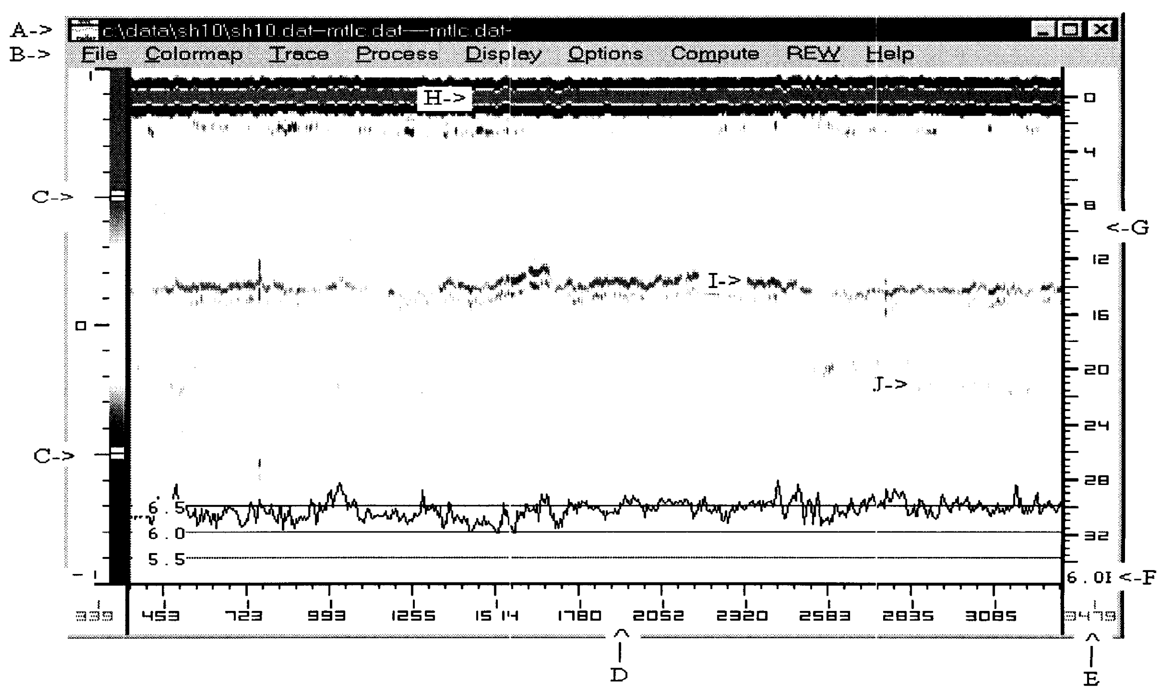


Figure 5. Color-Coded GPR Traces (COLORMAP).

on this figure are as follows A) files containing data, B) main pull down menu, C) button to define the color-coding scheme, D) distance scale (miles and feet), E) end location, G) default dielectric value used to convert the measure time scale into a depth scale, and F) depth scale. The important features of this figure are the lines marked H, I, and J. These lines represent the reflection from the surface, top, and bottom of base, respectively. The pavement is homogeneous, and the layer interfaces are easy to detect. The variation in surface dielectric, computed using Equation 1, is shown at the bottom of the figure.

When processing GPR data the first step is to develop displays such as Figure 5. From the display, it is possible to identify any clear breaks in pavement structure and to identify any significant anomalies. The intensity of the subsurface colors is related to the amplitude of reflection. Therefore, areas of wet base would be observed as bright red reflections (I) (see in Figure 5.)

While color-coded plots of surface condition are useful to rapidly identify anomalies, they do not provide any quantitative information. COLORMAP includes algorithms to calculate subsurface layer properties using the amplitude of reflections and the time delays between peaks. Using the amplitudes (volts) and time delays (ns) from Figure 1, it is possible to calculate layer dielectrics and layer thickness. The equations used are summarized below:

$$\epsilon_a = \left[\frac{1 + A_1 / A_m}{1 - A_1 / A_m}\right]^2 \tag{1}$$

where ϵ_a = the dielectric of the surfacing layer

A_1 = the amplitude of surface reflection

A_m = the amplitude of reflection from a large metal plate in volts (this represents the 100 percent reflection case)

$$h_1 = \frac{c \times \Delta t_1}{\sqrt{\epsilon_a}} \tag{2}$$

where h_1 = the thickness of the top layer

c = speed of e-m wave in air (5.9 in/ns two-way travel)

Δt_1 = the time delay between peaks A_1 and A_2

$$\sqrt{\epsilon_b} = \sqrt{\epsilon_a}\left[\frac{1-\left[\frac{A_1}{A_m}\right]^2+\left[\frac{A_2}{A_m}\right]}{1-\left[\frac{A_1}{A_2}\right]^2-\left[\frac{A_2}{A_m}\right]}\right] \tag{3}$$

where ϵ_b = the dielectric of the base layer

A_2 = the amplitude of reflection from the top of the base layer

$$h_{base} = \frac{c \times \Delta t_2}{\sqrt{\epsilon_b}} \tag{4}$$

where h_{base} = thickness of base layer

Δt_2 = time delay between A_2 and A_3

Using these equations it is therefore possible to calculate both layer thickness and dielectrics along the pavement under test. The thickness information is useful to DOT personnel for either quality control of new construction or structural evaluation of existing structures. What is not understood is the significance of the layer dielectric values and their variation along a highway. This significance is discussed further in Chapter 4 of this report.

PROCESSING GROUND-COUPLED DATA (ROAD DOCTOR)

In Finland a comprehensive Road Analysis package has been developed by Roadscanners, Inc. in cooperation with FinnRA. Road Analysis can be used to detect structural defects in roads or road networks, to ascertain their causes, and to propose suitable rehabilitation measures for each particular type of road defect in each road section. It also presents the possibility of leaving untreated those road sections with a reasonable life expectancy. By locating defects and implementing rehabilitation measures based on their causes, unnecessary construction work and incorrect rehabilitation measures can be avoided. Road Analysis includes an evaluation of:

1) overall pavement condition,
2) condition assessment of the unbound pavement structure,

3) subgrade damage related to frost fatigue,

4) drainage condition, and

5) local damage of the surveyed road.

The analysis is based on measurements conducted using ground penetrating radar techniques (Saarenketo and Scullion 2000), with the support of drill core samples, roughness, and rutting measurements, falling weight deflectometer (FWD) measurements, and visual observations of pavement surface condition.

A key tool in Road Analysis is the Road Doctor software, developed by Roadscanners, Inc., which is used for the integrated analysis of the pavement structure. In the first phase, Road Doctor processes the ground-coupled and air-coupled GPR data, and the thickness of the asphalt and other structural layers are calculated. In the next phase, FWD rutting and roughness survey data are imported to the Road Doctor database together with other reference data such as drill core information. If x,y,z information of the road under survey is available, the GPR data can be viewed with topography information, and all the layer interface information can be transferred to a road CAD system together with the coordinates. In Road Analysis, the road is divided into homogeneous sections based mainly on the GPR data and classified according to the subgrade soil quality and effect of the freeze-thaw process to the road structures. In addition structural course thickness and material properties are evaluated. Results of a detailed Road Analysis of the road structure, quality, and extent of the damages in road structures are reported to the pavement engineer to provide reliable information to support rehabilitation design decisions.

Road Analysis presents an effective working tool for selecting rehabilitation treatments. Using Road Analysis on the road network for rehabilitation programming the necessary investment and budgeting more effectively be carried out. These network level analyses can also be used, at a later date, when planning the implementation of rehabilitation measures at individual sites.

Examples of basic outputs from the Road Doctor software are shown in Figures 6 and 7.

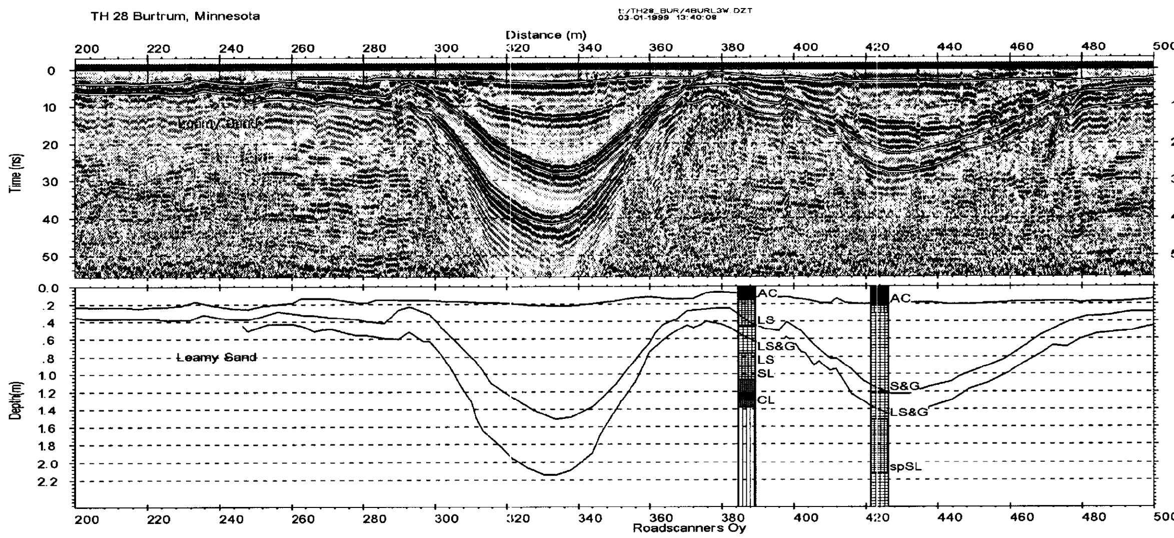


Figure 6. Using Road Doctor to Identify Varying Subgrade Conditions with Ground-Coupled GPR.

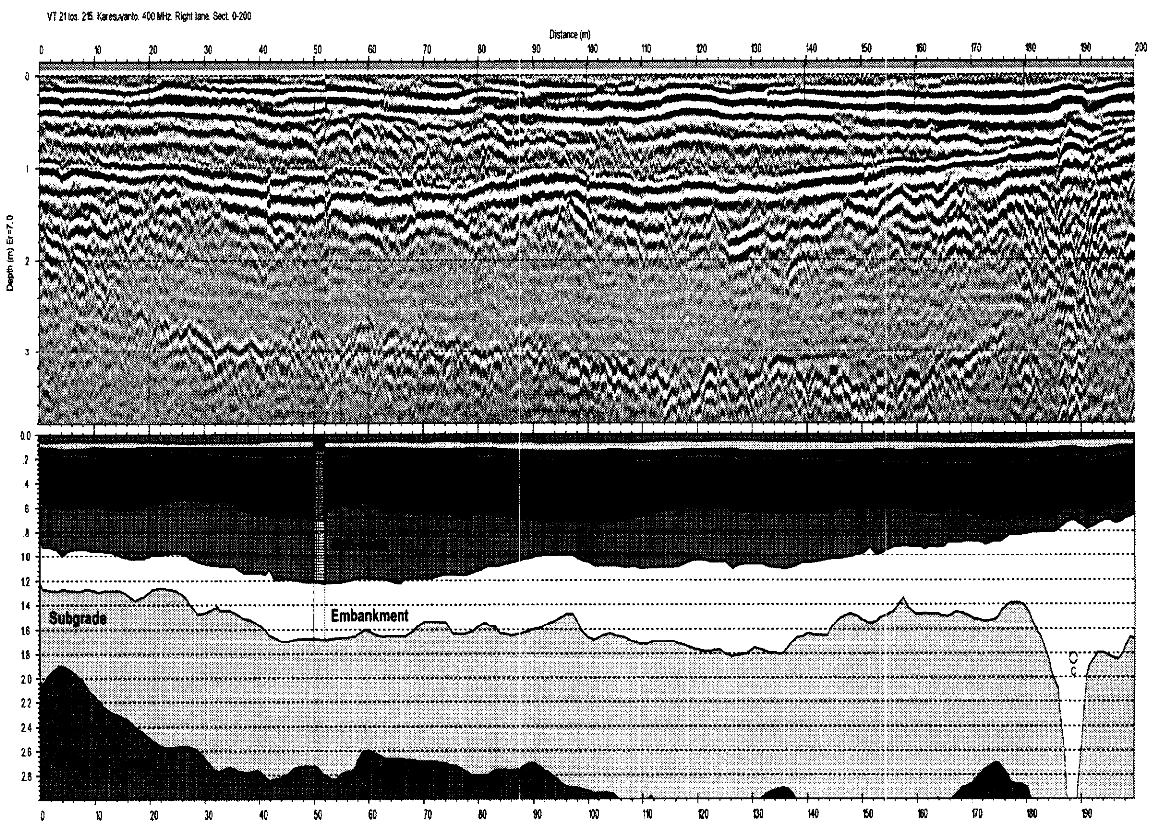


Figure 7. Using Road Doctor to Interpret and Display Subsurface Pavement Condition.

The lower part of Figures 6 and 7 shows the layer interpretation. Figure 6 demonstrates how the drill log information can be superimposed upon the GPR signals. As with all GPR interpretation it is essential to validate the interpretations. This validation is best achieved by reviewing and providing a preliminary interpretation of the GPR signals. This location should be drilled where major changes in subsurface signals are observed. This will permit the material types to be verified and the depth predictions to be calibrated.

Figure 7 shows how the 400 MHz data can be used to detect the presence of a wet weak layer beneath the pavement structure. The reflection from the wet (peat) layer is observed at the bottom of the GPR trace. With this type of data it is possible to determine the depth of cover above the problem layer.

Ground-coupled data provide some clear advantages over the air-launched data, primarily in the depth of penetration. However, the limitations of the ground-coupled systems are as follows:

1) The signals are generally noisier than air-launched signals. Special training is required to ensure that good data are being collected. The collected signal frequently requires substantial filtering to identify subsurface anomalies and layer interfaces.

2) As with all GPR the depth of penetration of the signals in clay subgrades is severely limited. In sandy/silty materials a 200 MHz antenna may effectively penetrate up to 15 to 20 feet. However in the heavy clays in east Texas, this antenna may only penetrate to a depth of 3 to 4 feet. This is primarily because the high-moisture content in the clay layer severely attenuates the GPR signal.

The Road Doctor package provides many features to integrate data from varying sources including visual condition data, pavement roughness data, and structural strength data from the FWD. Some of these capabilities will be demonstrated in the case studies.

CHAPTER 4. RELATIONSHIP OF COMPUTED LAYER DIELECTRICS TO ENGINEERING PROPERTIES

The engineering properties of most interest to highway engineers are the air void content of the HMA layer and the moisture content of the granular base layer. Both properties impact the computed layer dielectrics. Chapter 3 presented the methods of computing layer dielectrics from GPR data. As discussed below, to convert layer dielectrics to engineering properties it is necessary to generate laboratory calibration curves.

RELATIONSHIP BETWEEN BASE DIELECTRIC AND BASE MOISTURE CONTENT

In the mid 1990s a series of dielectric measurements were conducted in the laboratory on a range of base materials from around Texas (Saarenketo and Scullion 1995). The Percometer dielectric probe (Figure 8) manufactured by Adek, Ltd. (Plakk 1994) was used to measure the surface dielectric of these materials.

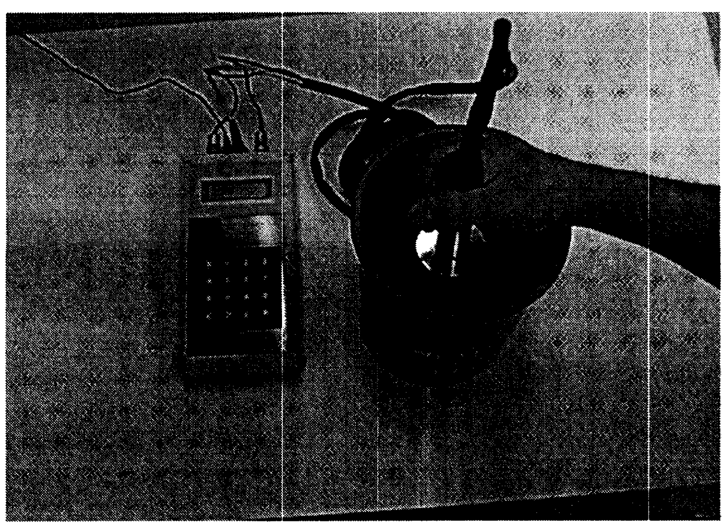


Figure 8. Laboratory Set Up to Measure the Dielectric Value for a Granular Base Using the Percometer.

Figures 9 shows typical results from a range of Texas base materials. This project concludes that 1) an increase in the base moisture content will cause an increase in base dielectric, and 2) the relationship between base moisture content and dielectric is not unique, it is material dependent. Based on this initial work, the researchers proposed to develop calibration curves for each material under investigation. These calibration curves are generated, using the Percometer, as an additional feature of the traditional optimum moisture content procedure, where samples are molded at a range of moisture contents to determine their maximum density. Using these calibration curves it is possible to convert the computed base dielectric to the volumetric base moisture content.

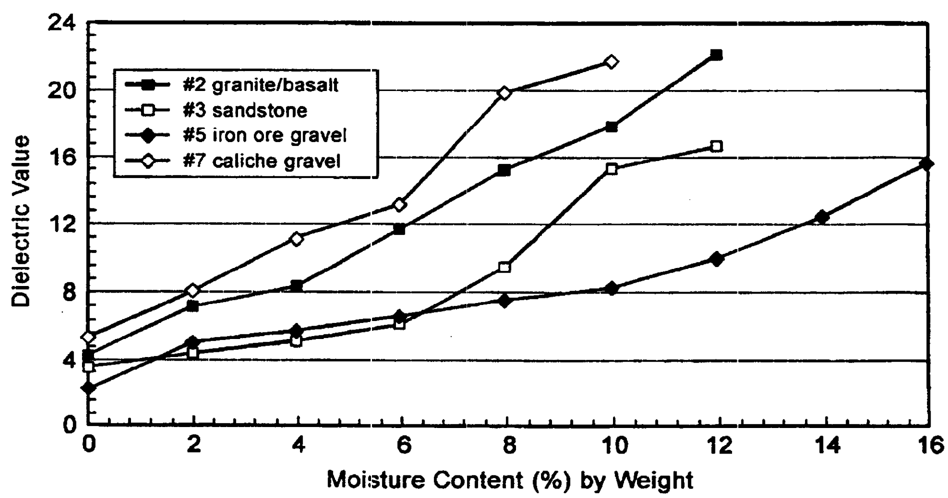


Figure 9. Correlation between Dielectric Values and Gravimetric Moisture Contents of Texas Aggregates (Saarenketo and Scullion 1995).

RELATIONSHIP BETWEEN SURFACE DIELECTRIC AND HMA AIR VOIDS

In the early 1990s several major studies were conducted in Finland to investigate the use of GPR for quality control measurements on new HMA overlays, (Saarenketo 1996, Saarenketo and Roimela 1998). As part of these studies, laboratory tests were performed to relate the HMA surface dielectric measured nondestructively with the Percometer probe to the laboratory determined air void content. Tests were performed on both laboratory molded and field samples. Figure 10 shows a typical set of results from the laboratory samples. There is substantial scatter in these data, but it is noted that the results are for a range of mixes with different aggregate types. The Finnish researchers proposed the following exponential relationship:

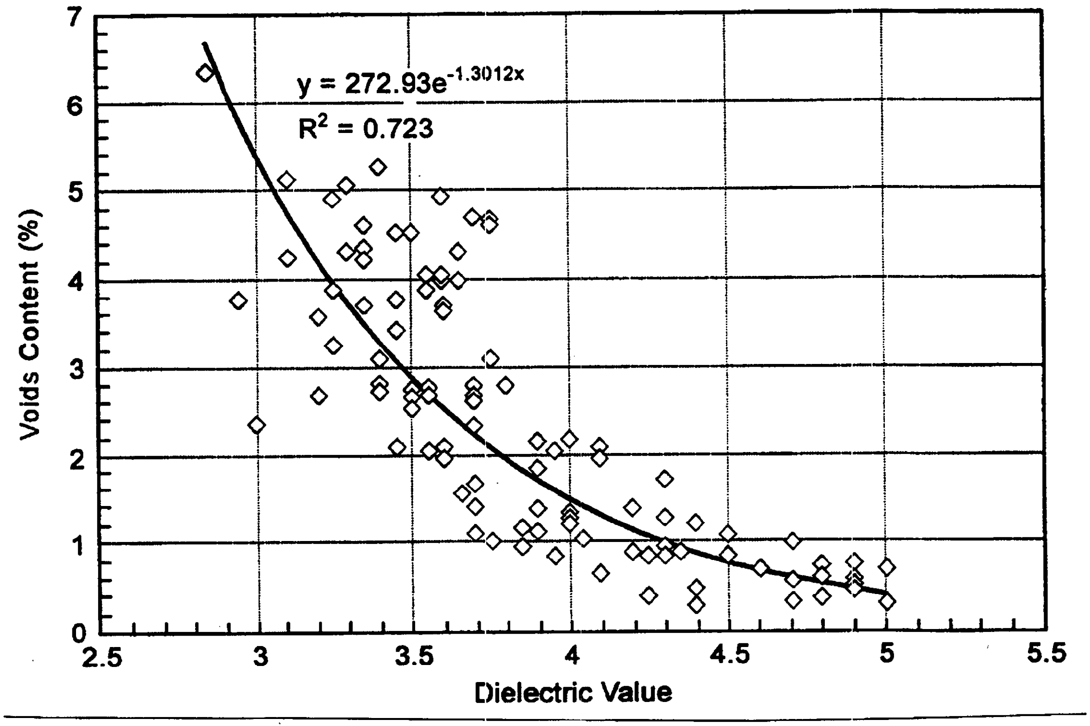


Figure 10. Laboratory Test Results Relating HMA Air Void Content to Measured Dielectric Values (Saarenketo 1996).

$$\% \text{ air voids} = 272.9 \text{ x exp. } [- 1.3012 * k * \text{ surface dielectric}] \quad (9)$$

where k is the lab determined calibration constant obtained from field cores.

This use of GPR for determining the air void content of asphalt pavement layers has recently been incorporated into the Finnish specifications (PANK 4122). For any particular new HMA layer the surface dielectrics are computed using Equation 1. The method includes taking two calibration cores and determining their air void contents in the laboratory. These values are used to calculate the calibration constant k in Equation 9. The measurement accuracy of air void content using GPR was reported to be +/- 0.9 percent (PANK 4122).

CHAPTER 5. CASE STUDIES

Numerous studies have been conducted in the USA to establish the accuracy of GPR for measuring the thickness of both flexible and rigid pavements. The Missouri DOT (Wenzlick et al. 1999) conducted a comprehensive study where the accuracy of GPR to determine the thickness of newly constructed HMA was calculated to be 1.7 percent. For older concrete sections the accuracy was found to be 2.8 percent. With regard to GPR accuracy, several additional factors need to be discussed. GPR can provide accurate thickness for newly constructed HMA pavements the layers are homogeneous and the interfaces are clear in the GPR signals. This level of accuracy cannot be obtained with older HMA pavements consisting of multiple asphalt layers. Accuracies of around 5 percent have been found with these pavements (Maser 1992). Furthermore, GPR thickness estimates are made if there is a distinct electrical contrast between layers. This is not always the case with older pavements where the base and subgrade materials may have merged. In these instances accurate base thickness estimates are not possible.

Applications of air-launched GPR on concrete pavements have had limited success within TxDOT. GPR was not capable of measuring the thickness of newly constructed concrete slabs because of the high attenuation of the GPR signals by concrete less than 30 days old. Furthermore little success has been obtained with void detection. Laboratory studies concluded that air filled voids have to be greater than 0.75 inches thick before they significantly impact GPR signals (Scullion et al. 1992). Also it has been difficult to distinguish between water filled voids and areas of saturated base.

Only limited studies have been conducted on the use of ground-coupled GPR in Texas. Work reported by Servas et al. (1997) outlines several applications where ground-coupled GPR can be successfully used to determine the presence of localized subsurface anomalies. These anamolies included the presence of subsurface springs, sinkholes, and buried metal tanks. Using ground-coupled GPR for site investigations prior to pavement design has not been undertaken in Texas. However, this application is in widespread use in Finland. Most construction projects of major new facilities require a GPR survey prior to any subsurface drilling (Saarenketo and Scullion 2000). The GPR data is first reviewed, and a drilling and sampling program is developed based on the major variations observed in the GPR data.

This section of the report proposes a series of case studies in which GPR has been successfully used in the pavement evaluation and rehabilitation design process. These case studies range from relatively simple applications of air-launched systems to identify breaks in pavement structure which were not apparent from the surface, to more complex forensic-type studies where the GPR data were useful in identifying the cause of rapid pavement deterioration.

CASE 1 USING GPR TO IDENTIFY HMA THICKNESS AND SECTION BREAKS (AIR-LAUNCHED)

By far the biggest use of air-launched GPR within the TxDOT has been in the area of evaluating flexible pavements for pavement rehabilitation or forensic purposes. The GPR data have been used in a coordinated approach with the falling weight deflectometer. The GPR testing is conducted first to determine layer thickness, detect breaks in the pavement structure, and identify any subsurface defects, particularly moisture damage. This approach has proven to be highly effective in Texas with its mature highway network and its focus on pavement preservation and rehabilitation. When dealing with older road networks where numerous sections have been widened and/or received partial rehabilitation, it is extremely difficult to maintain reliable layer thickness information.

The data shown in Figure 11 are from a short 2-mile section from a 15-mile forensic project. The highway was exhibiting some localized failures and only limited thickness information was available from the plan sheets. Surface condition looked similar because the section had recently received a thin resurfacing. From the data shown in Figure 11 this short section had three distinctly different pavement structures. The interpreted structure information is at the bottom of the figure. The highway had been widened and the old roadway had been buried beneath a flexible base, overlay and a new thin surfacing. The widened sections consisted of a stabilized subgrade, flexible base, and thin HMA surfacing. The GPR rapidly identified the old pavement (section 3), the new pavement (section 1), and areas of localized full-depth rehabilitation (section 2).

The important factor to remember from this case is that from the surface it was impossible to detect any changes in subsurface structure. Also for this section of highway the plan sheets were of little help in identifying changes. However, from the GPR data it was clear that major changes in structure were occurring. Once the subsurface structure was identified, it was clear that the pavement failures were associated with only the new pavement.

The cause of the failure was eventually linked to a failure of the stabilized subbase layer in section 1. In general the ability to provide subsurface maps such as that shown in Figure 11 has been well received by TxDOT engineers. These maps are the starting places for planning additional NDT and field coring.

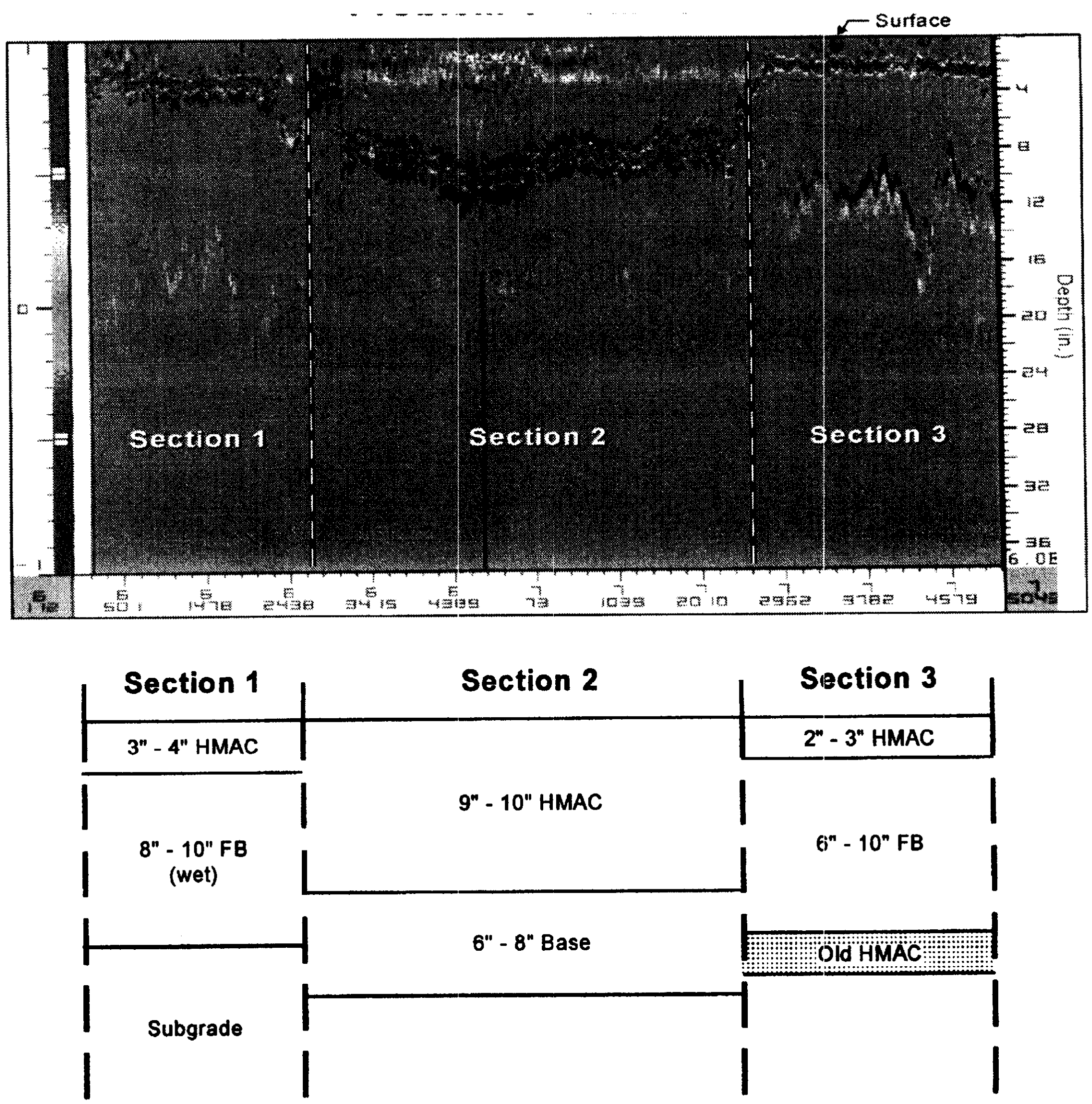


Figure 11. Raw GPR Data with Interpretation from FM 2818, near College Station, Texas.

CASE 2 MOISTURE TRAPPED IN BASE LAYERS (AIR-LAUNCHED)

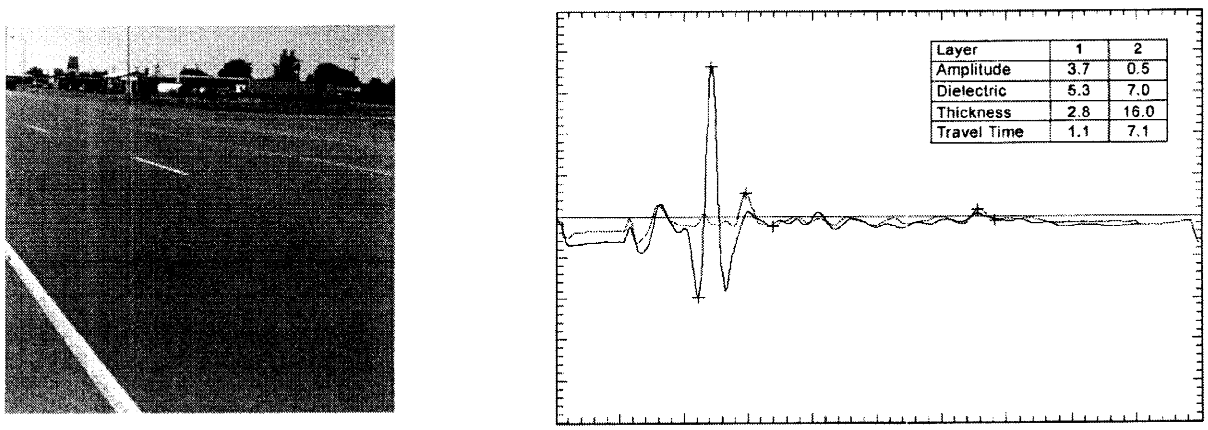
One major advantage of air-launched GPR is that it can rapidly and nondestructively detect areas of moisture concentrations in subsurface layers. By measuring the amplitude of peak A_2 in Figure 1 it is possible to calculate variations in base layer dielectric along a pavement section. In the past five years the dielectric properties of both natural and treated granular base materials have been under investigation. A new laboratory test called the tube suction test (TST) has been developed to evaluate the moisture susceptibility of base materials. The TST uses the Percometer surface probe shown earlier in Figure 8. It has been developed in a cooperative effort between the FinnRA and the TxDOT (Scullion and Saarenketo 1997). In this test the capillary rise of moisture within a compacted base sample is monitored via dielectric measurements on the surface. Based on field testing in Finland, it has been proposed that top quality aggregates should have a final surface dielectric of no more than 10. After 10 days capillary rise and aggregates that reach a value of 16 should not be used without some form of chemical treatment.

A base material which fails the TST will have a strong affinity for moisture. If moisture is available from the subgrade soils, from the shoulders, or from surface cracks then it will be "wicked" throughout the entire base. The dielectric value has been related to the amount of unbound water present in the base, and it is this "free" water that is associated with reductions in shear strength and poor cold weather performance. Efforts are underway in Texas to correlate the field performance of aggregates ranked by the TST. Figure 12 shows surface condition and base dielectric values (from GPR) from two sections in the Amarillo District. This district is a colder region in the Texas Panhandle that experiences numerous freeze-thaw cycles each year. The upper section was constructed with a gravel base that had passed the TST criteria for top quality materials.

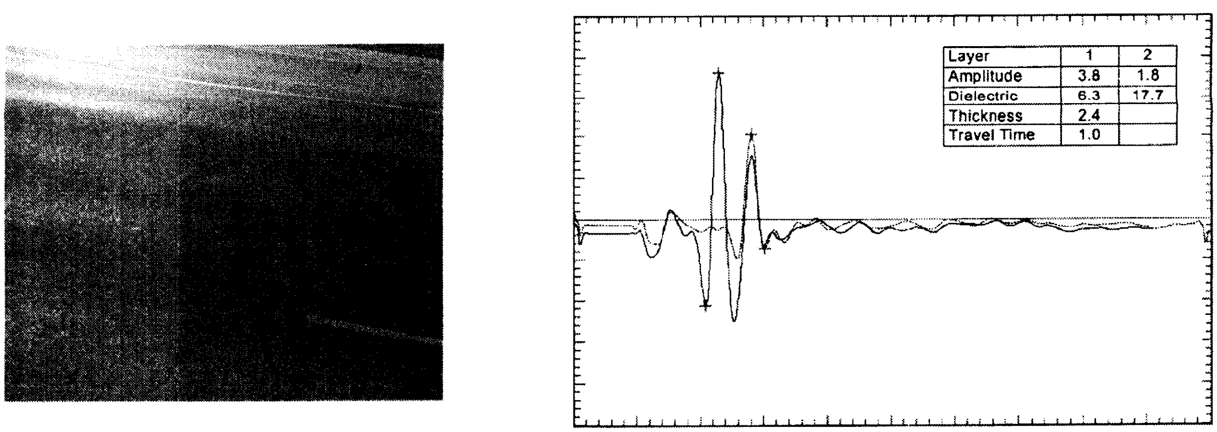
After four years the performance of the section has been very good. A typical GPR trace from this pavement is shown in Figure 12. The computed field dielectric is low at 7.0. These results should be contrasted with those in the lower part of Figure 12. This section was constructed with a caliche base which failed the TST. The section is performing poorly, and the GPR indicated that the insitu base had a high dielectric of 17.7.

The development of the TST procedure has been one of the "spin-offs" from the GPR research studies. It is hoped that these new tests can be used to supplement existing strength-based procedures when selecting aggregates for major highways in colder areas.

In this case study the GPR was capable of determining that the cause of the surface cracking was primarily base related. This capability provides districts with a useful tool to plan future rehabilitation work and also to assist in evaluating material performance in colder climates. This combination will lead to improved material specifications and better use of chemical stabilizers.



(a) Four-Year-Old Gravel Base on SH136 Which Passed Tube Suction Test Criteria.
Good Field Performance, Low Base Dielectric from GPR = 7.0.



(b) Four-Year-Old Caliche Base Which Failed the Laboratory Tube Suction Test Criteria.
Moderate Cracking, High Base Dielectric from GPR = 17.7

Figure 12. Influence of Base Moisture Content on GPR Signals and Pavement Performance.

CASE 3 FAILURE INVESTIGATION OF SH 47 (AIR-LAUNCHED AND GROUND-COUPLED)

This NDT evaluation was made as part of a forensic evaluation of SH 47 in the Bryan District. The pavement, as shown in Figure 13, was exhibiting rapid failures in terms of excessive roughness and wheel path distress. The total section length is almost 6.5 miles. Performance problems were first noted two to three years after opening the highway to traffic. The goals of the forensic study were to determine the cause of the problem, to provide recommendations on what to do next, and to give recommendations on how to avoid this problem in the future. The findings of the forensic investigation were forwarded to the TxDOT district in a Technical Memorandum, dated July 20th, 2001 (Scullion 2001). Only the findings relating to the GPR investigation will be reported in this section.

The pavement structure consists of an 8-inch lime-stabilized subgrade, 15 inches of flexible base, and a 2.5-inch HMA surfacing. Forensic investigations are normally broken up into the following phases:

- Phase 1: Assembling background information and performing NDT,
- Phase 2: Field verification studies and obtaining samples for lab testing, and
- Phase 3: Lab work and structural design.

In Texas ground penetrating radar is now routinely collected in the Phase 1 activities. In this project, the cause of the pavement failures was uncertain so both an air-launched and ground-coupled survey were conducted. The results of each will be discussed below.

Air-Launched GPR Results from SH 47

For analysis purposes the project was broken into two sections. Section 1 runs from the start of the project at the intersection with SH 21 (TRM 412) to about 1000 ft past the first major structure, about 1.2 miles. That section has relatively little distress. The second section is the remainder of the project about 5.3 miles in length. This section contains severe roughness and some wheel path cracking. The results described below are all from the eastbound direction. The data from the westbound direction are similar.

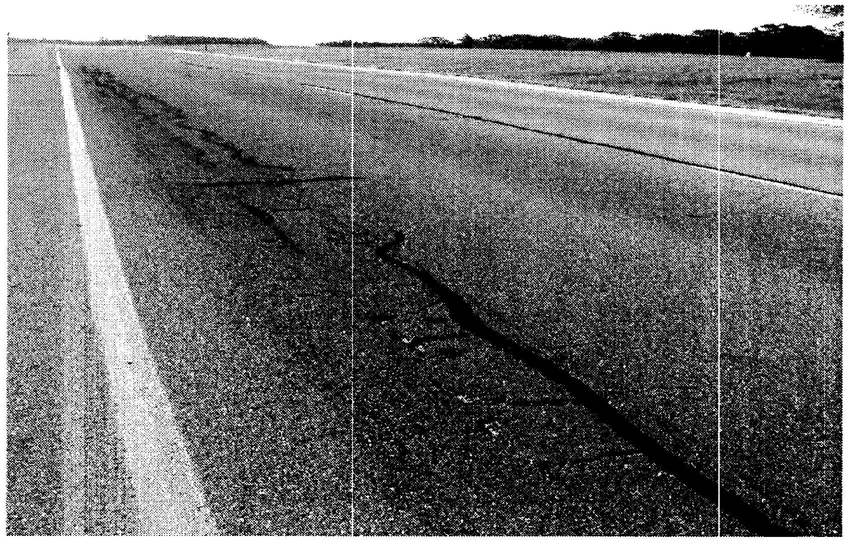
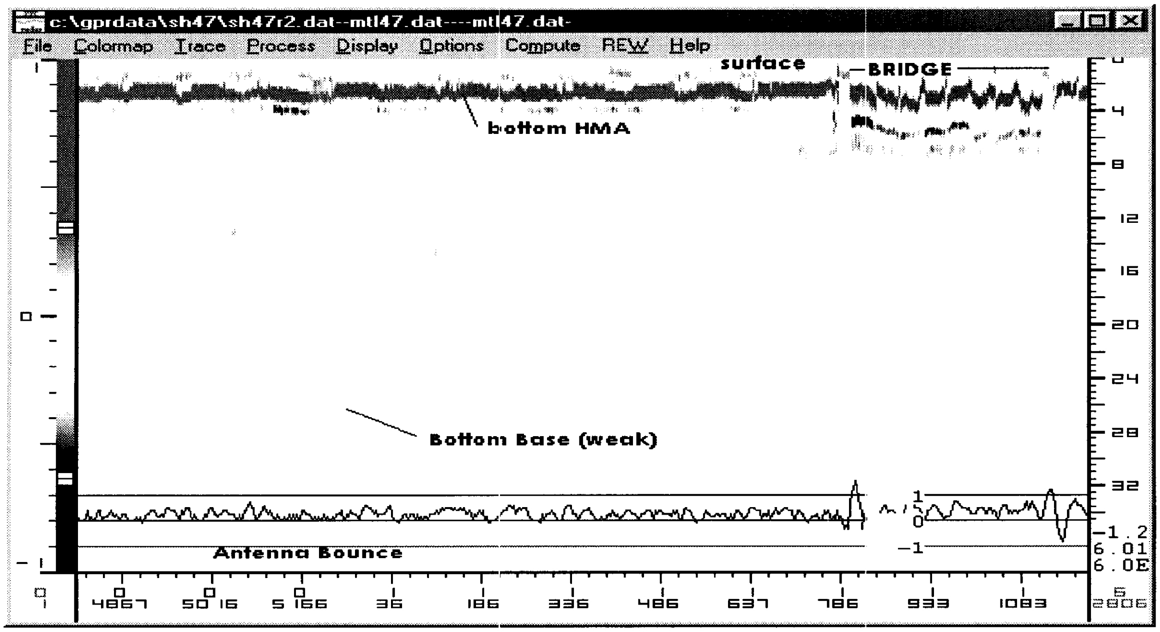


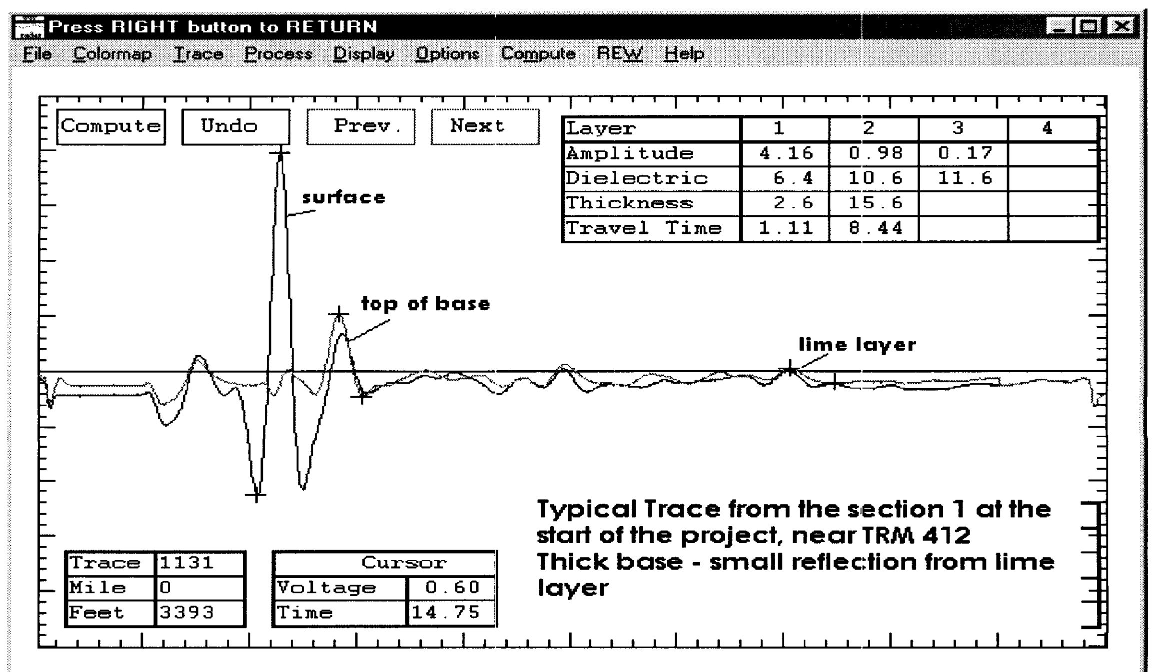
Figure 13. Structural Problems on SH 47.

Typical sets of GPR data are shown in Figures 14 and 15. Figure 14 shows data from section 1 just past A&M's Riverside campus entrance. In the upper figure the surface of the pavement has been normalized to the top of the figure. The bottom of the HMA layer is indicated by the solid red line about 2 to 3 inches beneath the surface. The depth scale in inches is at the right of the figure. At this location the structure consists of 2 inches of hot mix asphalt, and 15.5 inches of flexible base over an 8-inch lime-stabilized layer. Few strong reflections are found in the base. Faint reflections are observed at the mid-depth in the base and at the top of the lime layer. This pattern is thought to be ideal. There are no indications of any moisture problems in the lower layers. The line at the bottom of Figure 14 is a plot of changes in antenna height in inches. It indicates pavement roughness. The only sizable peaks are at the beginning and ending of the bridge.

Figure 15 shows GPR data from a problem area in section 2. The base thickness is 12.5 inches in this area. The major change here is the strong reflection from the top of the lime layer. This change indicates that the lime layer is holding significantly more moisture than the flexible base. From past experience, if the lime layer is wicking moisture then permanency problems can be anticipated. The antenna bounce at the bottom of the figure highlights the rough spots on the highway.

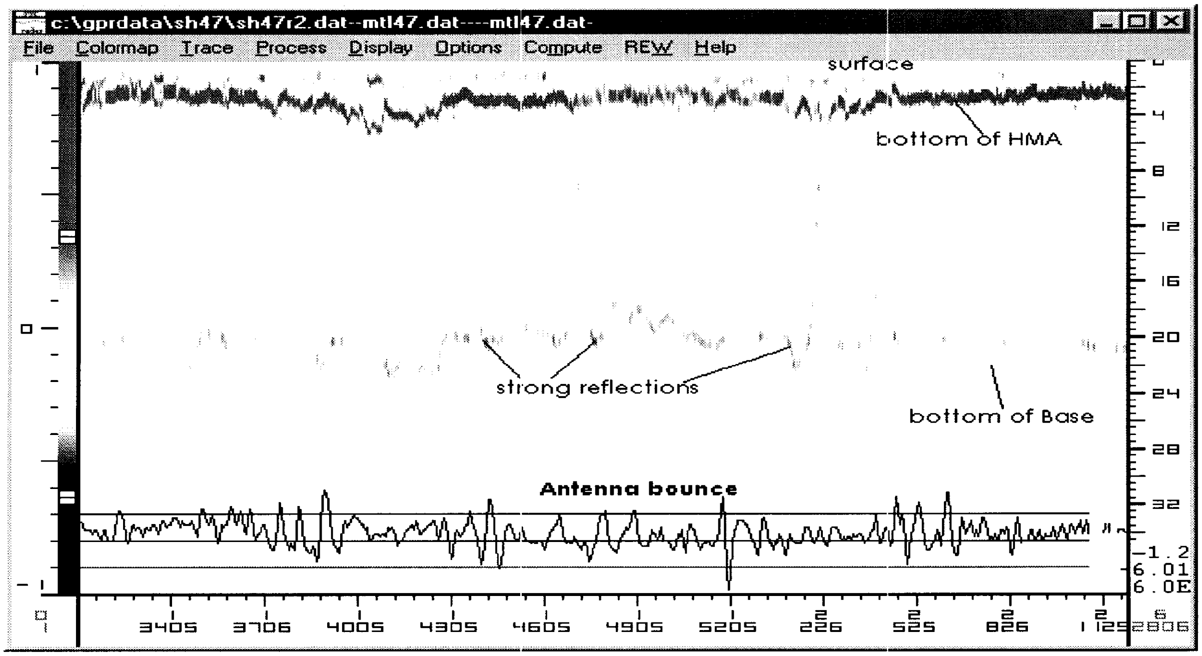


a) Colormap Display (Ideal case–no strong subsurface reflections low antenna bounce)

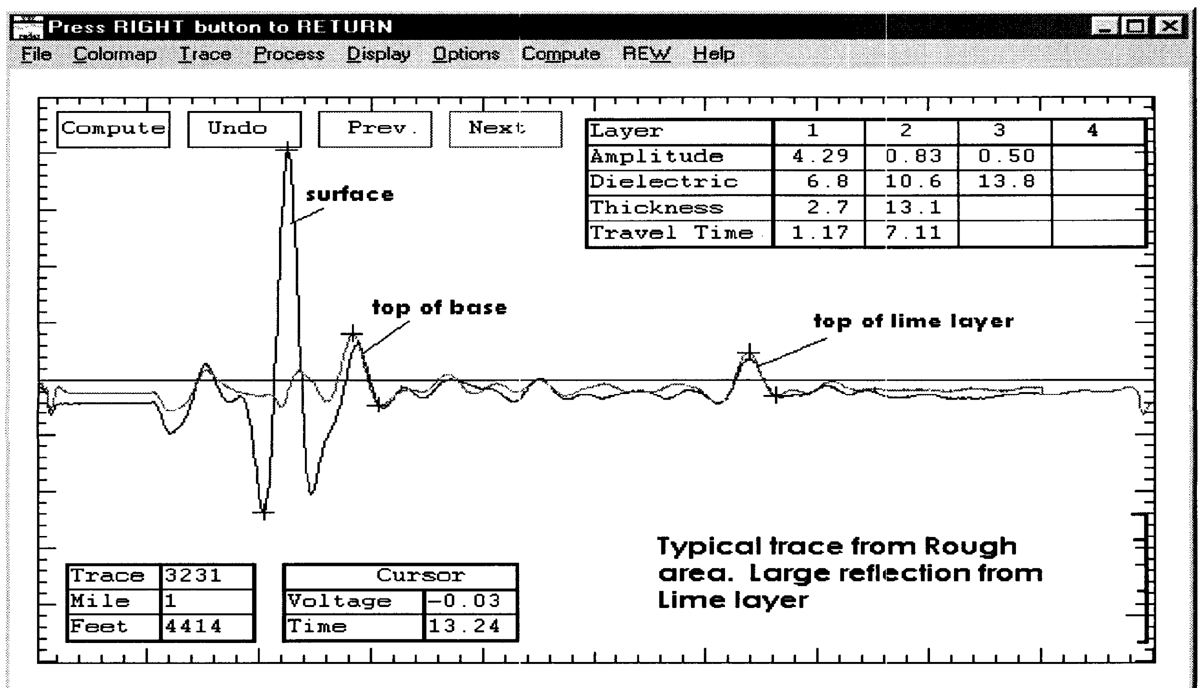


b) Individual GPR reflection (no problems)

Figure 14. Air-Launched GPR Data from Section 1 of SH 47. No Major Subsurface Problems Detected. (This Section Is Also Performing Well.)



a) Strong reflections from Subbaserough section



b) Individual trace from Section 2

Figure 15. Air-Launched GPR Data from Section 2 on SH 47. Strong Reflections from Lime-Stabilized Layer Indicate That This Layer Is Holding Moisture.

The indication from the GPR was that the cause of the pavement problems was at least partially attributed to a loss of stabilization in the lime-treated subbase. This finding was validated by subsequent falling weight deflectometer and dynamic cone penetrometer (DCP) testing. Figure 16 shows the DCP results. The DCP was collected at three locations on the outside shoulder in locations where large changes in FWD deflections occurred. The plot of cumulative blows versus penetration depth for all three sites is shown in Figure 16. The steeper slope produces weaker layers. These results confirmed the FWD interpretation.

Of the three DCP locations, site 5 had the lowest FWD maximum deflection of 13.4 mils, the penetration in the base was slow, and the DCP could not penetrate the lime-stabilized layer. From the DCP data, the base modulus was computed to be 85 ksi, which compares well with the FWD value of 100 ksi. This case is ideal.

Site 3 is the weakest location; the measured FWD deflection was 35.49 mils at an 8300 lb load. The DCP penetrated relatively fast through the base at 4.4 mm/blow. No lime-stabilized layer was detected. Just beneath the base the penetration rate was 33 mm/blow which was higher than at the top of the subgrade at 26 mm/blow. What was important at this location was that the penetration rate measured 30 inches below the surface. The rate increased to 94 mm/blow. This provided a layer with a CBR of 1.8 and design modulus of less than 4 ksi. This is extremely poor, just a little better than toothpaste.

Site 6 was the intermediate site with a FWD deflection of 27 mils. The penetration rate in the lime layer was variable. At the top of the layer it was 7.7 mm/blow but it increased to 14.8 mm/blow. The top of the subgrade had a penetration rate of 8.6 mm/blow. The presence of the lime layer was confirmed during drilling of this site. It was still possible to smell the lime in the soil, but the material was weak and still plastic. From this investigation it was clear that the pavement failure was attributed to both the loss of strength in the stabilized layer and the extremely poor subgrade soil conditions.

The DCP results clearly demonstrate the importance of having a stiff subbase layer. On site 5 the lime layer is stiff and confining to the base. The base modulus is computed to be high. However, in the other two sites the support and confining is not present. The computed base modulus value drops by a factor of more than 2.

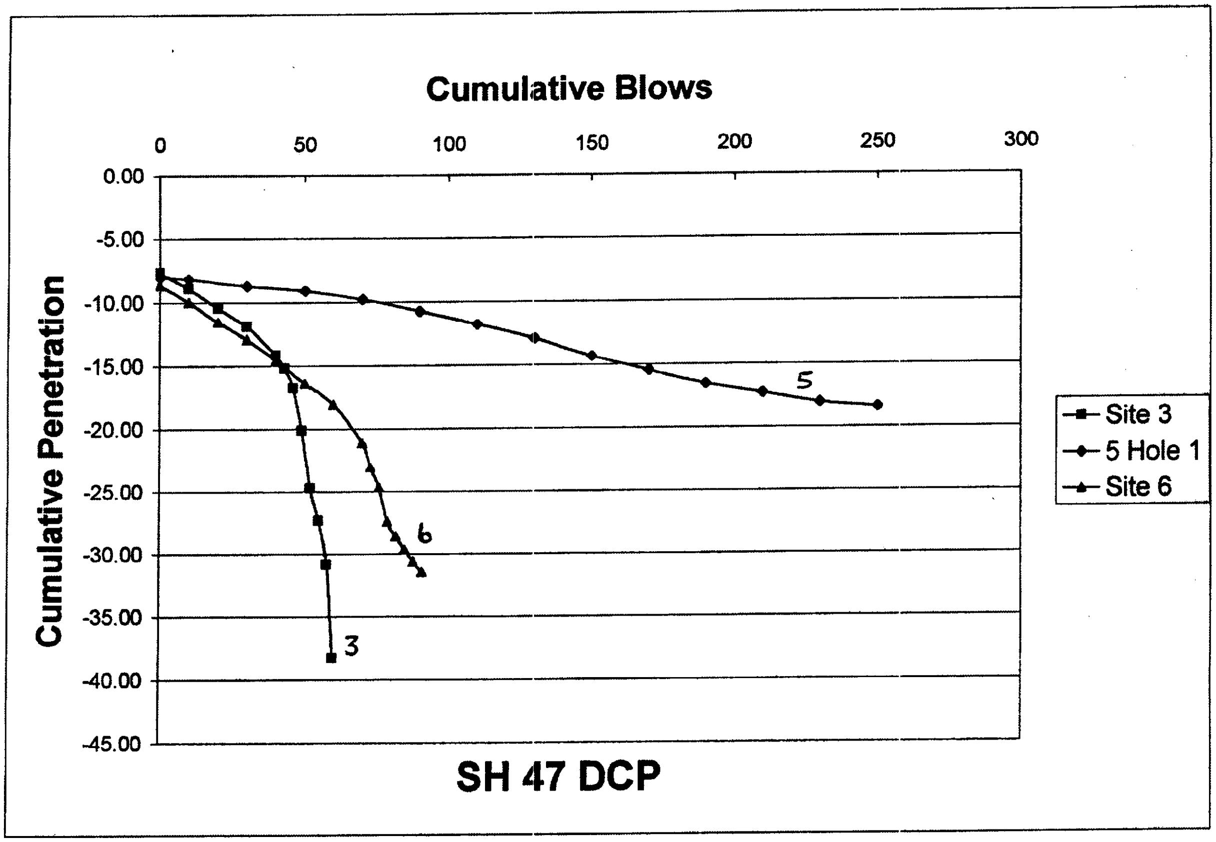


Figure 16. Validation Dynamic Cone (DCP) Data from SH 47 Showing Highly Variable Strengths for the Lime-Stabilized Layer. The DCP Results for Location 5 Are Judged To Be Ideal. However at Location 3 No Effective Lime Layer Was Present.

Ground-Coupled GPR Collected on SH 47

The major limitation of the air-launched GPR data is that the depth of penetration is limited to approximately 2 ft. It was suspected that the problems on SH 47 were initiated in the subgrade soils and it was thought necessary to conduct some deep penetrating radar surveys to attempt to locate the source of the problem and to identify good locations to conduct field borings.

Figures 17 and 18 show examples of the ground-coupled ground penetrating radar data collected on this project as processed by the Road Doctor package. These data were collected in the outside shoulder of the eastbound direction. The researchers used two antennas with different frequencies. Under ideal conditions, the 500 MHz will be effective down to a depth of

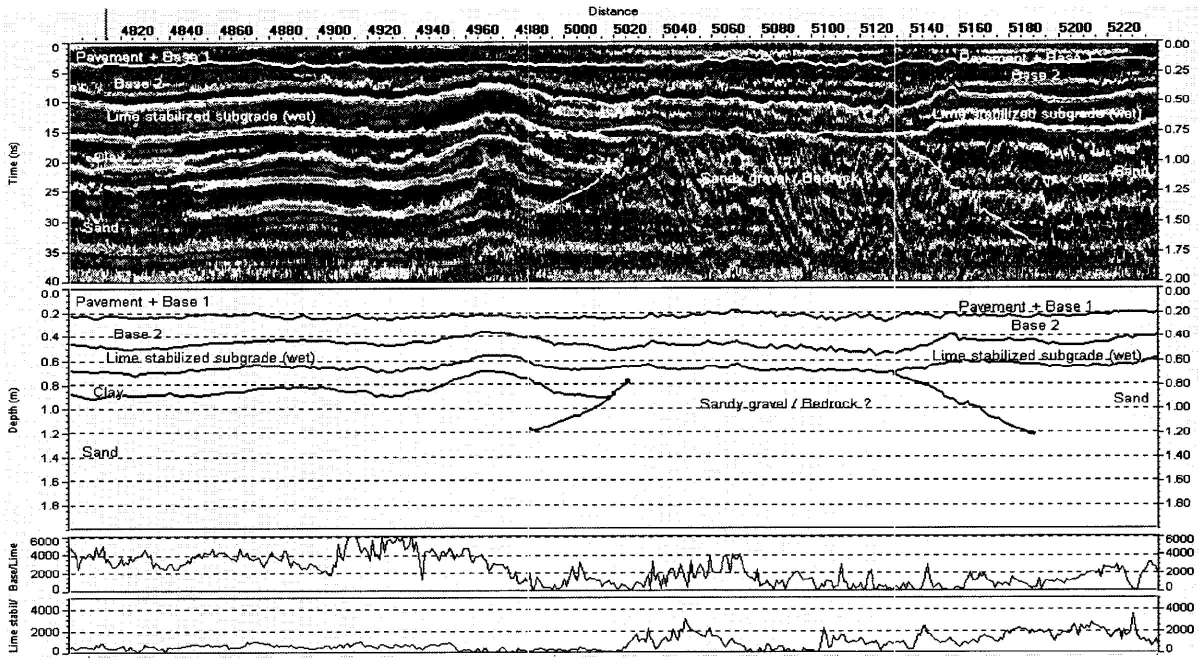


Figure 17. Road Doctor Results from Section of SH 47 Showing a Major Transition in Subgrade Support.

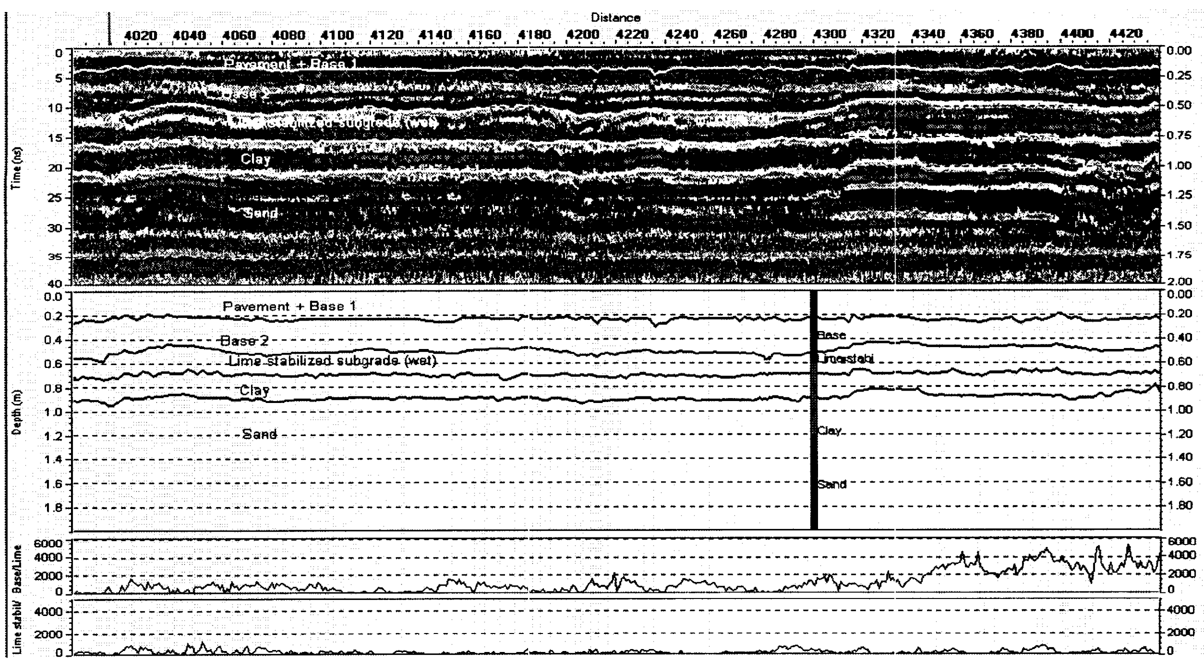


Figure 18. Typical Ground-Coupled Data from SH 47 Showing the Boring Log Information. The Subgrade Consisted of Interbedded Layers of Zero PI Saturated Sand and High PI Clay.

7–8 ft (2.5 m), whereas the 200 MHz should potentially penetrate deeper. However, as with all GPR systems the type of soil restricts the depth of penetration. The depth of penetration of all radar is severely limited in high PI clay materials. The data in Figures 17 and 18 are from the 500 MHz antenna showing the top 6 feet (2 m) of the section. The road surface is at the top of the figure, the depth scale on the right is in meters, and the distance scale on the top is also in meters.

The advantage of the deeper penetrating radar is apparent in these data. With the air-launched system it was impossible to obtain any information from beneath the lime-stabilized subbase. However with the ground-coupled data, it is possible to observe layering within the subgrade. In the 500 MHz data it was possible to track one or two distinct interfaces in the subgrade. In previous work it has been possible to use the GPR to define the soil type. This is based upon the GPR signature. Sandier materials will permit the GPR signals to penetrate, and several interfaces at various depths will be observed in the data. With clay soils containing substantial amounts of moisture the GPR signals will be severely attenuated. The top of the clay layer will be present, but few subsurface reflections will be observed in the data. However, in the project conducted on SH 47, researchers concluded that it was not possible to clearly define the soil type from the raw GPR data. This difficulty was primarily because of the extremely complex nature of the project and because the sand layers were saturated. The GPR was able to identify layer interfaces noting changes in soil type, but it was not possible to define the soil type. This was confirmed by the subsequent boring which found that the subsurface layers consisted of either heavy clay or saturated sand. Therefore it was concluded that to interpret the ground-coupled data it was necessary to conduct field drill logging. The benefit of combining GPR and drill logging is clear. The GPR can be used to scan the entire section; clear breaks in subgrade soil types can be defined. This information can then be used to select locations to perform soil explorations to identify the type of material in each stratum.

Figure 17 shows 500 MHz data from SH 47. At this location there is a clear transition from 5050 to 5120 m. Prior to the transition it was found that a thin clay layer was beneath the stabilized subbase. After the transition the subbase was directly over sand. The transition zone was found to be a zone of sandy gravel which had been exposed during the earth work. The reflections from the top of the lime-stabilized layer were strong in the 500 MHz data. Therefore this layer was annotated as being "wet" in Figures 17 and 18. Figure 18 illustrates the ability of

Road Doctor to annotate the data output with the drill log information. At this location the GPR data were collected in the main lanes, but the drill log information was collected in the shoulder. At this location a thin layer of clay is present beneath the pavement layers. This condition was found at several of the drilling locations. Figure 19 displays samples showing the transition from the clay to the sand layer.

Summary for SH 47

The conclusions from this investigation were that the pavement roughness and cracking problems were caused by two interacting factors.

Factor 1. The Lime-Stabilized Layer Is Disappearing

This is clear in all of the NDT data. The lime either never fully reacted or has leached out of this layer. The lime-stabilized subbase layer is wet. Strong reflections were observed for this layer in both the air-launched and ground-coupled GPR data. Of the five sites drilled, two sites still contained lime and the subbase layer was stiff. In another two the lime was detected but the layer was weak. In the last site there was no evidence of lime.

Factor 2. The Subgrade Soils Are Extremely Poor

In one location the DCP penetrated almost 4 inches per blow at a depth of 30 inches beneath the surface. This is very weak. At all five sites the soils were complex, with mixed layers of high PI clay and zero PI clean sand. The sand layers were saturated. It is clear that they are carrying moisture beneath this pavement. The ground-coupled GPR data indicated that the mixed sand and clay layers are present throughout section 2.

The pavement roughness is thought to be primarily:

1) pavement settlements where the lime layer has disappeared and the pavement has settled into the weak subgrade, and
2) swell caused by the high PI expansive clays.

Recommendations on rehabilitation options were provided in the forensic report. In this project both the ground-coupled and air-launched GPR data provided valuable insight into the cause and extent of the problem.

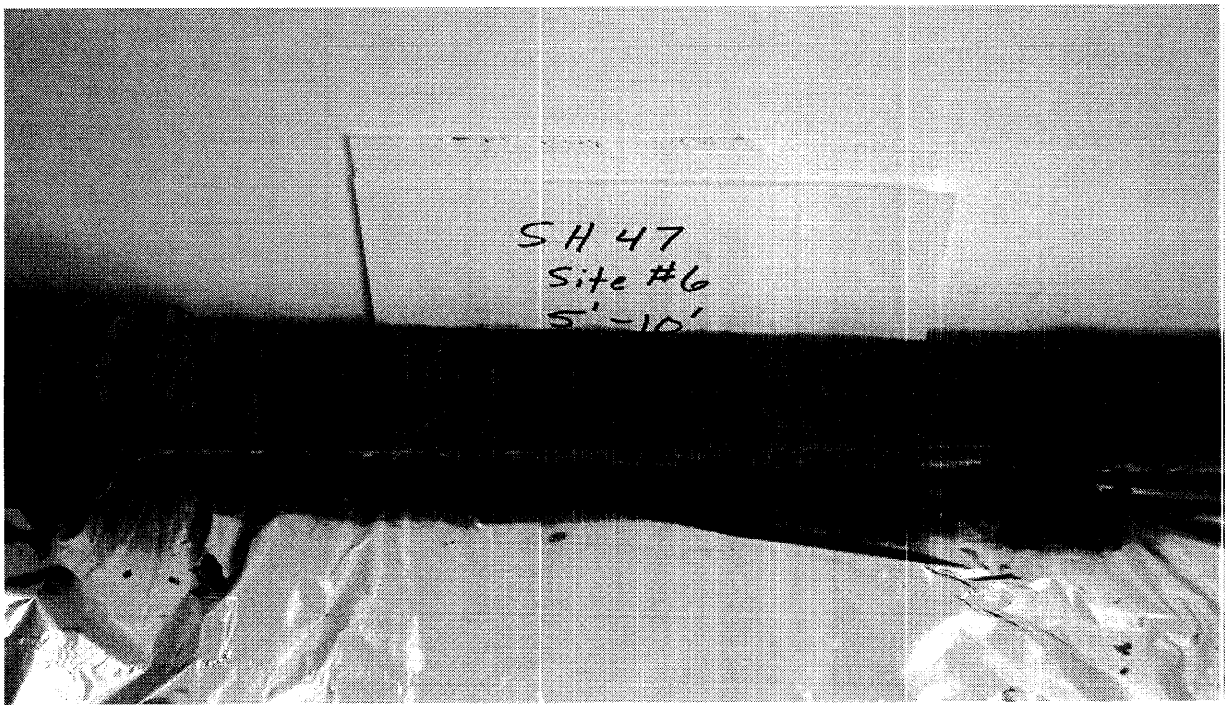


Figure 19. Verification Boring Results from SH 47. In the Worst Areas the Subgrade Was Found To Be Highly Variable and Saturated. Layers of Clean Saturated Sand Were Mixed with Layers of Highly Plastic Clay.

CASE 4 MAPPING AREAS OF SUBSIDENCE (GROUND-COUPLED)

FM 488 near Fairfield, Texas, was exhibiting severe distress in the form of pavement failures and excessive roughness. The highway had received several level ups, and TxDOT requested a subsurface investigation to aid in the selection of the appropriate rehabilitation strategy. It was known that part of the problems on the highway was a result of subsidence related to backfill over an old strip mining area. A ground-coupled survey was requested to help map out the extent of the problem areas.

Both TTI and Roadscanners, Inc. personnel conducted the survey in 1999. The data were processed by Roadscanners, Inc. and submitted as a site report (Saarenketo 1999). The figures included in this section were extracted from that report. The survey was carried out using the system shown in Figure 4, and both 500 MHz and 200 MHz ground-coupled antennas were used. The GPR data were collected using horizontal filters, auto-gain, and background removal techniques. The 500 MHz data were interpreted, and the pavement/base and base/subgrade interfaces were selected. The subgrade varied from sandy material to high PI material, and the interface between these two subgrade types were relatively easy to detect. Falling weight deflectometer data were also collected and linked to the GPR data as shown in Figures 20 and 21.

The data shown in these figures are described as follows:

- The top of the figure contains the distance scale in meters; this is directly on top of the filtered GPR data. The depth displayed in each figure is 2 m. Annotation is placed on top of the GPR data to denote layer interfaces, culverts, bridges, and areas where the subsurface soil types could be estimated. The reclaimed areas provided a distinct GPR signature.
- Below the GPR data is a sketch showing the estimated layer thickness with the same annotations as those placed on the GPR data.
- Two horizontal bars are included which denote areas thought to be either reclaimed land or expansive "exp clay" subgrade. These locations may not necessarily be expansive material, but the subgrade material was also measured to be weak from the FWD or wet from the GPR.

- The annotation area includes comments recorded manually as the data were collected. This is typically used to log areas of severe surface distress, transitions from cut to fills, or other information which may be useful in processing the data.
- The final graph shows the FWD data collected on this section of highway. Large variations in deflection bowl were observed along this highway. In one area the pavement had a thick cement stabilized base, and the deflections dropped significantly.

Figure 20 is taken from a location in the north of the project which was performing relatively well. The section had a reasonably good ride and little surface distress. The subgrade beneath the pavement was largely sandy type materials at this location. The total pavement thickness in this area was less than 19 inches (0.5 m). This should be compared with the results shown in Figure 21, which are from a section with severe pavement roughness. A major transition in subgrade type is observed to start at 7750 m. The reclaimed area is assumed to start here. It is clear that many level ups have been placed on this section because of subgrade settlements. The total pavement thickness in this area is close to 36 inches (1 m).

The entire project was approximately 9500 m (6 miles) long. The GPR data was processed in individual 500 m sections similar to those shown in Figures 20 and 21. Problems with settlements caused from pavement subsidence were first observed in a few localized areas starting at 6760 m. The major problem area was found to extend from 7750 m to 9100 m. Therefore on this project, the ground-coupled GPR was found to be useful in identifying the limits of the problem area. This information provides useful input for selecting the appropriate rehabilitation treatment for the entire section.

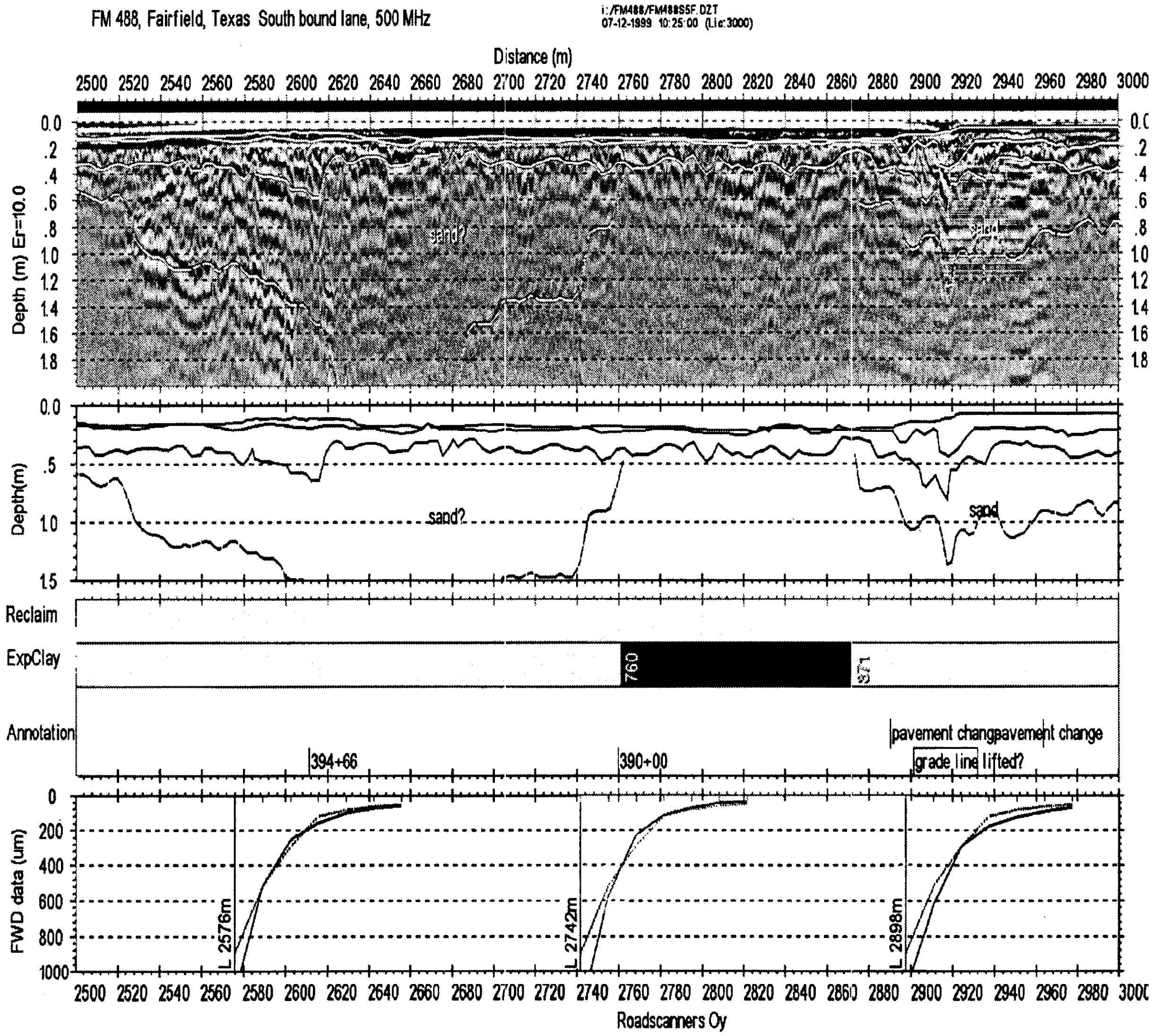


Figure 20. Road Doctor Display from a 500 m Section of FM 488. This Section Was Over an Area in Fairly Good Condition. The Subgrade in This Area Was Largely Sandy Silt.

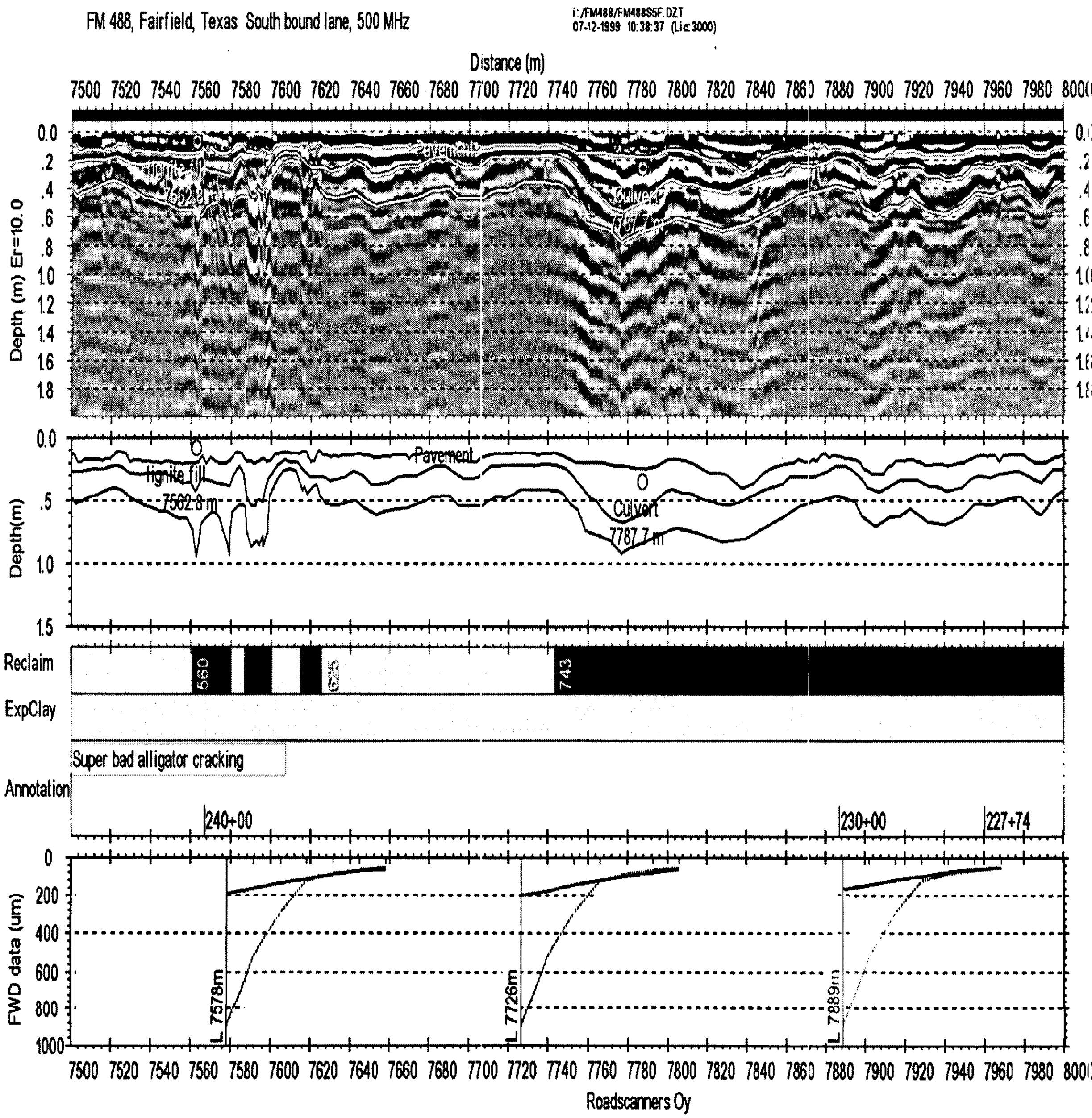


Figure 21. GPR Data from Badly Distressed Areas on FM 488. The Reclaimed Land Has a Distinctive Strong Repeating Reflections with Depth.

CHAPTER 6. THICKNESS DESIGN CONSIDERATION

INTRODUCTION

One task in this study addressed the issue of how to design the thickness of granular base overlays on top of stabilized subbase layers for low-volume roadways. These roadways typically have a two-course surface treatment as the final wearing surface. This pavement type has becoming more popular in Texas with the reported success of full depth reclamation projects where a flexible base layer is often placed over the treated layer. The recommendations in this section are based on discussions with several district pavement engineers as well as the results from earlier studies, in particular Report 3903-1, "Condition Evaluation of 25 Recycled Pavements in the Bryan District," (Syed and Scullion 1999) and Report 1287-2, "Identify Structural Benefits of Base and Subgrade Stabilization" (Little 1995).

TxDOT commonly uses these four methods of designing layer thicknesses for flexible pavements.

1) FPS 19W is the main tool used by district pavement design engineers. The structural input is the pavement layer moduli based on Falling Weight Deflectometer backcalculation.
2) FPS 11 is the earlier version of FPS where the layer properties is the layer coefficient, which are backcalculated from Dynaflect deflections. As TxDOT's Dynaflects have been largely replaced by the FWD's, this design method is used by only a few districts.
3) Texas Triaxial procedure is an older design method where the primary criterion is eliminating shear failure in the subgrade layer. The major design inputs are the subgrade triaxial class and the average of the ten heaviest wheel loads that will use the pavement. For the stabilized layer the district must also input a cohesiometer value. TxDOT no longer runs this test so the values used are often based on table look-ups.
4) Potential Vertical Rise Method (PVR) is used to evaluate the impact of swelling clays on the development of pavement roughness. The analysis is based on a

detailed soil survey where the soil type, Atterburg limits, and moisture contents with the top 10 ft of the pavement are measured.

Based on discussions with district personnel only two design procedures are commonly used for granular base thickness design. These are FPS 19W and the Texas Triaxial method. FPS 11 is not widely used because of the lack of Dynaflect data and the PVR method is only appropriate for swelling clay situations. Therefore recommendations for only FPS 19W and Texas Triaxial are given below.

DESIGN RECOMMENDATIONS FOR FPS 19W

From discussion with district pavement engineers the granular overlays are best designed using the pavement type 4 option in FPS 19W. This design type is hot mix asphalt, flexible base, stabilized subbase over the subgrade. The designers must input moduli numbers for each layer in the pavement structure. For low-volume roads the surface is usually a surface seal, so a design thickness of 0.3 inches and default moduli of 200 ksi is recommended. (This will have little impact on the final base and subbase thickness design.) The input subgrade modulus is district supplied and based on FWD analysis. The main unknowns in the calculation are the allowable thickness ranges for the base and stabilized subbase and their design moduli values. From discussion with district personnel the main variable in assigning a moduli value is the quality of the stabilized subbase material. If the treated layer is of good quality granular materials and the stabilizer content is selected based on laboratory testing and/or field performance studies, then relatively high moduli values can be assigned. If the material is either a blend of rock and subgrade material or mostly subgrade soils, then lower values should be used. The other unknown is the moduli value for the classes of flexible base overlay materials. Recommendations for each are given below:

• Range Thickness of Granular Base Overlay		4 – 12 inches
• Moduli Values for Granular Overlay	Class 1	70 ksi
	Class 2	50 ksi
• Thickness Range for Stabilized Layer		6 – 10 inches

- Moduli Values for Stabilized Sub-bases

Granular	100 ksi
Blend	65 ksi
Mostly Subgrade	35 ksi

The lower values for the stabilized subgrade material are based on Texas experience where the expectation is that high strength of the stabilized fine material cannot be counted on long term because of potential leaching. Note the 35 ksi can only be assumed if the subbase layer is a designed layer where the stabilizer content is based on laboratory testing including moisture susceptibility testing. If the subgrade is treated with lime to expedite construction then no long term benefits of stabilization can be assumed. In these cases a three layer design flexible base directly over subgrade should be performed (design type 1 in FPS 19W) with no subbase.

The higher moduli values for stabilized granular material can be used only if the design is based on laboratory testing, where the percentage stabilizer is selected based on both strength and moisture susceptibility testing. Furthermore districts should also be actively monitoring projects with the FWD to ensure that long term strengths are achieved in the field. Districts should adjust these values based on their long term monitoring studies.

To demonstrate these values within FPS 19W, a simple case study was performed to compute the required flexible base overlay for a full depth reclamation job in the Paris District, Delta County. The time to first overlay was set at 12 years and three levels of traffic loading were used, (0.3, 0.8, and 1.8 million twenty year ESAL's) representing a low, intermediate, and heavy traffic flow volume roadway in Texas. The results are shown in Figure 22. Note no designs were found feasible for the fine grained stabilized subbase at the high traffic level.

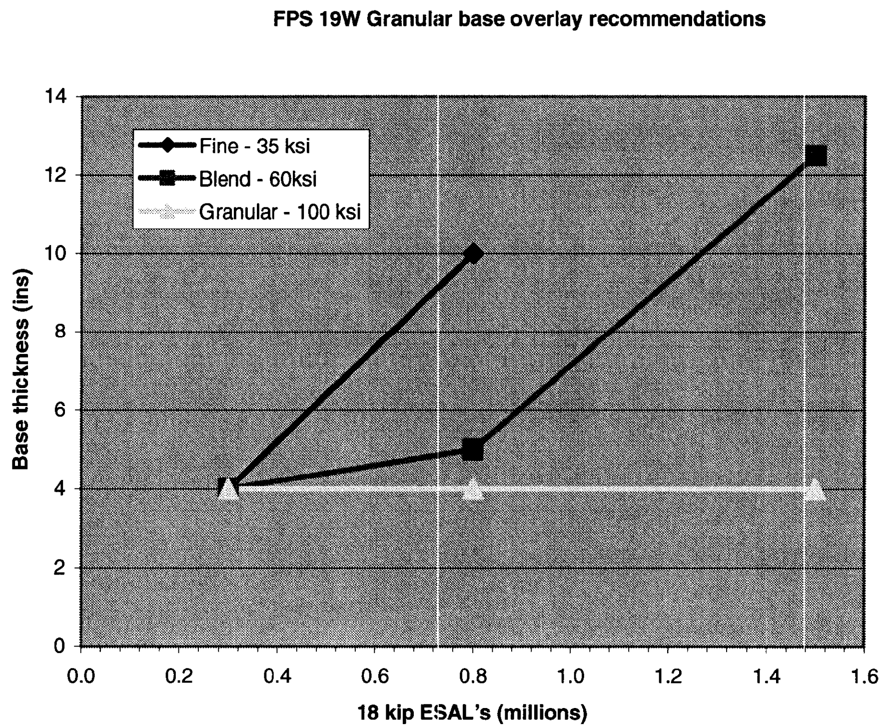


Figure 22. Example FPS 19W Base Thickness Designs for Low Volume Roadways with Different Stabilized Subbases.

TEXAS TRIAXIAL PROCEDURE

In the Triaxial Procedure the subgrade strength as measured by the Texas Triaxial Class and the average of the 10 heaviest anticipated design loads are used to compute the thickness of cover over the subgrade. This material is intended to be a flexible base. To account for a stabilized subbase a thickness reduction factor is computed based on the improved load spreading capabilities of the stabilized subbase. This is computed based on the cohesiometer value of the treated material. This testing was conducted by TxDOT, and representative values for typical materials were developed in the 1960s. The main decision is what cohesiometer value to apply to the treated layer. It is acknowledged that the value should be less than the 1000 value assigned to cement treated base greater than 3 inches thick and greater than the 250 value assigned to lime treated subgrade. The recommended cohesiometer value for stabilized subbases are as follows:

- Stabilizing mostly granular materials — Cm value 550
- Stabilizing blend of granular and fine material — Cm value 350
- Stabilizing mostly subgrade material — Cm value 250

Results from using these cohesiometer in the triaxial design for a typical low-volume road design are shown below in Figure 23. The assumption is that a 10 inch thick stabilized subbase will be incorporated into the pavement structure and that the triaxial class of the soil is 5.0 (poor). The influence of three qualities of design subbase layers and four traffic loadings is shown in Figure 23.

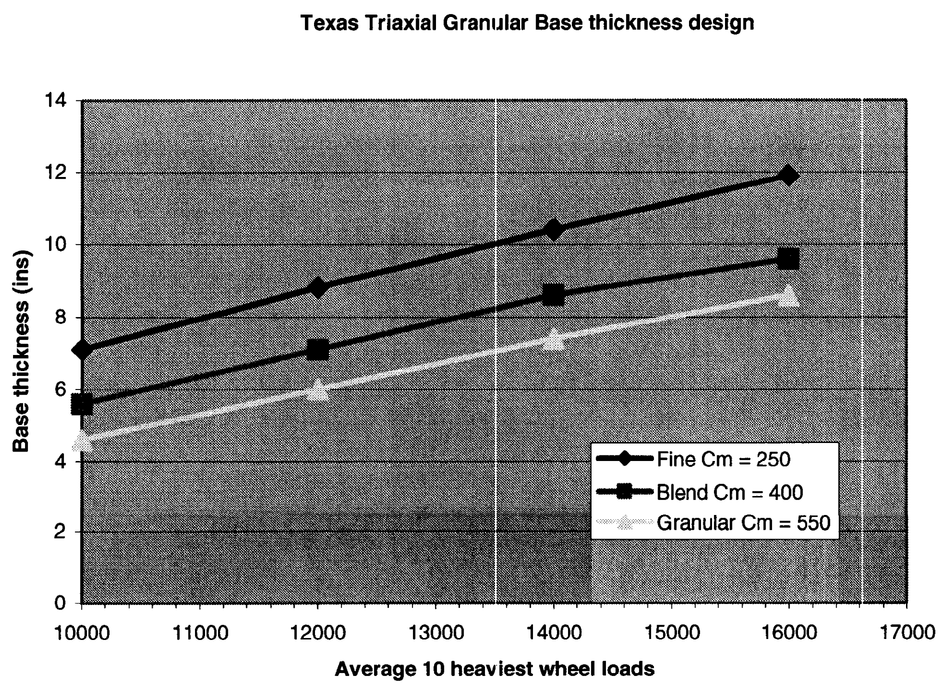


Figure 23. An Example of Using the Texas Triaxial Design Procedure to Compute the Granular Base Thickness for a Low-Volume Roadway.

CHAPTER 7. CONCLUSIONS

GPR technology has been successfully implemented within both FinnRA and TxDOT. This result comes from a long-term research effort where a) the strengths and weaknesses of GPR were clearly defined in early studies and b) software was developed so that signal interpretation could be performed by pavement engineers rather than GPR "experts." GPR reflections from pavements can be complex layers. In all cases GPR interpretation should not be attempted without the use of validation cores or validation borings. GPR will never eliminate field coring but it can certainly reduce the number of core holes required.

In using GPR for site investigation, if the problems are suspected to be in the HMA surface or base layer then air-launched systems should be used. They operate at highway speed but their effective depth of penetration is limited to 2 ft. The interpretation becomes complex when the pavement consists of many thin layers. Overlapping reflections from each layer can make interpretation difficult. GPR detects interfaces if there is a change in electrical properties (dielectric) between layers. In pavements the most significant factor which influences layer dielectric is moisture content (density is a significant but secondary factor). Therefore GPR will only provide meaningful information if there is a difference in either layer moisture content or layer density. One additional complication in wet bases and most concretes is that these high dielectric materials also significantly attenuate GPR signals, making it difficult, for example, to identify base conditions below a concrete pavement.

For investigations of subbase and subgrades in flexible pavements and for most applications on concrete pavements, ground-coupled GPR systems are recommended. A range of antenna types is available, which cover the range of depths typically required in pavement subgrade profiling. The limitations of ground-coupled systems are as follows:

- They are relatively slow with data collection speeds ranging from 2 to 8 mph.
- The data collection and processing is complex.
- There is a trade-off between penetration depth and layer thickness resolution. It is impossible to penetrate deep and identify thin layers.

Under normal operations, the GPR systems should be capable of identifying major changes of soil type, from a sand to a clay, based on a change in moisture content and signal attenuation. With sandy materials it is usually possible to identify subsurface layering. However with heavy clays, this is not the case. There is often energy reflected at the top of the layer but little or no reflections occurring with depth. This was, however, not the case on this project. The soils on SH 47 were found to be complex with bands of highly plastic soil on top of saturated layers of sand. Strong reflections were apparent throughout the section, but it was not possible to define the material type without exploratory drilling at a few select locations. The other application of subgrade profiling was more successful. The goal was to identify areas of substantial subgrade settlements. This was clear in the 500 MHz data.

The Road Doctor software package described in this report is the "state of the art" system for processing ground-coupled data. It is available at the Texas Transportation Institute. The ground-coupled sections tested in this project were all located in the Bryan District. Future studies should focus on evaluating GPR capabilities in other areas of the state.

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