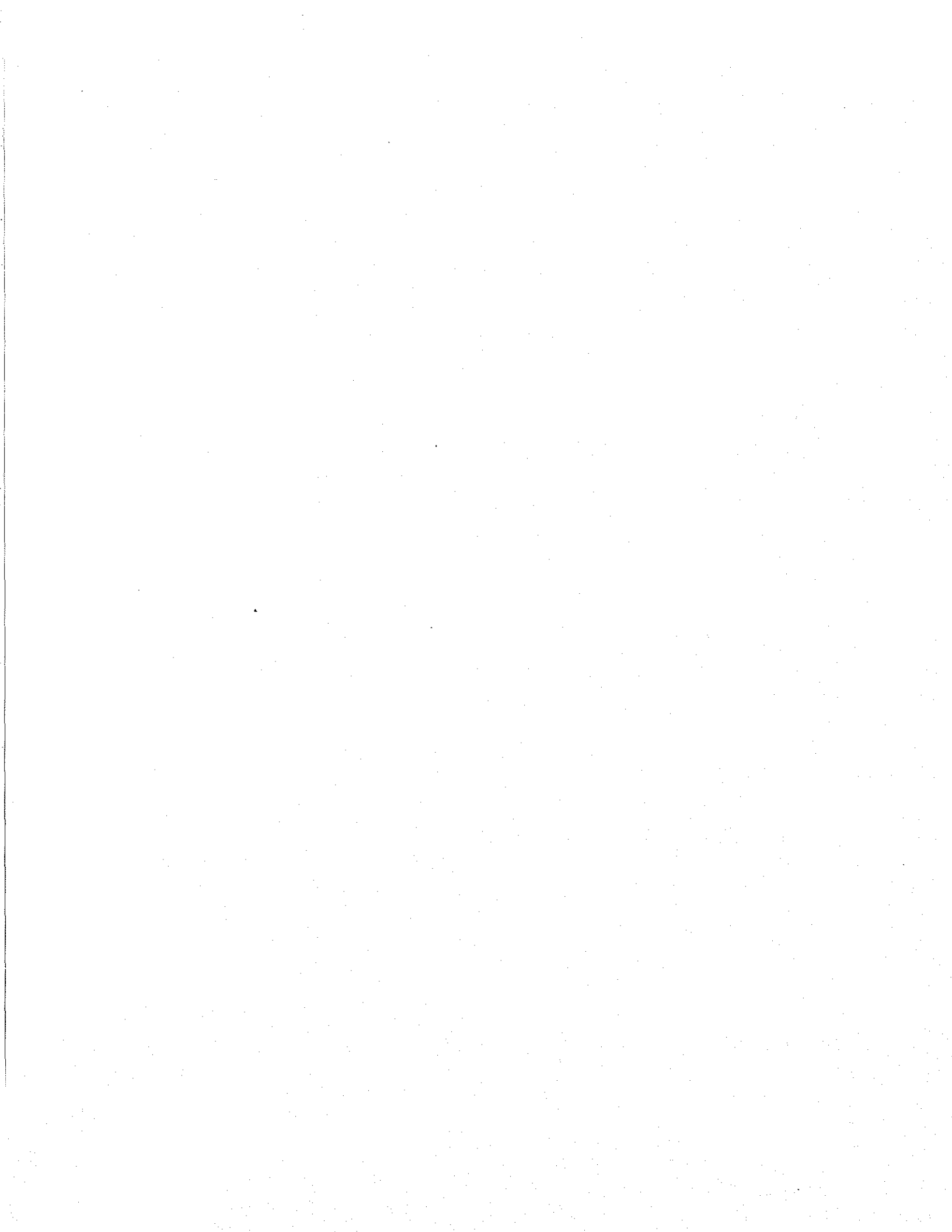


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16. Abstract <p>This report will describe the various kinds of information that can be obtained from roads and highways with Ground Penetrating Radar. In the last 5 years, attention has focused on measuring the thickness of the asphalt surfacing layer on flexible pavements with air-launched horn antennas. Other antennas are available with substantially different depths of penetration, and for use in a wide range of other pavement applications.</p> <p>The purpose of this report is to describe the range of applications of GPR in pavement evaluation. Cases include subgrade investigations, bedrock evaluations, locating sinkholes, detecting frost damage, and identifying defects such as stripping or voids and monitoring crack growth within the pavement structure. The large variety of cases, conducted in Texas and Finland, illustrates the unique ability of GPR to rapidly evaluate subsurface conditions. The sinkhole detection study represents our initial effort to use low frequency deep penetrating radar on Texas pavements. A unique feature of this paper is the proposed classification of the frost susceptibility of subgrade soils by their measured dielectric constant and electrical conductivity.</p>					
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**GROUND PENETRATING RADAR APPLICATIONS ON
ROADS AND HIGHWAYS**

by

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and

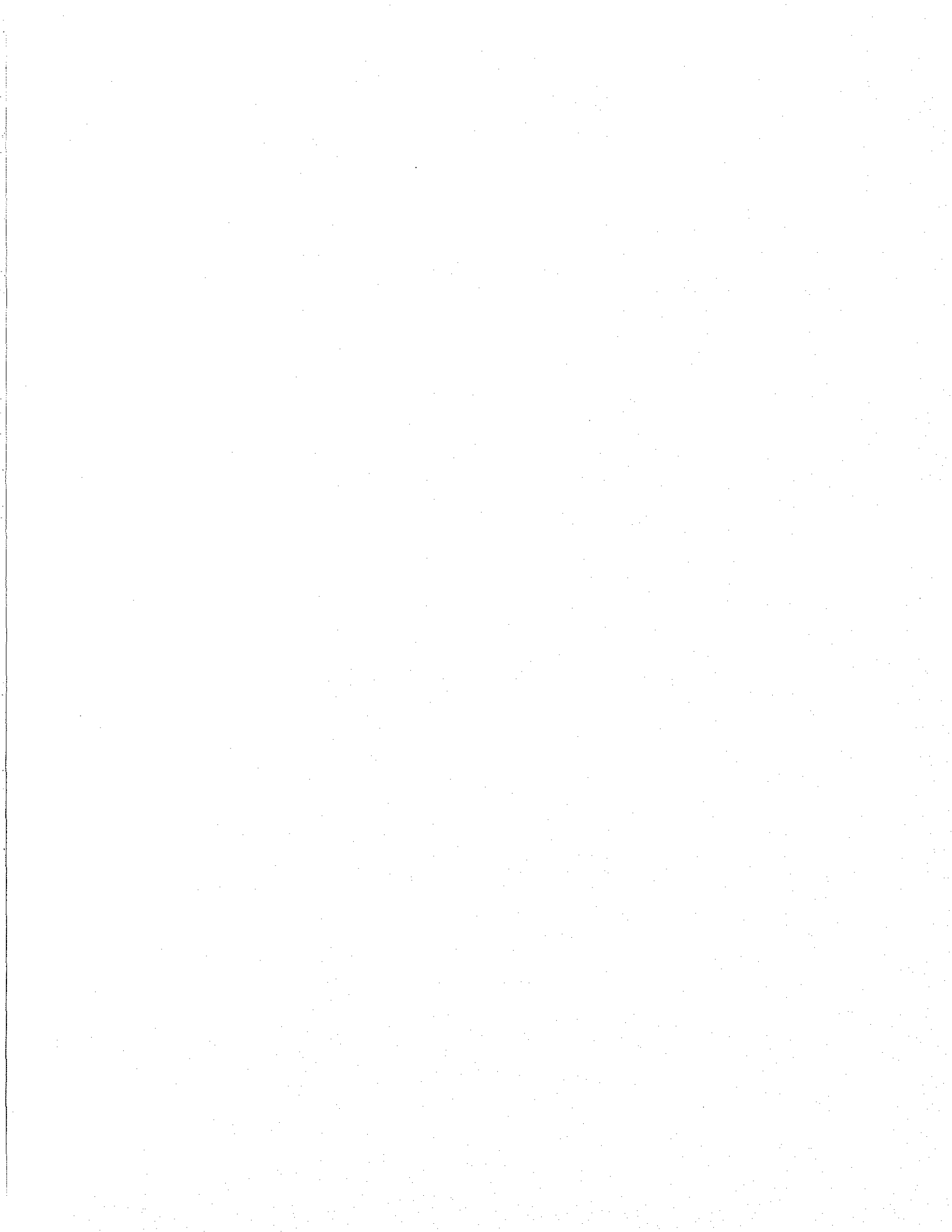
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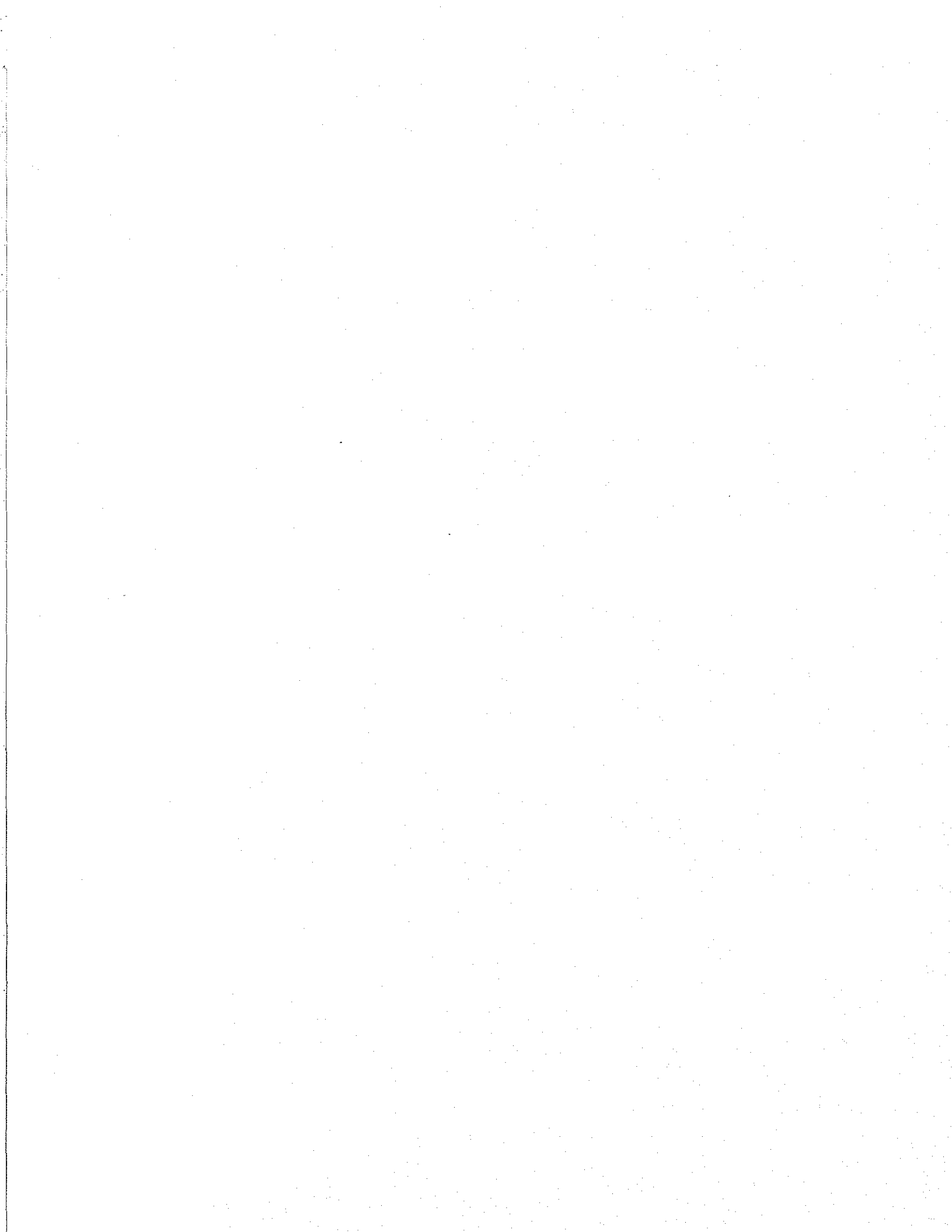
November 1994

TEXAS TRANSPORTATION INSTITUTE
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IMPLEMENTATION

This report presents an array of applications for both ground-coupled and air-launched Ground Penetrating Radar systems. This technology is relatively new to the pavements area, but it shows tremendous potential for assisting in subsurface evaluations. The Pavement Design Division has purchased an air-launched system that should be fully implemented within TxDOT by the end of 1994. In recent months, several applications for ground-coupled systems have been investigated; it is anticipated that these deep penetrating systems will be included in several upcoming projects.



DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein.

This report is not intended to constitute a standard, specification, or regulation, and does not necessarily represent the official view or policies of the Texas Department of Transportation. Additionally, this report is not intended for construction, bidding, or permit purposes.

The engineer in charge of this project was Tom Scullion, P.E. #62683.

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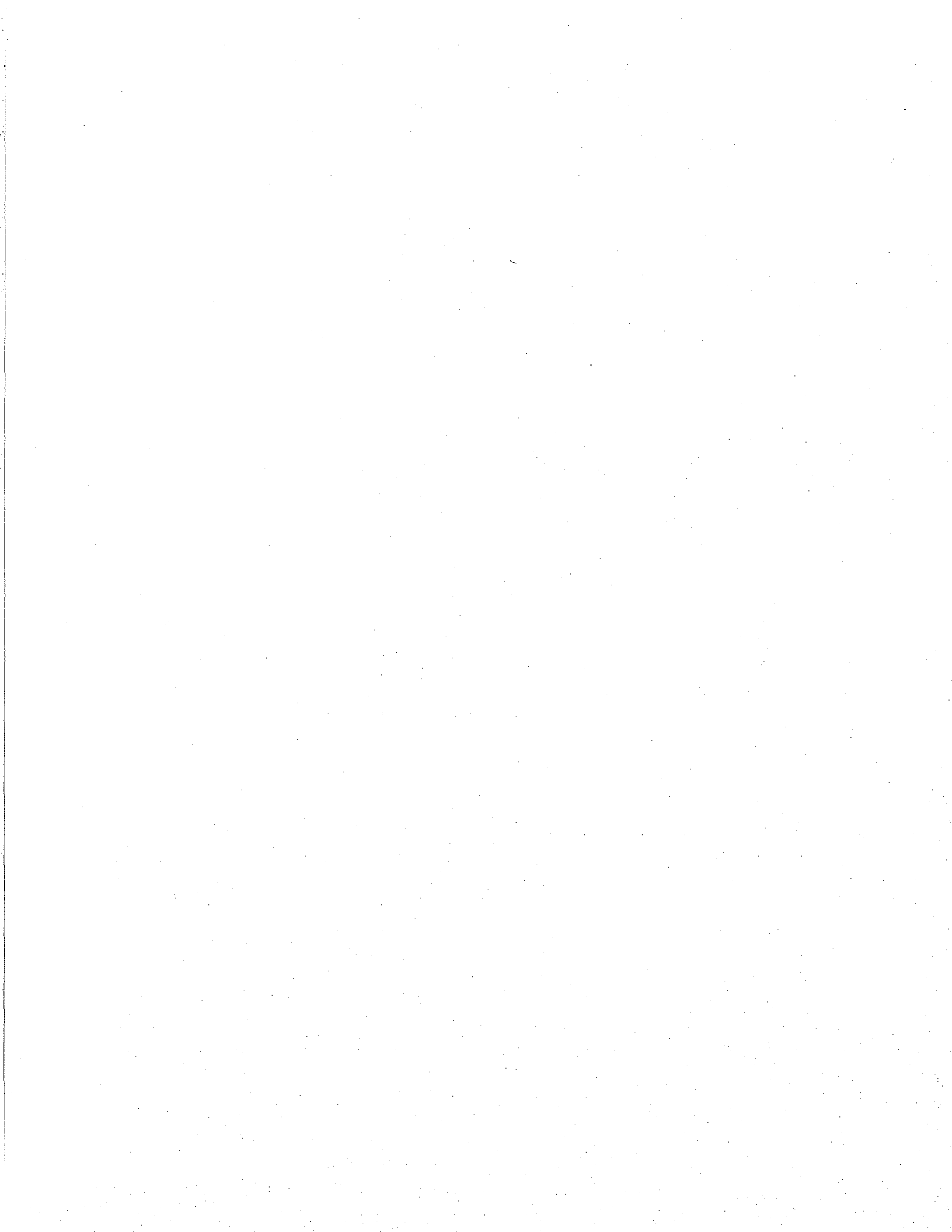
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SUMMARY

This report describes the types of GPR equipment, namely ground-coupled and air-launched. It discusses the advantages/disadvantages of both and presents results from a series of case studies. The air-launched systems are recommended for near surface measurements (> 0.5 m) where long lengths of highway are tested. The ground-coupled equipment provide the capability of penetrating deep within the pavement (up to 5 m) they are best utilized for defect detection and subgrade soil surveys.

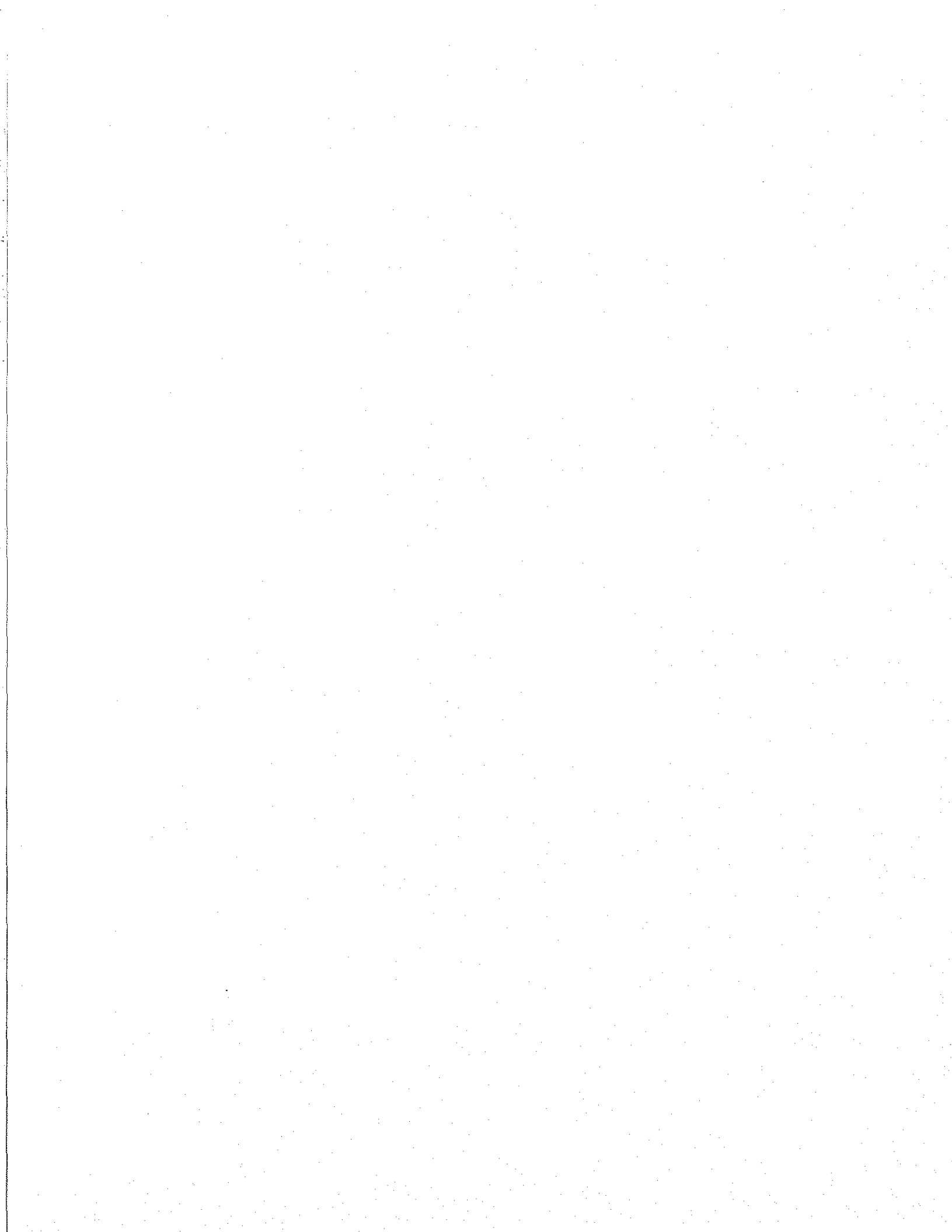
CHAPTER 1

INTRODUCTION

In the USA and Canada, most of the Ground Penetrating Radar (GPR) research in highway applications has been focused on pavement thickness measurements (Maser 1994), detecting voids under concrete slabs (Scullion et al. 1994), and detecting deteriorated areas in bridge decks (Manning and Masliwec 1994). These surveys have mainly been performed with high frequency (1.0 GHz) air-launched antennas. In contrast, in Finland most of the research and development work in road and highway applications has been performed with low frequency (100 - 500 MHz) ground-coupled antennas (Saarenketo 1992a). However, interest in pavement and bridge deck surveys has been growing in recent years (Saarenketo and Söderqvist 1993, Maijala et al. 1994).

The purpose of this report is to describe the types of GPR antennae available, to briefly discuss the types of data processing used in several applications, and to present case studies undertaken in both Finland and Texas. The work presented has been sponsored by both the Finish National Road Administration (FinnRA) and the Texas Department of Transportation (TxDOT). The Texas case studies are all from in-service pavements. Study 1923 was set up as a demonstration project in which the research staff were requested to evaluate if GPR is practical for implementation within TxDOT.

One of the main issues was whether the GPR data could give reliable results in a short time frame. Typically, the pavements were tested and a technical memorandum describing the results and recommendations was prepared no later than 2 weeks after testing.



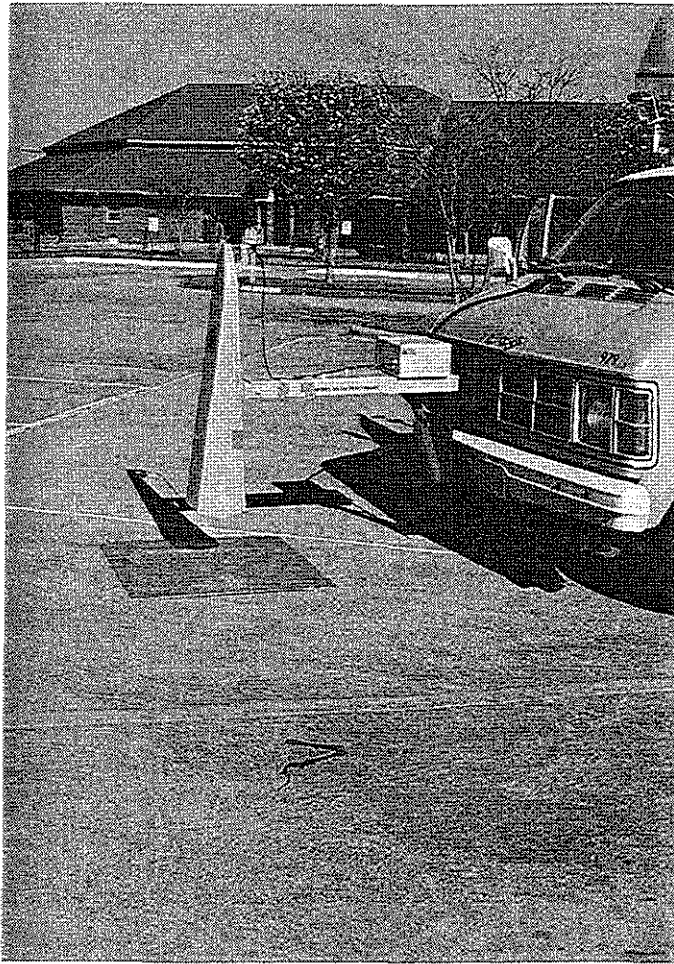
CHAPTER 2

GPR EQUIPMENT

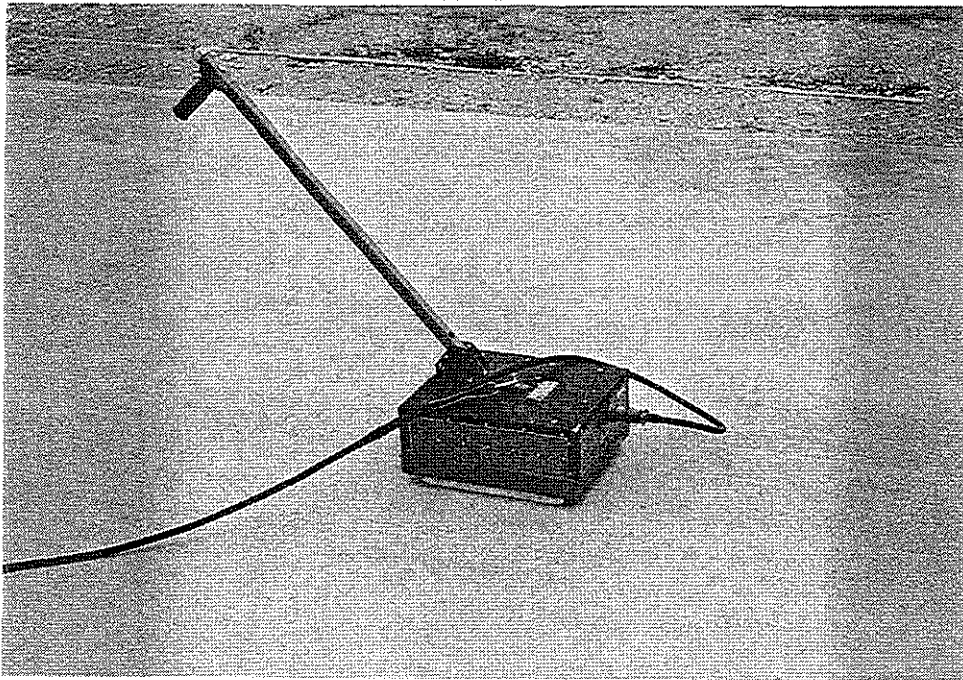
Ground Penetrating Radar systems use discrete pulses of radar energy. These systems typically have the following three components: 1) a pulse generator which generates a single pulse of a given frequency and power, 2) an antenna which transmits the pulse into the medium to be measured, and 3) a sampler/recorder which captures and stores the reflected signals from the medium. Once the return waveform is captured another input pulse is generated and transmitted into the medium. The radar antennae in common use fall into two broad groups: air-launched horn antennae and ground-coupled dipole antennae. Examples of both antenna types are shown in Figure 1.

The air-launched systems operate around 1 GHz, their depth of penetration in typical pavement structures is limited to approximately 0.5 m (20 in). During data acquisition these antennae are suspended approximately 0.3 m (12 in) above the pavement surface. They collect useful pavement layer information at close to highway speeds > 60 kph (40 mph). Currently three vendors manufacture and sell air-launched systems in the United States: 1) Pulse Radar, Houston, Texas; 2) Penetradar, Buffalo, New York; and 3) GSSI, North Salem, New Hampshire. In recent years attempts have been made to develop air-launched systems of different operating frequencies. GSSI has developed a 2.5 GHz system aimed at high resolution, near surface testing (Smith and Scullion 1993). Pulse Radar is in the process of developing a 500 MHz system to permit better penetration of thicker pavement structures (Pulse Radar 1994).

In contrast, the ground-coupled antennae operate in a wide range of central frequencies from 80 MHz to 1000 MHz. As Table 1 shows, the lower the frequency the larger the antenna and the greater the depth of penetration. The clear advantage of ground-coupled antennae is their depth of penetration and better vertical resolution. However, these surface-coupled systems have not yet been optimized for road work, the surface coupling and antenna ringing present problems. Typically, it is difficult to obtain any quantitative information from the near surface with these antennae. Another limitation of these systems is that they must remain in near contact with the medium. For highway work, data collection is limited typically to less than 10 kph (6 mph).



a) Air-Launched
Antenna (Penetradar)



b) Ground-Coupled
Antenna (GSSI)

Figure 1. GPR Antennas.

Table 1. Properties of Some Antenna Available in Finland (Ground Penetrating Radar 1992).

Model	Mean freq. MHz	Duration of pulse ns	Dimensions HxWxL cm	Weight kg	Resolutio n cm	Penet. Depth m
3112	80	18	38x132x84	64	46	40
3207	100	15	26x96x55		37	30
3110	120	12	31x97x55	19	31	30
3020	120	12	25x97x127	54	31	
3307	250	6			15	
3105	300	5	19x64x77	31	12	15
3102	500	3	15x31x36	4	8	6
3101D	900	1.6	8x18x33	2.3	4	2
3100	1000	1.5	4x10x17	8.8		1
H6/110	120	12		2.7	37	
ECHO-80	80	18	17x125x105	27	46	40

Footnote: Antennas numbers 3112, 3207, and 3110 are used for general purposes and in pairs, 3020 especially for ice measurements and 3307 for aerial purposes. ECHO-80 is a general antenna manufactured by the Swedish Radar Team and can also be used in antennae pairs. When paired antennae are used the transmission power can be increased from 60 W to 7500 W, thus improving penetration depth. Resolution values and penetration depths are given for a dry, non-conductive medium.

Conversion Factors:

1 cm = 0.39 in

1 Kg = 2.20 lb

1 m = 39.4 in

The leading manufacturer of ground-coupled systems is GSSI of New Hampshire, other manufacturers include Sensor and Software Inc. (Canada), Era Technology (UK) and RAMAC (Sweden).

One area of concern in GPR hardware has been that of performance specifications. How can a GPR user be sure that the unit to be purchased will provide GPR waveforms of sufficient quality for automated signal processing? To assist DOTs in purchasing equipment the Texas Transportation Institute has proposed the following 6 specification tests for air-launched horn antennas:

1. Signal Stability Test (Variations in amplitude of reflection),
2. Clutter Level Test (Signal/Noise),
3. Long Term Signal Stability,
4. Variation in Time Calibration (Measured wavespeed in air),
5. End Reflection Test, and
6. Penetration Test through Concrete.

If a unit passes these tests, the GPR waveforms collected can reliably compute quantitative layer properties. Several manufacturers use these specifications as quality control checks prior to delivery to customers. At present no specifications are available for ground-coupled units.

CHAPTER 3

GPR SIGNAL PROCESSING TECHNIQUES

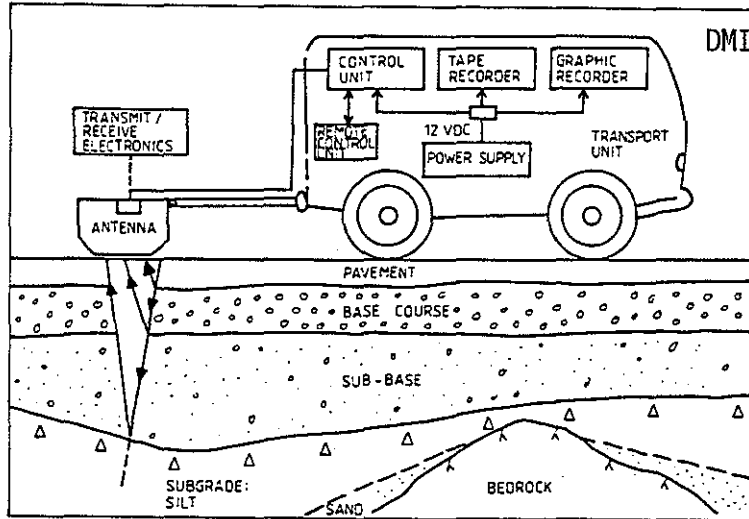
Figure 2 shows the principles of data acquisition and display for ground-coupled GPR systems. The GPR transmits short pulses of electromagnetic energy into the pavement structure; these pulses are then reflected and refracted at each layer interface. The reflected energy is collected and displayed as a waveform. Generally, the size of the reflected signal at each layer interface is a function of the dielectric contrast between the layers. In flexible pavements this contrast is largely dependent upon the moisture content contrast between layers. The ideal situation is a hot mix asphalt over a granular base over a clay subgrade. The variation in moisture content between layers will be substantial, resulting in clearly defined GPR return peaks. Conversely, GPR only provides useful information if there is an electrical contrast between layers. In several instances, such as granular base over a sandy/gravel subbase or concrete over cement treated base, there may not be sufficient contrast. In these instances the return from the interface may not be significant.

The traditional method of processing and displaying GPR data is shown in the lower part of Figure 2. The reflection amplitudes in each return waveform are transformed by means of a grey scale or color scale to a single line scan. In the typical grey scale conversion, the higher amplitudes are assigned darker colors. These transformed traces are then stacked so that the operator can observe variations in GPR signal as the system moves along the highway. Several signal processing techniques (filtering, clutter removal, etc.) obtain sharper GPR displays. However, interpretation of the final profile information (Figure 2b) is performed manually by experienced operators. As will be described later in this paper, the Finnish researchers have many years of experience in interpreting these GPR profiles.

The implementation of air-launched GPR systems over the past decade has promoted the development of automated signal processing software. The 1 GHz horn antennae, which passed the performance tests discussed earlier, produce relatively clean return signals in which the amplitudes of the return signals and the time delay between returning peaks can be measured. A typical GPR waveform from such a system is shown in Figure 3. The amplitude of return

PRINCIPLES OF THE GROUND PENETRATING RADAR SYSTEM

I MEASURING EQUIPMENT



II EXAMPLE OF RADAR DATA

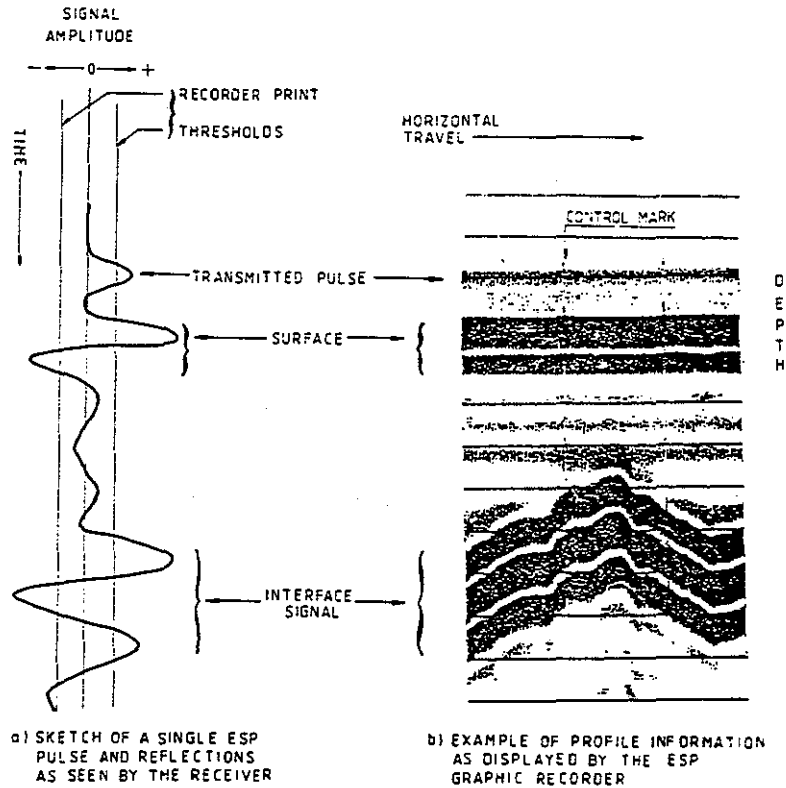


Figure 2. Principle of GPR for Ground-Coupled Antenna Systems.

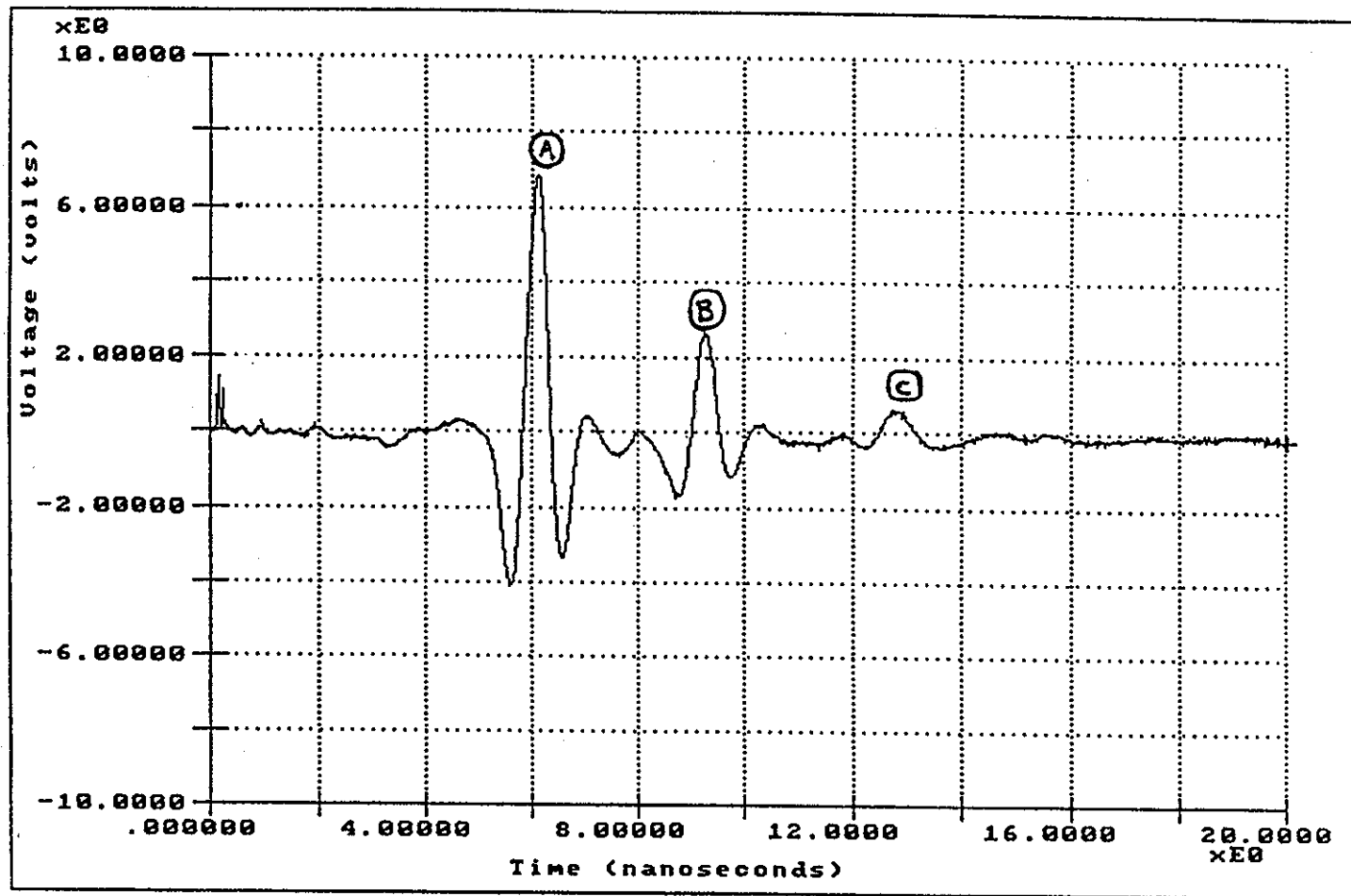


Figure 3. Typical GPR Waveforms from a 1GHz Horn Antenna (with end reflection removal).

Footnote: Peaks A, B, and C are Reflections from the Surface, Top of the Base, and Top of the Subgrade Respectively.

is a function of the layer dielectric whereas the time between peaks is related to the layer thickness. The principles of using automated signal processing have been given elsewhere (Maser and Scullion 1991). In these automated systems, the dielectric of the top layer is computed by comparing the amplitude of surface reflection from the pavement surface with the total reflection obtained from a large metal plate. This dielectric, together with the measured time delay between peaks, is used to estimate the thickness of the top layer. The accuracy of measuring the surfacing thicknesses has been demonstrated on a wide variety of pavements by Maser (1994).

CHAPTER 4

SUBGRADE SURVEYS AND SITE INVESTIGATIONS

4.1 INTRODUCTION

Subgrade surveys and site investigations with GPR can be classified into the following three categories: 1) new road alignment and site investigations, 2) strengthening and/or widening of an existing road, and 3) using the existing road as an information source for the design of the new roadway alongside the existing one. The basic problems are similar in each case, but the ways the GPR can be applied will vary.

In subgrade surveys for a new road alignment, GPR can determine the soil types and their boundaries, estimating the depth of bedrock, and evaluating the ground water level and frost susceptibility. The GPR data can also direct the other site investigations, ie. drilling etc., to the places which cover a variety of geological conditions, (Saarenketo 1992a), thus optimizing the use of these traditional methods.

In highway bridge site investigations, GPR has been used to monitor the bottom topography of rivers or lakes and to map the quality of the underwater sediments. This data is collected from the field and can also be used when comparing highway route alternatives.

In road strengthening projects and when constructing a new road alignment alongside the old roadway, most of the previously mentioned information is collected from the subgrade under the existing road. These subgrade data, combined with other GPR data from the existing layers, provides valuable performance information.

4.2 SUBGRADE SOILS

With GPR it is relatively easy to identify gravel, sand, and glacial till soils with A-1, A-2, and A-3 AASHTO soil classification, and the GPR method also has good performance with organic peat soils (Ulriksen 1982, Doolittle and Repertus 1988, Ground Penetrating Radar 1992, Saarenketo et al 1992). GPR has relatively good penetration depth in silty soils, but problems arise when surveys are carried out in fine grained A-4 to A-7 soils. In Finland GPR signal penetration in clay soil areas is normally about 2 m, which is adequate for the cable and pipeline

design staff, but may not be for highway design purposes.

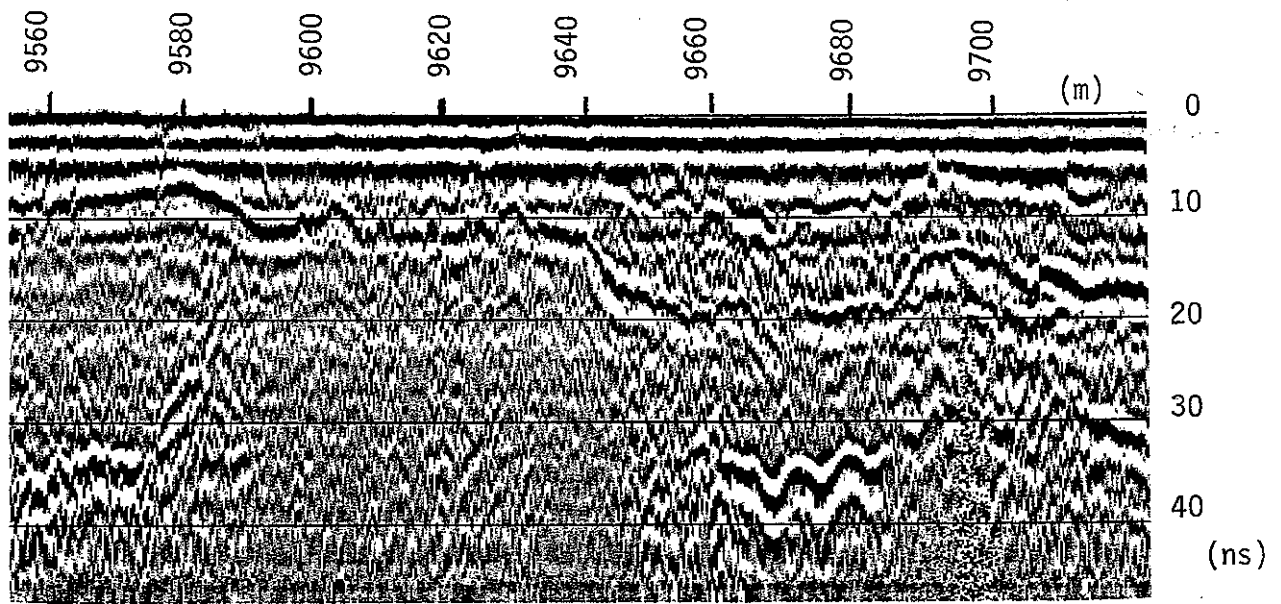
In the USA, penetration depth depends on the mineralogy and clay content of the clay soils. The penetration depth of 5 m (16 ft) has been achieved in areas of Site Oxidic soils, while radar signals penetrate only 0.15 m (.5 ft) in Vaiden type Montmorillonitic soils (Doolittle and Rubertus 1988). According to Doolittle (1987) the best areas in the USA for the radar in soil surveys are eastern and western states, while the greatest problems occur in the Mississippi-Missouri area in central states.

In many cases the soil type can be determined from the GPR data (Ground Penetrating Radar 1992), because every soil type has its own geological structure and dielectric and electrical conductivity properties; these properties cause a special "finger print texture" in a GPR profile. This knowledge has been applied especially when doing sand and gravel aggregate prospecting for highway construction purposes (Saarenketo 1992a). The most popular antenna type in soil surveys has been the low frequency (80-300 MHz) ground-coupled antennae.

4.3 BEDROCK DEPTH AND BEDROCK QUALITY

The depth of the overburden and location of the bedrock can usually be determined from a radar profile, providing that the radar signals can penetrate the overburden soil. The results can be used in design of grade lines, in design against uneven frost heave, and for other specific technical problems. The method also allows observation of bedrock stratification and major fracture zones when evaluating the stability of highway cutting walls in bedrock (Saarenketo 1992a). Similar information can also be obtained in highway tunnel surveys where both ground-coupled antennae and drill-hole antennae have been used (Westerdahl et al. 1992).

Identification of the bedrock interface is often difficult, and it may require a special interpretation technique. If the dielectric properties of bedrock and subgrade soil or road structure are very close, the reflected signal amplitude from the interface will be weak. Also, if the bedrock has been blasted under a road to a certain level, the transition zone from hard bedrock to road structures may be wide and no clear interface reflection can be observed in the radar trace (Figure 4). That is also the case in areas of weathering crust over bedrock. In all of these cases, the estimation of the bedrock interface has to be done by identification of the zone in the radar profile where the bedrock structures start. With this estimate, other reference



HW 21, Pello, Finland, GPR 500 MHz Data Interpretation

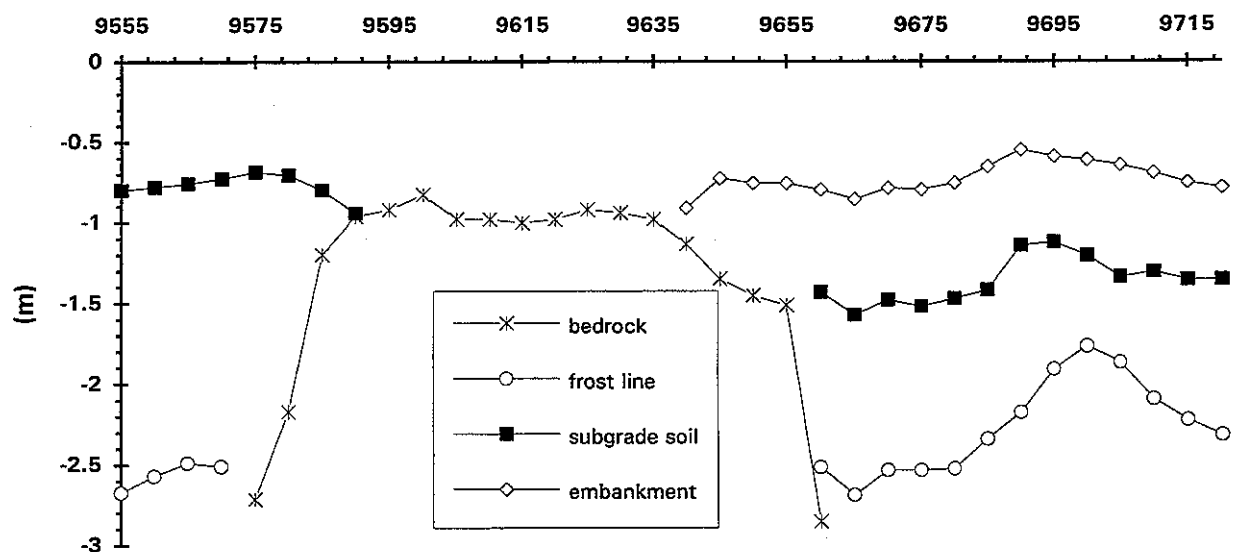


Figure 4. GPR Grey Scale Profile and Thickness Interpretation over a Bedrock Outcrop and Area of Uneven Frost Heave, Section 9555 - 9720 m, HW 21 Pello, Finland.

Footnote: Measurement with 500 MHz ground-coupled antenna were performed in March 1993 when the frost line was deep, but thawing has not yet started. The presence of bedrock can be seen by bedrock crack reflections and by the fact that the frost line reflection does not appear in that area. The blasted rock section under the highway between stakes 9605 - 9630 can also be identified. At the frost damage area in section 9680 - 9710 the frost line comes closer to the surface and the reflections come from a wider vertical area, which indicates the presence of ice lenses. The interfering noise in stake 9695 is caused by a near-by cellular phone.

data (ie. drilling, excavation pits or seismic survey data) will help the interpretation personnel to pick up the right interface and also calculate the wave velocity in the layer above the bedrock. However, in some cases in the USA, results of GPR surveys were more reliable and effective for determining the depth to bedrock than the estimates from auger boring (Collins et al. 1989).

If the GPR survey is performed in the wintertime, the areas of the bedrock closer to the surface than the frost level are easy to identify because frost line in the bedrock cannot be seen in the radar profile (see Figure 4).

In bedrock surveys with GPR, the recommended antenna is the lowest frequency ground-coupled antenna that can be used. When selecting an antenna, it is important to know the average thickness of the overburden and the antenna resolution; the antenna pulse length in soil should be shorter than the overburden thickness. In areas where the bedrock/soil transition is not clear, the lower frequency antennas usually provide better resolution.

4.4 SOIL MOISTURE AND GROUND WATER LEVEL

Because the dominating physical property of soil that affects the GPR signal velocity is volumetric water content, the GPR technique can measure the moisture content in subgrade soils and granular base layers. However, because the radar signals are so sensitive to the ground water level, its location can only be clearly determined in coarse grained sand gravel soils. All other soils have a capillary zone above the water table and this transition zone results in a blurred image in the GPR trace.

There are several GPR techniques that have been used for determining the base and subgrade moisture content. Maser and Scullion (1992) have used reflection technique with 1 GHz horn antennae to calculate the moisture content in base and subgrade, while other techniques used with ground-coupled antennae are CDP (Common Depth Point) (Ulriksen 1982), WARR (Wide angle and Refraction) (Annan and Davis 1976), and GPR-RSAD technique (Sutinen and Hanninen 1990). Direct dielectric constant measurement techniques that have been used with radar are TDR (Fellner-Feldegg 1969) and dielectric probes based on the capacitance measurements (Plakk 1994).

GPR also allows identification of moisture trapped in the road structure, and it has been used in surveys of road drainage systems (Saarenketo et al. 1994).

4.5 FROST SUSCEPTIBILITY AND COMPRESSIBILITY

Frost susceptibility and compressibility are closely related to the moisture content and the drainage characteristics of the subgrade, which can be estimated with GPR and other dielectric and electrical conductivity measurement devices. Saarenketo (1994) has proposed a frost susceptibility and compressibility classification for the subgrade soils in Finland which is based on the in situ measurements of dielectric constant and electrical conductivity (see Table 2).

Another procedure for evaluating potential frost action is performing GPR surveys in winter time when the frost is at its deepest penetration in the subgrade soils. At that time the dielectric constant of all the frozen structures and subgrade soils will be close to the value of frozen water (3.6-4.0). When analyzing the measured data the interpreter has to pay attention to the following phenomena: 1) the appearance of the frozen/non-frozen soil interface reflection, 2) the depth of frost table and clarity of the reflection, and 3) the effects of the frost action upon the road structures.

If the frost level cannot be identified from the radar data, this means that the subgrade soil has a very low dielectric constant and thus is non-frost susceptible. If the frost level reflection is very clear and the frost level is deep, this tells that the frost penetrates the subgrade without forming ice lenses which cause frost heave (see Figure 4). The uneven frost heave starts to exist when frost level come closer to the surface. The icy lenses that form in this case have a very distinct pattern in the GPR profile.

In frost surveys the best results have been achieved in Finland using a 500 MHz antenna and independently measuring dielectric constants and electrical conductivity of subgrade beside the road with a special dielectric probe (Saarenketo 1994).

In the case of road strengthening projects, or when constructing new lane(s) beside the old road, the best information about the compressibility of the subgrade soil and especially information about the changes in compressibility can be obtained indirectly with radar by surveying the existing road and then using this information when designing the new road. This technique can be applied especially when using preloading embankments over clay, silt, or peat subgrades (Saarenketo et al. 1992) and also when designing a new embankment over a lake (Saarenketo 1992b). A good example highlighting the information obtained from the old road embankment is the case in Highway 4 in Rovaniemi, Finland (see Figure 5).

Table 2. Frost Susceptibility Classification of Subgrade Soils in Finland by Dielectric Constant and Electrical Conductivity (Saarenketo 1994).

Dielectric constant	Electrical conductivity (uS/cm)	Soil type	Frost susceptibility	Compressibility and stability
< 8	< 8	dry sand and gravel	non frost susceptible	
8 - 15	< 8	dry glacial till	non frost susceptible	
15-22	<8	saturated sand and gravel	non frost susceptible	
10 - 15	8 - 15	moist silty sand or glacial till	slightly frost susceptible	
15 - 22	15 - 20	wet glacial till	extremely frost susceptible	
20 - 26	8 - 15	over saturated? glacial till	frost susceptible	stability problems
20 - 30	30 - 100	Silt	extremely frost susceptible	not compressive
30 - 50	> 100	Silty Clay, Clay	frost susceptible	compressive

Footnote: Dielectric values are given for 50 MHz central frequency measurements.

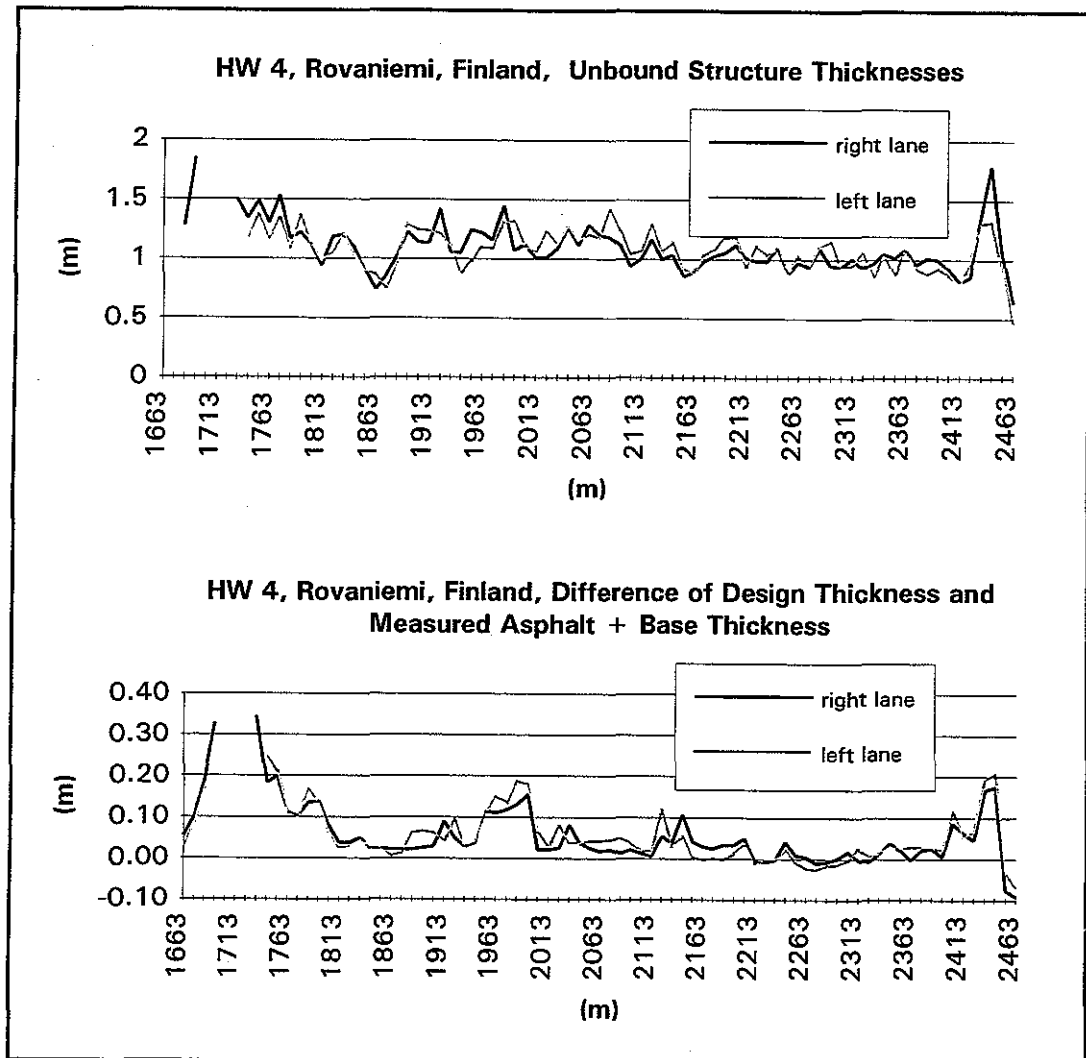


Figure 5. An Example of How GPR Can Be Used to Monitor Settlements of a Road Embankment Constructed on a Soft Soil in HW 4 Between Ounasjoki and Kulpinpuudas Bridge in Kemijoki River Valley in Rovaniemi, Finland.

Footnote: The data was collected from the old embankment and it was used to monitor the settlements when designing and constructing two extra lanes beside the old road. The upper profile which presents the thickness of unbound structural courses indicates the changes in the amount of settlements in road line when the preloading embankment was constructed. The subgrade can be divided into four sections. The first 200 m long section 1663 - 1863 indicates increasing thickness of highly compressible subgrade soil towards the bridge of Ounasjoki. The next two sections 1863 - 2163 and 2163 - 2433 indicate relatively homogenous compressibility during the construction where the first one will be settled about 0.2 m more than the last one. The last 30 m long section 2433 - 2463 indicates again highly compressible soil when coming to the Kulpinpuudas bridge. The lower profile which indicates the difference of measured asphalt and bitumen bound base and design thickness of these layers gives useful information about the areas where settlements after the construction can be expected. This data also shows four areas where more detailed site investigations and construction design were focused. Two of these were in both ends of the embankment near the bridges and there embankment piling was chosen as a strengthening method. Two other sections with anomalous settlement were selected to be under special control when the construction was done.



CHAPTER 5

GPR IN MONITORING ROAD STRUCTURES

5.1 PAVEMENT AND OTHER STRUCTURAL COURSES

As mentioned earlier, a major part of the research work in the USA has dealt with pavement thickness measurements. The radar thickness data has been collected for one of the following: a) network level surveys where thickness is required in the PMS data base (Fernando 1994), b) supplementation of Falling Weight Deflectometer data in the calculation of layer moduli (Briggs et al. 1991), or c) pavement design purposes. However, GPR can also be used for quality control purposes in asphalt paving projects (Figure 6). GPR can minimize the number of cores that need to be taken. In the future the GPR technique might be used for the real time asphalt density measurements in paving sites.

In most cases the identification of the reflection at the bottom of the base is relatively easy to locate, but the great variations in dielectric properties of base course materials sometimes cause problems in calculating actual base thicknesses. However, these changes of the dielectric constants of base course aggregates give information about the mechanical properties of that layer. In the future there is a need to develop more accurate dielectric models of different kinds of pavement materials which could be used to get more accurate thickness results. The basic research work on this problem is now being carried out at Texas A&M University with different types of Texas and Finnish aggregates.

GPR is also a very good non-destructive tool for evaluating the performance of special research highway structures; for instance, the USA has used radar by SHRP and MINNROAD, and in Finland radar has been used with experimental frost insulation structure surveys and geotextile surveys.

5.2 DAMAGE SURVEYS

In Finland the most popular application of GPR is in the investigation of various types of road damage. In these surveys, the clients are usually local road maintenance supervisors who require information on the cause of defects which have suddenly emerged and require immediate

HW21 Napapiiri-Korppikoski, Pello, Finland, Increase of Pavement Thickness in Right Wheelpath, Section 7700 - 8700 m.

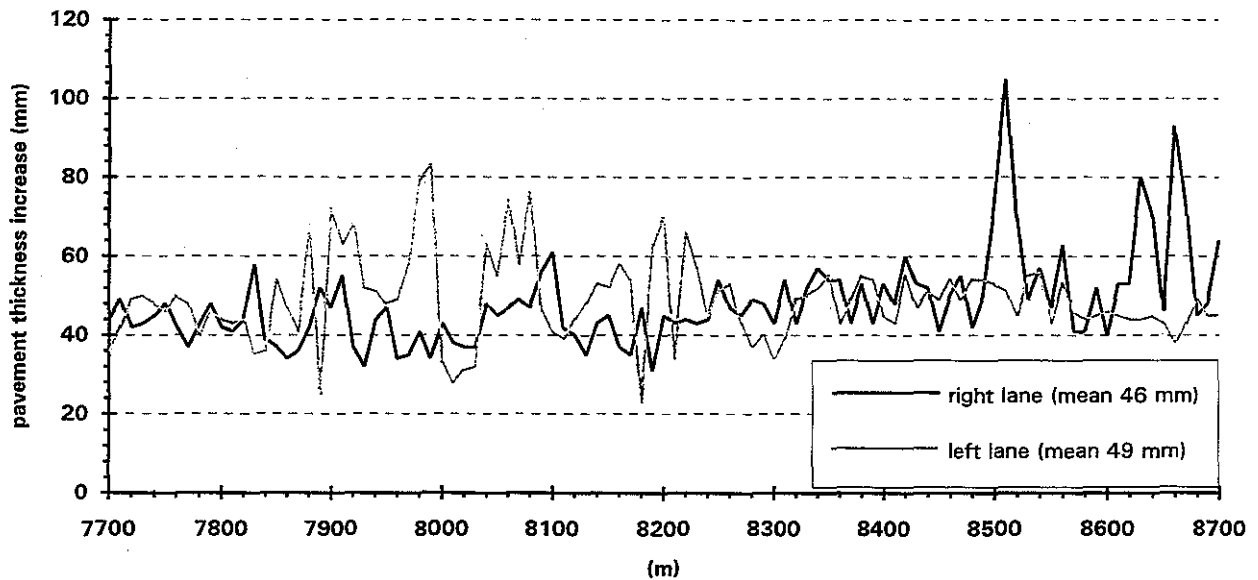


Figure 6. GPR Used to Measure Layer Thicknesses of a Heater/Planer and 40 mm (1.5 in) Asphalt Overlay Project on HW 21, Napapiiri-Korppikoski, Pello, Finland.

Footnote: The graph shows the difference in before and after thicknesses. Measurements were performed in outer wheelpaths of both lanes. The rut depths before the heater/planer and asphalt overlay were 5 - 10 mm (.2 - .4 in). The mean thickness is close to the 40 mm (1.5 in) required. The large spikes up to 0.1 m (4 in) indicate uneven locations where thick level ups were applied.

repair. In this work an ability to delimit the extent of the damage precisely can be of major economic importance. The ability to accurately identify the limits of the problem can save repair costs, and this typically covers the cost of the GPR survey.

In the USA the damage surveys have been concentrated mainly upon bridge decks, but there are many types of road damage that can be located with GPR.

A. Frost damage

In frost damage investigations the aim of the survey is to precisely locate damaged areas and to find the reason for the damage. If major frost damage has occurred the subgrade soils are always frost susceptible, but are there other contributing factors? These could include poor compaction, bad drainage, inferior materials, etc.

In Finland the most common reasons for uneven frost heave include: 1) subgrade soil and moisture transition areas, 2) presence of bedrock, and 3) boulders. However, in many cases the structural elements in the road body have also caused damages, including too steep transition wedges intended to distribute the frost heave movements over a large area and old culverts in the road structure. All these elements can be identified from GPR data, and in most cases the preliminary instructions and recommendations on the best repair methods can be given to the maintenance supervisor in the field.

B. Cracks and Crack Propagation

Locating subsurface cracks and finding reasons for their propagation is an area of growing interest particularly when performance based specifications are implemented. In these projects the contractor wants to know if the existing cracks in the pavement are only "surface cracks" or if they are caused by major structural defects, in which case these cracks will reappear on the road surface very soon after placing an overlay. In these cases, by knowing the reason for cracking it is often possible to select alternative pavement rehabilitation strategies in these areas, perhaps involving stabilizing the base or using geotextiles to prevent crack growth.

There has been considerable testing to determine if GPR methods can be used to locate cracks especially on bridges (Momayez et al. 1994), and some tests have also been reported from the highways (Maser and Scullion, 1992b). Most of the results have not been encouraging.

However, these tests have been made at highway speeds with only a few traces per meter and/or with horn antennae which monitor an area of 300 * 300 mm (12 * 12 in) with each trace. This procedure has inadequate resolution to identify vertical defects of this kind. Positive results have only been gained in cases where cracks have been large (Maser and Scullion 1991).

In Finland cracks in asphalt pavement have been detected using ground coupled 1.0 GHz antennae with very high sampling density (10-20 samples/m). In these cases it has been possible to follow the crack propagation and also to identify the cause of the cracks (see Figure 7), both of which are very useful information when predicting the performance of the pavement. This type of testing cannot be done at highway speeds and thus is only suitable for project level surveys.

Researchers have also performed some investigations to determine if GPR can give information about pavement fatigue (which is closely related to the crack propagation). The results of these tests have also been encouraging.

C. Stripping

In Texas, several old asphalt mixes constructed with river gravel have been found to be prone to stripping, and most have been buried beneath one or more asphalt overlays. Stripping is a moisture related mechanism by which the bond between the asphalt and aggregate is broken leaving an unstable low density layer in the asphalt. If possible, stripped layers should be detected and removed prior to placing a new overlay. This raises the following questions: 1) Is stripping present; 2) How deep is stripping; and 3) How widespread is the stripping? Small amounts of stripping can be removed by patching, while large amounts will require extensive milling.

The Texas Transportation Institute has conducted several surveys to identify the presence of stripping within existing pavements. If the asphalt layer is homogeneous (no stripping), then the GPR trace will resemble Figure 8 with a large reflection at the surface and another at the asphalt/base interface. If stripping is present, an additional peak will be observed between the surface and base reflections. An example of this is shown in Figure 8.

In the work conducted to date the severely stripped layer causes a large negative peak in the GPR waveform, indicating a low density layer. This work is best performed with a 1 GHz air-

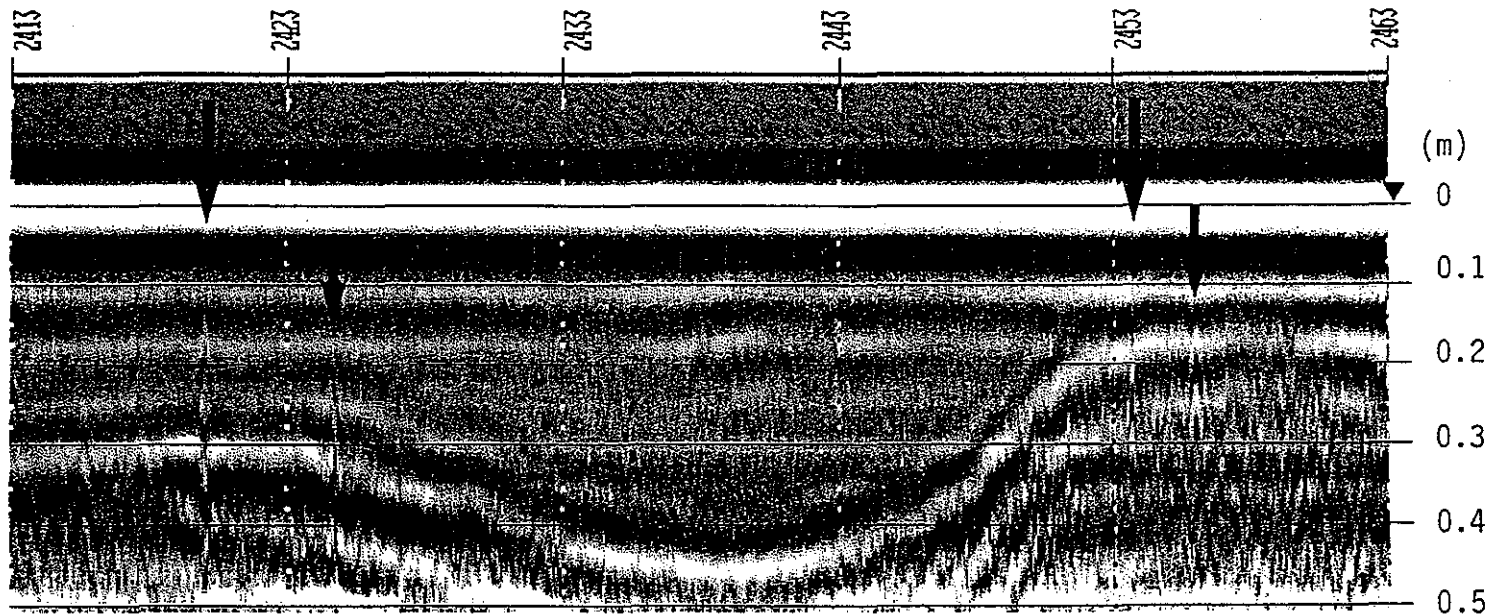
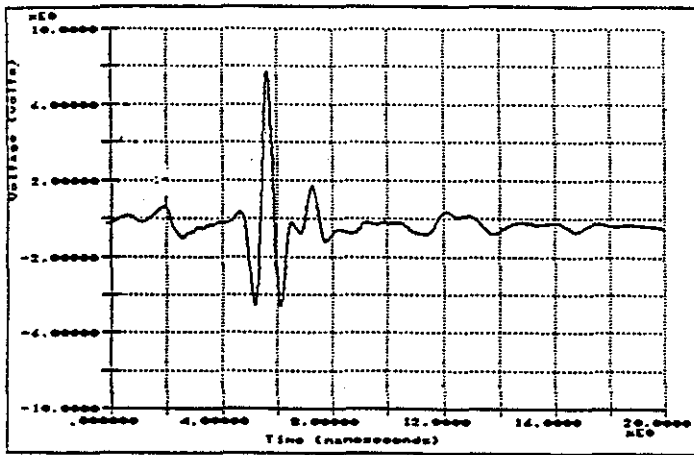


Figure 7. The Use of GPR in Locating Cracks in Asphalt Pavement, Section 2413-2463 on HW 4 Rovaniemi, Finland.

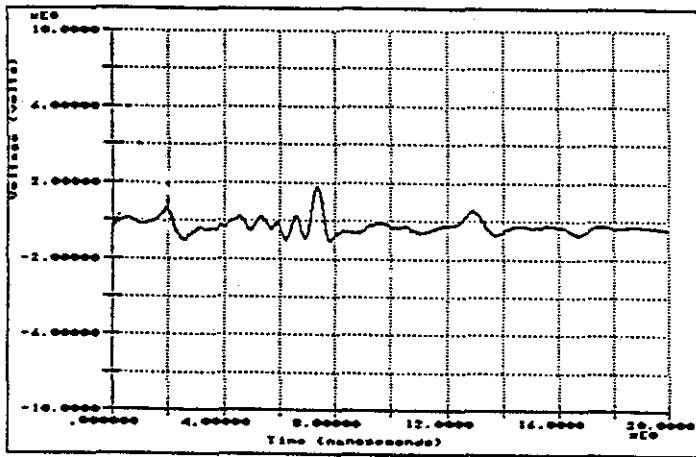
Footnote: When the survey was performed in 1992 two cracks on markers 2420.5 and 2454 had propagated to the surface, while the subsurface cracks on markers 2424.5 and 2455.5 had not reached the surface. Cracks can be identified as sharp hyperbola type reflection patterns with high frequency (1.0 GHz) ground-coupled antennae if the sampling density of 10 scans/m or more is used. There was no information about the existence of cracks in horn antenna data. The section in this figure presents a typical crack propagation in a case of post construction settlements in road structures (see also figure 5), where two cracks will form on both sides of the depression, one lies just on the depression shoulder and other the normally 1-4 m (3-12 ft) further away. If the depression is smooth the first crack to reach the surface is the one further away from shoulder, but if the pavement thickness changes substantially in a short distance, the first crack in pavement surface is located just on the depression shoulder as is the case at marker 2454.



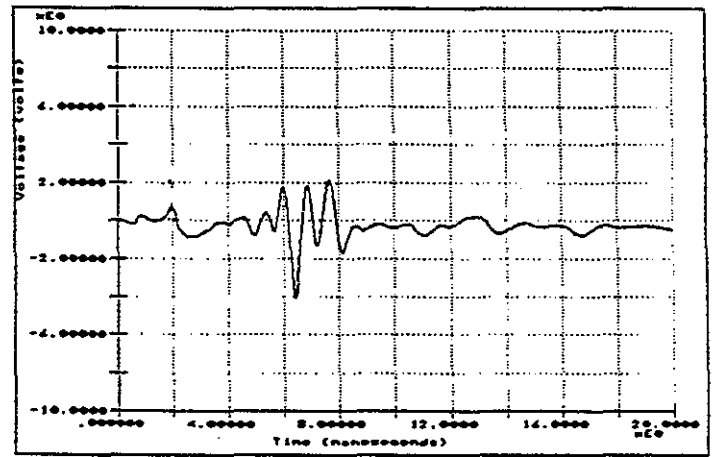
a. Original Trace (Non-stripping).



c. Original Wave Form (Stripping).



b. After Template Subtraction (Non-stripping).



d. After Template Subtraction (Stripping).

Figure 8. GPR Waveforms from Location on US 96.

Footnote: Traces a) and b) from intact asphalt, c) and d) from stripped area. The template subtraction involves removing the surface reflection from the trace. In trace d) a significant negative peak was found at 6.5 ns, this correlated to a low density stripped area approximately 80 mm (3 in) below the surface.

launched horn antennae.

Further work is needed in relating the levels of stripping deterioration to their impact on the GPR waveforms.

D. Void Detection

The formation of voids beneath concrete pavements is a serious problem. It is particularly noted on jointed concrete pavements built with stabilized bases. Over time the bases erode and the supporting material is frequently pumped out under the action of truck loads.

GPR detected the presence of moisture filled voids on US59 just north of Houston, Texas. In that case the 250 mm (10 in) thick concrete slab was resting on a cement treated subbase. If this structure were in good condition very little of the GPR energy should be reflected at the slab/CTB interface as the electrical properties of both materials are similar. However, if a moisture-filled void is present then a substantial reflection would be anticipated. In the work performed the amplitude of reflection of the slab/CTB interface was measured along the highway, and the results are shown in Figure 9. The high reflections were found by ground truth testing, to correlate with moisture-filled voids.

GPR can detect moisture filled voids beneath concrete slabs. However, work is needed to determine if GPR can:

- a. Detect the presence of air-filled voids beneath concrete slabs, and
- b. Distinguish between moisture-filled voids and saturated base layers.

At present, on typical highway slabs 250 to 350 mm (10 to 14 in) thick, it appears that GPR can only detect substantial air voids greater than 15 mm (0.6 in) in thickness. In the case of either a flexible base or a drainable base layer, GPR can detect the presence of large concentrations of water but cannot distinguish between water-filled voids and saturated layers.

E. Settlements and Landslides

In surveys attempting to determine the cause of settlements in Finland, GPR has been found especially effective in cases where there is uneven settlements in cross section profile. In this

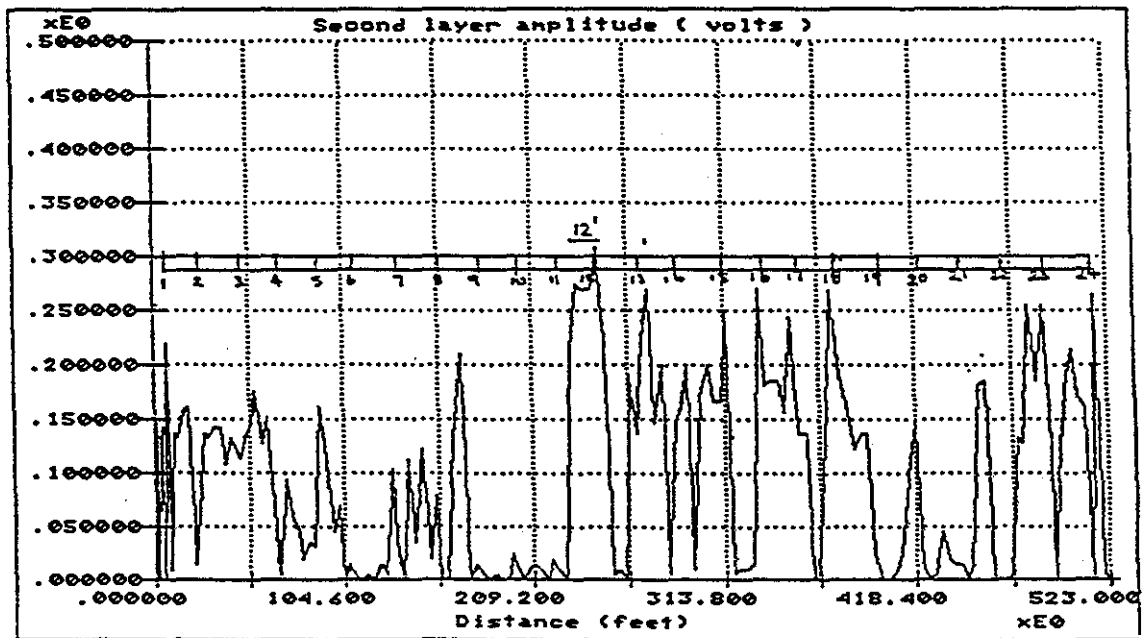


Figure 9. Variation in Amplitude from Beneath a 250 mm (10 in) Slab in Houston, Texas.

Footnote: The High Amplitudes were Correlated to the Presence of Moisture-Filled Voids Beneath the Slab.

case, in order to select the optimum repair strategy, surveyors must know the three dimensional shape of the road body and the shape of the soft soil.

GPR located the causes for slope failures that are common in mountain areas on roads built on steep slopes. In these cases the method located the areas of trapped moisture which caused these failures.

In the USA the method has great potential in surveys of damage caused by expansive clays, because these highly water absorbing soils should be readily identified with GPR.

F. Sinkholes

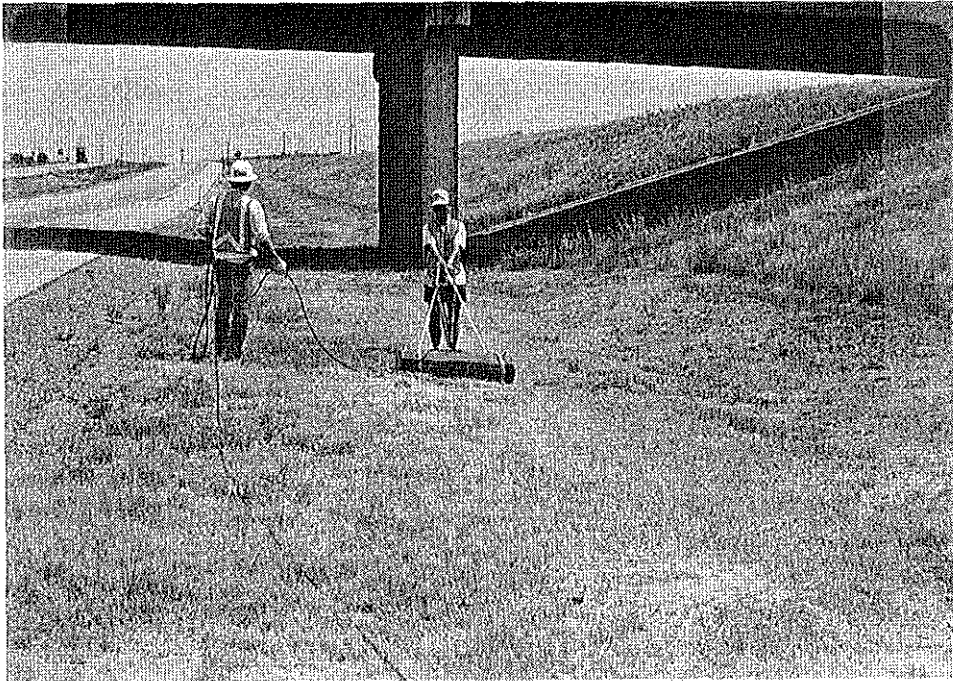
On August 30 and 31, 1994, a series of Ground Penetrating Radar runs were made on IH40 near Shamrock, Texas to determine if radar could detect sinkholes beneath the pavement. The equipment used was borrowed from Geophysical Survey Systems, Inc. of North Salem, New Hampshire. The equipment consisted of two antennae with central frequencies of 100 MHz and 300 MHz and a data logging system (SIR-10). Tests were conducted in both the east bound and west bound directions in an area where "gypsinks" were present in the Right-of-Way (ROW). GPR passes were made in the ROW (directly over existing gypsinks), in the asphalt shoulder and in the CRCP main lanes.

Figure 10 shows photographs from the site. The antenna shown is the 100 MHz ground coupled unit which can penetrate up to 4.5 m (15 ft) deep in the soils of this area. These were exploratory tests; if this equipment works, then the antennae can be mounted behind a test vehicle and data collected at up to 8 kph (5 mph).

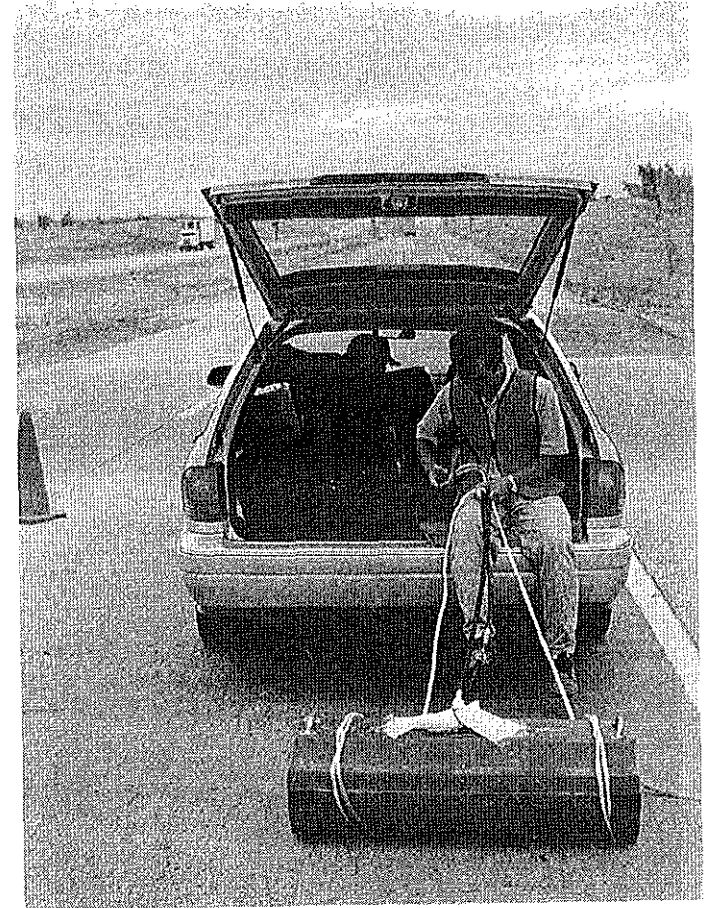
To process the return waveforms, signal processing techniques removed any unwanted noise from the GPR signals. A typical GPR color profile is shown in Figure 11, the Eastbound Right-of-Way in a path directly over the two surface sinkholes. The two surface sinkholes were at offsets of 58 and 73 m (190 and 240 ft). What is most interesting in this figure is the possible subsurface sinkhole between offset 42 and 45 m (140 and 150 ft) a depth of 2.3 to 3 m (8-10 ft). Similar subsurface patterns were found in several other places where no evidence was found on the surface; many of these seem to be narrow 0.3 to 1 m (1 to 3 ft) wide vertical channels to a depth of around 3 m (10 ft) where they connect to the existing geological structure (possibly bedrock).



a) Gypsinks in the Right-of-Way.
See Figure 3 for GPR Color Profile



b) Testing ROW with 100 MHz.



c) Testing Main Lanes.

Figure 10. Test Set-up Using GSSI 100 MHz Ground-Coupled Antenna.

SINK-HOLE DETECTION - IH 40 SHAMROCK

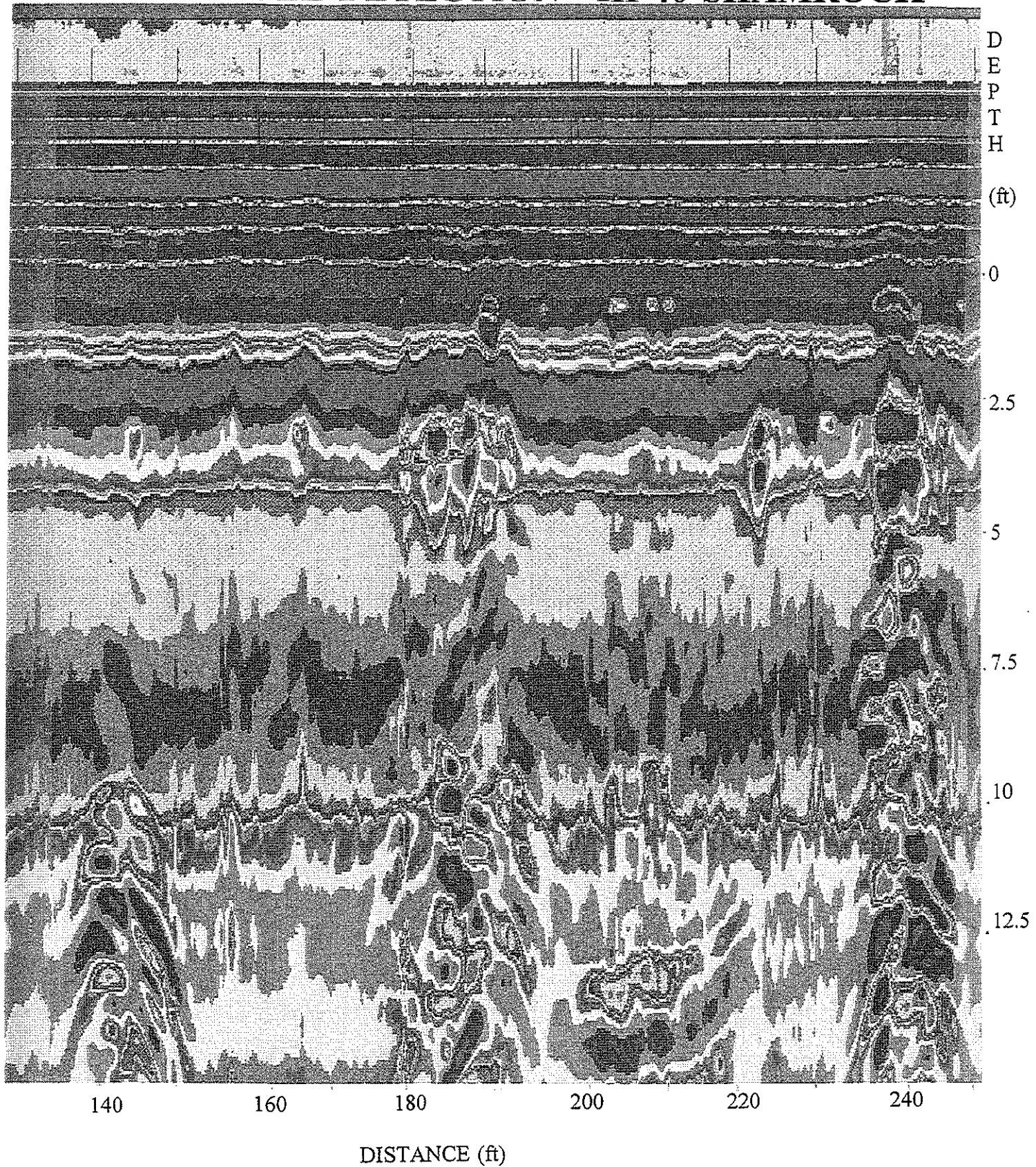


Figure 11. GPR Profile from Right-of-Way.

Figure 12 presents a summary of the subsurface formation in the ROW. The sinkholes that have reached the surface and those close to the surface are displayed.

G. Other Damage

Other types of damage detection to which GPR can be applied include pavement debonding, which has especially been a problem in bridge decks, and delamination of the concrete pavements caused by reinforcing steel corrosion (Manning and Masliwec 1990). Increased chloride content can also be seen in GPR data in the form of signal attenuation in concrete structures, prior to the observation of any surface damage (Maijala et al. 1994). Locating sinkholes beneath the highway has also been another successful application of GPR.

**Sinkholes under Eastbound Right Ditch of Interstate Highway 40,
Shamrock**

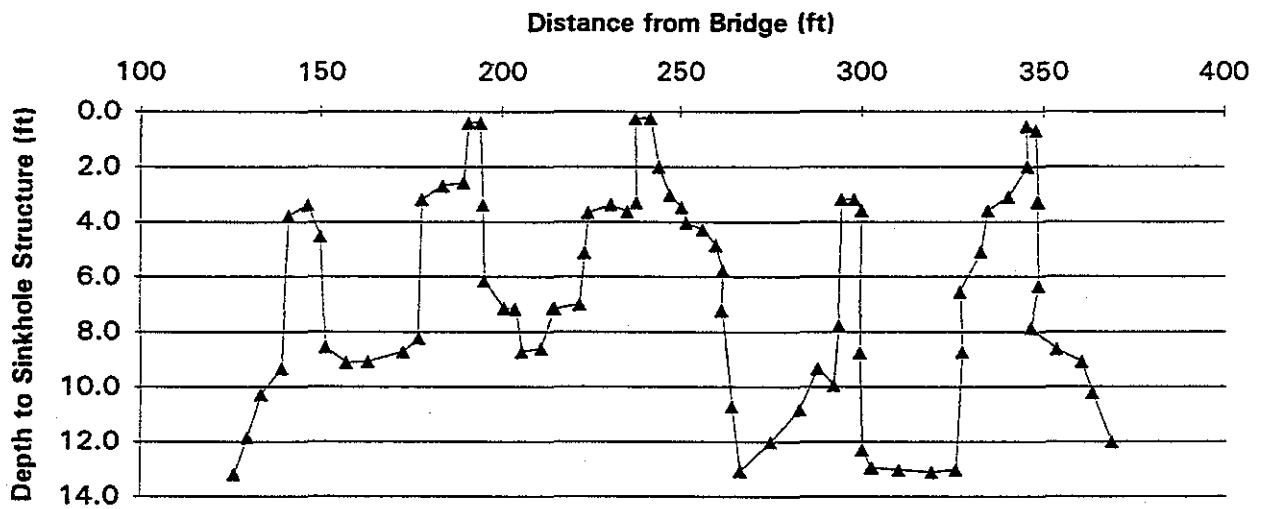
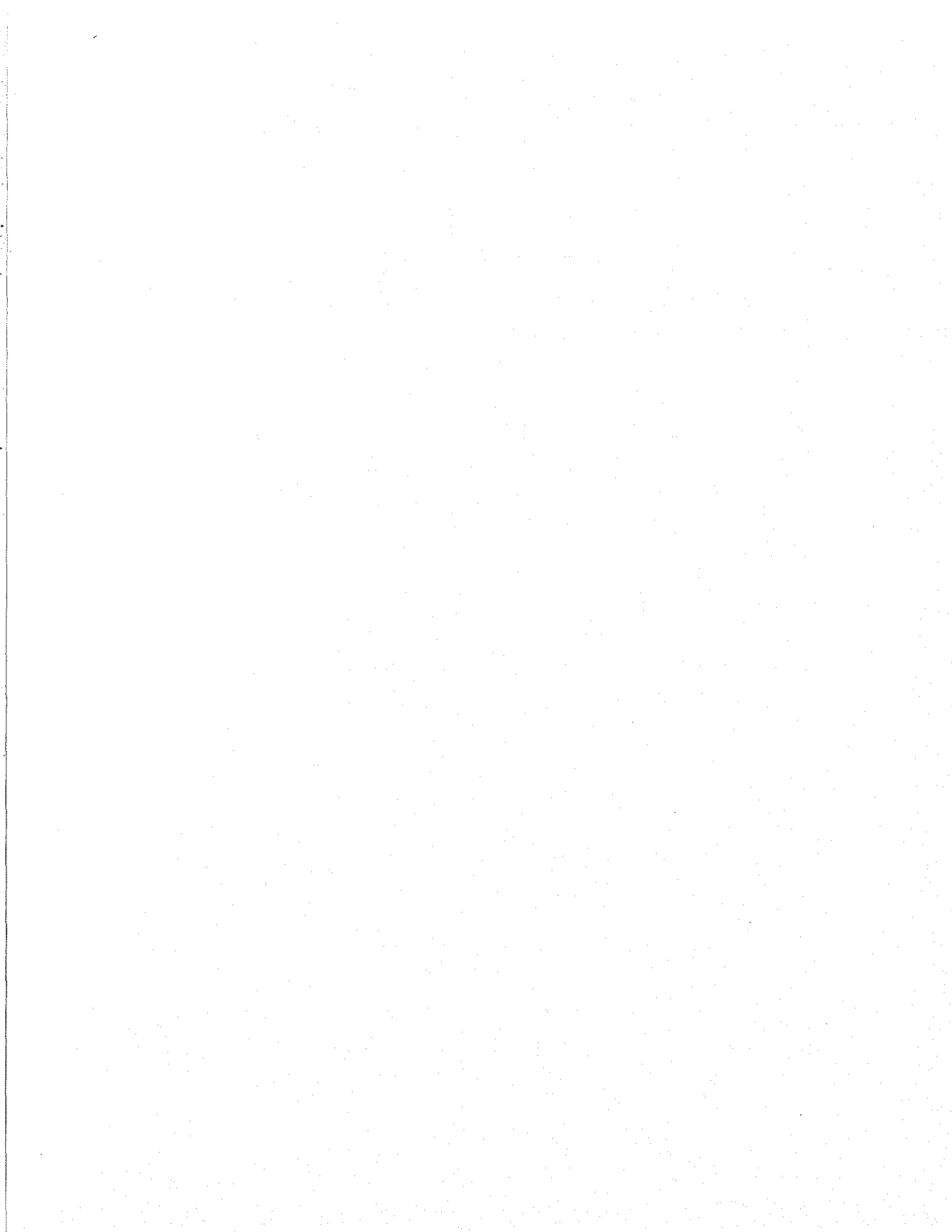


Figure 12. Sinkhole under Eastbound Ditch of IH40 near Shamrock.

Conversion: 1 ft = .3 m



CHAPTER 6

CONCLUSIONS

Even though the history of the GPR applications in roads and highways is relatively short, the method has proven a very useful tool to solve various kinds of highway engineering problems. However, there have also been many unsuccessful testing results and rash decisions made concerning the suitability of the method for certain applications. That is why the method with high frequency electromagnetic waves is not fully accepted in the engineering field. Furthermore, the performance of the GPR signal interpretation schemes is only now being adequately validated with carefully planned ground truth testing programs. In theory, GPR can be used in most road and highway structures and subgrades; however, its utility is somewhat limited in electrically conductive clays and glacial tills.

In road design projects GPR evaluates soils and base layers and probes the depth of the overburden. It gives information about the moisture content, frost susceptibility, and compressibility of soils. It can be applied to surveys of bottom topography of lakes and rivers, bridge site investigations, and surveys of erosion around bridge piers. It is also a cost effective method in aggregate prospecting.

In road construction and maintenance, the method can be applied in pavement design projects, in quality control surveys, and in locating and identifying damage in road structures.

However, GPR is not yet a common tool for non-destructive highway testing. Only part of the results can be processed automatically with limited user input, while most of the results so far have to be processed manually (which is time consuming and needs experienced staff). In many cases the things unseen in GPR data tell much more about the studied target than actual reflections. Roads and highways with a long construction history can be an extremely heterogenous research medium, and that is why other supportive research methods might be needed. The optimal use of GPR is minimizing the use of other destructive and more expensive methods and thus reducing costs without compromising the quality of the results.

REFERENCES

- Annan, A. P., J. L. Davis, and W. J. Scott, 1975. "Impulse Radar Wide Angle Reflexion and Refraction Sounding in Permafrost". Geological Survey of Canada, Paper 75-1C, p. 335-341.
- Briggs, R. C., T. Scullion, and K. R. Maser, 1991. "Asphalt Thickness Variation an Effect on Backcalculation". 2nd International Conference on Backcalculation, Nashville.
- Collins, M. E., J. A. Doolittle, and R. V. Rourke, 1989. "Mapping Depth to Bedrock on a Glaciated Landscape with Ground-Penetrating Radar." Soil Science Society of America Journal 53, p. 1806-1812.
- Doolittle, J. A. 1987. "Using Ground-Penetrating Radar to Increase the Quality and Efficiency of Soil Surveys. In Soil Survey Techniques Soil Science Society of America Special Publication 20, pp. 11-32.
- Doolittle, J. A. and R. A. Rebertus, 1988. "Ground-Penetrating Radar as Means of Quality Control for Soil Surveys." Transportation Research Record 1192.
- Fellner-Feldegg H. 1969. "The Measurement of Dielectrics in the Time Domain." The Journal of Physical Chemistry 73 (3), p. 616-623.
- Fernando, E. G., K. R. Maser, and B. Dietrich, "Implementation of Ground Penetrating Radar of Network-Level Pavement Evaluation in Florida." Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, Vol 1 of 3. p. 351-365.
- Ground Penetrating Radar, 1992. Geophysical Research Methods, The Finnish Geotechnical Society and The Finish Building Centre Ltd.
- Lau, C. L., T. Scullion, and P. Chan, 1992. "Using Ground Penetrating Radar Technology for Pavement Evaluations in Texas, USA." Geological Survey of Finland, Special Paper 16, p. 277-283.
- Majjala, P. , T. Saarenketo, and P. Valtanen, 1994. "Correlation of Some Parameters in GPR Measurement Data with Quality Properties of Pavements and Concrete Bridge Decks." Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, Vol 1 of 3. p. 393-406.
- Manning, D. G., T. Masliwec, 1990. "The Application of Radar and Thermography to Bridge Deck Condition Surveys." Ontario Ministry of Transportation, Research and Development Branch, MTO. MAT-90-11, 26 p.

Maser, K. R. 1994. "Highway Speed Radar for Pavement Thickness Evaluation." Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, Vol 1 of 3. p. 423-432.

Maser, K. R. and T. Scullion, 1991. "Automated Detection of Pavement Layer Thicknesses and Subsurface Moisture Using GPR." TRB Paper, Jan. 1991.

Maser, K. R. and T. Scullion, 1992. "Automated Pavement Subsurface Profiling Using Radar - Case Studies of Four Experimental Fields Sites." Transportation Research Record No. 1344, Transportation Research Board, Washington D.C.

Maser, K. R. and T. Scullion, 1992b. "Influence of Asphalt Layering and Surfacing Treatments on Asphalt and Base Layer Thickness Computations Using Radar." Texas Transportation Institute, Report 1923-1.

Momayez, M., A. Sadri, and F. P. Hassani, 1994. "A Comparative Study of Ground Probing Radar and Impact Echo Nondestructive Techniques for Detecting and Locating Buried Objects." Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, Vol 1 of 3. p. 433-448.

Plakk, T. 1994. "HF Permittivity Measurements by Capacitive Probe." Unpublished report, Adek Ltd. Estonia.

Pulse Radar, 1994. Personal Communications.

Saarenketo, T., 1992a. "Ground-Penetrating Radar Applications in Road Design and Construction in Finnish Lapland." Geological Survey of Finland, Special paper 15, p. 161-167.

Saarenketo, T., 1992b. "Use of GPR in Causeway Surveys, Reinikansalmi." Fourth International Conference on Ground Penetrating Radar. Excursion Guide, June 10. p. 40-41.

Saarenketo, T. 1994. "Dielectrisyys- ja sähkönjohtokykykymittausten käyttö pohjamaan routivuuden luokitteluun." Aloite 12.4.1994. FinnRA Road District of Lapland, 26 p. (In Finnish)

Saarenketo, T., K. Hietala, and T. Salmi, 1992. "GPR Applications in Geotechnical Investigations of Peat for Road Survey Purposes." Geological Survey of Finland, Special paper 16, p. 293-305.

Saarenketo, T. and M. -K. Söderqvist, 1993. "GPR Applications for Bridge Deck Evaluations in Finland." Conference Proceedings of The Non-Destructive Testing in Civil Engineering, 14-16 April 1993. The University of Liverpool.

Saarenketo, T., T. Nikkinen, and S. Lotvonen, 1994. "The Use of Ground Penetrating Radar for Monitoring Water Movement in Road Structures." In Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, vol 3 of 3. p. 1181-1192.

Scullion, T., C. L. Lau, and Y. Chen, 1994. "Pavement Evaluations Using Ground Penetrating Radar in Texas." Proceedings of the Fifth International Conference on Ground Penetrating Radar, June 12-16, Kitchener, Ontario, Canada, Vol 1 of 3. p. 449-463.

Scullion, T., C. L. Lau and Y. Chen 1992. "Implementation of the Texas Ground Penetrating Radar System". Texas Transportation Institute, Report 1233-1, Nov. 1992.

Smith, S. S. and T. Scullion, 1993. "Development of Ground-Penetrating Radar Equipment for Detecting Pavement Condition for Preventive Maintenance." Strategic Highway Research Program, SHRP-H-672.

Sutinen, R. and P. Hänninen, 1990. "Radar Profiling and Dielectrical Properties of Glacial Deposits in North Finland." Proceedings 6th International IAEG Congress, Amsterdam, 2, 1045-1051.

Topp, G. C., J. L. Davis, and A. P. Annan, 1980. "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines." Water Resources Research 16 (3), p. 574-582.

Ulriksen, C. P. F. 1992. Application of Impulse Radar to Civil Engineering. Doctoral thesis. Lund University of Technology. Department of Engineering Geology, p. 179.

Westerdahl, H., R. Austvik, and F-N Kong, 1992. "Geo-Radar in Tunneling - The Tunnel Radar." Geological Survey of Finland, Special Paper 16, p. 41-45.

