GROUND PENETRATING RADAR FOR PAVEMENT INVESTIGATION

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AN IMPORTANT NOTE FOR THE READER

The research detailed in this report was commissioned by Transit New Zealand when it had responsibility for funding roading in New Zealand. This funding is now the responsibility of Transfund New Zealand.

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EXECUTIVE SUMMARY

Evaluation of ground penetrating radar (GPR) as a non-destructive pavement investigation tool, and its application to uses in New Zealand, has been investigated. The study was undertaken in two stages between 1992 and 1995, during which time no major advances in the technology have been made.

1. Stage 1

The first stage of this study was to review international literature about GPR equipment that is used for the non-destructive evaluation of pavement structures; to assess and select the most suitable GPR equipment; and to select a company capable of carrying out non-destructive pavement evaluations in New Zealand with the selected GPR equipment.

The investigations undertaken in Stage 1 resulted in the selection of the GSSI SIR System-8 GPR equipment, and specialist GPR operator GB Geotechnics Ltd. The software used by GB Geotechnics Ltd included their own packages, RADCAD (to convert graphic records into digital format) and CRUNCHER (to process the raw digitised data), and the commercially available package GRAPHER (for standard graphing presentation).

2. Stage 2

The second stage involved field trials in New Zealand with the selected GPR equipment and software, and a specialist GPR operator (GB Geotechnics Ltd). The purpose of the trials was to assess the applicability of GPR equipment and software in the New Zealand pavement environment, specifically to determine:

- structural layers in pavements,
- layer thicknesses,
- moisture changes beneath pavements, and
- location of underground services (water, gas, electricity, sewers, etc.),

within the pavement. The trials were undertaken on sections of typical urban pavements (in Wellington City) and three sections of state highway (SH2 Western Hutt Road, SH56 Himatangi, SH3 New Plymouth).

In association with the GPR survey, vertical cores were taken from sites (22) within the sections of pavement surveyed. From these cores the structural layers of the pavement, the layer thicknesses, and the water contents of the layers were determined. Using plans of underground services (obtained from different service authorities), the most likely locations of these services along the trial sites were determined.

The core data and plans of underground services were correlated with the data obtained by GPR to evaluate the applicability of GPR as a tool to investigate New Zealand pavements. The report presented by GB Geotechnics is appended to the report.

3. Conclusions

The study showed that the GSSI SIR System-8 GPR equipment was able to identify structural layers in pavements where the dielectric properties of adjacent materials have significant contrast. Consequently the equipment was able to identify and determine thicknesses of the seal and basecourse layers. The measurement of concrete and subgrade thicknesses was less reliable because of either a greater attenuation of the electromagnetic wave and/or insignificant contrast between dielectric properties.

The success of GPR to identify underground services depends on the relative dielectric properties and the degree of contrast between the surrounding geological materials and the materials from which the services are constructed. GPR did not successfully determine moisture changes in pavement layers, but did identify the presence of most underground services.

Obtaining a knowledge and understanding of the limitations of GPR is a necessary pre-requisite for carrying out a GPR survey.

ABSTRACT

Ground penetrating radar (GPR) as a non-destructive pavement investigation tool, and its application for use in New Zealand, have both been evaluated. The study was undertaken in two stages between 1992 and 1995.

Stage 1 is a literature review and assessment of commercially available GPR equipment, as well as the selection of a system and system operator, to evaluate its use in New Zealand road pavements.

Stage 2 records the results of field trials of the selected GPR equipment (and operator) on selected sections of urban and state highway pavements.

Specific objectives of the trial were to determine:

- structural layers,
- layer thicknesses,
- moisture changes beneath pavements, and
- location of underground services.

GSSI SIR System-8 GPR equipment, operated by GB Geotechnics, was trialled. This equipment was able to identify structural layers in pavement materials that show significant contrast in relative dielectric properties. GPR was not successful in determining moisture changes in pavement layers but it did identify the presence of most underground services.

INTRODUCTION

Ground penetrating radar (GPR) was originally developed by the military to detect sub-surface non-metallic mines, but this technology is now available for looking beneath road pavement surfaces. Its application to this use in New Zealand was an objective of the research project reported here.

Other objectives of the project were to review the international literature for the application of GPR to the non-destructive evaluation of pavement structures in New Zealand; to determine the most suitable GPR system that was available in 1992 for use on New Zealand roads; and to select the appropriate company to operate the selected GPR equipment for field trials in New Zealand.

Internationally GPR has long been used on roads and bridges but since 1987 its use has increased markedly. GPR evaluates pavements to provide continuous profiles of specific information on structural layers and material properties. As roads have relatively simple geometry and are usually composed of homogeneous engineered materials, GPR is ideal for determining pavement profiles.

Methods other than GPR used for assessing deterioration in pavements are generally labour intensive, inconvenient and often unreliable but using GPR makes possible the detailed surveying of tens of kilometres of pavement in one day. High speed data collection rates, rapid logging and data storage rates are needed however and are being developed for GPR systems.

In 1992 when the study began, a range (albeit small) of GPR equipment, specifically designed for the non-destructive evaluation of pavement structures, was available on the market. The typical application of this equipment to pavements has been to measure layer thickness, identify thin or weakened areas, locate voids within the pavement, locate stripping in asphalt layers, and find areas of excess moisture. The data collected are combined with other measures of pavement condition to provide information for planning pavement evaluation and rehabilitation programmes. Equipment systems for data acquisition and data interpretation supplied as part of GPR are designed to be user friendly, with various options available for data evaluation and manipulation.

Development of GPR technology is continuing, and the technology has developed to such a state that its practical application is feasible although no major advances have been made from the time the study began until 1996. International literature indicates that substantial benefits in the evaluation of pavement structures can be derived from this non-destructive tool.

The present study of GPR systems was undertaken in two stages, and the report is structured in two corresponding parts, Parts 1 and 2.

Stage 1, described in Part 1 of this report, included a review of the international literature on GPR techniques for the non-destructive evaluation of pavement structures; a summary of the responses to a survey by questionnaire of the GPR equipment that was available in 1992; and a selection of the most suitable GPR equipment and operator for undertaking appropriate field trials using GPR on New Zealand pavements. Appendixes supply details about presentation of GPR data (Appendix 1), about the responses to the survey (Appendix 2), components of the GPR systems (Appendix 3), and of 1992 prices of GPR equipment (Appendix 4).

Stage 2, described in Part 2 of this report, was an evaluation of a field trial carried out on New Zealand pavements using the selected GPR equipment by the specialist operator. The applicability of GPR to evaluate the structure of New Zealand pavements was summarised. Appendixes for Part 2 include the report (Appendix 5) prepared by GB Geotechnics Ltd (also called GB Geotechnics) of the survey of pavements that they carried out in May 1993. Other data gathered during the survey are appended and include core logs and water contents of core-log samples (Appendix 6), layers identified by GPR (Appendix 7), the terminology used by Works Consultancy Services, Central Laboratories (WCL) and by GB Geotechnics (Appendix 8), locations of underground services along the survey lines (Appendix 9), and an evaluation of the success of GPR to identify structural layers and boundaries (Appendix 10).

PART 1: REVIEW AND ASSESSMENT OF GROUND PENETRATING RADAR SYSTEMS

(AVAILABLE IN 1992)

1. INTRODUCTION
2. APPLICATIONS FOR GPR
3. LITERATURE REVIEW
4. EXPERIENCE OF OPERATORS WITH GPR EQUIPMENT
5. SURVEY OF COMMERCIALLY AVAILABLE GPR EQUIPMENT
6. CONCLUSIONS

1. INTRODUCTION

Part 1 of this report includes an overview of the general theory and technology of short pulse radar which is now used, among other uses, for the non-destructive evaluation of pavement structures. Applications of GPR to obtain information about pavements, its outputs and the costs of using GPR surveys are described. A review of international literature on GPR techniques is made, and experiences from different operators are quoted. A survey by questionnaire of operators and suppliers of the GPR equipment that was available in 1992 is summarised and, based on the responses (given in detail in Appendix 2 to this report), the most suitable GPR equipment and its operator were selected to undertake field trials using GPR on New Zealand pavements.

1.1 Conventional Radar

RADAR, or RAdio Detection And Ranging, is a technique using reflected radio waves to locate distant objects, such as storms, aircraft and ships, that was developed during World War II. A pulse of electromagnetic energy is transmitted, and the time taken to receive its reflection from an object is used to calculate the distance to that object.

1.2 Short Pulse Radar

Short pulse radar is used in GPR and works on the same principle as conventional radar except that the distance to the reflecting object (e.g. pavement interface) from the transmitter-receiver is very short (Figure 1.1). To measure the correspondingly short travel time requires an entirely different design for the electronics used in both the transmitter and receiver.

Figure 1.1 Pavement interface reflections in a multi-layered road.

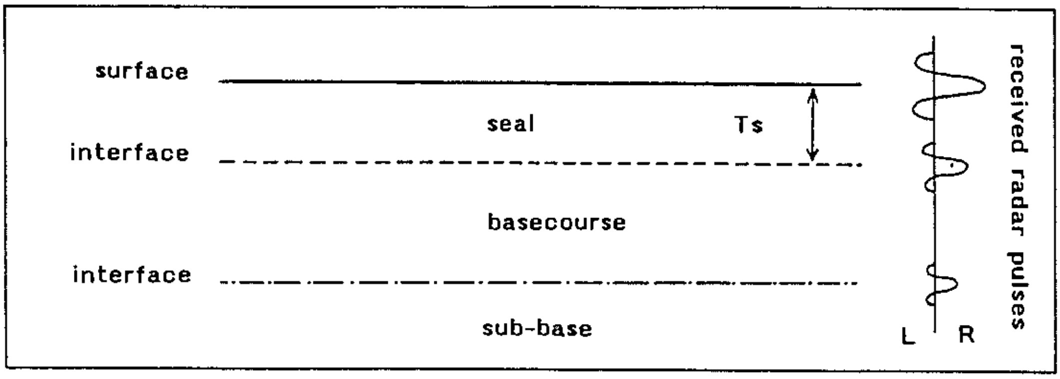

Figure 1.1 is of a multi-layered road and a representation of the received radar pulses (resulting from a single transmitted pulse) is shown along the right side. The first and largest pulse received is from the surface, i.e. the interface between air and seal; pulses are received from each distinct interface including the surface. The difference in travel time between the pulses reflected at the air/seal and the seal/basecourse interfaces is called Ts. It is a two-way travel time through the seal. The time the wave takes to travel once through the seal layer is therefore Ts/2. The seal thickness, THs, is given by:

$$THs = Vs \cdot Ts/2$$

where Vs is the velocity of the wave through the surface seal layer.

So, once the travel time (T) through a layer has been measured by the GPR, its thickness (TH) can be determined if the wave velocity (V) is known. The wave velocity in air is practically identical to the velocity of light in a vacuum, usually denoted *c*, and is very close to the value of 0.3 metres per nanosecond (ns). Wave velocity (V) in more dense materials is lower than *c*, namely:

$$V = c/\sqrt{E}$$

where E is the relative dielectric constant of the material.

For example, a typical E for asphalt is 9 and thus the layer velocity in an asphalt would be c/3.

Reflections from sub-surface layers are caused by contrasts in dielectric properties of different materials. Strength of the reflected signal is approximately proportional to the difference in dielectric constants at the material interface (Davis and Annan 1989). Thus E is required in order to determine the reflection coefficient, R, at an interface.

The reflection coefficient or R, which relates to the amplitude of the reflected pulse at each interface, is given by:

$$R = \frac{\sqrt{E1} - \sqrt{E2}}{\sqrt{E1} + \sqrt{E2}}$$

When E1 = E2, i.e. dielectric constants of the two materials are similar, R = 0 so that all the electromagnetic energy is transmitted through the interface, and no energy is reflected.

When E1 is not similar to E2, e.g. when a wave in air (E1 = 1) strikes a concrete surface (E2 = 7), the above formula gives R = – 0.45. The minus sign means that the reflected pulse is inverted or has changed polarity with respect to the incident pulse, i.e. the reflected pulse is the mirror image of the incident pulse.

In the opposite case when the reflected wave travels back through concrete (E1 = 7), into air (E2 = 1), and R = + 0.45, the reflected pulse is not inverted. Pulse inversion or polarity change is important for interpreting the return travel of a pulse reflected from a void beneath a pavement layer. Although thin voids require more detailed analysis, this simple inversion phenomenon is the basis of any analysis. Note in Figure 1.1 that all the pulses have the same polarity (i.e. they peak to the right). This means that the E values increase with depth. This increase is typical in pavements as deeper layers commonly contain more water which has a higher dielectric constant, i.e. E = 81 for pure water.

Not all the electromagnetic energy is reflected from the pavement layers. Attenuation of the energy occurs because these layers are conductive to some extent due to moisture and soluble salts within the pavement structure. Material conductivity and attenuation characteristics enable the sub-surface stratigraphy to be inferred from the character of the GPR return signal.

2. APPLICATIONS FOR GROUND PENETRATING RADAR

2.1 General Applications

A GPR system can provide pavement engineers with sub-surface information for planning at road network level, such as reconstruction of a section of state highway, or detailed rehabilitation design at project level such as determining the appropriate remedial measures required for rehabilitating a pavement. Both the degree of detail and frequency of measurement depend upon the particular requirement of the project being carried out.

GPR systems are also designed for more general applications and may be used to examine the infrastructure of roads, bridges and buildings; and to locate bedrock, pipes, tanks, sink holes and other underground obstructions. Further applications include mapping of ground water, analysing soil stratigraphy, profiling lake and river bottoms, and studying rock formations. In the environmental field GPR is used to locate underground storage tanks and buried drums; delineate landfill boundaries and burial trenches; and to identify hydrocarbon plumes that are leaching into neighbouring soil and water supplies.

2.2 Application for Network Pavement Evaluation

At the network level, i.e. national highway system, evaluation extending over kilometres of state highway involves a reconnaissance survey for which very large quantities of data are collected. The objective of pavement evaluation is to check whether the intended function and expected performance of the pavement is being achieved, and to obtain sufficient information on which to base current and future budget estimates.

For a network evaluation, GPR can be used in conjunction with other methods of non-destructive evaluation of a pavement structure (road roughness, Benkelman Beam, skid resistance, etc.) by measuring thickness of the layers at the point of testing, and providing an overall thickness profile of the test section. For these other methods, data are generally collected every 0.15 km.

Additionally, GPR may be used in a reconnaissance to evaluate the sub-surface extent and severity of physical deterioration that has manifested itself as a small area of surface distress. Analysis of the data leads to a general plan for rehabilitating the system, such as selecting candidate projects and identifying a target rehabilitation category (e.g. seal coats, overlays, reconstructions).

2.3 Application for Project Pavement Evaluation

At the project level, the objective of pavement evaluation is to collect detailed information about a pavement with a problem. This enables the decision maker to identify the problem, and the extent of rehabilitation needed.

Traditionally this information has involved a review of structural and surface conditions to determine the structural improvement that is required. For example, if the pavement has failed, then reconstruct; if some pavement life remains, then overlay. Additional patch and repair requirements can be determined by the surface manifestations of distress. For example, where heavy cracks show, then excavation may be required; where spalled joints occur, then shallow patching may be required.

2.4 Application for Rehabilitation Design

With the advent of more sophisticated techniques of rehabilitation (e.g. milling, cold planing, multiple recycle techniques, etc.) more information is required to determine the most appropriate technique. This determination requires a knowledge of the sub-surface profile and has traditionally been obtained by coring, and extrapolating between cores. Extrapolation has been shown in many cases to be inadequate. GPR can provide a continuous profile of thickness of layers for use in rehabilitation operations. It can also be used for detection and definition of voids. Detecting voids assists in the decision of appropriate sub-surface restoration techniques. Additionally, GPR can be used to identify weakened or stripped areas, and to assign appropriate properties in overlay thickness calculations.

GPR provides a new information source to accomplish cost-effective rehabilitation design for the pavement industry. The pavement engineer now uses surface condition studies (e.g. RAMM condition rating, etc.), structural evaluation (e.g. deflection testing, laboratory testing), and pavement section analyses to determine the structural section and the sub-surface condition of the pavement. These conditions include sub-base problems, voids, debonding, improper drainage, etc. All these information sources are then used as criteria for deciding a rehabilitation design.

2.5 GPR Outputs

GPR systems can use colour screen display or a colour printout to display the raw GPR data. The amplitude of the reflected signal is broken into a number of colours (usually 16) and displayed on a computer screen.

Layers, each reflecting a pulse, appear as lines on the screen. The distance between the lines is directly related to the layer thickness. The colour is particularly useful in showing up anomalies such as voids where subtle amplitude changes can be important.

At the completion of a GPR survey a report is prepared from the interpreted data. A variety of formats - from raw data as collected in the field through to comprehensive CAD (Computer Aided Draughting) profiles of sub-surface conditions - are possible. Examples of GPR data presentation are in Appendix 1 to this report.

2.6 Road Survey Costs at 1992

Based on a report by Ferne (1989), a comparison was made for this report of typical costs of a range of systems including GPR. Table 2.1 has been reproduced from Ferne's report, but not all of these systems have been used in New Zealand. However some typical costs (in 1992 NZ$) of surveys carried out in New Zealand have been estimated (J.Patrick pers.comm. 1992) and are appended as footnotes to the table.

Table 2.1 Costs of GPR and other road survey systems (from Ferne 1989).

Type of survey system	Equipment cost (£UK)	Typical daily output (km)	Typical survey cost per km (£UK/km)
Visual condition survey	–	–	150[4]
Bump integrator[1]	25,000	120	12.50[5]
High speed road monitor	250,000	150	25[6]
Deflectograph[2]	150,000	12	150
Falling weight deflectometer	100,000	200 points (over 1 km)	2000
Ground radar[3]	<100,000	15	100[7]
Detailed structural investigation	–	–	1500+

Notes:

(1) In New Zealand the bump integrator is called a roughometer.
(2) The deflectograph is a form of truck-mounted automated Benkelman Beam.
(3) Ground radar is a short expression for GPR.

Typical costs (1992 NZ$) of surveys carried out in New Zealand:
(4) $90 to $100 per km.
(5) $6 per km.
(6) $50 to $100 per km depending on parameters monitored.
(7) $350 per km (expected cost).

3. LITERATURE REVIEW

3.1 International Literature

An international literature review was carried out using the following key words:

- pulse radar
- ground probing radar
- ground penetrating radar
- non-destructive testing
- pavement investigations
- roading investigations
- cavity
- void

Most of the references obtained were published before 1990 and generally considered unsuitable for reviewing GPR technology which was developing at a rapid rate. Only nine relevant publications were located and they are summarised in Section 3.2 of this report. The *Proceedings of the Fourth International Conference on Ground Penetrating Radar*, held in Finland from 8-13 June 1992, contains some of the latest developments in GPR technology.

3.2 Reviewed Papers

3.2.1 ASTM (1987)

ASTM D4748-87, the standard published by the American Society for Testing and Materials (ASTM 1987), describes the operating principles for GPR, its different uses, interference sources such as other electromagnetic sources, the apparatus, the hazards of a GPR survey, calculations and standardisation to establish relative dielectric constants, additional calculations and the precision of data. The ASTM standard gives background information for the GPR operator in planning and carrying out a pavement evaluation survey.

A short section of the ASTM standard is allocated to the procedure or field technique for carrying out a GPR survey. The brevity of the procedure section indicates the difficulty in defining the procedure for a GPR survey in which the field techniques are dependent on the client's requirements, on GPR equipment used, the local pavement conditions, the traffic conditions, etc. A standard field technique to cover all these possibilities is unrealistic to devise. Instead consideration and evaluation of those factors that influence the accuracy, resolution and repeatability of the data are included.

3.2.2 Ballard and Baston-Pitt (1991)

Ballard and Baston-Pitt of GB Geotechnics discussed the use of GPR to measure the thickness of the bound pavement layers in their report prepared for the UK Department of the Environment Transport and Road Research Laboratory (TRRL). Also detailed and discussed were comparisons between bound layer thickness determined by coring and by GPR techniques. The field techniques used were both rapid and highly flexible, and provided an accuracy of 8% to 4% in thickness assessment. They demonstrated that the system was repeatable across different instruments, analysis methods and construction materials. A change in sub-base moisture content was identified as the cause for a measurable variation in travel time of the radar signal to identical construction boundaries over a four month period.

3.2.3 Chung and Carter (1991)

Chung and Carter's publication for the Research and Development Branch, Ontario Ministry of Transport, Canada, described a search for an improved method to conduct pavement condition surveys. Using a radar-based Deck Assessment by Radar and Thermography (DART) system, test sites were selected to study the performance of GPR on pavements. The results showed that GPR can provide both a non-destructive measurement of the pavement thickness and a remote sensing assessment of the pavement cavities caused by transverse cracking. Results indicated that, for waveforms to be sampled at every 10 cm with the Penetradar Corporation GPR equipment, the antenna must travel at less than 10 km/h. At faster speeds, the result is reduced resolution of data.

3.2.4 Clemena, Spinkel and Long (1985)

This paper discussed the suitability of GPR for assessing concrete pavements. The authors stated that a minimum of five lane miles (or eight lane kilometres) of pavement per hour with minimal traffic interruption can be achieved with a GPR survey. The location reference unit (distance measuring device) used was considered insufficiently accurate, and Clemena et al. suggested that an accuracy of ± one foot (0.305 meter) needs to be achieved. At the time of this New Zealand study (1992), some seven years later, accurate distance measuring and relocation of specific markers is a problem still to be resolved.

3.2.5 Weil (1992)

This paper addressed the non-destructive testing of concrete pavements. Infrared thermography was discussed along with GPR as a separate or combined means of quickly, efficiently and economically evaluating large concrete pavement areas and structures. The application of these techniques was demonstrated with case histories which involved the location of voids, delaminations in concrete structures, deterioration of bridge decks, highways and airport pavements.

3.2.6 Fenner (1992)

Fenner considered advances in radar technology. He discussed the concept of varying the centre frequency of a broad band width antenna. Field measurements and results were presented to illustrate the advantages, e.g. at 900 MHz the variable frequency antenna had twenty five times more radiated power than the standard GSSI 900 MHz antenna. A new high speed multiple channel radar system, which takes advantage of the broad radiation patterns of GPR antennae to perform beam steering and focusing functions, was also examined.

3.2.7 Parry and Davis (1992)

Parry and Davis considered that GPR has several pitfalls generated by equipment limitations when it is applied to road and bridge evaluations. In their paper, limitations such as pulse length, sampling rates and jitter were examined, and they suggested other limitations are introduced when standard assumptions are used. They reported that radar development programs were underway to provide improvements in GPR equipment which include:

- multi-channel data to capture a wider range of information simultaneously during profiling;
- semi-automated interpretation to process very large files and integrate GPR data with chainage (called "meterage" in New Zealand) and other information;
- effective self-calibration capability to provide accurate layer thickness estimates;
- sufficient band width to resolve 50 mm-thick layers;
- better amplitude fidelity to detect deterioration parameters reliably.

The particular needs of the end client were cited as one of the pitfalls associated with the application of GPR to pavement evaluation.

They considered that it is extremely important to be able to tie the GPR data into known reference points while collecting data. One possibility they suggest is to use GPS (Global Positioning System). Nevertheless, the software must be capable of handling extremely large files and be able to locate and go to specific chainage (meterage) locations within a file.

3.2.8 Maser (1992)

Maser examined technology which had been developed as an economical means for evaluating pavement layer properties and estimating quantities of deterioration in bridge decks. Examples of this technology included air-coupled horn antennae, PC-based digital data acquisition and software for computing pavement properties from raw waveforms. Two integrated hardware/software systems, PAVELAYER for pavements and DECAR for bridge decks, were also described.

3.2.9 Lau, Scullion and Chan (1992)

These authors at the Texas Transportation Institute have been evaluating GPR for highway applications. Their approach involved modelling wave propagation in pavement structures, measurements of the dielectric properties of highway materials (hot mix, asphalt, portland cement, concrete and granular base materials), and evaluating the use of a 1 GHz antenna in several field studies aimed at layer thickness measurements and void detection. Their paper concluded that GPR appears to be an exciting new technology which can substantially assist engineers in pavement evaluations. They believed future work needs to be focused on developing better signal processing techniques.

3.3 Summary

The literature review shows that GPR systems provide an efficient and economic means of evaluating pavements and bridge decks. Developments in hardware and software technology for GPR systems are still being undertaken to ensure they better suit the needs of pavement engineers.

4. EXPERIENCE OF OPERATORS WITH GROUND PENETRATING RADAR EQUIPMENT

To obtain quality data efficiently from a GPR survey, the experience of the operator and interpreter are of prime importance.

4.1 Works Central Laboratories' Experience

Since 1986 WCL has operated GPR equipment in New Zealand, to detect service cables and pipes, tunnel voids, underground cavities, buried objects, for stopbank investigations and pavement investigations.

However, the OYO YL-R2 GPR system, which is the system that WCL operates, is not well suited for roading applications as it is designed for penetrations of 1 to 10 m thickness, and is not convenient to use as a road profiling tool. Data collected are not digital, and hence filtering and data manipulation are not possible once the signal has been recorded.

4.2 Selected Operators' Experience

Information on a range of GPR equipment used in pavement evaluation, and records of successful work carried out by experienced operators, are presented in this Section 4.2. The information (in italic type) is extracted verbatim from written communications between the researcher (WCL) and selected companies (Penetradar Corporation, GSSI, Pulse Radar Inc., and GB Geotechnics Ltd).

4.2.1 Penetradar Corporation (USA)

Penetradar Corporation made the following comments on their system:

"The Penetradar radar is currently being used by several organisations for similar pavement related applications" (i.e. similar to Transit New Zealand's requirements). *"These applications include the absolute measurement of multi-layer asphalt and concrete pavement thickness* (the Penetradar Corporation radar claims a first layer thickness measurement accuracy of approximately ±5%). *Air- and water-filled voids can be detected between pavement layers (debonding) and beneath both rigid and flexible pavements. The Penetradar system is also being used for detection of moisture accumulation within and beneath pavement layers deterioration of concrete and asphalt pavements as well as other pavement and bridge deck related applications.*

"Our Penetradar radar systems have been evaluated several times by different organisations against other ground penetrating radar systems and have been selected each time as the optimal equipment and technology for pavement and bridge deck

inspection. These evaluations have been conducted by the US Federal Highway of Transportation, New England Consortium of States, Strategic Highway Research Program (SHRP), Virginia Department of Transportation, CETE in France and the Autostrad in Italy. Several states in the US and Canadian provinces are presently using Penetradar equipment for inspection of bridge deck and highway pavement. Currently, we are providing a dual Penetradar IRIS system, installed in a vehicle, to the Italian Autostrad to be used for network level pavement inspection of the Italian highway system."

4.2.2 Geophysical Survey Systems Inc. (GSSI) (USA)

GSSI correspondence states that *"GSSI have been awarded an important R and D contract from the USA Strategic Highway Research Program (SHRP) to produce 1 GHz and 2.5 GHz horn antennae for highway applications. These will fit onto the GSSI, SIR System-10. GSSI won this contract against Pulse Radar, Penetradar, etc. A multi-channel horn antennae radar system has already been delivered by GSSI to the Swedish Road Authorities."*

An example of output from a GSSI, SIR System-10 is included in Appendix 1. *"This example is of a sub-surface subsidence area developing beneath the pavement of the four lane Pacific Highway south of Newcastle, Australia. This subsidence resulted in a one meter wide cavity opening up. The data was recorded with a 500 MHz GSSI antenna. Thirteen similar voids were located in a 600 meter stretch of highway. All of the voids detected with the radar had no surface expression."*

4.2.3 Pulse Radar Inc. (USA)

An example of a project by Pulse Radar is a *"GPR survey and analysis of data for 227 lane miles* (378 km) *of pavement in Beauregard Parish. For the project, radar runs were made in one lane in one direction in the inside wheel path for each highway. The purpose was to define changes in the longitudinal profile that would indicate changes in the design section. This information would be input into the GIS as one method of segmenting the network. Other segmentation parameters include traffic volume, accident history, surface condition, etc.*

"The data was collected in less than three days. It must be noted that Beauregard Parish is largely rural and excellent traffic control was provided by the Louisiana Department of Transportation and Development (LDOTD). The data was then analysed for changes in design sections. Beginning and ending control section log mile reference positions were defined for each segment. Construction variability, patches, bridge decks and other variations were not considered for this network study. An important side benefit is that, should the LDOTD wish to evaluate these segments for more detailed project level information (thickness variations, percent of deteriorated subsurfaces, etc.) the existing data can be used. This eliminates the need for additional field data collection. In addition to the termini of the segments, the number of layers and an estimate of the thickness of each layer were provided. If the type and exact thickness of each layer are required for the database, results

from the GPR study can help minimise and optimise coring operation. By using GPR for segmentation, the State has realised significant time and dollar savings in addition to having a more accurate information base."

4.2.4 GB Geotechnics Ltd (UK)

In correspondence received from GB Geotechnics, this company states that *"since 1982 GB Geotechnics has pioneered the use of radar in pavement investigations and the service now provided by GB Geotechnics plays a major role in the standard specification of remedial and quality control works. The company has been involved in a series of trial investigations working in conjunction with the Department of the Environment's Transport and Roads Research Laboratory (TRRL). Following on from these successful development projects, GB Geotechnics is now an approved supplier of non-destructive testing services to government bodies, including the Department of Transport, local authorities, and to major consulting engineers and contractors.*

"GB Geotechnics' involvement in many of the major strategic road construction and widening works completed in the UK during recent years, together with a large number of routine investigations of existing pavements, has consolidated the company's pre-eminence in this expanding field.

"GB Geotechnics has recently completed an investigation of the construction and condition of the M27 between Junctions 2-4 and 8-10, at the request of the Highways Department of Hampshire County Council, acting for the Department of Transport.

"The County Council is currently in the process of drawing up plans for major maintenance of this section of the M27, which has a history of cracking slab movement and other signs of defect.

"In order to plan the optimum remedial path, the County Council commissioned a survey using impulse radar in conjunction with a deflectograph rocking slab investigation to identify the nature and extent of the defects within the pavement structure. In particular, the survey was required to establish the thickness of both the bound and unbound construction materials, to assess the level of moisture content within the unbound materials and the level of support beneath the concrete, and to identify any defective joints."

5. SURVEY OF COMMERCIALLY AVAILABLE GROUND PENETRATING RADAR EQUIPMENT

5.1 Suppliers of GPR Equipment

To obtain appropriate information for a review of the range of GPR equipment available in 1992, a total of 11 companies that manufacture, supply and/or operate GPR equipment were considered for the review of GPR equipment. Some facts about the companies are summarised in Table 5.1.

Table 5.1 Companies that manufacture, supply and/or operate GPR equipment.

Company Name	Contact Personnel	Country	GPR Equipment supplied
Geophysical Survey Systems Inc. (GSSI)	Gregory Mills	UK	GSSI SIR System-10
Pulse Radar Inc.	Anita M Scott	USA	RODAR-II
Sensors and Software Inc.	Steve Cosway	Canada	pulseEKKO 1000
Penetradar Corporation	Anthony Alongi	USA	Penetradar Model PS-24
GB Geotechnics Ltd	Jon Baston-Pitt	UK	Consultants; use GSSI SIR System-8 & in-house developed software
Georadar Research Pty Ltd	Richard Yelf	Australia	Consultants and agents; use GSSI SIR System-10
OYO Corporation	Roger Caldwell	UK	Now merged with GSSI
ABEM	Leif Lofberg	Sweden	Borehole radar equipment only
Infrasense Inc.	Dr Kenneth R Maser	USA	Supply GPR software only
A-Cubed Inc.	Peter Annan	Canada	No longer supply radar equipment
Equipment Surveys and Consultancy for Highway Maintenance	Managing Director	UK	Do not supply radar equipment; consultants only
Bureau de Recherches, Geologiques et Minières	Managing Director	France	Do not supply radar equipment

GSSI Inc., Pulse Radar Inc., Sensors and Software Inc., and Penetradar Corporation were manufacturers of their own brands of GPR equipment in 1992, and also were offering their services as GPR consultants and researchers. Georadar Research were acting as agents for GSSI GPR equipment and offering their services as GPR consultants and researchers. The other companies were either operators or consultants of GPR equipment and borehole radar equipment or suppliers of GPR software. Two other companies, Infrasense Inc., a supplier of GPR software programs, and GB Geotechnics Ltd, a software supplier and potential operator, were approached later in the project for information about the systems they supply. Of these 11 companies (Table 5.1), four consultants whose equipment covered the range of GPR systems available in 1992 were selected to receive the GPR equipment questionnaire (Table 5.2).

Table 5.2 GPR consultants selected, and the manufacturing companies and equipment they represent.

GPR consultant and/or supplier	GPR equipment manufacturer	Model of GPR equipment manufactured
Georadar Research Pty Ltd	GSSI	SIR System-3, 8 and 10
Pulse Radar Inc.	Pulse Radar Inc.	RODAR-II
Sensors and Software Inc.	Sensors and Software Inc.	pulseEKKO 1000 and IV
Penetradar Corporation	Penetradar Corporation	PS-24

5.2 Survey of GPR Equipment

5.2.1 Survey Questionnaire

The full questionnaire is provided in Appendix 2 to this report. The questionnaire was designed to obtain basic and specific information from GPR manufacturers and suppliers about the equipment they supply, specifically about the following five components of equipment and the costs:

- GPR system
- Antennae
- Data acquisition system
- Software
- Accessories
- Costs to purchase and/or lease

5.2.2 Responses to Survey Questionnaire

The original data provided by the consultants in their responses to the questionnaire are held on Transit New Zealand file PR3-0070 (and are available for perusal on request). Detailed summaries of the responses are listed in Appendix 2 following the questionnaire, and tabulated summaries of the five components and costs are given in this Chapter 5. The basic components constituting each of the GPR systems considered for this project are listed in Appendix 3 to this report.

When accumulating and assessing data for the equipment evaluation, comparing corresponding information from the different manufacturers was difficult, mainly because the equipment specifications cannot be measured at the same point for the different systems under the same conditions. For example, the pulseEKKO 1000 system is a fully digital system with all timing controlled by a PC, while the GSSI SIR System-10 runs at a fixed clock rate and is analogue until the signal is digitised at the PC.

If a GPR manufacturer produced more than one model of GPR equipment, the most technically advanced system was considered, i.e. GSSI SIR System-10 (and not System-8 or -3), and Sensors and Software pulseEKKO 1000 (not pulseEKKO IV).

5.3 Summary of Responses to Survey Questionnaire

5.3.1 GPR System

Equipment designed specifically for pavement and bridge deck inspection applications were GSSI SIR System-10 (manufactured by GSSI), RODAR-II (Pulse Radar Inc.), and Penetradar Model PR-24 (by Penetradar Corporation). Sensors and Software supply multiple application equipment, pulseEKKO 1000, that is not suitable for pavement profiling applications. PulseEKKO 1000 is a static system which requires the antennae to remain in one position for a period of time for signal stacking. As this type of surveying is unsuitable for high volume pavement inspection work, the pulseEKKO unit was not considered further in the research for this report.

Component	**GSSI System-10**	**PulseRadar RODAR-II**	**Penetradar PR-24**
Mounting	rack-mountable hand-towable	rack-mountable	rack-mountable hand-towable
Recommended operating speed	2-10 km/h	10-90 km/h	0-65 km/h
No. of operating antennae	up to 4 antennae/ GPR system	2 antennae / GPR system	1 antenna / GPR control unit; maximum of 3 units
Type of recording system	Analogue converts to digital signal	Analogue converts to digital signal	Analogue converts to digital signal
Power requirements	12V DC, 180W, or 110/240V AC, 180W	12V DC, or 120V AC, 500W	12V DC, or 110/220V AC, 750W
Weight	28.5 kg	<21 kg	c.70 kg

5.3.2 Antennae

Component	**GSSI System-10**	**PulseRadar RODAR-II**	**Penetradar PR-24**
Position of antennae	NSC; suspended non-contacting TEM horn	Suspended non-contacting TEM horn	NSC; suspended non-contacting TEM horn
Arrangement	Monostatic Low frequency bistatic	Monostatic	Monostatic
Centre frequency	80 MHz - 1.0 GHz NSC; 1.0-2.5 GHz TEM	1 GHz TEM	600 MHz - 2 GHz
Transmit pulse rate	Operator-selectable 2 to 78 kHz	Set rate of 5 MHz	1 kHz
Waveform recording rate	0-125 scans/s, 16 bit data resolution	50 scans/s, 8 bit data resolution	50 scans/s, 8 bit data resolution
Power supply	Central GPR system	Power supply/control unit	GPR control console

NSC Near-surface contacting antenna TEM Transverse electromagnetic antenna
Dimensions see Appendix 2

5.3.3 Data Acquisition System

Component	GSSI System-10	PulseRadar RODAR-II	Penetradar PR-24
PC compatibility	Fully PC compatible	Fully PC compatible	Fully PC compatible
HardwareRequirements (a) Computer board	286 PC minimum + SCSI	386/20 PC + SCSI	486/33 PC + SCSI
(b) RAM	16 MB	640 kB	16 MB
(c) Mass storage	Internal DAT	Internal HD + 150 MB DAT backup, external 1300 MB DAT	Internal 1 GB HD, external DAT
(d) Hard disk	No internal HD	Internal HD	Internal HD
(e) Floppy disk drive	Internal FD 3.5 inch	Internal FD	Internal FD 5.25 inch
(f) DOS version	DOS 5.0	DOS 3.1 + later	DOS 5.0
(g) Mouse operated	Yes	Yes	Yes
Maximum data recording rate	512 samples/ scan; 2 channels each operate at c.45 scans/s	100 scans/s	1,000,000 samples/s
Real time digital signal enhancement	Provided	Not provided	Provided
Availability of printouts in field	B/W laser-quality	No printouts in field	Colour printout
Colour monitor requirements	19-cm VGA monitor; Super VGA for office	VGA monitor included	Super VGA monitor included
Distance measuring device	Provided (see App.2)	Provided	Provided
Power requirements	110/240V AC; or 12V DC	120V AC, 60 Hz only	110/220V AC, 60 Hz; or 12V DC
Dimensions, Weight	See App.2	See App.2	See App.2

DAT digital audio tape
HD hard disk
FD floppy disk drive
DOS disk operated system
VGA video graphic adaptor
SCSI small computer system interface

5.3.4 Software

Component	GSSI System-10	PulseRadar RODAR-II	Penetradar PR-24
Display modes	Scan, wiggle plot, colour linescan	Oscilloscope trace, colour linescan plots	Oscilloscope traces, colour linescan
Range gain	Fully user-controlled, or AGC	No range gain	Fixed range gain
Vertical filters (VF)	IIR, FIR filters	No VF controls	VF control by radar hardware
Horizontal filters (HF)	IIR, FIR, stacking, background removal	No HF controls	No HF controls
Input/Output(I/O)Ports	8 options (see App.2)	6 options (see App.2)	6 options (see App.2)
Digital signal processing functions	5+ functions (see App.2)	No information	2 functions available, more being developed (App.2)
Data capturing Data recording Data processing Data analysis Data display	Uses RADAN-III software package: see Section 5.3.5	Uses RDAS2 for data capture: see Section 5.3.5	Uses RDA, RDP software: see Section 5.3.5
Mouse operation	Yes	Yes	No
Menu-driven software	Yes	Yes	Yes
Data transfer for seismic reflection programs	Data can be transferred See comment *	Data can be transferred	No information

AGC Automatic Gain Control
IIR Infinite Impulse Response FIR Finite Impulse Response
HF Horizontal filter VF Vertical filter
I/O Input/Output ports

*Comment: The data produced by GSSI System-10 can be imported into seismic reflection packages, but because of the difference in size of the two data sets, Georadar Research pointed out that "many seismic data packages are not suitable for handling very large radar sections". Software packages dedicated to the analysis of GPR data would seem to be more efficient and are recommended rather than using seismic reflection programs.

5.3.5 Software for Data Capture, Recording, Processing, Analysis, & Display

Information on data capturing, recording and display software was available from all three suppliers. Two other companies, Infrasense Inc. and GB Geotechnics Ltd, also provided information about the systems they supply.

However, the information was difficult to evaluate without having practical experience of the software. Also most GPR software suppliers were reluctant to submit their products (other than demonstration samples) for evaluation, so any trial of a GPR system will involve the trialling of the software provided by the supplier of the GPR equipment hardware.

The suppliers did not separate their responses according to the requests because separate software programs are not generally supplied for each function requested. Therefore suppliers' responses are combined for all the requests, and responses are grouped according to supplier.

The software used by all five suppliers is as follows, but see Appendix 2 for details:

Data	Georadar	Pulse Radar	Penetradar	Infrasense	GB Geotechnics
- capturing - recording - processing - analysis - display	Uses RADAN-III software package: can determine layer thickness, moisture, voids, steel, under-ground services, etc.	Uses RDAS2 for data capture; PULSE3.EXE, PULSES3.EXE for graphical displays: can determine voids, layer thickness, moisture, stripping	Uses RDA, RDP software: can determine layer thickness, steel. Voids & moisture identification being developed	Uses PAVE-LAYER for layer thickness & properties	Uses RADCAD, CRUNCHER for recording, & processing data; GRAPHER for display

5.3.6 Accessories

Component	GSSI System-10	PulseRadar RODAR-1I	Penetradar PR-24
Fibre optic data links	Yes	No	No
Length of cables	Uses standard 30m; up to 200m on order	Uses 10-20m cables	Uses 6m cables; optional lengths

5.3.7 Costs to Purchase or Lease

The costs given by the five suppliers to purchase or to lease their equipment are given in Appendix 2, A2.3.7, with further details in Appendix 4 to this report.

6. CONCLUSIONS

6.1 GPR Equipment

The GSSI SIR System-10 would be the most suitable GPR equipment for trialling on New Zealand pavements for road surveys for the following reasons:

- The system can be set up as a specialised pavement investigation tool.
- The system can be used as portable or truck-mounted equipment.
- The highway operating speed allows for the collection of detailed data.
- Up to four antennae can be used at any one time, giving full lane coverage at the same depth, or at different centre frequencies to collect data from a range of depths.
- Antennae are air-coupled, non-contacting and monostatic for easy use on pavements.
- A wide range of centre frequencies is available, depending on the application.
- It operates on a 12V DC power supply as well as 110/240V AC, 180W.
- It weighs 28.5kg.
- Eight or 16 bit data can be collected, providing high data density.
- A distance measuring device is incorporated in the GSSI SIR System-10.
- Fibre optic cables of any length can be employed.
- A variety of display modes are available with GSSI SIR System-10, with user-controlled range gain or AGC facility. It uses both IIR and FIR vertical and horizontal filters. A range of digital signal processing functions are provided.
- Software supplied with GSSI SIR System-10 is RADAN-III. It enables determination of pavement layer thicknesses (if wave velocities are known), identification of moisture, voids, reinforcing steel, underground services, etc.

6.2 GPR Software Packages

The software package was determined according to the selected operator because the software packages for each system are not interchangeable with other GPR equipment unless modifications are made to the programs.

6.3 GPR Operator and Interpreter

Operation of equipment and interpretation of GPR data are as important in obtaining accurate pavement profiles as the equipment deployed.

Interpreting the data, although aided by and interactive with software, is dependent on the skills of the interpreter to determine the possible combinations of material parameters and layer thicknesses.

6.4 Costs of Equipment

The 1992 costs to lease equipment and to hire an operator were within the scope envisaged for this research project. Excluding travel and accommodation for operator, freight and labour, the costs to lease range from approximately NZ$39,000 to NZ$64,000 (as at 1992).

Details of 1992 prices of the components of these three systems are listed in Appendix 4 to this report for reference.

6.5 Selection of GPR Equipment and Operator

As the GSSI SIR System-10 was not available from GB Geotechnics, the GPR equipment package recommended for trialling on New Zealand pavements was their GSSI SIR System-8 equipment, with their software packages RADCAD (to convert graphic records into digital format) and CRUNCHER (to process the raw digitised data or to amend previously processed data), together with the commercially available GRAPHER (which is a standard graphing software package). They were considered to provide the most flexible and comprehensive packages for data presentation.

All data acquisition, data reduction and reporting was carried out by GB Geotechnics personnel.

Although not all recommended functions are provided by the GSSI SIR System-8, or by any of the other GPR packages, it provided the best possible available compromise at the time.

PART 2: FIELD TRIALS WITH A SELECTED GROUND PENETRATING RADAR SYSTEM

7. INTRODUCTION

Part 2 of this report documents a field trial, begun in 1993, using GPR as a pavement investigation tool. The purpose of the investigation was to assess the applicability of GPR and associated software to New Zealand pavement conditions by surveying sections of three state highway and four urban pavements.

Correlations have been made between the GPR data and information collected from core samples and from existing plans of underground services of the surveyed pavements to show the performance of GPR in determining structural layers, layer thicknesses, moisture changes, and the location of services.

8. EQUIPMENT AND FIELD TRIAL

8.1 GPR Equipment

The GPR equipment and personnel of GB Geotechnics were used throughout the field trial. The equipment comprised a GSSI SIR System-8 GPR unit and a range of three GSSI antennae operating at 500 MHz, 900 MHz and 1 GHz centre frequencies. An analogue graphic scanning recorder produced a hard copy of the GPR data.

Both in-house developed and commercially available software packages were used to analyse the collected data. They included: RADCAD, CRUNCHER and GRAPHER.

8.2 Field Trial

8.2.1 Sites for Field Trials of GPR

Sites for the field trial to determine the suitability of GPR for New Zealand pavements were chosen to include ranges of sub-base conditions, of construction methods, of construction materials, of changing moisture conditions, and a variety of services. For this purpose sections of three rural state highway and four urban pavements were selected and include:

- a 2 km section of State Highway (SH) 2, Western Hutt Road, near SH 58 – Haywards intersection, Wellington region

- a 2 km section of SH 56, Himatangi, Manawatu region

- a 2 km section of SH 3, New Plymouth, Taranaki region

- a 150 m section of Webb Street, Wellington City
- a 150 m section of Mulgrave Street, Wellington City
- a 180 m section of Lambton Quay, Wellington City
- a 130 m section of Featherston Street, Wellington City

Before the GPR survey was run, the selected road surfaces were marked on the road edge at 5 m intervals for the urban Wellington sections, and at 25 m intervals for the state highway sections. These marks, along with permanent landmarks, provided common reference positions on the GPR records and on the road for future relocation and comparisons.

The GPR unit and printer were housed in a 4WD vehicle and the antennae were towed approximately 2 m behind, on a purpose-built sleigh. The sleigh allowed the antenna to be located as close as possible to the road surface but still be protected from it.

By engaging the low ratio gear, the 4WD was moved as slow as 3 km/h for the detailed survey using the 1 GHz antenna. The 500 MHz antenna was generally towed at a speed of 5 km/h. As the sleigh and antenna moved past the metre road marks and permanent landmarks, a corresponding mark was put onto the GPR record.

Generally four passes of each wheelpath (both right hand (RHWP) and left hand (LHWP)) were made: one pass for each of the three frequency antennae plus a repeat pass using the antenna that resolved the most useful information. As the survey proceeded, a black and white printout was produced displaying reflections received by the GPR unit. The data were interpreted by GB Geotechnics in Cambridge, England. Appendix 5 to this report is a reproduction of the complete report that GB Geotechnics produced from the field trial.

To run the GPR survey continuously and at a constant speed, traffic control was necessary. On SH 2, which is a dual carriageway in each direction, the appropriate road signs together with marker cones and a moving barrier were adequate for road control. The moving barrier was a truck moving behind the 4WD vehicle. It carried a large flashing arrow to warn rear approaching traffic to move into the outside lane. On SH 56 near Himatangi and SH 3 near New Plymouth, where the highway is one lane in each direction, two persons with stop/go paddles were used to control the traffic. On the urban road sections a combination of signs, cones and/or stop/go paddles were used as appropriate.

8.2.2 Pavement Construction

Pavement construction data were obtained from Works Consultancy Services, Wellington Office, Civil Operations Group (hereafter denoted WCS).

8.2.3 Core Logs

After the GPR had been run, areas with typical pavement structure and no services were identified from the GPR record. Five locations on the state highway trial sections, and two on the urban sections, were selected for calibration purposes. At these locations, 150 mm diameter core holes were drilled into the subgrade material or to a maximum of one metre. The cores were drilled using dry coring techniques and samples of the seal, basecourse, sub-base and subgrade were taken to identify the structural layers and boundaries, depths, material types and water contents. Thirty eight specific sites were chosen for drilling. Backfilling the holes was carried out to the specifications of the road owners.

The drilling was carried out by WCL. Cores were logged at WCL using *"Guidelines for the Field Description of Soils and Rocks in Engineering Use"* (NZ Geomechanics Society 1988).

8.2.4 Water Contents

Water content measurements were made on the 38 samples, in accordance with the New Zealand Standard test, *"Determination of the Water Content, NZS 4402:1986, Test 2.1"* (SANZ 1986). These measurements are recorded, with the core logs for the specific materials sampled, in Appendix 6 to this report.

8.2.5 Location of Services

Data for the urban roads within Wellington City were collected from the authorities responsible for services, i.e. Wellington Gas Co. Ltd (Enerco in 1996) for underground gas pipes, Wellington City Council for water and drainage (i.e. stormwater and sewerage) pipes, Telecom for buried telecommunication services, and Capital Power for underground power cables. Data on services for the rural highways were obtained from the relevant authorities in Hutt City, Palmerston North and New Plymouth.

The locations of each of these services were marked on a master plan for the trial and tabulated for each section of road surveyed. Only the surface locations of the services have been taken into account when making comparisons as the depths of most services were unknown. The plans of services supplied by the authorities displayed approximate locations, in many cases, of only those services which were in use. Other pipes and cables may exist underground but did not appear on the supplied plans and hence were not on the trial master plan.

9. SITE DESCRIPTIONS

9.1 Locations

9.1.1 SH 2, Western Hutt Road

A 2 km section of SH 2, of the Western Hutt Road about its intersection with SH 58 Haywards Hill, was surveyed using GPR (Figure 9.1). The surveyed lane begins 845 m south of the roadside marker 962 corresponding to Transit New Zealand (Transit) RP (route position marker) 962/0.85 *, and extends north for 2000 m (RP 946/14.74). The northbound left (inside) lane was surveyed in both wheelpaths. A transverse line was surveyed across the northbound left lane at 1900 m (from 0 m **).

SH 2 is a four lane carriageway over the 2 km section surveyed. The SH 2–SH 58 intersection is between 845 and 868 m from 0 m, along the GPR survey line. The feeder lanes extend for approximately 170 m each side of the intersection (i.e. between 675 m to 1038 m from 0 m).

9.1.2 SH 56, Himatangi

A 2 km section of SH 56 (Himatangi to Palmerston North highway, Manawatu region) was surveyed from RP 14/13 (0 m) eastwards to RP 14/11 (2000 m) (Figure 9.2). The eastbound lane (towards Palmerston North) was surveyed in both wheelpaths. A transverse line was surveyed across the eastbound lane at 1700 from 0 m.

This section of highway is two lanes wide, one lane in each direction. A side road, Kellow Road, intersects State Highway 56 at 925-950 m from 0 m.

9.1.3 SH 3, New Plymouth

A 2 km section of SH 3, south of New Plymouth, Taranaki region, was surveyed from RP 240/3.41 (0 m) to RP 240/5.41 (2000 m) (Figure 9.3). RP 240/3.41 corresponded to zero on the GPR survey line. The two wheelpaths of the southbound lane were surveyed. A transverse line was surveyed across SH 3 at 75 m from 0 m, i.e. at the southern extreme of the Holy Oak Terrace turnoff.

Generally this section of highway was two lanes wide except for the last 500 m or so which is three lanes wide, i.e. a passing lane in the northerly direction.

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* An example of a route position (RP) is defined as follows: RP 962/0.85 is a position identification, i.e. 962 = ERP Established Route Position, and 0.85 = route position measured by its distance in km along the road surface from the preceding ERP.

** Distances in meters from 0 m, given in this context, are distances from origin, at 0 m, of the survey line.

9.1.4 Webb Street, Wellington City

As shown in Figure 9.4, a 150 m section of Webb Street, from Victoria Street to Upper Cuba Street, was surveyed in each wheelpath of both the eastbound and westbound lanes. A transverse line was surveyed across both lanes at 85 m from 0 m.

9.1.5 Mulgrave Street, Wellington City

A 150 m section of Mulgrave Street was surveyed from Pipitea Street to Aitken Street (Figure 9.4). Mulgrave Street has two lanes of one-way traffic running southward with narrow parking lanes each side. A transverse line crossing the left southbound lane only was surveyed at 135 m from 0 m. Four surveys were made, with at least one for each of the three frequencies of antennae.

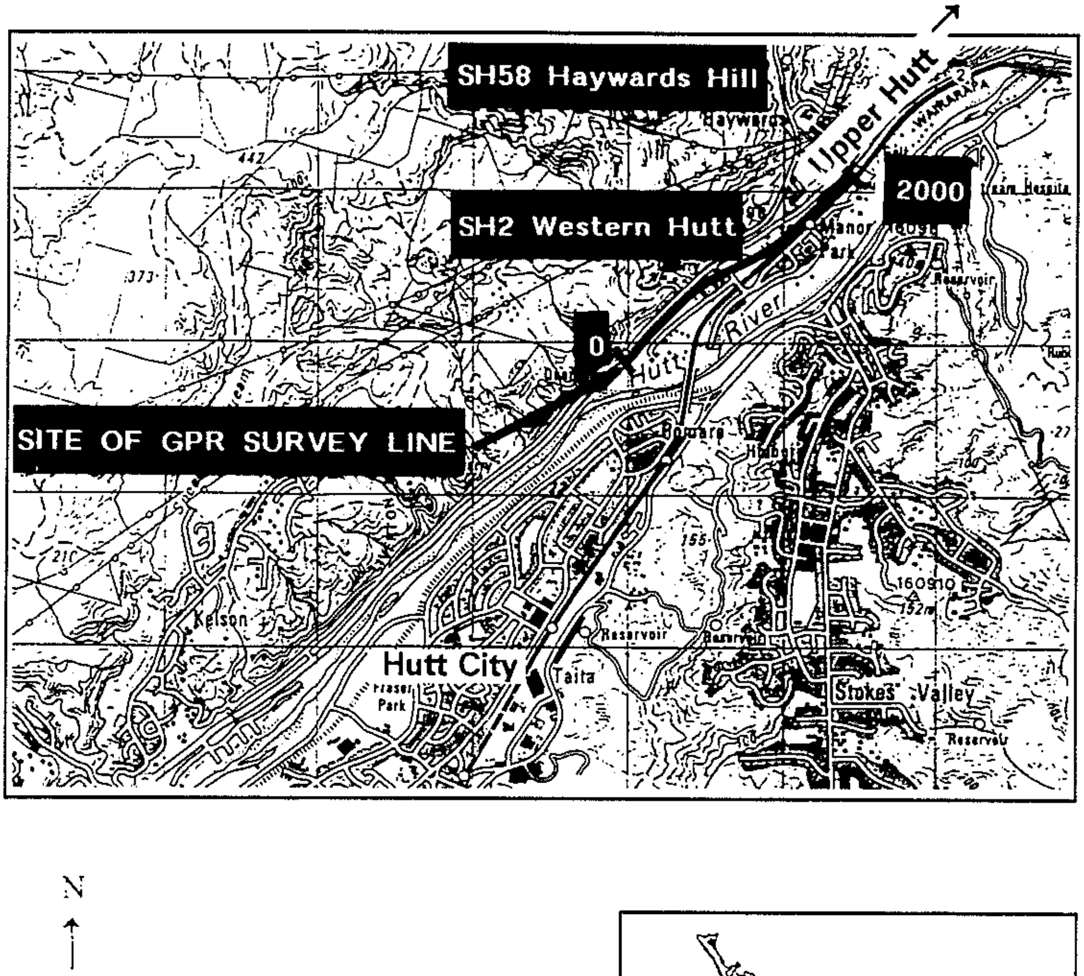
9.1.6 Lambton Quay, Wellington City

As shown in Figure 9.4, a 180 m section of Lambton Quay from Stout Street to Brandon Street was surveyed in each wheelpath of each southbound lane. Lambton Quay is a dual carriageway in each direction consisting of two general traffic lanes approximately 3.8 and 3.0 m wide and a parking/bus lane approximately 3.6 m wide. A transverse GPR line crossed all lanes at 60 m from 0 m. All three frequency antennae were used for this survey.

9.1.7 Featherston Street, Wellington City

A 130 m section of Featherston Street from Ballance to Johnston Streets was surveyed (Figure 9.4). Featherston Street has two one-way traffic lanes (of 3.8 m width) with parking lanes (of 2.4 m width) each side. The GPR survey was run in each wheelpath of each traffic lane using all three frequency antennae.

Figure 9.1 Location of 2000m GPR survey line on SH2 Western Hutt Road, about intersection with SH58 Haywards Hill, Wellington Region.
Scale 1:50,000; Map source NZMS260 R27.



Location map, North Island, New Zealand, showing locations of GPR surveys and lines:

Figure 9.1	Intersection SH2-SH58, Wellington
Figure 9.2	SH56, near Himatangi, Manawatu
Figure 9.3	SH3 near New Plymouth, Taranaki
Figure 9.4	Four survey lines in Wellington City

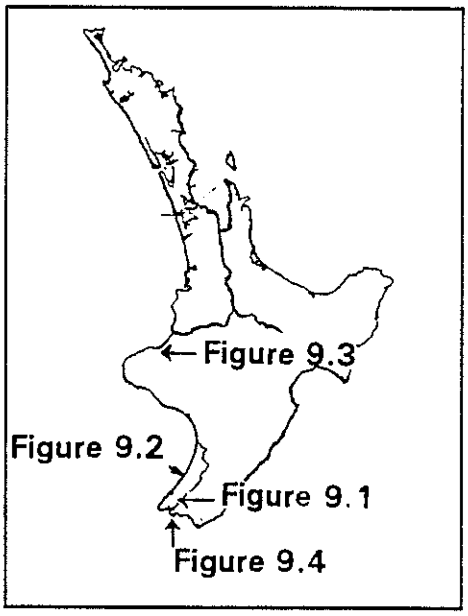
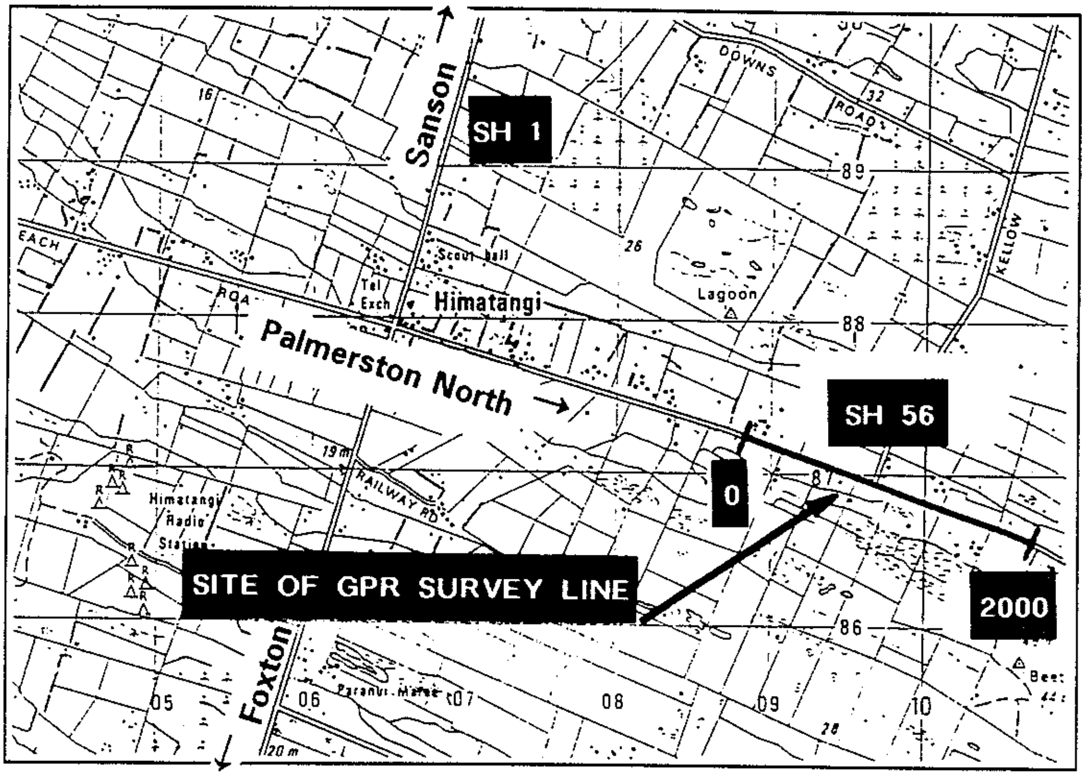


Figure 9.2 Location of 2000m GPR survey line on SH56 near Himatangi, Manawatu Region. Scale 1:50,000; Map source NZMS260 S24.



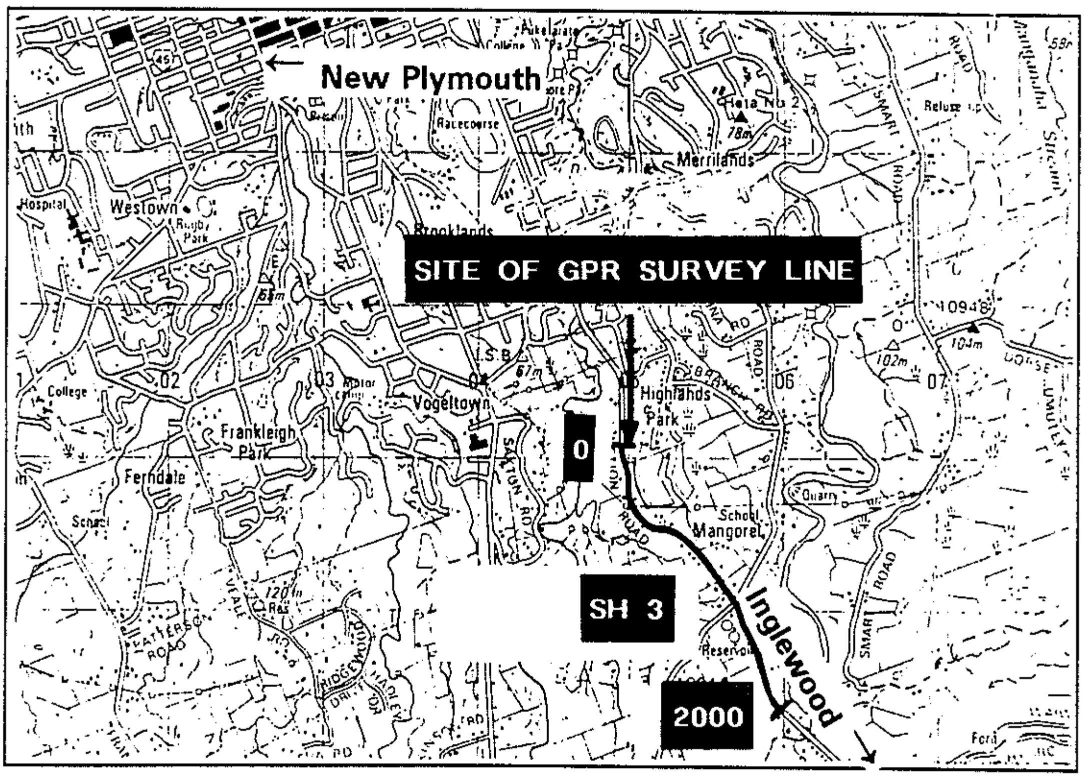
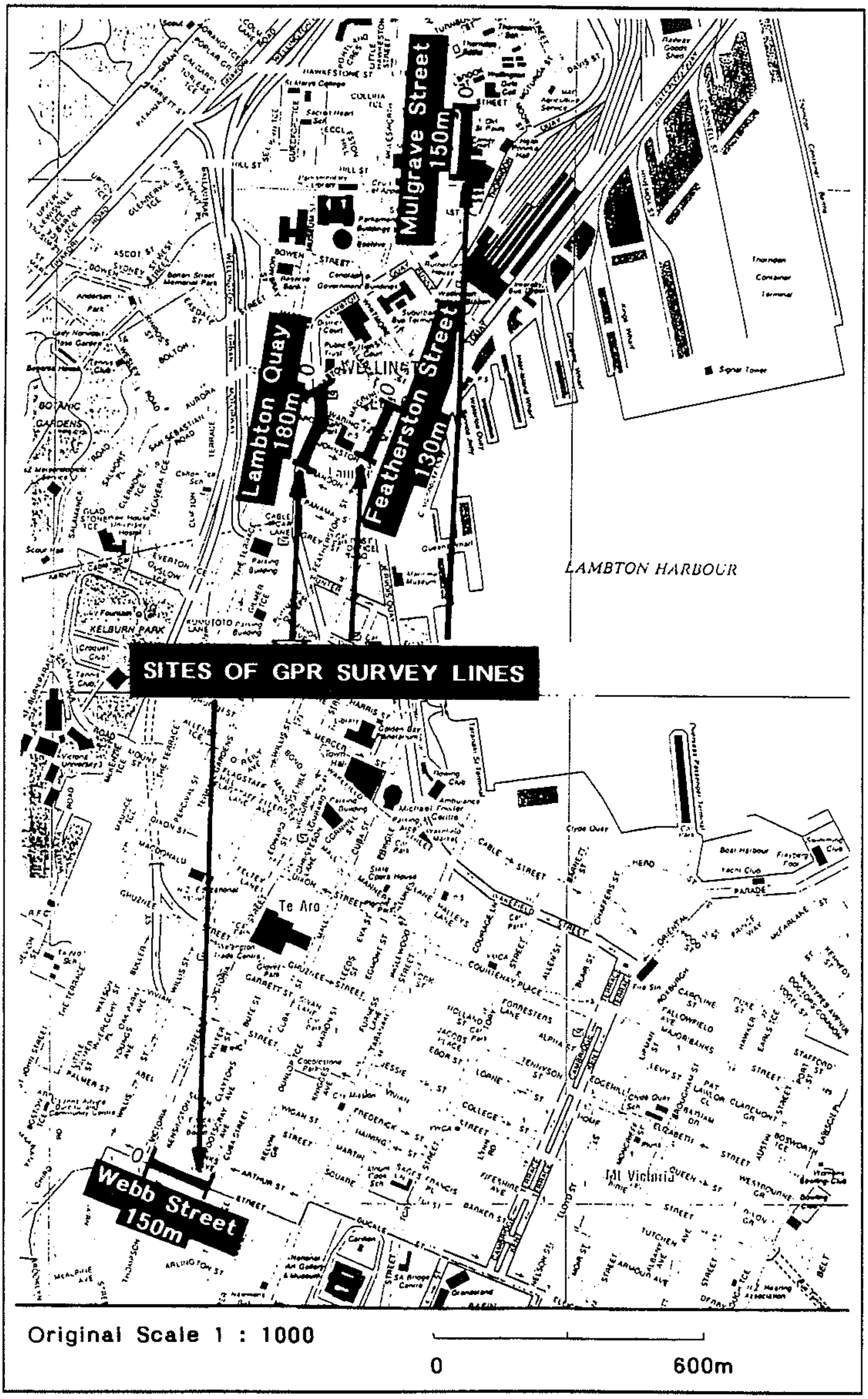


Figure 9.3 Location of 2000 m GPR survey line on SH3 near New Plymouth, Taranaki Region. Scale 1:50,000; Map source NZMS260 P19.

Figure 9.4 Locations of four GPR survey lines, Wellington City, North Island.
Original scale 1:1000; Map source Streetfinder 271-37.



9.2 Pavement Construction

The construction of the pavements, including the thicknesses and kinds of structural layers, as identified by GPR in 1993 is detailed in Appendix 7 to this report. The terminology for the layers and boundaries that is used by WCL and the terminology used by GB Geotechnics are compared in Appendix 8. A GPR survey can detect changes in the dielectric constant of adjacent layers but cannot necessarily identify the exact nature of the material. Hence the descriptions of materials given by WCL for the core logs are different from those used by GB Geotechnics.

The following pavement descriptions were reported from the "as-built" drawings for each section of road surveyed.

9.2.1 SH 2, Western Hutt Road

SH 2 from RP 962/0.85 (0 m) north to RP 946/14.74 (2000 m) was constructed in 1974. The surface was friction course laid in 1993 over asphaltic concrete.

9.2.2 SH 56, Himatangi

The surfacing of SH 56 between RP 14/13 (0 m) to RP 14/11 (2000 m) consisted of multiple layers of chipseal.

9.2.3 SH 3, New Plymouth

Surfacing of SH 3 from RP 240/3.41 (0 m) to RP 240/5.41 (2000 m) consisted of multiple layers of chipseal.

9.2.4 Webb Street, Wellington City

In Webb Street, from Victoria Street to Upper Cuba Street, the pavement is reported to consist of 60 mm of chipseal, overlying 100 mm of gravel basecourse, over a clay sub-base.

9.2.5 Mulgrave Street, Wellington City

The pavement construction of Mulgrave Street, from Murphy Street to Aitken Street, is reported to consist of 100 mm of AC (asphaltic concrete) and chipseal, laminated, overlying 250 mm of a lean mix (or lime-stabilised basecourse), on a clay subgrade.

9.2.6 Lambton Quay, Wellington City

Lambton Quay, from Stout Street to Brandon Street, is reported to consist of 100 mm of AC, overlying 250 mm of concrete, over 100 mm of clay, over 550 mm of beach gravel sand, over rotten rock base (weathered greywacke) to a depth of 1600 mm.

9.2.7 Featherston Street, Wellington City

Between Ballance Street and Waring Taylor Street the pavement is reported to consist of 70 mm of AC, overlying 230 mm of reinforced concrete, over subgrade of clay and rock.

9.3 Core Logs and Water Contents

Details of the core logs and water contents of samples obtained from the 38 drill holes are tabulated in Appendix 6 to this report. The volcanic ash and the clay subgrades had the highest water contents compared to sands and greywacke gravels.

9.4 Locations of Services

The locations of services are tabulated in detail in Appendix 9 to this report. Only the kinds and number of services are listed here.

9.4.1 SH 2, Western Hutt Road

Four drainage culverts cross SH 2 (see Appendix 9 for details of locations, e.g. at 405 m, 1500 m, 1675 m and 1912 m from 0 m). High voltage 33 kV power cables cross at two points, and 11 kV power cables cross SH 2 at three points. A pedestrian subway through which telephone cables and power cables are carried runs beneath the highway.

Buried within the top 50 mm of pavement and intersecting the GPR survey line at one point are more power cables, and water-filled tubing used for a pavement moisture monitoring programme.

9.4.2 SH 56, Himatangi

A fibre optic Telecom cable crosses SH 56 at right angles. No other services were reported at this site.

9.4.3 SH 3, New Plymouth

Water pipes of PVC and steel run along the grass verges adjacent to SH 3, but cross at three locations. A number of hydrants are associated with the PVC pipe. However, they are also beyond the pavement and therefore beyond the GPR survey area.

Telecom underground cables in this area are generally placed alongside farm fences, and hence are beyond the survey area. These cables cross SH 3 at eight locations.

The underground power cables are generally located beneath the grass verges close to fences. They cross the highway at four places.

9.4.4 Webb Street, Wellington City

Many service lines are buried beneath Webb Street including gas, water, drainage, Telecom and power.

A gas line runs along the eastbound lane with leaders to properties on the northern side of the road at three places. On the southern side of the road a gas line runs beneath the footpath, i.e. beyond the GPR survey area.

Water pipes run the full length of the GPR survey lines. Both followed approximately the centreline of each lane. One leader runs from the northern side across both lanes at approximately 18 m from 0 m. Fire hydrants are at the surface at a number of locations.

Drainage pipes run along the centreline of the road for the total length of the GPR survey line and on the westbound lane from Thompson Street towards the start of the GPR line (0 m). Leaders run northwards off the eastbound lane at three places, and southwards off the westbound lane at seven places.

Telecom cables run beneath the footpath on the northern side of the road and cross the road at three locations. From 0 to 10 m, a cable crosses obliquely from the centre of the road to the northern footpath to join these cables.

A 33kV cable lies approximately along the centreline of Webb Street from 0 to 60 m, at which point the cable veers towards the southern side of the road where it continues to run adjacent to the footpath in the LHWP of the westbound lane.

9.4.5 Mulgrave Street, Wellington City

A gas line runs the full length of the GPR survey line in the left lane of Mulgrave Street with leaders crossing both lanes at two places.

Water mains run along the left lane, approximately in the LHWP, with two leaders to the east and one to the west.

Drainage pipes run adjacent to the centreline in the left lane from 17 m to 150 m (from 0 m) and adjacent to the footpath in the right lane for the total length of the GPR survey line. Three leaders from the drainage pipe near the centreline run eastward and two run westward.

Telecom cables are laid beneath the footpath, except for one cable which crosses Mulgrave Street at right angles.

Power cables are buried beneath the road adjacent to the footpath of the left lane with cables crossing the road at three locations.

9.4.6 Lambton Quay, Wellington City

Gas pipes cross Lambton Quay at an oblique angle at two locations along the GPR survey line.

Water mains run the full length of the GPR survey line within the southbound carriageway approximately midway across the width of the lanes. Leaders run to the east at different angles at three locations, and one is to the west.

Drainage pipes run within the left southbound lane, a number cross mainly at intersections, and another runs parallel to the footpath and within the left lane for part of the Quay.

Telecom cables are buried beneath the southbound lane adjacent to the median strip, and three cross the Quay.

Power cables are buried beneath the footpath for the total length of the GPR survey line, with other power cables crossing at five locations.

9.4.7 Featherston Street, Wellington City

A gas line runs along the centreline of the right lane of Featherston Street. In total ten separate pipes lie below the right hand lane and leaders run to the west (right side of the road) at six locations, and to the east (left side of the road) at five locations.

A water pipe runs adjacent to the gas pipe from Ballance to Waring Taylor Streets, with leaders west and east down Waring Taylor Street.

Drainage pipes are numerous along this section of Featherston Street with three main pipes, six leaders to the west (right) side and eight to the east (left) side of the road. Pipes cross the Featherston/Waring Taylor Street intersection at three places.

A Telecom cable runs the total length of the GPR survey line along the RHWP of the right lane, with a leader to the left (eastern) side of the road.

Power cables lie beneath the footpath on both sides of Featherston Street except for a section where a cable is buried under the left lane adjacent to the footpath. Cables cross the full width of the street at six points.

10. COMPARISONS OF KNOWN DATA WITH GROUND PENETRATING RADAR RESULTS

10.1 Structural Layers and Boundaries

An assessment of material type has been made by GB Geotechnics based on the pattern of reflectivity obtained from both within a particular construction layer and from the boundaries between adjacent layers, compared with the responses obtained from known materials at core locations and from typical construction materials encountered during previous investigations of a similar nature. (from Report by GB Geotechnics (King et al.) 1994, given as Appendix 5 to this report).

Appendix 10 to this report includes a tabulated summary of the structural layers and boundary data identified using GPR and presented in GB Geotechnics' Report. Figure 10.1 shows the structural layers and boundaries (and their names) that are likely to occur along the survey lines of the state highways and urban roads selected for the trial. Often more than one boundary is indicated within the basecourse materials. Boundaries are identified in Appendix 10 by numbers, e.g. boundary 1, boundary 2, etc.

A subjective evaluation of the continuity of the boundaries as identified by the GPR survey has also been made. A rating ranging from very poor to very good has been allotted to each section of pavement. The ratings and corresponding "% interface identified" listed in Table 10.1 have been determined from an evaluation of the information displayed in the graphic presentations in GB Geotechnics' report (Appendix 5 to this report).

Table 10.1 Ratings used for describing continuity of the structural boundaries.

Symbol	Rating	% interface identified
VG	Very good	85-100
G	Good	60-85
S	Satisfactory	40-60
P	Poor	15-40
VP	Very poor	0-15

The structural boundaries identified by GB Geotechnics using GPR have been summarised and rated as follows:

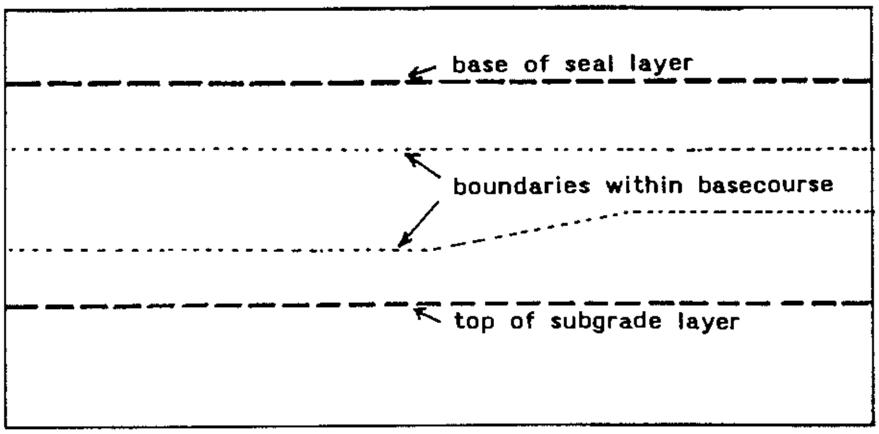
(1) On rural state highways:
- G-VG (60-100%) for the base of the seal,
- G-VG (60-100%) for boundaries within the basecourse,
- S-VG (40-100%) for the top of the subgrade.

(2) Urban roads:
- S-G (40-85%) for the base of the seal,
- VP-G (0-85%) for boundaries within the basecourse,
- P-S (15-60%) for the base of the concrete,
- VP-VG (0-100%) for the top of the subgrade, and base of the basecourse.

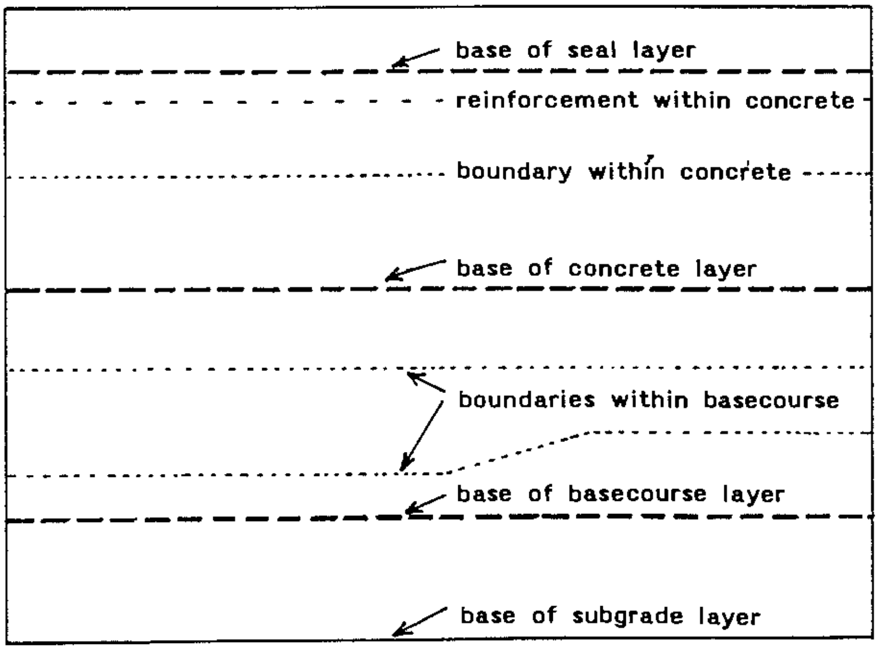
Figure 10.1 A diagrammatic representation of pavement construction layers and the terminology used by GB Geotechnics to describe the layers and boundaries.

Note: GB Geotechnics and WCL have used different terminology to describe the layers. Tables relating the two terminologies are supplied in Appendix 8 to use when comparing the core-log descriptions (described using WCL terminology, as in Appendix 6 to this report) with the structural layers identified by the GPR survey (using GB Geotechnics terminology, as in this Chapter 10 and in Appendixes 7 and 10).

State Highways



Urban roads



Differences in terminology result from the different parameters being described. For example, descriptions of layers in core logs are made from direct observations, e.g. silty clay with fine sand, whereas descriptions of layers in a GPR survey are made by analysis of the GPR data, e.g. of changes in dielectric properties.

The GPR survey has identified other structural features as well as identifying structural layers and boundaries. These structural features include areas of deconsolidation within the construction materials, disturbance and possible mixing of materials at boundaries, areas of deconsolidation within subgrade materials on the rural sections, and areas of increasingly deconsolidated material indicating disturbance. These areas often coincide with buried services which may have been dug up for maintenance or, in the case of SH 2, coincide with a subway. Because plans of these features do not exist, this information cannot be correlated with factual data.

To define structural layers using GPR, sufficient contrast in dielectric properties must occur within the layer materials. With the aid of core logs and characteristic GPR data such as relative dielectric constants, a particular construction material can be identified and extrapolated along the surveyed line.

Typical values of relative dielectric constant (E) for these pavement materials are:

	E
Asphalt	9
Basecourse	5-9
Gravel	5-9
Dry sand	3-6
Saturated sand	20-30
Clay	5-40 (depends on type of clay minerals and silt+sand content)

The contrast in dielectric properties, for example between basecourse (E=5-9) and greywacke (estimated E at 5-9) is low, but that between basecourse (E=5-9) and volcanic ash (estimated E at 40) is high. The greater the contrast in the dielectric properties of adjacent layers, the more energy is reflected from the interface to be received and displayed by the GPR for identification.

GPR has identified the base of the seal on state highways successfully. Boundaries within the basecourse materials have also been identified well. Such definite identification indicates that the dielectric properties of the seal and basecourse at all three state highway sites have enough electrical contrast that GPR can detect the changes between the structural layers. This also indicates that little attenuation of the GPR signal occurs when it is passing through the upper pavement layers.

On the other hand the ability of GPR to identify the top of the subgrade materials at the survey sites ranges widely. At SH 2, Western Hutt Road/Haywards intersection, with gravel and weathered greywacke subgrade, the identification is satisfactory (i.e. 40-60% of the boundaries were identified). The ability of the GPR to identify the upper boundary of the subgrade at SH 56, Himatangi, is good (60-85%). At SH 3, New Plymouth, where the subgrade is mostly volcanic ash, identification is very good (85-100%).

Although GPR may not clearly define the structural boundary at all locations, e.g. the base of the seal at Webb and Mulgrave Streets, this lack of definition in itself provides additional information to the pavement engineer. For example, GB Geotechnics state in their report for Webb and Mulgrave Streets that:

> *... the boundary at the base of the seal material and that at the base of the basecourse are often poorly resolved. This implies that the seal material in these areas is defective, and that the basecourse in these areas may be contaminated with clay and moisture from the clay based subgrade below. Alternatively, the subgrade may be formed of a similar material to the basecourse.*

At Lambton Quay and Featherston Street, which are both seal over concrete construction, the seal/concrete boundary was identified for about 80% of the survey. Identification of the bases of the concrete, sub-base and subgrade boundaries is generally poorly defined for both these sites. GB Geotechnics interpret this poor definition to mean that:

> *... the boundary at the base of the seal with the concrete is often poorly resolved indicating that the degree of bond between the two materials is moderate to good. There are a few areas where the boundary is well resolved implying that the bond is poor.*

GB Geotechnics have also identified extensive areas of material disturbance in the subgrade. Often these areas extend across the full width of the road which suggests that they are related to the subgrade geology.

10.2 Layer Thickness and Depth Assessment

The thicknesses of the different structural layers at each site have been presented by GB Geotechnics on drawings for each of the sites surveyed. The structural layers identified are represented by different colours which are described in an associated key. Two examples of the graphical representations of the interpreted GPR data are given in GB Geotechnics' report (Appendix 5 to this report).

Core-log data were used by GB Geotechnics for calibration purposes during their interpretation of the GPR data. Locations of core logs are shown on their drawings.

The ability of the GPR survey to identify layer thicknesses is evaluated by the rating system used for describing the continuity of structural layers, given in Table 10.1 (also in Appendix 10 to this report).

GB Geotechnics make the following statement about the accuracy of the depth assessments:

> *Given the variation in the nature and condition of the construction materials encountered within the scope of the investigation, depth assessments for the bound layers can be assumed to be better than ±8% of the quoted figure. Relative accuracy within any section is good to better than ±4%.*

Where material boundaries were resolved by GPR, a layer thickness can be read from these graphical presentations of the interpreted GPR data in GB Geotechnics' report, Appendix 5 to this report. To calculate a layer thickness from the GPR data collected in the field, a reliable assessment of the electromagnetic wave velocity (V) for the materials is required. These velocities are calculated using the equation:

$$V = c/\sqrt{E}$$ (see Chapter 1, Part 1 of this report)

where c is the electromagnetic wave velocity in air (0.3 m per nanosecond),
and E is the relative dielectric constant.

From core-log thicknesses (TH), values of the electromagnetic wave velocity and the relative dielectric constant can be back-calculated at core locations using the equation:

$$TH = V \cdot T/2$$

where V is the electromagnetic wave velocity,
and T/2 is the one-way travel time through the layer.

Values of V and E are then used to calculate layer thicknesses over the remainder of the GPR survey line.

The correlation of layers identified from GPR data with those identified from core logs collected in the field, is outlined in Appendix 7 to this report.

The number of times (expressed as percentages) that layer thicknesses were successfully identified by GPR at core locations are:

- 90% successful for the base of the seal layer;
- 60% for material boundaries within the basecourse on the state highways surveyed;
- 30% for the top of the subgrade on the state highways surveyed;
- 60% for the base of the basecourse layer on Wellington City roads surveyed;
- 60% for the base of the concrete layer;
- 25% for boundaries within the subgrade.

10.3 Moisture Data

Moisture content*** is a bulk property of the pavement, according to GB Geotechnics, and so, after the moisture data from both wheelpaths have been analysed and checked for any possible discrepancies, it is reported along only one of the wheelpaths. Therefore where a state highway survey line has only one reported moisture profile it has nevertheless been fully investigated.

Moisture data for the urban pavement survey lines were more variable, as explained by GB Geotechnics in their communication to WCL (11 February 1994):

> *A full data set was collected from all sections of urban pavement, but the highly variable nature of these evolved urban pavements prevented a reliable assessment of the moisture content of the pavement over the short lengths surveyed. This is not therefore a failure of the survey. It does, however, indicate that the technique is probably not suitable for moisture evaluation by these means over short lengths of complex urban pavements.*

In their Report (Appendix 5 to this report), GB Geotechnics present moisture information, in the graphical representation, as a black horizontal line to represent an average moisture content, with peaks and troughs indicating high and low moisture contents respectively. These changes in moisture content are relative to that particular highway only and the data cannot be compared between sites.

At core-log sites, a comparison of laboratory measured water contents and GPR measured moisture changes has been made. To represent this GPR data in a table, the peaks and troughs have been measured and converted to a number between +1 and −1 to indicate high and low moisture contents respectively (see Table 10.2).

WCL's core-log water contents in Table 10.2 are an average value of the water contents of each pavement layer at a particular location. Where water contents were not determined for a layer at a particular location, water content values for similar layers at other locations were averaged and included in the calculation of the overall average water content of the pavement. These extrapolated water content values are shown in parentheses.

Correlation between trends in relative moisture change data obtained from GPR survey and water contents measured from core-log samples was poor. No logical conclusion can be drawn to relate one to the other.

GPR moisture content data were not available for the urban pavements so comparisons could not be made with water contents from core logs.

*** Moisture content - term used by GB Geotechnics for 'water content'
Water content - term used by WCL based on definition in NZS 4402:1986

Table 10.2 Relative moisture change data obtained by GPR survey and water contents (%) obtained by laboratory measurements of core-log samples.

Core location (m from 0 m)	GB Geotechnics' relative moisture change	WCL's core-log water content (%)
SH 2		
45	No data	3.4
625	+0.19	7.1
755	+0.13	(5.8)
1550	0	7.0
SH 56		
675	+0.31	3.6
725	+0.25	No data
1150	−1.00	(5.0)
1575	−0.13	3.3
1900	−0.50	4.8
SH 3		
75	+0.13	No data
900	+0.13	No data
976	0	24.3
1201	No data	24.3
1900	No data	(24.2)

% in parentheses are calculated using average values for similar layers at other locations.

10.4 Location of Services

10.4.1 Explanation of Conventions

A service noted on a plan is indicated on the tables in Appendix 9 to this report by the distance (m) of its location from zero (0 m) of the GPR survey line. The data have been split into wheelpaths for the rural state highway sections to correspond with the runs made for the GPR survey. For the urban sections where four GPR runs were made, one in each wheelpath along each survey line, the services located in each wheelpath have been added up and presented as a total for one lane. Note that a service may occur in just one of these wheelpaths.

Services that are placed longitudinally, as in urban sections, are listed at the bottom of each table. Identifications of longitudinal services by GPR are mentioned in Section 9.4 of Part 2.

Services identified by the GPR survey which are not shown on the plans of services (obtained from the relevant authorities and companies responsible for the services) are not listed in the tables in Appendix 9.

If a correlation is apparent, the location of the service has been highlighted in bold and underlined on the tables in Appendix 9. In the urban surveys, if the GPR data indicated that the service is under one wheelpath only or if the location of the service is more than 4 m different to the provided data, a question mark "?" has been used alongside the location.

Data collected from the various authorities are not always accurate, hence some flexibility has been allowed in judging whether the GPR survey has identified the service or not. This flexibility relates to the distance along the GPR survey line, as well as the diameter and depth of the service. For example, a pipe crossing the road at right angles may be identified in one wheelpath to be 400 mm deep and in the other wheelpath to be 700 mm deep, or it may be shown as a large diameter pipe in one instance and a small diameter pipe in the other. In another case more than one service may be intersected but they are shown on the GPR data as one large diameter pipe. In all these cases the GPR data have been deemed to correctly show locations of services.

The method of counting services is different in Sections 10.4.2 to 10.4.4 to that used in Sections 10.4.5 to 10.4.8 to describe the location of services. For the Wellington City GPR surveys, four GPR runs were made at each site, i.e. one in each wheelpath, and the services located beneath wheelpaths of each lane were added together and presented as being in one lane. The service may occur just once or twice across a lane.

10.4.2 SH 2, Western Hutt Road

Of the 24 services identified along this 2000 m section of highway, the GPR has successfully recognised 17 of them. Although the pedestrian subway at 1435 m from 0 m is like a large culvert, it has been identified as an area of deconsolidation within the construction material at this location.

10.4.3 SH 56, Himatangi

Only one service, a Telecom cable, is known to exist along the 2000 m of highway surveyed at Himatangi. This was located by GPR in one wheelpath only.

10.4.4 SH 3, New Plymouth

Thirty services were identified from the plans along the 2000 m section of highway near New Plymouth. Of these only one, a Telecom cable, was located by GPR.

10.4.5 Webb Street, Wellington City

On this urban road, 43 transverse services were known (from the plan of services) to cross the line surveyed by GPR. The GPR survey accurately located 33 services and so missed 10. Although GPR did not always locate the water pipe at 18 m, the trench containing this service was located along three of the four wheelpaths. GPR does not clearly identify oblique angled changes so the Telecom cable crossing obliquely from 2 to 10 m from 0 m in the LHWP of the eastbound lane is indicated by a zone of disturbed material.

GPR detected a number of longitudinal services that are probably gas and/or water, Telecom, power, and drainage.

GPR on the transverse section at 85 m from 0 m correctly identified one water main out of five services that run along the road at this location.

10.4.6 Mulgrave Street, Wellington City

Forty various services, running at right angles to the GPR survey line, have been identified from the plans of services to be buried beneath the survey section of Mulgrave Street. Using GPR, 33 of these were distinguished successfully.

A longitudinal drainage pipe at 600 mm deep was partially identified in the RHWP of the right lane. A pipe was correctly identified in the RHWP of the left lane (at 400-500 mm deep) and a water pipe in the LHWP of the left lane at 400-700 mm depth.

10.4.7 Lambton Quay, Wellington City

From the plans, 63 services were known at 1993 to traverse this section of Lambton Quay. The GPR survey recognised successfully only 30 of these services. In the LHWP of the left lane and to some extent the RHWP, trenches are apparent from the GPR data at the intersections of the side roads, i.e. Waring Taylor and Brandon Streets. At these intersections services run both parallel to and at right angles to Lambton Quay.

A number of unspecified targets (possibly metal) have been identified, especially from 120-180 m on each GPR run and 0-20 m from 0 m in the RHWP right lane and to a lesser extent scattered along the runs. Irrigation pipes in the garden along the median strip are possibly responsible for these unspecified signatures.

A longitudinal service, possibly a water pipe, has been identified by GPR in the RHWP of the left lane at 600-900 mm depth.

10.4.8 Featherston Street, Wellington City

Of the 79 occurrences of services known to run at right angles to this section of Featherston Street, the GPR survey has successfully located 25. A number of services cross the intersection of Featherston and Waring Taylor Streets (65-75 m from 0 m). Although the GPR did not identify all the services at the intersection it did indicate a zone of deconsolidated material which is likely to be the trench in which these services are located.

This section of road was particularly difficult to survey because of the complex network of excavations. A narrow strip between resealed trenches was chosen for running the survey. The transverse section at 40.5 m from 0 m indicated four of the expected seven services.

10.5 Summary of Services Located by GPR

Table 10.3 lists the services located by GPR as a percentage of the total number of services identified from the plans for each section of pavement surveyed. It also includes a breakdown of the total services into the individual services, to indicate which are more likely to be identified.

Table 10.3 Services located by GPR as percentage of total number of services identified on plans.

Pavement section	Subgrade	% of services located by GPR					
		Total	Gas	Water	Drainage	Telecom	Power
SH 2	greywacke	63	*	*	75	0	64
SH 56	sand	50	*	*	*	50	*
SH 3	volcanic ash	3	*	0	*	6	0
Webb St.	clay	77	67	50	70	93	100
Mulgrave St.	clay	83	75	80	82	100	83
Lambton Quay	w greywacke	48	63	63	63	25	31
Featherston St.	fill	32	33	25	27	50	33

* Service does not occur at this pavement location.
w weathered

11. SOFTWARE

The hard copy printout collected in the field was used by GB Geotechnics for the data interpretation. A digitising tablet was used to convert the data to a format suitable for computer processing. The software packages RADCAD, CRUNCHER and GRAPHER were used in the analysis of the data to evaluate the thickness and depth values of the material layers from the travel time data collected, and for presentation of the results.

The software packages RADCAD and CRUNCHER are developed in-house by GB Geotechnics. GRAPHER is a commercially available software package designed to give full flexibility to the manipulation of data in graphical format.

As all data reduction and interpretation were carried out at GB Geotechnics' offices in the United Kingdom, no first hand experience of this process was obtained by the researcher. GB Geotechnics have graphically presented an interpretation of the GPR data for each site surveyed, two examples of which are reproduced in Appendix 5 to this report.

The graphical presentations of the GPR data made by GB Geotechnics for the state highway survey lines are presented for each wheelpath of the one lane that was surveyed, i.e. a total of two 2000 m long sections. For convenience the data are split into 0-1000 m and 1000-2000 m sections. The data from each wheelpath of a lane are presented one above the other in the graphical presentation (Appendix 5) for conveniently comparing across a lane. A moisture change profile is given for one wheelpath of the lane surveyed at each state highway site.

For the urban sites the data are presented for each wheelpath of each lane of the survey line, i.e. a total of four 130-180 m long sections. The data for the left and right wheelpaths are located one above the other in the graphical presentation (in Appendix 5) for conveniently comparing information across a lane.

Each graphical presentation includes a depth and horizontal scale in metres, core locations, layer boundaries marked in colours, underground services, and areas of material disturbance. They include keys to assist in understanding the graphical presentation, and they are shown on the examples in Appendix 5.

Most GPR interpreters present their GPR pavement evaluation data as an overlay on the printout of the raw data, i.e. the radargram. This overlay can be confusing and difficult to understand for those not familiar with the interpretation of GPR data. However, GB Geotechnics presents the data clearly displayed in an easily understood format. The use of colours and recognisable symbols for layer boundaries, services, disturbed ground, etc. contribute to this understanding.

The moisture content data are displayed beneath the structural layer, thickness and underground services data, at the same scale so that direct comparisons at specific distances can be made. The key is descriptive and supplies sufficient information to understand the drawing without referring to the text.

12. CONCLUSIONS AND RECOMMENDATIONS

GPR accurately identified the presence of seal and basecourse layers and also accurately determined their thicknesses. It was less reliable in determining concrete and subgrade thicknesses, because of poor contrast in dielectric properties between the adjacent materials, because of a moderate to good bond between the two adjacent materials.

Nevertheless, the presence of poor data or the absence of data relating to structural boundaries can provide useful information on the material properties and the nature of the bond at the boundary.

For a field survey designed to locate underground services, which are surrounded by materials of low electrical conductivity (e.g. dry sands and gravels), the probability of detecting the services is high. Services constructed from metal (cables and steel pipes) are more recognisable than those constructed from PVC or concrete.

The selected system did not successfully determine moisture changes in pavement layers.

The software packages used in the interpretation and presentation of the GPR data are of a high standard and produced clearly displayed data in an easily understood format.

This project has highlighted the need for the GPR operator and interpreter to fully understand the requirements of the project as perceived by the client. Therefore, essential points to discuss at early stages in the project planning should include the information the client would like from the survey, how the survey could be designed to obtain such results, and the associated costs. If these details are considered, the GPR is capable of providing information about the pavement that is useful and accurate for the client.

GPR (e.g. GSSI SIR System-8 or better) is recommended for use in the New Zealand pavement environment to determine:

- structural layers
- layer thicknesses, and
- the location of services.

A further evaluation of GPR for determining moisture changes in the road profile is recommended, and for better definition of pavement structures and locations of services. Then, as the technology advances, the use of GPR can be extended.

APPENDIXES

1. PRESENTATION OF GPR DATA

2. SURVEY OF GPR EQUIPMENT QUESTIONNAIRE & SUMMARY OF RESPONSES

3. COMPONENTS OF GPR SYSTEMS CONSIDERED FOR TRIAL ON NEW ZEALAND PAVEMENTS

4. ESTIMATED PRICES OF GPR EQUIPMENT AS AT 1992

5. REPORT FROM GB GEOTECHNICS LTD: A NON-DESTRUCTIVE INVESTIGATION OF PAVEMENT CONSTRUCTION & CONDITION

6. CORE LOGS AND WATER CONTENTS

7. LAYERS IDENTIFIED BY GPR AT CORE LOCATIONS

8. TERMINOLOGY USED FOR STRUCTURAL LAYERS AND BOUNDARIES

9. LOCATION OF SERVICES ALONG GPR SURVEY LINES

10. IDENTIFICATION OF STRUCTURAL LAYERS AND BOUNDARIES USING GPR

REFERENCES

APPENDIX 1
PRESENTATION OF GPR DATA

PRESENTATION OF GPR DATA: Examples

Example 1. GSSI SIR System-10 and RADAN-III Software, from Georadar Research

Example 1 is of output from GSSI SIR System-10 equipment and RADAN-III software. It shows a sub-surface subsidence developing beneath a highway. The subsidence later opened up as a 1 m wide cavity.

Examples 2 and 3. RODAR-II and RDAS Software, from Pulse Radar

Example 2 from the Pulse Radar RODAR-II system and RDAS software, for US Highway 59 - Corrigan, Texas, demonstrates one way of presenting information extracted from a GPR survey.

Example 3, also from the Pulse Radar RODAR-I1 system and RDAS software, shows presentations of different features within the pavement of an in-service road, that demonstrates four ways in which the GPR data can be used.

1. In-service road section, as known from existing information, is presented first.
   The collected GPR data are then presented below it in three ways:

2a - d. Radar output (radargram) showing four examples (a-d) corresponding to four sections of the in-service road;

3. Thickness data presentation - sketch indicating the structural layers and layer thicknesses;
4. Plan data presentation - plan indicating areas of voids, moisture, and stripped asphalt.
   (HMAC – hot mix asphaltic concrete)

Example 4. GSSI SIR System-8, from GB Geotechnics

Example 4 is output from a GSSI SIR System-8 and GB Geotechnics' RADCAD and CRUNCHER software packages, together with commercially available GRAPHER.
"Presentation Example B" is from an investigation for widening a modern three lane motorway of bituminous construction. The eight graphs presented show the following information:

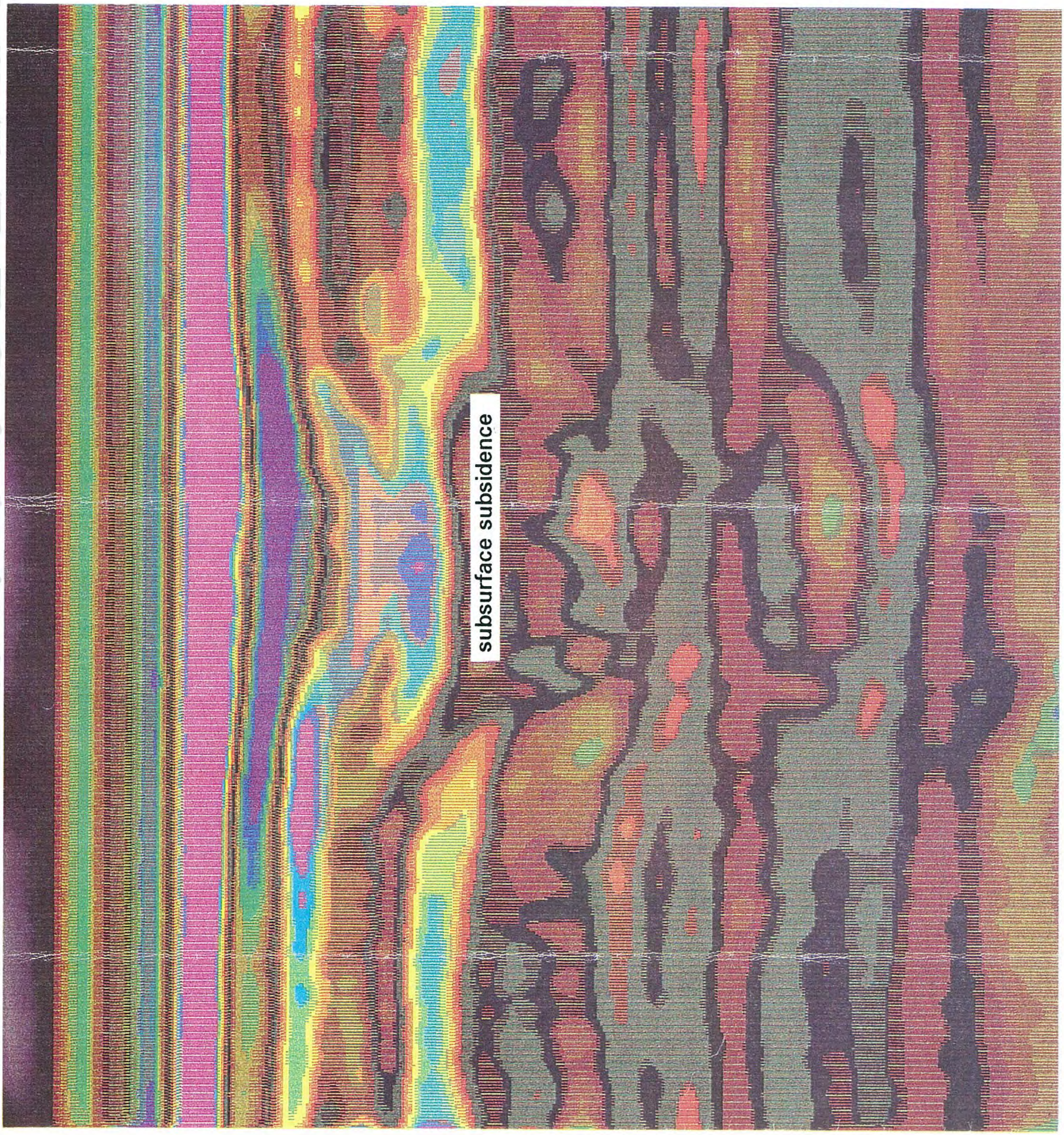
1. Deflection - measurements determined from information supplied by means other than GPR are presented across the top of Example 4 for comparison with the GPR data interpretations (2-8) below.

2-4. Construction Thicknesses - representation of layer thicknesses and structural layers of three parts of the road:
   2 - hard shoulder of North-South Wheel Path (NSWP),
   3 - Lane 1 of NSWP,
   4 - Lane 2 of NSWP.

5-6. Delamination at two different pavement boundaries:
   5 - at DBM 2/DBM 1 boundary;
   6 - at DBM 1/HRA boundary.
   (DBM–dense bituminous macadam; HRA–hot rolled asphalt)

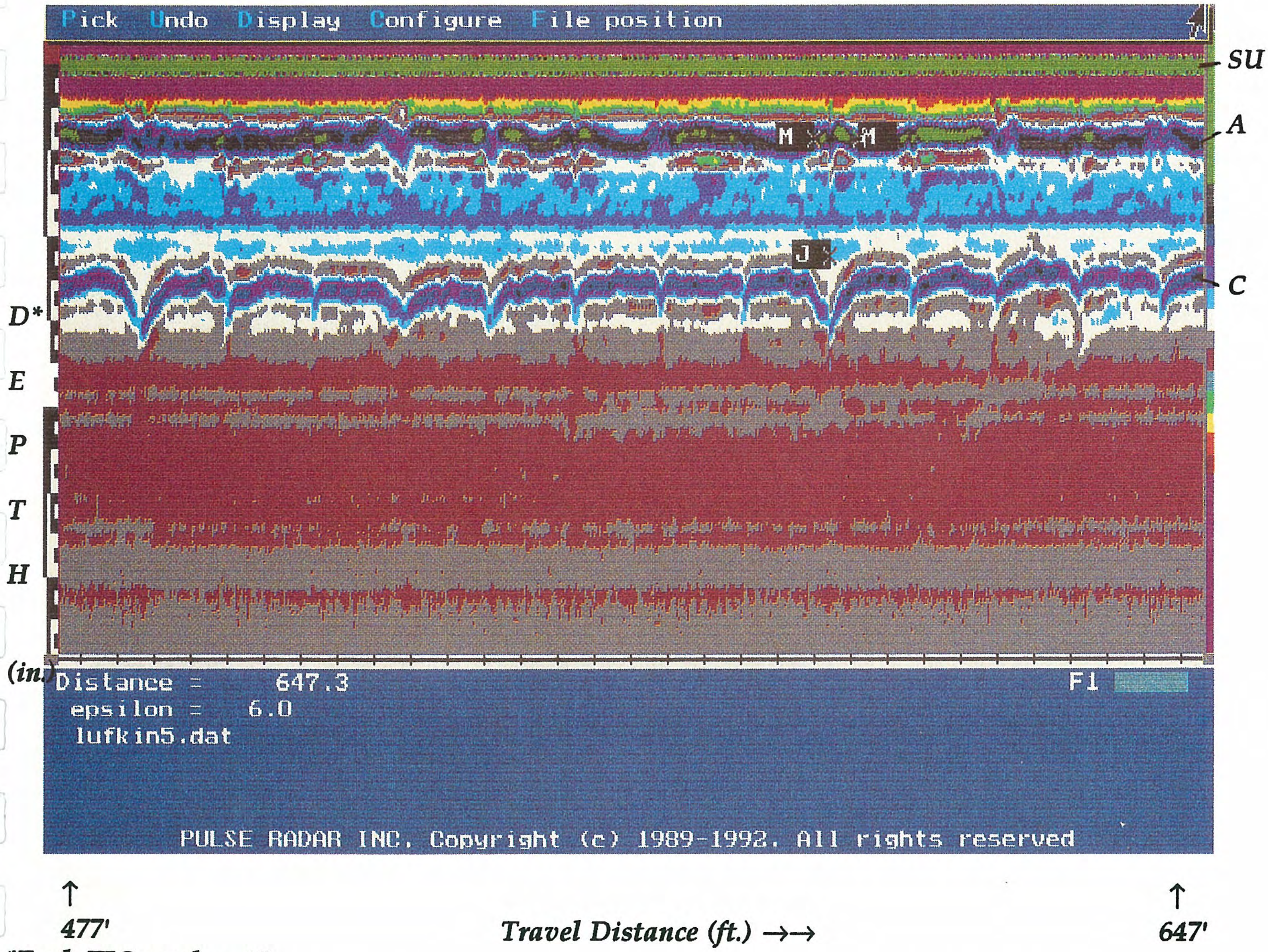
7. Voiding /Poor contact at HRA/sub-base boundary.
8. Other structural details and relocation.

Example of output from GSSI SIR System-10



EXAMPLE 2

U.S. HIGHWAY 59 - CORRIGAN, TEXAS
Asphalt Jointed Concrete
September 1990



**Each TIC mark = 1"*

Feature	*Description*	*Location (ft.)*	*Depth (in.)*	*Color*
SU	*Surface*	*n/a*	*0*	*Green*
A	*Asphalt/Concrete Interface*	*647*	*5*	*Black*
C	*Concrete Base Interface*	*647*	*13.5*	*Dark Blue/Purple*
J	*Joint*	*580*	*n/a*	*n/a*
M	*Moisture*	*577 → 585*	*5.0*	*Green*

NOTE: *Joint spacing is 15 feet. Only one joint location and one moisture location are marked.*

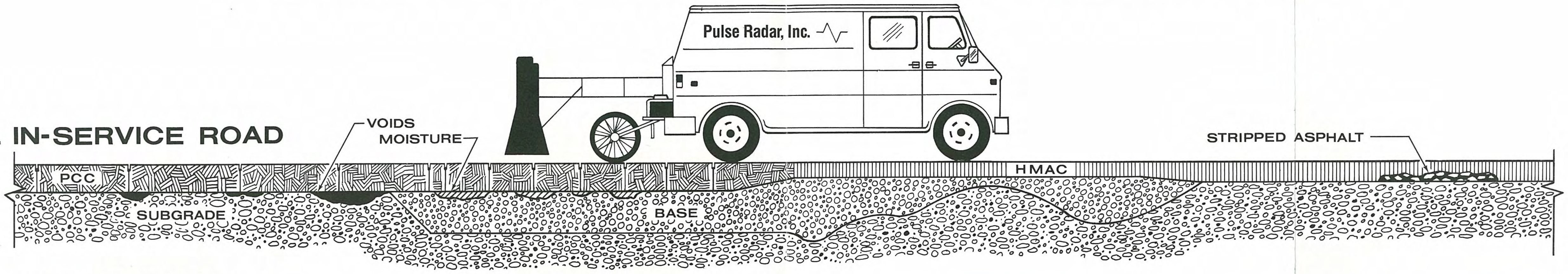
PULSE RADAR, INC.
HOUSTON, TEXAS

(713) 977-0557

THE RODAR™ SYSTEM

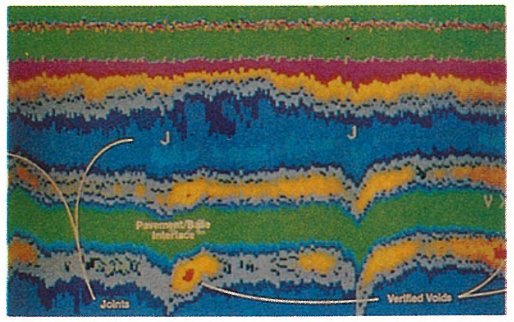
COLLECTION / INTERPRETATION / PRESENTATION

1. IN-SERVICE ROAD



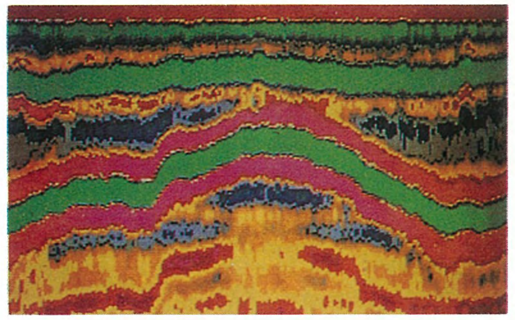
2. RADAR OUTPUT

a.

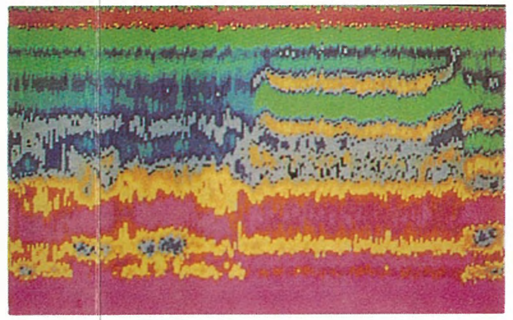


b.

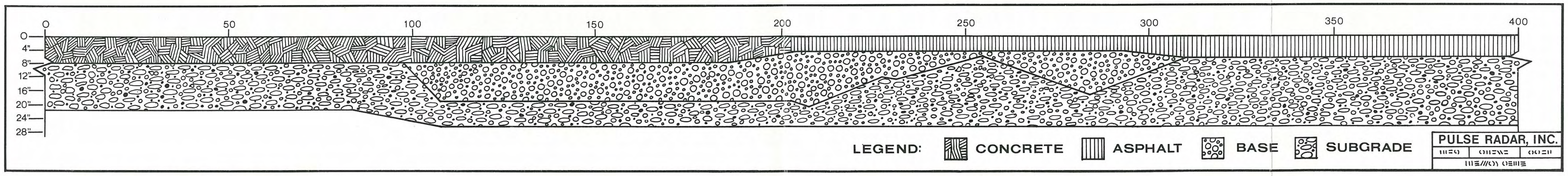
c.



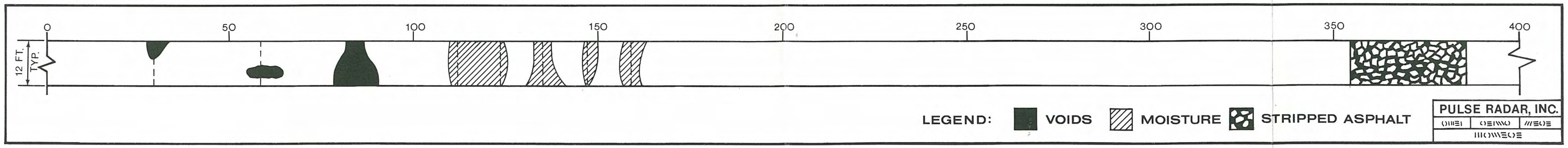
d.



3. THICKNESS DATA PRESENTATION



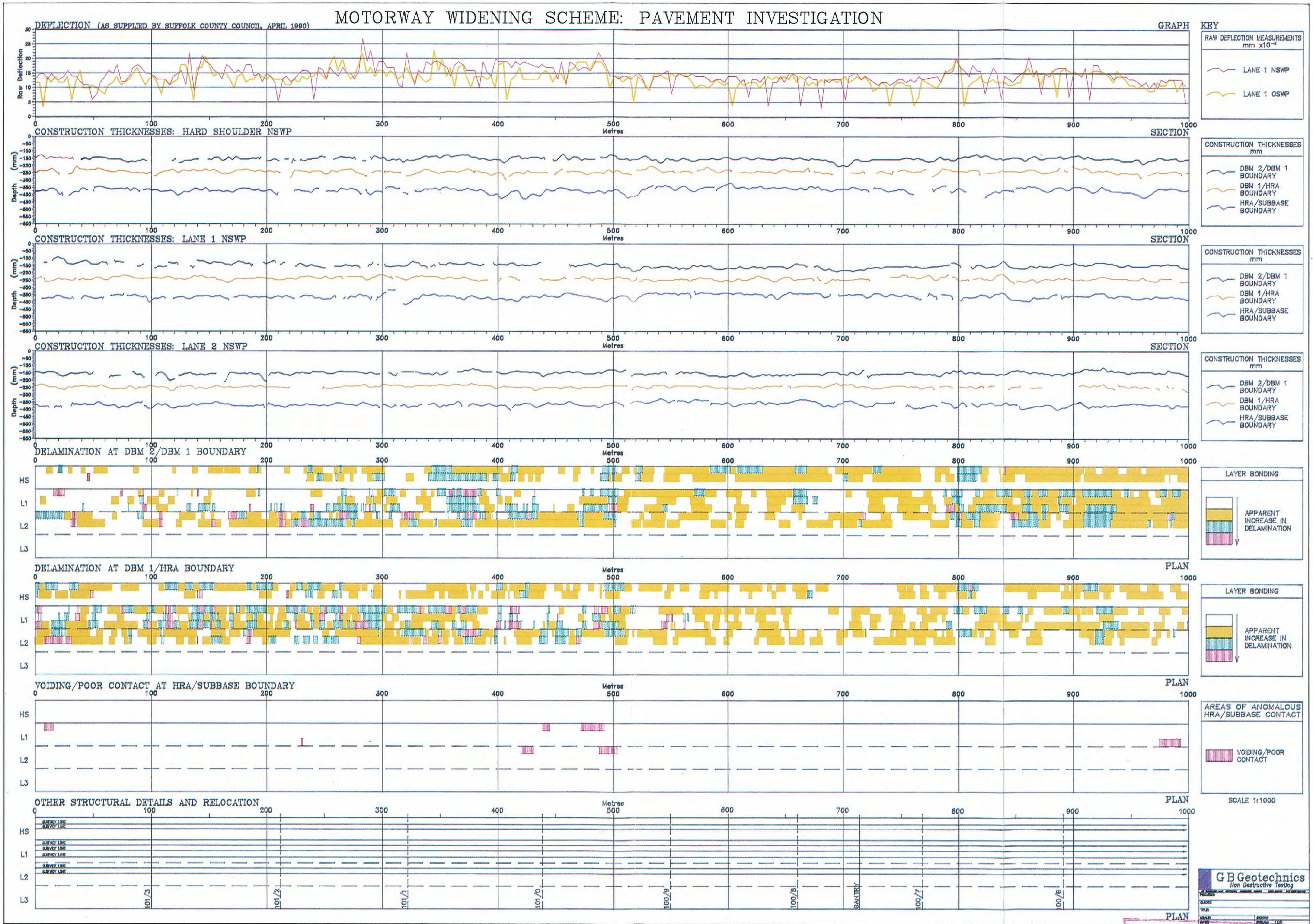
4. PLAN DATA PRESENTATION



RODAR ™ is a registered trademark.

PRESENTATION SAMPLE B

EXAMPLE 4



1.
2.
3.
4.
5.
6.
7.
8.

APPENDIX 2
SURVEY OF GPR EQUIPMENT

QUESTIONNAIRE & SUMMARY OF RESPONSES

GPR EQUIPMENT QUESTIONNAIRE
(Reproduced as presented to respondents)

Radar System

(1) Primary Applications of the System	
(2) Portable or Truck-Mounted?	
(3) Operating Highway Speed	
(4) No. of Antennae Can be Used at Any One Time?	
(5) Digital System?	
(6) Power Supply	
(7) Dimensions and Weight	

Antennae

(1) Contact or Non-Contact System	
(2) Are Transmit and Receive Antennae Separate	
(3) Centre Frequency (MHz) and Antennae Dimensions?	
(4) Transmit Pulse Rate (Hz)	
(5) Waveform Recording Rate (scans/s)	
(6) Power Requirements	

Data Acquisition System

(1) Fully PC-Compatible	
(2) Hardware Requirements (a) Computer board (b) RAM (c) Mass storage (d) Hard disk (e) Floppy disk drive? (f) DOS version required? (g) Mouse	
(3) Maximum Data Recording Rate	
(4) Real Time Digital Signal Enhancement	
(5) What Printouts are Available in the Field	
(6) Colour Monitor Requirements	
(7) Distance Measuring Device	
(8) Power Requirements	
(9) Physical Dimensions and Weight	

Software

(1) Display Modes	
(2) Range Gain	
(3) Vertical Filters	
(4) Horizontal Filters	
(5) Inputs/Outputs	
(6) Digital Signal Processing Functions: filtering, deconvolution, migration, range gain, Hilbert Transform, arithmetic functions, etc.	
(7) Data Capturing Software	
(8) Data Recording Software	
(9) Data Display Software	
(10) Data Processing Software	
(11) Data Analysis Facilities	
(12) Is Software Mouse Operated	
(13) Is Software Menu Driven	
(14) Can Data be Transferred To and Used in Seismic Reflection Programs	

Accessories

(1) Fibre Optic Data Links	
(2) Length of Cables from Antennae to Radar Unit	

Cost to Purchase and/or Lease

Unit	Cost to purchase	Cost to lease
Radar Unit/Master Control Console		
Data Acquisition Unit		
Data Analyser		
Computer Interface/Display Control Unit		
Digital Tape Recorder		
Antennae		
Data Processing Software		
Graphic Recorder		
Colour Printer		
Cables		
Distance Marker Device		
Power Distribution Unit		
Miscellaneous		
Training Course in New Zealand, for Time You Estimate Necessary (Approx.)		

SUMMARY OF RESPONSES TO QUESTIONNAIRE

A2.1 Suppliers of GPR Equipment

To obtain appropriate information for a review of the range of GPR equipment available in 1992, a total of 11 companies that manufacture, supply and/or operate GPR equipment were considered for the review of GPR equipment. Some facts about the companies are summarised in Table A2.1.

Table A2.1 Companies that manufacture, supply and/or operate GPR equipment.

Company Name	Contact Personnel	Country	GPR Equipment supplied
Geophysical Survey Systems Inc. (GSSI)	Gregory Mills	UK	GSSI SIR System-10
Pulse Radar Inc.	Anita M Scott	USA	RODAR-II
Sensors and Software Inc.	Steve Cosway	Canada	pulseEKKO 1000
Penetradar Corporation	Anthony Alongi	USA	Penetradar Model PS-24
GB Geotechnics Ltd	Jon Baston-Pitt	UK	Consultants; use GSSI SIR System-8 & in-house developed software
Georadar Research Pty Ltd	Richard Yelf	Australia	Consultants and agents; use GSSI SIR System-10
OYO Corporation	Roger Caldwell	UK	Now merged with GSSI
ABEM	Leif Lofberg	Sweden	Borehole radar equipment only
Infrasense Inc.	Dr Kenneth R Maser	USA	Supply GPR software only
A-Cubed Inc.	Peter Annan	Canada	No longer supply radar equipment
Equipment Surveys and Consultancy for Highway Maintenance	Managing Director	UK	Do not supply radar equipment; consultants only
Bureau de Recherches, Geologiques et Minières	Managing Director	France	Do not supply radar equipment

GSSI Inc., Pulse Radar Inc., Sensors and Software Inc., and Penetradar Corporation were manufacturers of their own brands of GPR equipment in 1992, and also were offering their services as GPR consultants and researchers. Georadar Research were acting as agents for GSSI GPR equipment and offering their services as GPR consultants and researchers. The other companies were either operators or consultants of GPR equipment and borehole radar equipment or suppliers of GPR software. Two other companies, Infrasense Inc., a supplier of GPR software programs, and GB Geotechnics Ltd, a software supplier and potential operator, were approached later in the project for information about the systems they supply.

Of these 11 companies (Table A2.1), four consultants whose equipment covered the range of GPR systems available in 1992 were selected to receive the GPR equipment questionnaire (Table A2.2).

Table A2.2 GPR consultants selected, and the manufacturing companies and equipment they represent.

GPR consultant and/or supplier	GPR equipment manufacturer	Model of GPR equipment manufactured
Georadar Research Pty Ltd	GSSI	SIR System-3, 8 and 10
Pulse Radar Inc.	Pulse Radar Inc.	RODAR-II
Sensors and Software Inc.	Sensors and Software Inc.	pulseEKKO 1000 and IV
Penetradar Corporation	Penetradar Corporation	PS-24

A2.2 Survey of GPR Equipment

A2.2.1 Survey Questionnaire

The questionnaire (see previous 2 pages) was designed to obtain basic and specific information from GPR manufacturers and suppliers about the equipment they supply, specifically about the following five components of equipment and the costs:

- GPR system
- Antennae
- Data acquisition system
- Software
- Accessories
- Cost to purchase and/or lease

A2.2.2 Responses to Questionnaire

The original data provided by the consultants in response to the questionnaire are held on Transit New Zealand file PR3-0070 (and are available for perusal on request). The information is summarised in this Appendix. The systems were then reviewed from the responses, and the GPR system that was most appropriate for use on New Zealand pavements was selected.

When accumulating and assessing data for the equipment evaluation, comparing corresponding information from the different manufacturers was difficult, mainly because the equipment specifications cannot be measured at the same point for the different systems under the same conditions. For example, the pulseEKKO 1000 system is a fully digital system with all timing controlled by a PC, while the GSSI SIR System-10 runs at a fixed clock rate and is analogue until the signal is digitised at the PC.

If a GPR manufacturer produced more than one model of GPR equipment, the most technically advanced system was considered, i.e. GSSI SIR System-10 (and not System-8 or -3), and Sensors and Software pulseEKKO 1000 (not pulseEKKO IV). As different GPR systems operate on different principles, some of the requests were inappropriate for some systems and no reply was received for them.

Numbers in parentheses and headings (in bold type) within Sections A2.3.1 - A2.3.6 refer to the numbers and statements used in the Questionnaire and used in the responses. The basic components constituting each of the four GPR systems considered for this project are listed in Appendix 3.

A2.3 Summary of Responses to Questionnaire

A2.3.1 GPR System

(1) Primary applications for GPR system

Background:

GPR systems that are designed specifically for highway and bridge deck inspection applications are used for non-contacting, near-range applications, and have ground penetration depths of about 2 m. Dedicated systems are easier to handle and produce quality data at an economic rate. High rates of data collection allow the system to be operated at near-highway speeds about 40-80 km/h, depending on the detail of coverage that is required of the survey.

GPR systems that are designed for more general applications may be used to examine a range of underground structures and materials, as described in the Introduction to Part 1 of this report. General application GPR systems do not use high data collection rates and are operated at speeds up to 5 km/h.

Responses:

Equipment designed specifically for pavement and bridge deck inspection applications were GSSI SIR System-10 (manufactured by GSSI), RODAR-II (Pulse Radar Inc.), and Penetradar Model PR-24 (by Penetradar Corporation). These three systems can be used in a profiling mode, i.e. continuously moved over the survey line while being towed by a vehicle.

Sensors and Software supply multiple application equipment, pulseEKKO 1000, that is not suitable for pavement profiling applications. PulseEKKO 1000 is a static system which requires the antennae to remain in one position for a period of time for signal stacking. As this type of surveying is unsuitable for high volume pavement inspection work, the pulseEKKO unit was not considered further in the research for this report.

(2) Mounting of GPR system

Background:

GPR equipment, being designed for different uses, will require different ways of mounting for their transport. For example, portable systems may be loaded into a van or 4WD vehicle for transportation and surveying. The antennae of these portable systems may also be hand-towed along the relatively short survey lines used on a detailed survey of a stretch of pavement or for a bridge deck.

Alternatively, for longer highway surveys where high volumes of data are collected, the antennae can be rack-mounted for permanent or semi-permanent fixing on a vehicle or towed (see (3)), or the complete GPR system maybe permanently mounted in a dedicated vehicle.

Responses:

The GSSI SIR System-10, Pulse Radar RODAR-II, and Penetradar PS-24 are all rack-mountable.

The GSSI SIR System-10 and Penetradar PS-24 are also portable for hand-towing the antennae.

(3) Operating highway speed

Background:

The highway speed at which the antennae may be towed determines the amount, detail and quality of data that a GPR system will collect and thus the recording and processing of data. The speed therefore depends on the type of survey requested and the data acquisition abilities of the equipment. For example, 5-10 km/h is recommended for detailed pavement and bridge deck surveys.

A truck-mounted system operates at speeds between 5 and 100 km/h depending on the detail of data required and the data collection abilities of the system.

Responses:

GSSI SIR System-10 has been used from 0 to 100 km/h, but 2-10 km/h is recommended.

Pulse Radar recommended an operating speed range of about 10-90 km/h for RODAR-II.

Penetradar PS-24 can use unlimited speeds but typically its operating speed range is 0 to 65 km/h.

(4) Number of operating antennae

Background:

Multiple antennae inputs allow the simultaneous operation of antennae with different centre frequencies. If several adjacent and identical antennae are used, a wider coverage per pass is achieved. Alternatively, a set of antennae can simultaneously scan to obtain different data at different depths. While one or two channels are standard, some manufacturers offer four independent channels as an optional extra.

Responses:

GSSI SIR System-10 is capable of up to four channel recording (with the option of additional channels on special order), so that four antennae or antennae pairs of the same centre frequency can be run to collect data from the same depth over the entire pavement width, or antennae of different centre frequencies can be used to collect data from a range of depths.

Pulse Radar RODAR-II is capable of two channel operation with one GPR system. It has the least acceptable antennae arrangement.

Penetradar PS-24 is able to operate on one channel per GPR control unit with the possibility of linking three GPR units for simultaneous recording.

Penetradar PS-24 system has the advantage over the GSSI SIR System-10 of one radar board allocated to each recording channel, allowing for potentially greater data acquisition speeds. The disadvantage with this system is its price, as the price of each of the three radar control units is US$72,500.

(5) Type of recording system

Background:

In any GPR pavement evaluation survey, very large volumes of data are recorded at high data collection rates and later recalled for interpretation. Therefore, reliable high speed and high volume data storage is essential. A digital recording system provides for such rapid collection and recording of large amounts of data. Such a system allows for critical data acquisition parameters such as gain, sampling, scanning and filtering to be set before recording, and later altered during data analysis. If both manual and automatic adjustment of parameters are available to the operator a wide range of control is possible.

Where settings can be stored digitally the operator has full repeatability of the set-up used on a previous run. Digital inputs/outputs allow the system to utilise a wide variety of PCs and PC-compatible devices.

Responses:
All three GPR systems are capable of converting the incoming analogue signal to a digital signal, so they are then able to record and retrieve this digital data quickly.

GSSI SIR System-10 has an MF-10 mainframe which contains the analog/digital (A/D) radar board for GPR data conversion.

Pulse Radar RODAR-II has its A/D converter located in the central control unit.

Penetradar PS-24 has a master control console that controls GPR data conversion, either A/D or D/A.

(6) Power requirements

Background:
For field operation, equipment should preferably be battery powered, or use fuel-powered generators. AC or DC power may be optional, depending on the location where the GPR is to be used. Systems requiring a high operating current for field use pose difficulties with requirements for large amounts of battery power. For office use an optional 110/220 volt AC power supply should be available.

Responses:
GSSI SIR System-10 operates from a 12 volt DC power supply, drawing 180 watts. An AC 110/240 volt, 180 watts power module is also available as an option.

Pulse Radar RODAR-II power supply control unit is operated either by 12 volt DC or 120 volt AC, 500 watts, power supply.

Penetradar PS-24 operates from 12 volt DC (batteries), or a 110/220 volt AC, 750 watt (max) power supply.

(7) Dimensions and weight

Background:
The dimensions determine if the GPR equipment is portable or needs to be mounted in a vehicle. Dimensions and total weights that are given for the systems do not include those of antennae, or of antennae mounting equipment. For dimensions of data acquisition units see A2.3.3(9), and of antennae see A2.3.2(3).

Responses:
GSSI SIR System-10 data acquisition equipment, i.e. the Mainframe and the control/display module, weigh 28.5 kg.

Pulse Radar RODAR-II data acquisition equipment weighs less than 21 kg. Equipment includes antennae transceiver unit, computer, monitor, power supply, and digital audio tape (DAT).

Penetradar PS-24 triple radar system weighs approximately 70 kg and is housed in a van, four-wheel drive vehicle or small truck. Equipment includes computer, printer, monitor, oscilloscope, keyboard, and triple radar system.

For vehicle-mounted equipment, weights of the mounting frames that are required to place and secure the equipment were not included, except for Penetrader PS-24 system.

A2.3.2 Antennae

(1) Position of antennae

Background:
Antennae may be either in near-surface contact with the ground or suspended (non-contact) about 30-50 cm above the ground

Near-surface contacting antennae are generally hand pulled or towed behind a vehicle. They sit in a trolley, sleigh, or on wheels and are towed at low speed. Near-surface contacting antennae generally range in frequency from 80 MHz to 1 GHz.

Suspended TEM (transverse electro-magnetic) horn antennae, of higher frequency (1.0-2.5 GHz), are used for shallow investigations, high speed highway applications, and are rack-mounted on a vehicle.

Responses:
All but Pulse Radar supply near-surface contacting antennae.

All suppliers offer suspended non-contacting TEM horn antennae.

(2) Arrangement of antennae

Background:
The transmit and receive antennae are either monostatic antennae (i.e. the transmit and receive antennae are housed in one unit) of low to high frequency (100 MHz - 1 GHz), or bistatic antennae (i.e. transmit and receive antennae are physically separated as two units) of low to medium frequency (80 - 500 MHz). Bistatic antennae enable WARR (Wide Angle Reflection Refraction) surveys to be carried out for velocity determinations of sub-surface materials.

Responses:
GSSI SIR System-10, Pulse Radar RODAR-II, and Penetradar PS-24 are all supplied with monostatic antennae.

GSSI SIR System-10 is also supplied with some bistatic antennae.

(3) Centre frequency (MHz) and antennae dimensions

Background:
The centre frequency determines the depth of penetration versus the resolution of the data obtained. The higher the centre frequency the less the depth of penetration but the higher the data resolution. Centre frequencies equal to and greater than 500 MHz are best suited to pavement evaluation work because of the thicknesses of the pavement materials and the detail of data required.

The physical dimensions - height, length, width and weight - of the antennae are significant where the equipment has to be moved by hand.

Responses:
GSSI SIR System-10 operates at centre frequencies of 80 MHz to 1.0 GHz for near-surface antennae, and 1.0-2.5 GHz for TEM horn type antennae.

From GSSI's brochure on SIR System near-surface antennae, the lower the centre frequency the greater the dimensions and weight, e.g.

Centre Frequency	Dimensions	Weight
80 MHz	38 x 132 x 84 cm	64 kg
500 MHz	18 x 39 x 42 cm	7 kg
1 GHz	3.8 x 10 x 16.5 cm	1.8 kg

TEM antennae also decrease in dimensions and weight as the centre frequency increases,

Centre Frequency	Dimensions	Weight
1 GHz TEM	102 x 21.7 x 32 cm	6 kg each
2 GHz TEM	60 x 21.7 x 19.3 cm	2.5 kg each

Pulse Radar RODAR-II antenna used for pavement evaluation work has a centre frequency of approximately 1 GHz.

Penetradar PS-24 operates at centre frequencies of 600 MHz to 2.0 GHz.
No physical dimensions were supplied in response to the questionnaire for RODAR-Il and PS-24.

(4) Transmit pulse rate

Background:
The transmit pulse rate determines the rate at which electromagnetic energy is directed into the ground. Higher rates are used for shallow, detailed pavement investigations. The rate may be selected by the operator using software or be pre-set by the manufacturer.

Responses:
GSSI SIR System-10 has an operator-selectable transmit pulse rate ranging from 2 to 78 kHz.

Pulse Radar RODAR-II operates at a set transmit pulse rate of 5 MHz, which is significantly higher than that for the other systems reviewed.

Penetradar PS-24 operates at a transmit pulse rate of 1 kHz.

(5) Waveform recording rate (scans/s)

Background:
The waveform recording rate is determined by the rate at which the analogue to digital (A/D) converter can sample. The data sampling, i.e. 8 or 16 bit, determines data resolution.

Responses:
GSSI SIR System-10 has a waveform recording rate of 0-125 scans/s at 16 bit data resolution.

Both Pulse Radar RODAR-II and Penetradar PS-24 have waveform recording rates of 50 scans/s at 8 bit data resolution.

(6) Power requirements

Background:
Some antennae require a separate power supply and others are powered from the GPR control unit. This information is needed to plan power requirements for field work and to indicate additional weight and bulkiness which may be added to antennae.

Responses:
In the GSSI SIR System-10 the antennae plug into and draw power from the system power supply, which is housed within the MF-10A Mainframe, i.e. the central GPR unit.

Pulse Radar RODAR-II antennae draw power from the power supply/control unit supplied as part of the GPR system.

Penetradar PS-24 antennae derive power from the GPR control console.

A2.3.3 Data Acquisition System

(1) PC compatibility

Background:
If systems are PC-compatible, data can be transferred directly, using a high speed serial link, from the internal mass storage facility of the data acquisition system to an independent PC for data analysis, interpretation and presentation.

Responses:
All three GPR systems are fully PC-compatible.

(2) Hardware requirements

(a) Computer board

Background:
To drive the software, a computer board is either incorporated by the manufacturer into the data acquisition system and/or an external computer is used. Minimum hardware requirements are necessary to operate the system software.

Responses:
GSSI SIR System-10 has a minimum requirement of a 286 PC for its operation.

Pulse Radar RODAR-II requires a 386/20 PC.

Penetradar PS-24 requires a 486/33 PC.

A SCSI (small computer system interface) is necessary for rapid data transfer from the data acquisition system to an external computer.

(b) RAM

Background:
The RAM (Random Access Memory) can be used for file storage allowing instantaneous recall and playback. It can also be utilised for screen scroll, printer functions and running software programs.

Responses:
A range of RAM are required by the three different systems.

GSSI SIR System-10 requires 16 Megabytes (MB).

Pulse Radar RODAR-II - 640 kilobytes (kB)

Penetradar PS-24 - 16 MB.

(c) Mass storage

Background:
The mass storage facility could be a hard disk, digital audio tape (DAT) or optical disk. The hardware required for storage can be incorporated into the data acquisition/radar control unit or be an independent unit such as a DAT recorder.

Responses:
GSSI SIR System-10 has an internal DAT.

Pulse Radar RODAR-II has an internal hard disk drive, an internal 150 MB DAT backup system, and an external mass storage of 1300 MB DAT.

Penetradar PS-24 has an internal 1 GB (Gigabyte) hard disk, and an output to an external DAT.

(d) Hard disk
Background:
A hard disk drive, as well as being a means of mass storage, allows for the use of data-processing software in the field.

Responses:
GSSI SIR System-10 has no internal hard disk drive.

Pulse Radar RODAR-II and Penetradar-24 have internal hard disc drives.

(e) Floppy disk drive
Background:
A floppy disk drive provides a backup for data storage if the hard disk overloads. It allows programs to be loaded from floppy disk to the hard disk or on to digital tape.

Responses:
GSSI SIR System-10 has an internal floppy disk drive, 3.5 inch.

Pulse Radar RODAR-II has an internal floppy disk drive.

Penetradar PS-24 has an internal floppy disk drive, 5.25 inch.

(f) DOS version
Background:
DOS (disk operated system)-based programs can be loaded and used for data acquisition, data file backup, and an initial on-site analysis of data. The versions of DOS used by each GPR system were requested.

Responses:
GSSI SIR System-10 uses DOS 5.0.

Pulse Radar RODAR-II uses DOS 3.1 and later versions.

Penetradar PS-24 uses DOS 5.0.

(g) Mouse operation
Background:
Mouse-operated software is generally easier to move within, compared to using key strokes.

Responses:
All three data acquisition systems use mouse-operated software.

(3) Maximum data recording rate (data point/s)
Background:
The data recording rate can be a restriction to the GPR survey when high speeds and multiple antennae are being used.

Responses:
GSSI SIR System-10 - a maximum recording rate had not been reached by Georadar Research Inc. in 1992. It typically records 512 samples (16 bit) per scan, and with two channels each operating at approximately 45 scans per second.

Pulse Radar RODAR-II has a maximum recording rate of 100 scans per second but information about maximum data points per second was not given.

Penetradar PS-24 has a maximum digitising rate of 1,000,000 samples per second.

(4) Real time digital signal enhancement
Background:
This facility provides immediate feedback of recorded data that enables the integrity of the data to be evaluated. With this facility the user is able to evaluate the selected GPR settings and optimise future settings for on-site conditions.

Responses:
GSSI SIR System-10 and Penetradar PS-24 provide real time digital signal enhancement.
Pulse Radar RODAR-II does not.

(5) Availability of printouts in the field
Background:
For an initial field evaluation and for planning the remaining survey, a hard copy of the data is useful.

Responses:
GSSI SIR System-10 uses a graphic thermal printer connected to the control/display module to obtain laser-quality black and white printouts of data.

Pulse Radar RODAR-II does not produce a printout of data in the field.

Penetradar PS-24 can produce a colour printout (using an external colour printer) in the field.

(6) Colour monitor requirements
Background:
The colour monitor requirements indicate the quality of the colour display. The colour display is useful in the field for monitoring data as they are collected, for monitoring changes made by the digital signal enhancement facility, and for an initial field interpretation of the data. In the office, higher quality colour monitors can be used for further data analysis and interpretation.

Responses:
GSSI SIR System-10 has a 19-cm colour VGA monitor as part of the control/display module. In the office a Super VGA colour monitor can be used for viewing data.

Pulse Radar RODAR-II includes a VGA monitor in their GPR system.

Penetradar PS-24 system includes a Super VGA colour monitor as part of the data acquisition and processing system.

(7) Distance measuring device

Background:

A distance measuring device provides encoded distance information that can be superimposed directly on the GPR data. It allows areas of interest to be referenced and re-visited.

Responses:

GSSI SIR System-10, Pulse Radar RODAR-II and Penetradar PS-24 systems all provide distance measuring devices.

The GSSI SIR System-10 distance measuring device records data at pre-determined distance increments only, thus eliminating the errors that occur when antennae are towed at an uneven rate.

Penetradar PS-24 includes a vehicle-mounted distance measuring device. The most accurate that they provide is an optical device capable of 1.25 cm resolution.

(8) Power requirements

Background:

AC or DC power may be optional, depending on the location where the GPR system is to be used. Systems requiring a high operating current for field use pose difficulties with requirements for large amounts of battery power.

Responses:

All three data acquisition units operate as part of their respective GPR systems and run off the central power supply, as do their radar control units and antennae.

GSSI SIR System-10 operates from either a 110/240V AC or a 12V DC system.

Pulse Radar RODAR-II operates only from a 120V AC, 60 Hz power supply.

Penetradar PS-24 operates from a 110/220V AC, 60 Hz, or from 12V DC power supply.

(9) Dimensions and weight of data acquisition unit

Background:

Physical dimensions and weights of the data acquisition systems were requested to determine if a system was suitable for portable use, as well as for vehicle-mounted use. Monitors for viewing data, keyboards for manipulating data, and equipment for storing mass data were included in the responses.

Responses:

GSSI SIR System-10 Total weight = 28.5 kg

- Mainframe (includes data acquisition unit, digital tape storage unit, floppy disk drive, and DC power supply):
  H = 30.5 cm x W = 29.2 cm x D = 21.6 cm, weight 10.5 kg.

- Control display module:
  H = 44.1 cm x W = 38.1 cm x D = 17.8 cm, weight 18 kg.

Pulse Radar RODAR-II Total weight = 15.8 kg

- Computer: H = 17.8 cm x W = 38.1 cm x D = 43.2 cm, weight 6.8 kg.
- Monitor: Standard 14" (35 cm) desktop variety, weight 4.5 kg.
- DAT: H = 8.9 cm x W = 14.0 cm x D = 24.1 cm, weight 0.9 kg.
- Power supply control unit: H = 13.9 cm x W = 43.2 cm x D = 33 cm, weight 3.6 kg.

Penetradar PS-24 (triple radar operation) Total weight = 57.6 kg
The data acquisition and processing system includes five items and is designed to be rack-mounted in a vehicle.

- Computer:
  H = 17.8 cm x W = 48.3 cm x D = 58.4 cm, weight 14.5 kg.
- Monitor:
  H = 40 cm x W = 48.3 cm x D = 34.3 cm, weight 20.5 kg.
- Keyboard:
  H = 4.4 cm x W = 48.3 cm x D = 26.7 cm, weight 1.8 kg.
- Printer:
  H = 26.4 cm x W = 48.3 cm x D = 17.5 cm, weight 11.8 kg.
- Oscilloscope:
  H = 13.3 cm x W = 48.3 cm x D = 17.5 cm, weight 9 kg.

Note: The Penetradar data acquisition dimensions include the mounting racks for each item.

A2.3.4 Software

(1) Display modes

Background:
Available display modes include scan, wiggle plot, colour gradient map of amplitude versus distance (colour linescan), and the traditional signal voltage versus time (oscilloscope) display. Different display modes provide information on different aspects of the reflected signal and are useful to the operator for interpreting the data.

Responses:
GSSI SIR System-10 provides a variety of display modes including scan, wiggle plot or both linescan and wiggle together, and colour linescan.

Pulse Radar RODAR-II provides an oscilloscope trace and colour linescan plots.

Penetradar PS-24 provides oscilloscope traces, and colour linescan plots.

(2) Range gain

Background:
Range gain is a manually adjusted or automatically set function which allows the operator to maximise the information they can extract from the GPR data.

Responses:
GSSI SIR System-10 has a fully user-controlled range gain or an Automatic Gain Control (AGC) facility.

Pulse Radar RODAR-II is not provided with range gain.

Penetradar PS-24 has a fixed range gain.

(3) Vertical filters
Background:
Vertical filters are used to eliminate high frequency noise and distorted data, enabling the GPR operator to more accurately interpret data.

Responses:
GSSI SIR System-10 has Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) filters.

Pulse Radar RODAR-II is not provided with vertical filter controls.

Penetradar PS-24 provides vertical filtering by the radar hardware rather than by software control.

(4) Horizontal filters
Background:
These filters are used to improve the signal-to-noise ratio of data and to eliminate low frequency signals. They enable the GPR operator to more accurately interpret the GPR data.

Responses:
GSSI SIR System-10 has IIR, FIR, stacking, and background removal filters.

Pulse Radar RODAR-II and Penetradar PS-24 are not provided with horizontal filter controls.

(5) Input/ Output (I/O) Ports
Background:
Input/output ports allow for necessary GPR components and optional accessories to be plugged into the GPR control unit, and to be operated as part of the GPR system.
They can include:

- antennae channels
- hard or floppy disk drive
- printer port
- serial port (RS-232C)
- SCSI port for external hard disk
- port for tape recorder
- external keyboard
- colour monitor and keypad
- 12V DC or optional 120/220V AC input power
- marker/distance measuring device input

Responses:
GSSI SIR System-10 has input and output ports that offer the options of:

- GPR system power supply
- digital tape unit
- 3.5" floppy disk drive
- solid state RAM/ROM disk
- analogue/digital radar board
- antennae
- SCSI serial, parallel and peripheral ports for keyboard, colour monitor and computer printer
- distance measuring device input

Pulse Radar RODAR-ll provides input/output ports for

power supply	printer
digital tape storage facility	antennae
computer, keyboard, colour monitor	distance measuring device

Penetradar PS-24 provides input/outputs ports to:

power supply	printer
digital tape storage facility	antennae
computer, keyboard, colour monitor, and video	distance measuring device

(6) Digital signal processing functions

Background:
The digital signal can be processed using different functions to "clean up" the data so the operator can better carry out the interpretation, e.g. filtering out a particular frequency created by a stray source near the field operation, or migration of data to better define the location of an underground service.

Responses:
GSSI SIR System-10 provides filtering, migration, deconvolution, Hilbert transform, arithmetic functions and others.

Pulse Radar RODAR-ll did not provide information on this facility.

Penetradar PS-24 provides high frequency noise rejection, signal clutter subtraction, and are presently developing a deconvolution process.

(7) Data capturing software

Background:
The data capturing software is incorporated in the main GPR control unit and provides the operator with control over the GPR system. It contributes to the quality of data gathered.

The data capturing software enables the operator to configure hardware parameters, such as the time window to be recorded, the sampling interval, the number of times a record is stacked, and selection of the number of radar signals to be digitised (for more than one channel recording). In addition, the operator can vary the type of data display on the screen and examine the waveform before the GPR system is set to survey mode of operation.

Responses: see combined responses in Section A2.3.5.

(8) Data recording software

Background:
Data recording software enables a header file to precede the actual GPR data. The header file contains parameter selections as well as user comments, test site information, reference locations and other related information. Raw GPR data files are generated in a format compatible with the PC data processing software.

Responses: see combined responses in Section A2.3.5.

(9) Data display software
Background:
Digitised GPR waveforms and location information can be displayed on either an oscilloscope, an internal colour monitor, or an external colour monitor.

The digitised GPR waveform can be displayed as a signal voltage v time display (typical oscilloscope display), a continuous display of individual waveforms or an intensity modulated colour display (colour linescan).

Responses: see combined responses in Section A2.3.5.

(10) Data processing software
Background:
The data processing software works in conjunction with the data acquisition program. Facilities for "cleaning up" the data, i.e. filtering, migration, deconvolution, etc., enable the operator to interact with and better interpret the GPR data in preparation for analysis.

Responses: see combined responses in Section A2.3.5.

(11) Data analysis software
Background:
The data analysis software is capable of thickness determinations of multiple layer pavements, identification of changes in pavement structures and in relative moisture content, identification of voids, of reinforcing steel depth, and of underground services.

Responses: see combined responses in Section A2.3.5.

(12) Mouse-operated software
Background:
Any software package supporting a mouse allows for easier operation of that software.

Responses:
Software from GSSI and Pulse Radar use a standard two button mouse. Penetradar software does not use a mouse.

(13) Menu-driven software
Background:
Software using on-screen menu systems are easier and quicker to use than an operator exactly typing in the command required.

Responses:
Software for GSSI SIR System-10, Pulse Radar RODAR-II and Penetradar PS-24 are menu driven.

(14) Data transfer for seismic reflection programs
Background:
For specialised interpretation of reflection data a number of seismic reflection programs are available. To use these programs to aid interpretation, the reflection data produced by the GPR unit need to be in a compatible format.

Responses:
Both Georadar Research (for GSSI SIR System-10) and Pulse Radar (for RODAR-II) reported that the data produced with their equipment can be imported into seismic reflection packages, but Georadar Research pointed out that "the main difference between GPR and seismic data is size of data sets. Many seismic type packages are not suitable to handling very large radar sections". It would seem that software packages dedicated to the analysis of GPR data are more efficient and are recommended over seismic reflection programs.

A2.3.5 Combined Responses to Questions (7) to (11)

The suppliers did not separate their responses according to the requests because separate software programs are not generally supplied for each function requested. Therefore suppliers' responses are combined for all the requests, and responses are grouped according to supplier.

Software packages were difficult to evaluate without having practical experience of the software. Also most GPR software suppliers were reluctant to submit their products (other than demonstration samples) for evaluation, so any trial of a GPR system will involve the trialling of the software provided by the supplier of the GPR equipment hardware.

(1) GSSI Inc.

SIR System-10 has a fast (machine code level) custom operating system and a dedicated radar board for data capturing.

GSSI produce RADAN-III (as supplied by Georadar Research Inc.), a GPR signal processing software package designed to record, process, analyse and display data acquired with GSSI SIR series equipment. A list of the features of RADAN III is supplied by GSSI and is available from the author of this report.

GSSI's RADAN-III software enables the determination of pavement layer thicknesses (if wave velocities are known), as well as identification of moisture, voids, reinforcing steel, underground services, etc.

(2) Pulse Radar Inc.

Pulse Radar made available a demonstration disk of their data processing software (RDAS). Pulse Radar use RDAS2 software for data capturing specifically PULSE.EXE and PULSES.EXE which write data to disk and tape respectively.

The playback programs PULSE3.EXE and PULSES3.EXE produce two types of graphical displays of the return signal amplitudes. Further details were supplied by the company.

This software is capable of determining layer thickness, locating voids, locating deteriorated areas (stripping) and areas of excess moisture in pavements, together with identifying areas of debonding and delamination in asphalt covered bridge decks.

(3) Penetradar Corporation
Penetradar Corporation has a data capturing system in which the GPR signal is captured in real time from up to 3 GPRs simultaneously. Penetradar Corporation produce Radar Data Acquisition (RDA) and Radar Data Processing (RDP) software. All data can be stored to hard disk or to an internal DAT mass storage backup facility. Details about the features are available from the author of this report.

GPR data can be displayed in:
- Waveform display - continuous display of digitised and recorded waveforms.
- Colour intensity plot - continuous display of radar (GPR) waveforms in colour intensity format.
- RDP (radar data processing) automatic software is currently available for pavement layer thickness measurement, bridge deck deterioration detection, and asphalt cover thickness and reinforcing steel bar depth measurement.

Penetradar Corporation was developing software for void detection and moisture measurement at the time the questionnaire was being answered.

(4) Infrasense Inc.
Infrasense Inc. (not listed in Table A2.2) developed two software packages for the interpretation of GPR data from a pavement investigation. PAVELAYER computes the thickness and properties of pavement layers, and DECAR is a software package for highway bridge deck condition surveys.

PAVELAYER consists of four functions:
1. The digital data acquisition hardware for the conversion of the analogue radar data to digital format.
2. The software NOTEBOOK, which is used in conjunction with the data acquisition system and is employed for organising the pavement survey data collection, for initiating and terminating data acquisition, for recording pavement section numbers and locations with the collected data, and for keeping a record of the survey.
3. Manipulation of the data, also carried out by the software NOTEBOOK, to organise and present the results in a convenient and understandable way.
4. The software function ANALYSIS is used to analyse the raw radar waveforms and compute pavement layer thicknesses and properties.

Although not specifically mentioned in the correspondence from Infrasense Inc., other software packages would be required for the presentation of data.

(5) GB Geotechnics Ltd
GB Geotechnics Ltd (not listed in Table A2.2) stated that software sales do not fall into the mainstream of their business, that they have developed inhouse software but do not market the product for sale.

Data interpretation employing the GB Geotechnics software packages is a three stage process:
1. The RADCAD program converts graphic records into a digital format, and offers the opportunity for the user to flag any discrete features such as construction joints or cracks.
2. The CRUNCHER program processes the raw digitised data, or amends previously processed data. Data can also be incorporated from other sources, such as deflectograph or falling weight deflectometer. The program is tailored to enable depth, thickness, moisture and time

calculations to be generated in an expedient manner. Selected data can be filtered using a variety of functions.

3. The analysis and presentation process involves plotting by standard graphing software packages. GB Geotechnics use the GRAPHER and AUTOCAD standard software programs, which they suggest are highly suitable.

Examples of data presentation by GB Geotechnics (using GSSI SIR System-8) are presented in Appendix 1 to this report, along with examples from Georadar Research (using GSSI SIR System-10 equipment) and Pulse Radar Inc. (using RODAR-II equipment and RDAS software).

A2.3.6 Accessories

(1) Fibre optic data links

Background:

The transmitter and receiver cables are connected to the GPR control unit by cables. Fibre optic data links are not sensitive to external electronic noise, such as radio signals, and therefore are recommended for the transfer of quality data between the antenna and the GPR control unit.

Responses:

GSSI SIR System-10 uses fibre optic cables and connectors as data link equipment.

Neither Pulse Radar RODAR-II nor Penetradar PS-24 systems use a fibre optic link.

(2) Length of cables between antennae and control unit

Background:

If using GPR equipment that is not mounted on a vehicle, the length of cable from antennae to GPR control unit determines the distance that the antennae can be extended from the data acquisition unit, and hence the length of line that can be surveyed without moving the equipment to another site.

Different length cables for different applications are convenient, e.g. vehicle-mounted GPR work requires a short cable (10 m) capable of reaching from the vehicle to the antennae. For work where the antennae are hand-towed a longer cable is more convenient.

Fibre optic data links improve data quality and overcome cable-handling difficulties sometimes experienced with wire cables.

Responses:

GSSI supplies cable at standard 30 m length, but makes cables up to 200 m long to order.

Pulse Radar RODAR-II is provided with 10 to 20 m long cables.

Penetradar PS-24 is provided with standard 6 m (20 ft) cables with optional lengths.

A2.3.7 Cost to Purchase and/or Lease

Background:

Two categories of information were requested in this section of the questionnaire: the cost to purchase the components, and the cost to lease the components for a period of two months.

The miscellaneous section allowed for other components that the manufacturer chooses to include. The cost of a course to train, in New Zealand, a local operator to use the GPR equipment was also requested.

Responses:
Appendix 4 to this report contains the prices sent by each of the suppliers listed in Table A2.2 as well as a detailed list of the additional components necessary for a pavement evaluation system. These prices are for a system capable of recording data from a minimum of two independent antennae and, in the case of the GSSI SIR System-10, four independent antennae.

All prices quoted here have been given by the three hardware suppliers plus the two software suppliers. They are in New Zealand dollars (1992) and exclude costs for freighting and import handling.

(1) Georadar Research: The purchase price of the "standard" GSSI SIR System-10 is $86,640. This includes a mainframe unit, i.e. radar and data acquisition units, display/control unit, antennae cables, remote marker, manual and training course for two people in the US. As listed in Appendix 4 to Part 1 of this report, additional items bring the price up to approximately NZ$216,500.

The price to lease GSSI equipment is 17.5% of the cost price per month plus freight and import handling costs. However, not all the items in the purchase price would necessarily be required for an evaluation. The approximate price to lease was NZ$39,000 at 1992.

(2) Pulse Radar Inc.: This company was unable to give a price breakdown for the RODAR-II GPR equipment as they sell it only as a "system". Pulse Radar Inc. believe it is not feasible to lease their equipment overseas. With the customer supplying the vehicle, the instruments and equipment necessary for data acquisition of highways and streets, the price is NZ$132,800 f.o.b. (free on board). This price is for the basic equipment, including antenna boom and complete instructions for mounting the equipment. The $132,800 also includes operating and service manuals plus four days' instruction/training at their Houston (Texas) facility for one representative. They are also available for telephone consultation. This price does not include a distance measuring device which would cost an estimated NZ$4,000.

An additional charge of $7,420 is for the Digital Audio Tape (DAT), hardware and software. It is assumed that the price does not include optional accessories such as transmit cases, digital thermal graphic recorder, and colour paint jet printer. These additional costs are listed in Appendix 4 to Part 1 of this report.

(3) Penetradar Corporation: The purchase of a Penetradar PS-24 two radar system would cost approximately NZ$424,000. This would include a rack-mounted double Penetradar PS-24 radar control console, ACPRO data acquisition/processing system with a distance measuring device, a master control console, and software (data acquisition, PavePro and BridgePro). See Appendix 4 to Part 1.

The price to lease the Penetradar Corporation equipment is 15% of the cost to purchase per month of leasing. This price is f.o.b. Niagara Falls, New York, USA, so it excludes freight and import handling costs also. The approximate price to lease in 1992 was NZ$63,600.

(4) Infrasense Inc: They submitted a price of NZ$9,230 (1992 CAD$6,000) a month each for the lease of their software packages PAVELAYER and DECAR. The leasing fees would be applied to the ultimate cost of purchase, should a purchase be made.

(5) GB Geotechnics: They supplied the following price:
For digitisation and pavement analysis software packages NZ$16,000 (1992 UK£4,500)

The costs given by the five suppliers to purchase or to lease their equipment are as follows:

Component	**Georadar - SIR System-10**	**Pulse Radar RODAR-II**	**Penetradar PS-24**	**Infrasense software**	**GBGeotechnics - SIR System-8**
GPR	$86,640	$132,800	$423,980	–	–
Additions	$72,260	$11,420	–	–	–
Accessories	$57,630	$57,630	$52,130	–	–
Software	–	–	–	–	$16,000
Total to buy	$216,530	$201,850	$476,110	–	–
Lease	$39,000	not available	$63,600	$9,230	–

All prices in NZ$ as at 1992

APPENDIX 3
COMPONENTS OF GPR SYSTEMS CONSIDERED FOR TRIAL ON NEW ZEALAND PAVEMENTS

PENETRADAR PS-24

Note: All prices are in New Zealand dollars $(1992).

Basic system, including:	$
• Rack-mounted Double Penetradar PS-24, including 2x TEM Horn antennae	268,880
• ACPRO data acquisition/processing system with DMI	62,900
• Master control console	46,200
• Software:	
- Data acquisition software	9,260
- PavePro	18,370
- BridgePro	18,370
Total Price	$423,980
Grand Total (including additional recommended accessories but excluding the computer facilities)	$476,110

ADDITIONAL RECOMMENDED ACCESSORIES

The following additional accessories are recommended for all the above systems and are included in the grand totals for each system:

• 486/33 MHz computer with:	
- floppy disk drive (1.2 or 1.44 MB)	
- 12 Mb RAM	
- hard drive 80 MB	
- VGA monitor	
- mouse	
- SCSI device interface card	5,500
• Digital Thermal Graphics Recorder	20,780
• External Exabyte tape drive	6,400
• Video display unit/colour monitor, interfaces and cables	11,950
• Colour print jet printer	(estimated) 13,000
Total Price	$57,630

APPENDIX 5
REPORT FROM GB GEOTECHNICS LTD

A non-destructive investigation, using pulse radar, of the pavement construction and condition of three State Highways (SH 2, 56, and 3), and four urban roads (Webb Street, Featherston Street, Mulgrave Street and Lambton Quay, Wellington), New Zealand, carried out in April and May 1993

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CONTENTS

A NON-DESTRUCTIVE ASSESSMENT OF PAVEMENT CONSTRUCTION AND CONDITION

INTRODUCTORY SUMMARY

This report documents an investigation of the pavement construction and condition of sections of State Highways SH2, SH3 and SH56 and of Webb Street, Featherston Street, Mulgrave Street and Lambton Quay in Wellington, New Zealand.

The objective of the investigation was to evaluate the applicability of ground penetrating radar equipment and software in the New Zealand environment. The specific objectives were to show its performance in the determination of: structural layers in pavements, structural layer thickness, moisture changes beneath pavements and location of services.

The results of the investigation show that for most of construction materials encountered, sufficient electrical contrast exists at the boundaries to determine the structural layers within a road. Given suitable calibration information it is then possible to calculate the thickness of each material layer. The accuracy of the measurements is dependent upon the accuracy and reliability of the calibration information available.

Analysis for moisture content within the construction materials has been carried out for the lengths of State Highway surveyed. It is clear that significant variations in the moisture content of the unbound layers exist, and that these are likely to affect the integrity of the roads.

Associated with the moisture content are areas of intermixing between the clay subgrade and sandy gravel basecourse due to hydraulic pumping action.

Other capabilities of the technique have been demonstrated, including the location of underground services and the location of areas of disturbed and deconsolidated unbound material.

Data interpretation was based on experience and knowledge of what signals look like when reflected from bitumen, concrete, compacted unbound material, clay, and so on. Thickness assessment was based on core information provided by the client.

INTRODUCTION

Purpose

This report documents a non-destructive investigation of the construction and condition of sections of three State Highways and four urban roads in the Wellington area of New Zealand, using Impulse Radar.

The investigation forms Stage 2 of a two stage research project "Evaluation of Pulse Radar as a Pavement Investigating Tool" (PR3-0070).

The purpose of the investigation was to provide an evaluation of the applicability of ground penetrating radar equipment and software in the New Zealand environment. The specific objectives were to show its performance in the determination of:

- structural layers in pavements
- structural layer thickness
- moisture changes beneath pavements
- location of services during pavement surveys.

Terms of Reference

The survey was carried out by GB Geotechnics Ltd in association with Works Consultancy Services Ltd, Central Laboratories, at the request of Transit New Zealand.

As the main investigative technique was Impulse Radar, the findings given in this report are based on indirect measurements and the interpretation of electrical and electromagnetic signals. The findings represent the best professional opinions of the authors, based on their experience and the results of destructive methods of coring, drilling and exposure carried out elsewhere on similar materials. Such tests have substantiated most of the conclusions which have been drawn.

This is the final report of this investigation. It therefore supersedes any previous reports whether written or oral, and completes all work currently ordered under this contract.

Overview of Report

This report is in five parts:

- a description of the survey
- the results of the survey
- an explanation of the way in which the results have been presented
- a discussion of the results
- conclusions.

In addition, appendices at the rear of the report describe in more detail the Impulse Radar technique: its principle of operation, scientific theory, capabilities and calibration.

THE SURVEY

The surveys were conducted on 30th April and 1st, 2nd, 4th and 5th May 1993.

Location of Survey Areas
The sections of pavement which were surveyed within the scope of this investigation included sections of three State Highways: SH2, Haywards Hill; SH3, New Plymouth and SH56, Himatangi. Four urban pavements in Wellington were also surveyed: Webb Street, Featherston Street, Mulgrave street and Lambton Quay.

SH2 Haywards Hill
The section of pavement surveyed extended 2km northwards from a zero reference point located at Route Position 962/0.85.

The pavement consists of a dual carriageway with two running lanes in each direction. The survey information was collected from both the left hand wheelpath (LHWP) and the right hand wheelpath (RHWP) of the left lane (Lane 1) of the Northbound carriageway.

SH3 New Plymouth
The section of pavement surveyed extended 2km southwards from a zero reference point located at Route Position 240/3.41.

For the majority of the surveyed section, the pavement consists of a single carriageway with one running lane in each direction. An additional "crawler" lane exists towards the end of the section. The survey information was collected from both the LHWP and the RHWP of the Southbound Lane.

SH56 Himatangi
The section of pavement surveyed extended 2km eastwards from a zero reference point located at Route Position 14/13.00.

The pavement consists of a single carriageway with one running lane in each direction. The survey information was collected from both the LHWP and the RHWP of the Eastbound Lane.

Webb Street
The section of pavement surveyed, extended from Victoria Street in the west to Cuba Street in the east. The pavement consists of a single carriageway with one running lane in each direction. The East and Westbound lanes were both surveyed. The survey information was collected from the LHWP and the RHWP of each lane.

Featherston Street
The section of pavement surveyed, extended between Ballance Street to the north and Johnston Street to the south. The pavement consists of a one-way system with two lanes running in the southbound direction. Both lanes of the carriageway were surveyed. The survey information was collected from the LHWP and the RHWP of each lane.

Mulgrave Street
The section of pavement surveyed, extended between Pipitea Street to the north and Aitken Street to the south. The pavement is part of a one way system heading Southbound and consists of two central running lanes and a bus/parking lane to either side. The Left and Right lane of the Southbound carriageway were both surveyed. The survey information was collected from the LHWP and the RHWP of each lane.

Lambton Quay
The section of pavement surveyed, extended between Stout Street to the north and Brandon Street to the south. The pavement consists of a dual-carriageway with two running lanes and a bus/parking lane in each direction. The Left and Right lane of the Southbound carriageway were surveyed. The survey information was collected from both the LHWP and the RHWP of each lane.

Relocation
All the State Highway sections surveyed were marked at 25m centres in advance of the investigation and all collected data has been referenced to these marks. In the urban roads, marks were at 5m centres.

This referencing system should provide for a longitudinal relocation accuracy of better than ±2m on State Highway and ±1m on the urban roads.

Survey Instrumentation
The system used was the GSSI SIR-8 system of ground penetrating radar, operating at selected centre frequencies between 500MHz and 1000MHz, with all recovered signals recorded on an analogue graphic scanning recorder, enabling on-site interpretation and quality control, as well as providing hard copy permanent record for off-site analysis.

The data was collected at a survey speed of 5 km/h, the equipment being carried in and operated from a survey vehicle with the transducing elements towed from the rear.

Survey lines were profiled using transducers with centre frequencies set at 500MHz and 900MHz operated at varying control settings. This multi-frequency approach was adopted in order to obtain as complete a characterization of the subsurface as possible.

In full scale investigations, working to a fully specified brief, arrays of up to four antennae are deployed to maximise recovered information and minimize traffic disruption.

In this research project, a single radar system was used and therefore a number of survey line positions were repeated to provide a range of data from each position.

Survey Logistics
All surveys were conducted during the daylight hours with normal traffic flow conditions.

The traffic management provided for the survey took the form of a simple rolling closure and Stop/Go boards where necessary.

Calibration and Accuracy of Measurement
The results from some 22 core samples were provided by Works Consultancy Services, Central Laboratories in order to provide an accurate calibration of material type and thickness. Values for the propagation velocity of radio energy through the materials forming the pavement structure have been derived from this information.

Different bulk velocity values were derived for each of the sites investigated.

An assessment of material type has been made based on the pattern of reflectivity obtained from both within a particular construction layer and from the boundaries between adjacent layers, compared with the responses obtained from known materials at core locations and from typical construction materials encountered during previous investigations of a similar nature.

Given the variation in the nature and condition of the construction materials encountered within the scope of the investigation, depth assessments for the bound layers can be assumed to be better than ±8% of the quoted figure. Relative accuracy within any section is good to better than ±4%.

For the unbound materials no correction is made for variations in included moisture: depth estimates are expected to be good to better than ±15%.

PRESENTATION OF RESULTS

The analysed results of the radar investigation are presented on the attached sheets, Drawing Numbers SH2-1, SH2-2, SH3-1, SH3-2, SH56-1, SH56-2, WEBB-1, WEBB-2, FEATH-1, FEATH-2, MUL-1 , MUL-2, LAMB-1 and LAMB-2, which combine the analysis of the structural layer thickness with an interpretive analysis of the radar data indicating variations in material properties and the location of buried services.

In the case of the four urban sites, there are two sheets for each site to present the results from the investigation of each lane, whilst for the State Highways each sheet presents the results from a 1000m length of the pavement.

Construction Detail
Continuous thicknesses have been plotted for all of the identified structural components of the pavement, presented as a longitudinal section along each wheelpath of each of the lanes surveyed. The values are based on a moving point average over ±600mm horizontally with a result given at 0.5m intervals.

On the left is the depth scale in millimetres, calculated from the surface at any point. The total depth to the base of each material boundary has been calculated and the boundaries plotted as different colour traces. The colours used and the materials they represent are as follows:

- Blue - base of the seal layer
- Red - base of the basecourse or concrete
- Green - steel reinforcement
- Brown - top of subgrade or other materials

Along any particular record of a material boundary, breaks can be noted in the various traces. This is due to the response from the interface between the two layers at these points being reduced in amplitude such that a reliable assessment of material thickness could not be achieved and indicates areas where the properties of the two materials are similar.

Areas of less well bound materials, or materials with an increased void content, have been represented by zones of black shading. An increasing density of shading from stippling to cross-hatching has been used to represent decreasing compaction or increasing void content.

Areas of poor concrete slab support have been indicated using red hatching beneath the trace used to represent the base of the slab.

All core locations have been indicated on the longitudinal sections and the core logs reproduced at the bottom of the page.

Location of Underground Services

A large number of linear features, which are likely to be services, were detected and located under the carriageway of all urban sections of pavement investigated, ranging in depth from the near surface to a depth of approximately 1000mm.

As a general principal the transverse survey lines will describe the position of main services aligned longitudinal to the pavement and the longitudinal survey lines the branches from these main services.

Where the evidence indicates that these are most probably services, as opposed to point singularities, black circles have been plotted to indicate a service set transverse to the survey line and a thick black trace to indicate a service set normal to the survey line. The location of the resolved services are indicated on the Longitudinal and Transverse Sections. Two sizes are indicated based on estimates of diameter and graded as large and small.

If there is uncertainty in the detection of a service then a '?' symbol has been plotted adjacent to a black circle or the black trace representing the service has been dashed. The Symbol 'X' has been used to represent an unspecified target, thought to be metallic but possibly not a service.

No attempt has been made to classify the located services into type, absolute diameter, or to determine whether or not the service is currently in use.

Moisture Content

Where appropriate, an assessment has been made of the apparent relative included moisture content, for the construction materials down to the base of the pavement construction. The results have been plotted in graphical format, expressed as the difference in travel time, in nanoseconds (ns), between two discrete frequencies.

The horizontal black line represents an average moisture content with peaks and troughs indicating high and low moisture content respectively. Areas of higher apparent moisture content have been highlighted by the use of blue vertical shading.

Where breaks in the trace occur this is due to the boundary at the base of the pavement construction not having been adequately resolved by at least one of the two instruments required for the analysis.

RESULTS OF INVESTIGATION

Radar signals returned from the interior of a structure contain a wide variety of information. Not all this information is of engineering value, and much relates to the electrical properties of the material of which it is made.

The purpose of the analysis therefore is to identify the information contained in the signals which relate directly to the engineering problem in hand.

Some consideration needs to be given to the nature and cause of the signals recorded however, and Appendices A & B at the end of this report give a general explanation of the basic theory and operation of the Impulse Radar technique.

The fundamental information from which measurements are made are:

- the travel time of the signal, which combined with the calibration of velocity defines the depth of target found
- the amplitude and phase of the signal which defines the contrast between the different materials
- the continuity of the signal which shows the shape of the objects found.

Once the various structural components have been identified in the radar signals, the analysis is then essentially comparative. Comparisons can be made firstly within the data collected from similar targets over the total survey, and a basic response of the structure identified. Secondly, comparison is made with the numerous similar structures that we have surveyed elsewhere. Any unusual responses are identified as anomalies.

During an investigation, each survey line will be profiled typically a number of times using a variety of frequencies and equipment settings. The purpose of this is to enable a full characterization of the structure and the results of each individual profile are not necessarily presented.

In the same fashion, both transverse and longitudinal survey lines are usually surveyed. A combination of the information gained from all surveyed lines is then used to enable the fullest possible reporting on the structure. Sufficient figures are generated to adequately illustrate the findings of the investigation.

Moisture Content Analysis Theory

In order to produce a profile of the relative moisture content within the unbound materials the base of these materials must be identified and resolved throughout the entire length of the pavement section within the data collected from both high and medium frequency devices.

Ideally these two data streams should be collected simultaneously to ensure comparison between common points within the pavement structure. Appendix A provides more detail on the theory of moisture analysis.

Moisture content is a bulk property of the pavement and as such is only reported along one wheelpath after the data from both wheelpaths has been analysed and checked for any possible discrepancies.

Although the collected data is not ideal in the above respects, a moisture profile has been generated for the three sections of State Highway surveyed. The results provide an effective overview of the moisture profile of the State Highway sections and indicate the principles of the technique within this trial investigation.

Although a full data set was collected from the urban pavements, the highly variable nature of these evolved pavements prevented a reliable assessment of the moisture content from being made over the short sections surveyed. The main reasons for this being: significant variations in the construction materials, discontinuous material boundaries and the presence of numerous services beneath the pavement.

General Construction and Condition

A description of the construction and condition has been provided below for each of the pavement sections investigated.

SH2 Haywards Hill

The section of pavement surveyed was found to be of flexible construction, consisting of a seal wearing course over sand and gravel basecourse built over the natural sands and gravels, which cover the Greywacke rockhead.

Throughout the majority of the survey area a material boundary was identified at a depth of 160-200mm. This boundary has been assumed to represent the base of the bituminous materials, referred to as seal within the core descriptions.

Beneath this level a layer of varying thickness, but generally in the range 100-200mm, was identified. This generally well compacted material is assumed to be the basecourse. The core information refers to the materials as sandy gravel.

The relatively weak reflection from the base of this layer suggests a similarity between these materials and the underlying materials which are therefore considered likely to consist of unbound sands and gravels. Within these lower materials one area was identified at approximately chainage 255m which appears to be less compacted or deconsolidated.

A large number of additional interfaces of relatively high amplitude were observed at depths of between 500mm and 1400mm. The slope and arrangement of these interfaces suggests that they may be folds or fractures within the Greywacke.

Four areas of disturbed ground were identified which may be the result of local variations in the subgrade geology, or of post-construction deconsolidation. Three of these four areas extend across the full lane width.

SH3 New Plymouth

The section of pavement surveyed was found to be of flexible construction, consisting of a seal wearing course over sand and gravel basecourse over sands and gravels.

Throughout the majority of the survey area a material boundary was identified at a depth of 30 to 90mm. This boundary has been assumed to represent the base of the bituminous materials, referred to as seal within the core descriptions.

Beneath this level, a 70-150mm layer of generally well compacted material assumed to be the basecourse was identified. The core information refers to this material as sandy gravel.

The relatively weak reflection from the base of this layer suggests a similarity between this layer and the underlying materials which are therefore considered likely to consist of unbound sands and gravels.

Two areas of poor compaction or deconsolidation were identified between chainage 1100 and chainage 2000. These are both associated with a thinning of the basecourse.

A signal of relatively high amplitude was obtained from a boundary at a depth of 500 to 1000mm. The characteristics of the response and its depth is consistent with a boundary with materials of volcanic origins.

A variation was observed in the amplitude of the signals reflected from this material boundary. In some areas the response was of low amplitude and the boundary intermittent and poorly defined. This response is typical of areas of intermixing of construction materials or of locally different underlying materials.

Beneath this level, and within the subgrade materials, generally undifferentiated material was recorded to a depth of 1500mm which was the maximum potential scan depth of the instrumental settings used. Three sections of pavement were identified towards the southern end of the surveyed section where the ground is disturbed due to either local variations in the subgrade geology, or to post-construction deconsolidation. All three of these extend across the full lane width.

The construction at some locations, such as between chainage 735 and 860, is consistent with an overlayment in the past.

SH56 Himatangi

The section of pavement surveyed was found to be of flexible construction, consisting of a seal wearing course over sand and gravel basecourse over sands and gravels.

Throughout the majority of the survey area a material boundary was identified at a depth of 50-100mm. This boundary has been assumed to represent the base of the bituminous materials, referred to as seal within the core descriptions.

Beneath this level, a 100-150mm layer of generally well compacted material was identified: this is assumed to be the basecourse. The core log refers to this as sandy gravel.

The relatively weak reflection from the base of this layer suggests a similarity between the basecourse and the underlying materials which are therefore considered likely to consist of unbound sands and gravels.

Within this lower layer the materials were generally found to be homogeneous and well compacted with the exception of a few areas where the response suggested that the materials may either be locally different or less well compacted.

A signal of relatively high amplitude was obtained from a boundary at a depth varying between 500mm and 1400mm. This boundary was well defined between chainages zero and 1000 but less well defined for the remainder of the surveyed area. The nature of the response suggests that this may be a boundary with materials of a high clay content.

A variation was observed in the amplitude of the signal reflected from this material boundary. In some areas the response was of a decreased amplitude and the boundary less well defined and apparently intermittent. This type of response is typical of areas of intermixing of construction materials, particularly where the subgrade has a high clay content.

Beneath this level, and within the subgrade materials, generally undifferentiated material was recorded to 1500mm, which is the maximum depth resolved by the instruments at the settings used.

One area was identified, however, around chainage 1460 where the subgrade is disturbed. This may be the result of local variations in the subgrade geology, or of post-construction deconsolidation. The disturbance extends across the full lane width.

Webb Street

This pavement section comprises a thin layer of bituminous material on an unbound basecourse overlying a clay subgrade. Throughout the majority of the surveyed area, a material boundary was identified at a typical depth of 50-90mm. This boundary has been assumed to represent the base of the bituminous materials, referred to as seal by the core descriptions.

The boundary at the base of the seal is often poorly resolved, suggesting that the quality of the seal in these areas is reduced. The low radio velocities recorded for this material corroborates this, indicating that the seal has a relatively high moisture content.

Beneath the seal, a construction layer of approximately 100-150mm was identified, the base of which was generally well resolved. This generally well compacted material is assumed to be the basecourse, which the core information describes as sandy gravel. Overall, the layer is homogeneous with only minor variations in compaction.

The data suggests that the basecourse overlays clay for most of the area surveyed. In some areas however, the reflectivity is locally reduced, indicating intermixing of materials across the boundary, and the movement of water and clay into the basecourse.

The materials below the basecourse are generally well compacted and homogeneous, with little material differentiation evident below a depth of 500mm, except in areas associated with services.

Sections of the road, particularly between chainage 45 and 65 on the Eastbound carriageway and between chainage 0 and 65 Westbound, indicate that the original pavement structure has been overlaid with varying amounts of material, presumably to maintain road levels.

Many underground services were detected, ranging in depth from 100mm to 1000mm. The majority of the larger services are placed at a depth of 600mm. The transverse section at 85m identifies only two main longitudinal services. The services plotted on the longitudinal section are probably connections to the main longitudinal service placed under the RHWP of the Westbound carriageway.

More services were identified below the RHWP than the LHWP, suggesting that there are more connections to properties on the south of the road than to the north.

Many services were associated with localised reductions in the compaction and homogeneity of both the basecourse and the clay subgrade. These areas are probably the result of trenching and backfilling of the excavation for each service.

Featherston Street
This section of pavement comprises a reinforced concrete slab overlain with bituminous materials. The slab is supported by an unbound granular basecourse.

Throughout most of the surveyed area the bituminous materials appear to be in two distinct layers, each 40-60mm thick, giving a maximum thickness of 130mm over the concrete. The reflectivity of the boundary is higher than expected for two essentially similar materials. This suggests that the compaction of one or both of the bituminous lifts is defective, or that the two lifts have debonded. The calculated velocity for the total thickness of seal material, using the two cores, is low and indicates that the seal may have a high included moisture content.

The boundary at the base of the seal with the concrete is of low amplitude and often poorly resolved, indicating that the degree of bond between the two materials is moderate to good. However, there are several areas where the boundary is of high amplitude and well resolved, indicating probable delamination.

The underlying concrete is typically 150mm to 250mm thick and the condition of the concrete appears to be moderate to good. The concrete is reinforced, typically with longitudinal bars set at 100mm centres and transverse bars at 150mm to 200mm centres. It is not possible to determine from the collected data whether the concrete was constructed in bays, or as a continuous layer: in several isolated areas there is evidence to suggest that it is in bays 5m long.

From the Radar data the base of the concrete is poorly resolved which indicates that there is little voiding immediately beneath the slab and therefore the level of slab support is good.

The base of the concrete was not resolved between chainage zero and chainage 60 along the southbound left lane RHWP where the survey line position coincided with a backfilled longitudinal.

Within the materials below the slab, little material differentiation was evident below a depth of 500mm. Most of the material is well compacted and reasonably homogeneous: it is referred to in the core log as gravel with sand and silt. This material type is uniform throughout the total area surveyed with the exception of trench backfill which is typically less well consolidated and appears to contain imported material.

Of the four urban sites surveyed, Featherston Street appears to have the least underground services. This may be due to the fact that the carriageway is reinforced and that many of the services are placed preferentially below the footpaths.

Mulgrave Street
Overall the general nature and condition of the bound pavement structure, the granular supporting materials and the number of services are very similar to that determined at Webb Street described above.

The seal material from chainages 30 to 120 on the LHWP of the Right Lane is somewhat thicker than the rest of the section surveyed, ranging between 150mm and 200mm above the background average of 50mm to 100mm as determined also by the two cores.

The depth to the bottom of the basecourse is greater than that at Webb Street and is generally at c.300mm to 400mm.

Like Webb Street, the boundary at the base of the seal material and that at the base of the basecourse are often poorly resolved. This implies that the seal material in these areas is defective, and, that the basecourse in these areas may be contaminated with clay and moisture from the clay-based subgrade below. Alternatively, the subgrade may be formed of a similar material to the basecourse.

The major difference between the pavement structure at Webb Street and Mulgrave Street is the nature and condition of the materials below the basecourse. At Webb Street the subgrade is entirely clay based with only a few granular inclusions, most of which appear to be associated with service trenches.

At Mulgrave Street the nature and condition of the subgrade varies widely. Whether this is due to variations in the drift geology, or is a result of trenching and excavation to lay services, is unknown. It is likely to be a combination of both.

Extensive areas of material disturbance have been identified in the subgrade. These areas extend across the full width of the road which suggests that they are related to the subgrade geology. The areas of worst disturbance (shaded black on the accompanying drawings) appear to be in areas of gravel based subgrade, while the areas of better consolidation coincide with clay-rich areas.

Many underground services were resolved, set transverse to the pavement, the majority located between a depth of 400mm and 1000mm. Much of the LHWP of the left lane runs directly over two main longitudinal services at depths of approximately 600mm and 900mm.

Lambton Quay

This section of pavement comprises unreinforced concrete overlain by a thin layer of bituminous material. Throughout the majority of the surveyed area, a material boundary was identified at a typical depth of 60-110mm. This boundary has been assumed to represent the base of the bituminous materials, referred to as seal by the core logs.

The boundary at the base of the seal with the concrete is often poorly resolved indicating that the degree of bond between the two materials is moderate to good. There are a few areas where the boundary is well resolved implying that the bond may be poor. The derived velocity for the seal material, using the two cores, is low and suggests that the seal may have a high included moisture content.

From the core information and the radar data, the material which underlies the seal is comprised of unreinforced concrete typically 250mm to 350mm thick. Within the body of the concrete a flat, intermittent, boundary was resolved, occurring at or above mid-depth. This indicates that the concrete was laid in two lifts. In general, the top layer appears homogeneous and well compacted, whereas the lower layer appears to be of a slightly lower quality with areas of disturbance and reduced compaction. The lower concrete units appear to be in good condition at the two core locations.

The base of the concrete is generally well resolved. In most cases the degree of slab support is moderate to good but in some areas, denoted with red shading on the longitudinal sections, the granular material supporting the slab is voided.

Within the subgrade material below the slab a boundary is occasionally resolvable at a depth of between 500mm and 700mm. Typically the material is consistent with a clay based subgrade, described in the cores taken from the LHWP of the Right Lane as clayey gravel, clayey sand and clayey silt. From the Longitudinal section taken along the Right Lane it is evident that the nature and degree of compaction of the subgrade materials is reasonably constant throughout the survey length.

This contrasts with the longitudinal section of the Left Lane which shows the subgrade materials to be highly variable. Much of this change is probably due to trenching and ground disturbance associated with the emplacement of services.

Many services were resolved, ranging in depth from 250mm to 1000mm. The larger services resolved under the LHWP of the Left Lane at chainages 50 to 60, and 120 to 130, are probably the main longitudinal services aligned longitudinally to and running down Waring Taylor Street and the next junction further south.

Several unspecified targets, probably metallic, were resolved at or near the boundary between the seal and the concrete. These have been denoted with the symbol 'X' on the longitudinal section. Their exact function is not clearly understood but they may either be services or steel dowels associated with concrete jointing. These features map across wheelpaths in general, but not in their exact position.

DISCUSSION

The specific objectives of this survey were to assess the performance of ground penetrating radar in the determination of:

- structural layers in pavements
- structural layer thickness
- moisture changes beneath pavements
- location of services.

In addition to these points, a number of other aspects of structural interest have been identified:

- unusual material velocities
- disturbance and deconsolidation of the subbase and subgrade layers
- clay pumping.

Each of these seven points are discussed separately below.

Identification of Structural Layers in Pavements
It has been shown that for the majority of construction materials encountered sufficient change in velocity occurs at the material boundaries to provide a reflection between one material and the next - indicating a vertical change in the structural layers. Within each of these layers, or rather between the resolved interfaces, individual characteristic responses can provide the additional information needed to apply a material description to the layer. Where this detail is unclear, then an isolated, targeted core can provide this information, which can then be extrapolated across a significant distance between the horizontal construction changes that are identified.

Where the boundary between structural layers such as that between a seal layer and a basecourse is not resolved no distinction between the layers has been made. The most probable reason for the lack of electrical contrast between the layers is that the lower part of the bound unit may have disintegrated.

Structural Layer Thickness
Where material boundaries were resolved a layer thickness has been provided. To convert a travel time reading into a depth measurement a well established function is employed. This function relies on a reliable assessment of the radio frequency velocity for the material under investigation.

The velocities derived from the radar data and the core logs have been given in Appendix C.

Since obtaining layer thickness by this method relies on the reliability of the derived material velocity, the accuracy can depend upon the selection of calibration material. The accuracy of core measurements is therefore significant, of particular importance is the accurate location of the core sample along and across the road, and how the core log describes anomalies such as broken, or incomplete samples.

When using derived material velocities the standard procedure is to reject any velocity that falls outside one standard deviation of the mean of all values. For this trial project the number of calibration samples was low, and the samples could not be treated in this fashion.

A spurious result could therefore have a significant effect upon the applied velocity and ultimately on the reported thickness.

From this and other similar work, a number of points can be made concerning the use of cores as a means of providing the calibration for continuous layer thickness:

- the overall material composition of the road structure has a significant effect on the propagation velocity of radio waves within it, and therefore the overall accuracy with which radar can be used to assess the thickness with no indication of the composition.

- variations in composition along a carriageway of the same general construction are unlikely to significantly affect the accuracy of assessment provided that a standard velocity can be established. The consistency of the two seal velocities at the Featherston Street site supports this point.

- the radar data can be used to select the optimum location from which a core will provide a valid calibration data. Experience has shown that a precise match between the location of radar and coring sampling is necessary.

- a single core location selected on this basis is sufficient for calibration purposes in any length of common construction type: no significant increase in accuracy is achieved by increasing the number of core samples.

Moisture Changes Beneath Pavements
Due to the extreme variations in the thickness and nature of the unbound construction materials encountered within the investigation of the State Highways, the base of the subbase materials has not always been adequately resolved by both instruments. Therefore analysis for variation in moisture content has been difficult and the results presented here are not necessarily representative of the full capabilities of the technique in this area.

The highly evolved nature of the urban pavements prevented a reliable assessment of the moisture content over the short lengths surveyed. This is not a failure of the survey but does indicate that the technique is probably not suitable for moisture evaluation by these means over short lengths of complex urban pavements.

With respect to the future use of this approach two points should be made: firstly, any future survey should involve the two systems running simultaneously so that any significant variations in material thickness will not cause difficulties when comparing data streams from slightly mismatched locations.

Secondly, the frequent detection of clay rich materials within the granular material may explain why the higher frequency transducer was unable to resolve the base of the granular layer as often as the lower frequency transducers.

As detection by both frequencies is necessary to provide direct moisture content measurement this suggests that such measurement may be problematic in the New Zealand road network if high clay content materials are widespread. Please refer to the discussion on clay pumping on page 30.

Location of Services
When reporting on the layout of underground services the information is normally presented in plan and section, which indicate the depths, relative size, and positions of individual services.

To achieve this, the information is collected from profile lines set transverse to the main pavement axis which locates the main services. The information from each transverse survey line is then compiled to generate a plan of the total pavement area.

The investigation of each urban site in this survey concentrated on the collection of longitudinal profiles to determine the pavement construction and condition. These longitudinal profiles will detect connections from the main services but will not comprehensively map services laid parallel to longitudinal survey lines. The connecting services have been indicated on the longitudinal sections, and the main services indicated on the transverse sections provided. A much higher level of detail on the layout of services can be provided when the survey approach is geared towards the service location.

Unusual Material Velocities
It should be noted that radio velocities in typical bituminous materials in the UK range between 10.5 and 13cm/ns. The velocities determined from the seal materials surveyed in New Zealand in this investigation are much lower and range from between 7.3 and 8.8cm/ns.

These lower velocities could be explained either by an unusually high moisture content, or by the different aggregate type used. As further work and research is done on New Zealand roads, those velocities which represent typical and defective materials will become clearer.

These results may also show another phenomenon which has not been noted before in the analysis of pavement construction. Some core results, when compared with the radar time records, indicated that the velocity increased with depth. Normally increasing moisture content would be expected to dramatically reduce radio velocities through unbound materials.

Clay Pumping
Across the majority of sites surveyed where the subgrade is clay rich there is evidence of extensive mixing between the subgrade and the granular roadbase.

A good example where clay subgrade appears to have mixed with the unbound pavement materials is at Himatangi SH56 between chainage 1100 and 1200. The sandy gravel basecourse is deconsolidated, the subbase - subgrade boundary is only intermittently resolved, and the moisture profile shows a trough.

Two reasons for clay pumping can be put forward: firstly, the generally thin bound layer may provide little protection from vibrating traffic which would lead to cyclical forces that would promote the mixing of these materials. Secondly, clay is more likely to flow because of the more plastic state of the roadbase caused by elevated moisture content. The latter could be associated with cracking of the thin bound layers of the roads surveyed in this project.

Where an assessment of the moisture content is not possible a plot of areas of clay pumping may prove useful since a correlation is likely.

CONCLUSIONS

The main survey objective was to determine the performance of ground penetrating radar and associated software in the New Zealand environment to determine:

- structural layers in pavements
- structural layer thickness
- moisture changes beneath pavements
- location of services during pavement surveys.

The conclusions relating to each of these is discussed below:

- Where the integrity of the construction is good the structural layers have been successfully resolved in both the urban roads and the State Highways. The non-resolution of boundaries between bound materials is often indicative of the breaking up of the bound material, while boundaries between unbound materials may not be detected where intermixing has occurred.

- Layer thicknesses have been resolved for both the urban roads and the State Highways. Accuracy and continuity is likely to be better for the State Highways where the construction is more uniform. The radio frequency velocities determined are unique to the New Zealand environment. This emphasizes the importance of reliable local calibration data in the determination of material thickness and type.

- It has been possible to produce a moisture assessment for the State Highways. It is apparent that there are significant variations both within and between the pavement sections surveyed. We recommend a comparison of peaks and troughs in the moisture profile with the surface condition of the road, the local topography, and the presence and effectiveness of the drainage facilities.

- It is possible to identify buried services from data collected at scheme level pavement assessment speeds. It is clear however that by simply reporting from two profile positions comprehensive mapping of services is not possible. The level of reporting provided here may be of value as an add-on to a scheme level road survey, but a targeted service investigation is required to comprehensively map all buried utilities.

In addition to these main points, the survey findings highlight certain aspects related to the consolidation of the road materials and to clay pumping:

- The consolidation of the subbase and subgrade materials has been assessed and areas of disturbance and reduced consolidation plotted. Where defects have been mapped on the State Highways they tend to extend across the full road width - in the urban roads they tend to be more localised because of more variable construction, extensive reinstatements, and buried services.

- Extensive areas of clay pumping within areas of clay-rich subgrade have been mapped. It is recommended that the surface condition of the roads in these areas is inspected to assess the relationship between clay pumping and pavement deterioration.

APPENDIX A: THE NON-TECHNICAL BASICS OF IMPULSE RADAR

Principles

Impulse radar is a technique for examining the interior of solid materials (the ground, walls, roads...), non-destructively using radio waves. The principles are much the same as for the better-known "everyday" radar used in the earth's atmosphere to locate and track aircraft or rain clouds. With both techniques pulses of radio waves sent from an antenna move through a medium reflecting or bouncing off any sudden changes in its composition, such as objects imbedded in it. The reflected radio wave is detected, typically by the same transmitting antenna, thus revealing the existence of the imbedded object. Analysis of the reflected wave can yield information on both the location of the imbedded object and certain of its properties (size, shape, composition...).

Capabilities

Just as everyday radar can find aircraft or rain clouds in the earth's atmosphere, so impulse radar can find objects imbedded in or behind solid materials: steel reinforcing bars inside concrete, metal fixings behind a brick wall, and so on.

But whereas everyday radar typically operates in only one medium (air), albeit of varying density (lower and upper atmosphere, outer space), impulse radar can operate in various media (earth, brick, stone, concrete, bitumen...). This includes operating in air, water or other fluids when these fluids are inside solid media: for example, the air pockets in gravel or moisture between the plaster and brick layers of a wall. Indeed, one use of impulse radar is to detect the presence of air or water, often where they should not be: unwanted voids in supposedly solid concrete or water films trapped between the asphaltic lifts of highway construction.

Advantages

Impulse radar is an extremely flexible analysis technique with many advantages:

- It is non-destructive; it can discover what's inside a wall without tearing it down, or the construction of a road or bridge without drilling core samples.

- It is quick; a road can be surveyed by towing an instrument at, say 50 kph, giving data for many kilometres of that road in less time than it takes to take one core sample.

- It is versatile; it can be used for walls, roads, bridges, earth... any time of the day, in virtually any weather, with portable equipment and as few as one or two operators.

- It is powerful; data collected can often give preliminary results on the spot, on-site and can yield more detailed results after computer analysis in an off-site laboratory.

- It is inexpensive; because of the advantages listed here, impulse radar can often provide far more information per dollar than other techniques.

Theory and Operation

Appendix B on the next page describes some more-technical aspects of impulse radar: its scientific theory and an explanation of how a typical survey is conducted.

APPENDIX B: THE THEORY AND OPERATION OF IMPULSE RADAR

Method

Surveying with impulse radar is achieved by drawing a transducer over the surface to be investigated at a slow speed: pulses of energy are transmitted into the material which are reflected from internal surfaces or structural changes. The returning signals from each vertical scan build, as the transducer is moved, into a continuous profile of the interior of the material.

Frequency

Each transducer is set to a specific centre frequency: higher frequency devices can resolve smaller targets but lower frequency devices achieve better penetration. By using data streams from several different frequency transducers a composite profile of the sub-surface can be drawn and the information from the differing responses can be correlated.

A plane of energy is in fact transmitted rather than a ray or beam: this plane is normally set parallel to the direction of the survey, such that all information streams refer to material directly beneath the survey line.

Radio waves passing through a homogeneous isotropic medium will travel at a velocity determined by the relative permittivity of the medium and its conductivity at the propagating frequency. At the interface between that medium and another of differing permittivity or conductivity a proportion of the energy will be reflected back and the remainder will continue at a new velocity. The strength of the reflection is determined by the electrical contrast between the two media. The recording system measures the travel time to and from such an interface, and the amplitude, phase and frequency of the returning signal.

Discrete targets within a medium may cause energy to be reflected and scattered: some discontinuities of high contrast and confined dimension may resonate at radio frequency (this applies particularly to voids and conductive targets). The setting up of any resonance and its associated frequency is largely determined by the dimension of the target and its material. The presence of an ionising contaminant within the materials can also give rise to resonant eddy current signals, which can normally be separately identified by virtue of their amplitude and phase.

Penetration Limits

Signal attenuation is per unit wavelength, however and sets depth of penetration limits on this for any given frequency in any material, which will obviously be shallower for higher frequencies. Equally, target resolution decreases with increasing wavelength, thus the selected frequency is a balance between penetration and resolution.

Since signal attenuation is largely a function of the conductivity of the materials under investigation, the lower frequency transducers are operated for deeper penetration through soils and fill which are generally more conductive than structural materials; the higher frequency components of the spectrum are rapidly attenuated with increasing depth in unbound material, but the resolution of the longer wavelengths of the lower frequency components tend to integrate out the finer detail of any feature. Overlapping information, however, is available from all frequencies.

Taking the elements of total velocity through each material, together with the overall pattern of reflectivity and the presence of resonating targets, a good assessment of material condition can be achieved.

Material Interface Recognition
It is possible to predict the electrical contrast between materials, and to a reasonable order of accuracy, therefore, predict the likely reflectivity from the interface between these two materials. The recording levels were therefore set for the survey such that the base response from fully cured, but possibly waterlogged, reinforced concrete would give rise to a low amplitude response.

Reflectivity
A high amplitude response recorded from within the concrete can be caused by a number of conditions. The most likely causes are poor contact between the materials, a low level of compaction or a high moisture content. These conditions would give rise to a stronger than normal electrical contrast at a material interface or from a distinct zone within a body of concrete.

Detection of Underground Services
Where a degree of uncertainty in the detection of a service exists then this has been indicated on the sections. There are a number of reasons for reduced confidence relating to the interpretation of a signal as a service, these include:

1. Variable or inconsistent character or amplitude of the response between adjacent survey lines or between differing frequencies on the same survey line.

2. Lack of adjacent survey lines to provide corroborative data.

3. A very weak amplitude response or a very small apparent diameter.

4. Poor definition of a service due to its location in locally disturbed ground, such as poorly backfilled trenches, where minor voids and inclusions may mask, or be mistaken for, buried services.

Moisture Analysis
Over the range of frequencies used within the scope of pulsed radar investigations both the real and the apparent permittivity of most dry structural materials is constant, mainly because resonances below 20GHz have not been found in geologically sourced materials.

The same does not apply to water which has a well established resonance at 2.4GHz, which due to consequential electrical losses results in a rapid change of apparent permittivity around that frequency.

In the case of pulsed echo sounding systems, the apparent permittivity of materials containing free moisture increases rapidly as the centre frequency of propagation approaches this value: the travel time increases for higher frequencies.

To take advantage of this relationship, the data streams from two independent antennae systems are necessary, where the centre output frequency of the devices are separated by more than one octave and set either side of the corner frequency for microwave absorption. Note that in practice it is necessary to use a frequency removed from the resonant frequency of the water: too much absorption would result in undetectable energy levels being returned from depth which would make redundant the whole approach.

Since it has been shown that other non-frequency dependent variations in the transmission properties of the material, such as composition, density or thickness, will be equal for both propagating waves set to either side of the transition corner frequency, any difference in travel time to a defined point within it will be proportional to the moisture content of the material.

Software

Various in-house developed and commercially available software packages are used in the analysis of the collected data in order to convert the travel time values recorded by the radar system into values relating to thickness and depths of material layers.

The packages used include:

- RADCAD
- CRUNCHER
- GRAPHER

APPENDIX C - DERIVED VELOCITIES

The values derived for the velocity of propagation of radio energy through the construction materials, on which all calculations of material thickness have been based, are:

Location/Core	Material	Velocity (cm/ns)
SH2 Haywards Hill	Seal	8.8
SH2 Haywards Hill	Gravels	9.8
SH3 New Plymouth	Seal	8.4
SH3 New Plymouth	Gravels	10.1
SH56 Himatangi	Seal	8.5
SH56 Himatangi	Gravels	9.8
Webb St Core 1	Seal	8.2
Webb St Core 1	Gravels	9.8
Webb St C2	Seal	8.3
Webb St C2	Gravels	9.0
Featherston St C1	Seal	6.9
Featherston St C1	Concrete	10.3
Featherston St C2	Seal	7.3
Featherston St C2	Concrete	9.1
Mulgrave St C1	Seal	8.8
Mulgrave St C1	Gravels	8.5
Mulgrave St C2	Seal	7.7
Mulgrave St C2	Gravels	10.6
Lambton Quay C1	Seal	8.1
Lambton Quay C1	Concrete	9.1
Lambton Quay C2	Seal	7.6
Lambton Quay C2	Concrete	9.2

APPENDIX D - PROJECT STAFFING

GB Geotechnics provides a structured management of all projects within a Quality Assured scheme audited to BS5750/ISO9000 (February 1994), but also closely monitors Quality Control at all stages. The company is an Associate Member of the British Institute of Non-Destructive Testing, and a founder member of the Impulse Radar Users Association.

The management team for this project included:

Project Director
Jonathan Baston-Pitt, BSc. Technical Director, has some 10 years experience in the application of non-destructive testing to the structural investigation of engineered structures, with particular expertise in Pavement Maintenance.

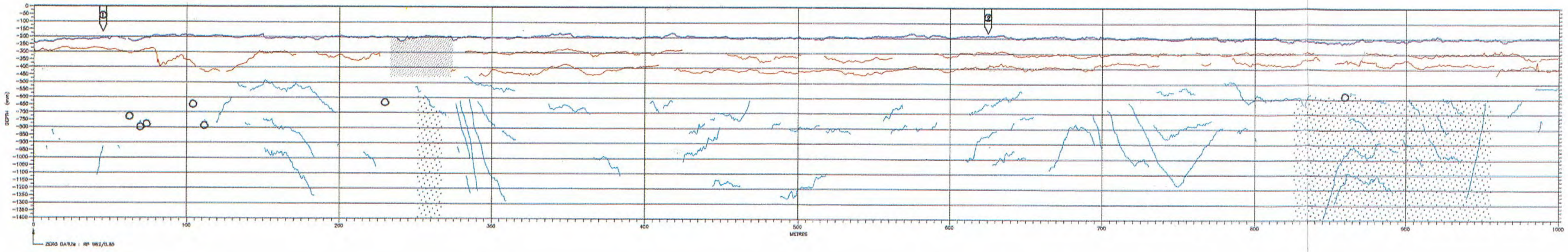
Project Managers
Nicholas Fleming, BSc. Project Manager with 8 years experience in the non destructive investigation of structures with particular responsibility in GBG for the mapping of Underground Services and Utilities. Personal responsibility for investigations of many town centres within the UK to map the location of existing services prior to pedestrianization schemes.

Mark King, BSc. Project Manager with 7 years experience in the non-destructive investigation of structures with particular responsibility in GBG for the investigation of pavements. Personal responsibility for the investigation of over 3000km of pavement within the UK including the M25, M4, M5 and other major motorways and trunk roads.

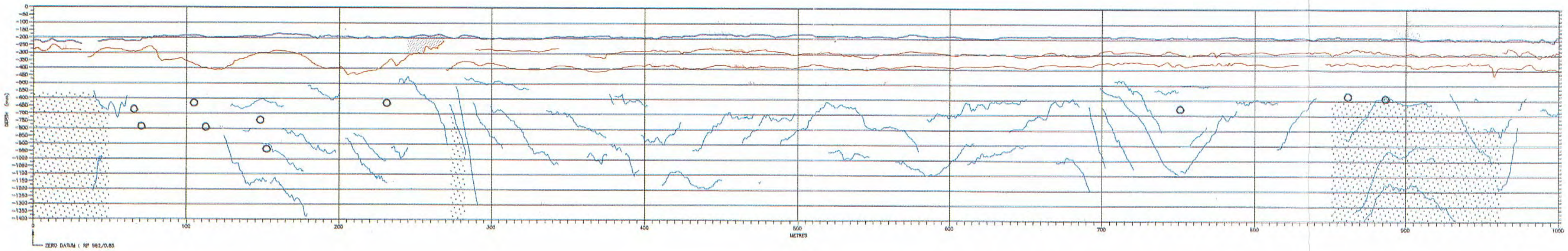
Site Operations Manager
Nicola Kilgour, BSc. 5 years experience in the collection and analysis of pulsed radar data. Responsibility for logistical arrangements and maintenance of data quality.

HAYWARDS HILL, SH2 : NORTHBOUND LANE 1

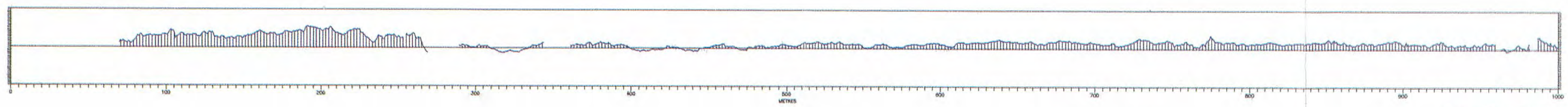
CONSTRUCTION DETAIL : LHWP SCALE HORIZONTAL 1:1000 VERTICAL 1:10



CONSTRUCTION DETAIL : RHWP SCALE HORIZONTAL 1:1000 VERTICAL 1:10



MOISTURE CONTENT : RHWP



KEY

1. Base of seal (bituminous)
2. Base of, or boundary within, basecourse materials (sandy gravel)
3. Top of subgrade or other material boundary
4. Areas of deconsolidation within construction materials
5. Disturbance and possibly intermixing of materials at boundary
6. Areas of deconsolidation within subgrade materials
7. Core location
8. Increasing apparent moisture content within construction materials
9. Services

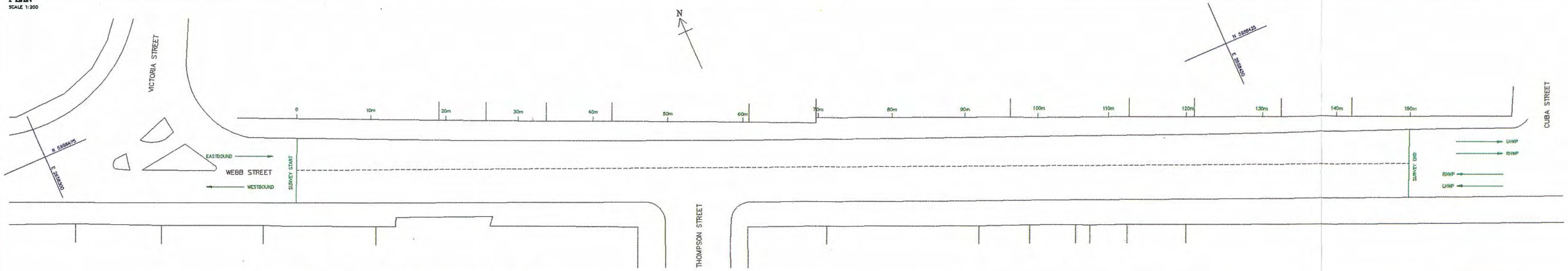
G B Geotechnics
Non Destructive Testing

PROJECT:	RESEARCH PROJECT PR3-0070		
CLIENT:	"WORKS CONSULTANCY SERVICES"		
TITLE:	GROUND PENETRATING RADAR TRIAL NEW ZEALAND PAVEMENTS		
SCALE:	AS SHOWN	DRAWN: AF	MANAGED: MK
DATE:	NOV 93	DWG.No: SH2-1	

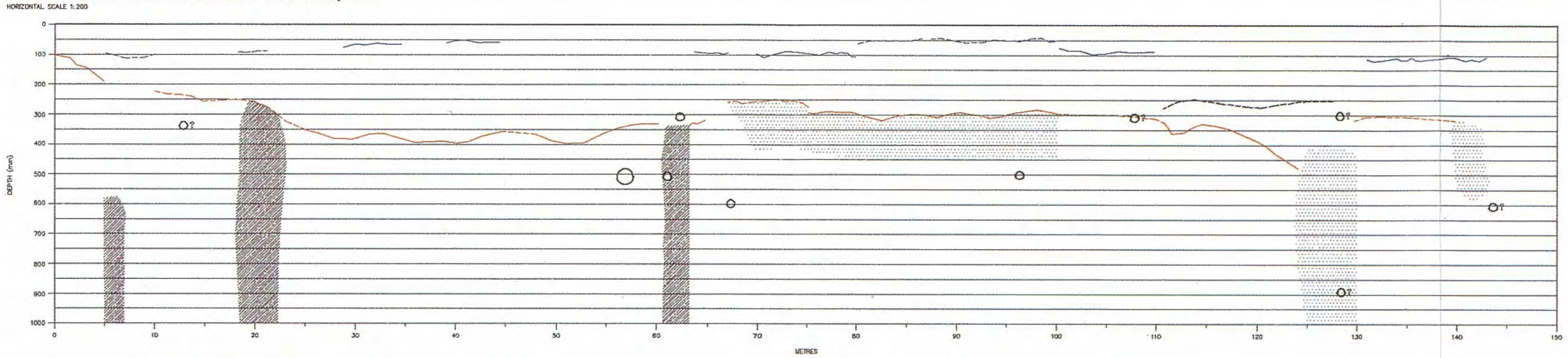
CAD filename: SH2a1

WELLINGTON CITY: WEBB STREET

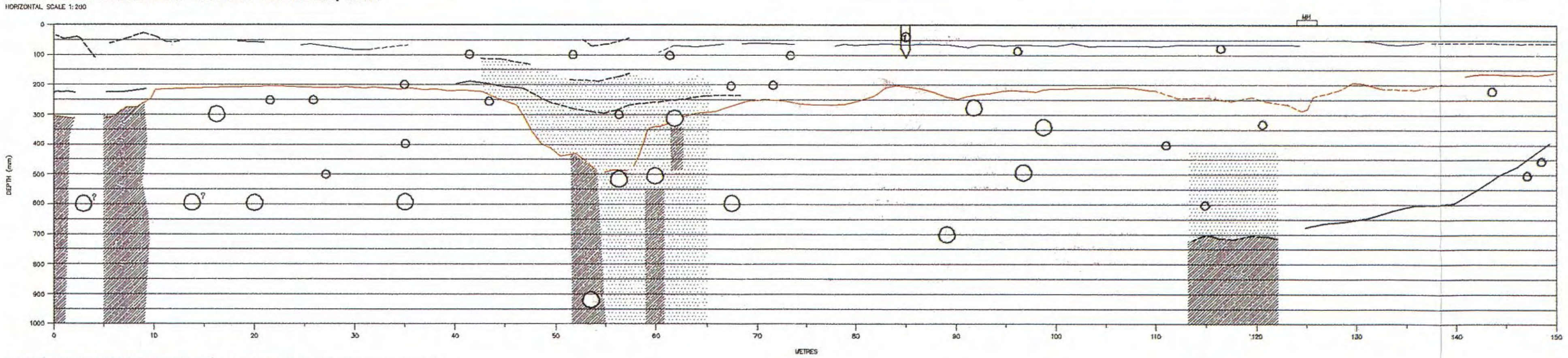
PLAN
SCALE 1:200



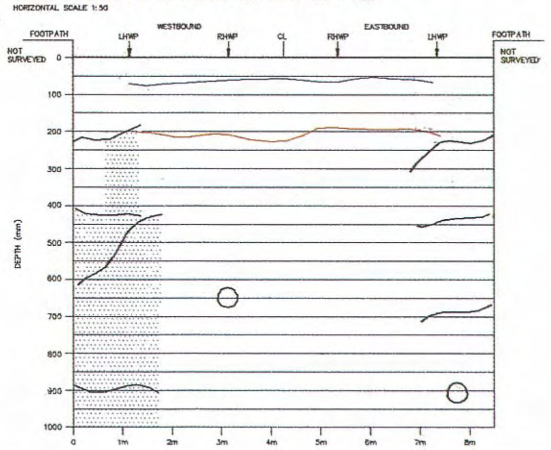
INTERPRETED LONGITUDINAL SECTION: EASTBOUND, LHWP
HORIZONTAL SCALE 1:200



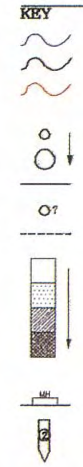
INTERPRETED LONGITUDINAL SECTION: EASTBOUND, RHWP
HORIZONTAL SCALE 1:200



INTERPRETED TRANSVERSE SECTION AT 85m
HORIZONTAL SCALE 1:50



KEY



1. Base of seal (bituminous)
2. Material boundary
3. Base of basecourse (sandy gravel)
4. Service of increasing diameter (cross section)
5. Location of service (long.section)
6. Possible service (cross section)
7. Possible service (long. section)
8. Increasing deconsolidation/ material disturbance
9. Manhole
10. Core location

CORE RESULTS
CORE 1, EASTBOUND AT 85m RHWP

DEPTH (mm)		LAYER	MATERIAL DESCRIPTION
FROM	TO		
0	65	65	SEAL
65	200	135	SANDY GRAVEL (BASECOURSE)
200	600	400	BROWN SILTY CLAY
600	1500	900	ORANGE SILTY CLAY

CAD filename: WEBB-1

G B Geotechnics
Non Destructive Testing
40 Cambridge Lane, Bottisham, Cambridge CB5 9DU 0223 812454 FAX 0223 812487

PROJECT:	RESEARCH PROJECT PR3-0070
CLIENT:	"WORKS CONSULTANCY SERVICES"
TITLE:	GROUND PENETRATION RADAR TRIAL NEW ZEALAND PAVEMENTS
DRAWN: SC	CAD: PM: APP:
DATE: NOV 93	SCALE: AS SHOWN DWG.No: WEBB-1

APPENDIX 6
CORE LOGS AND WATER CONTENTS

WCL teminology is used to describe Core Logs
See Appendix 8 for terminology

SH 2 Western Hutt Road - SH58 Haywards Intersection

Distance (m)	Depth (mm)	Description	Water content (%)
Left (Inside) Northbound Lane - Left (inside) wheelpath			
45	0 - 200	Seal,	–
	200-340	sandy GRAVEL fine to coarse with silt and clay, yellowish brown with grey (basecourse),	4.2
	340-1000	GRAVEL fine to coarse with sand, silt and clay, brown with grey.	2.5
625	0 - 160	Seal,	–
	160-410	sandy GRAVEL fine to coarse with silt and clay, brownish grey (basecourse),	4.4
	~410-530	GRAVEL fine to coarse with sand, silt and clay, yellowish brown with grey,	6.7
	~530-940	clayey GRAVEL fine with sand and silt, yellowish brown,	10.3
	940-	greywacke?	nm
Left (Inside) Northbound Lane - Right (outside) wheelpath			
755	0 - 175	Seal,	–
	175 - 280	sandy GRAVEL fine to coarse with silt and clay, greyish brown (basecourse),	nm
	280 - 370	GRAVEL fine to coarse with sand, silt and clay, greyish brown,	nm
	370 - 430	GRAVEL fine to coarse with sand, silt and clay, yellowish brown,	5.9
	~430 -700	clayey GRAVEL fine to coarse with sand and silt, yellowish brown with grey,	6.2
	~700 -800	silty GRAVEL fine with sand and clay, yellowish brown.	nm
1550	0 - 160	Seal,	–
	~160-600	sandy GRAVEL fine to coarse with silt and clay, brown intermixed with grey (basecourse),	5.9
	~600-800	silty GRAVEL fine to coarse with sand and clay, yellowish brown with grey.	8.1

Distance is in metres from origin (0m)

nm not measured

– WC% of seal, concrete was not measured

SH 56, Himatangi

Distance (m)	Depth (mm)	Description	Water content (%)
Eastbound Lane - Left (inside) wheelpath			
675	0 - 80	Seal,	–
	80-180	sandy GRAVEL predominantly fine, with some silt and clay, dark grey (basecourse),	3.7
	180-210	fine SAND and fine to coarse GRAVEL, pale brown,	3.4
	210-950	fine SAND with some silt and clay, yellowish brown.	nm
725	0 - 45	Seal,	–
	4 -165	sandy GRAVEL with some clay and silt, greyish black (basecourse),	nm
	165-190	CLAY,	nm
	190-900	fine SAND with some silt and clay, yellowish brown.	nm
1900	0-85	Seal,	–
	85-250	sandy GRAVEL fine to coarse with silt, yellowish brown grey (basecourse),	3.1
	250-970	fine SAND, yellowish brown.	6.4
Eastbound Lane - Right (outside) wheelpath			
1150	0 - 60	Seal,	–
	60-200	sandy GRAVEL fine to very coarse with some silt, yellowish brown grey (basecourse),	5.4
	200-950	fine SAND with some silt and clay, yellowish brown.	nm
1575	0 - 90	Seal,	–
	90-220	sandy GRAVEL fine to very coarse with some silt, yellowish brown grey (basecourse),	2.7
	220-970	fine SAND with some silt and clay, greyish brown yellow.	3.8

Distance is in metres from origin (0m)
nm   not measured
–   WC% of seal, concrete was not measured

SH 3, New Plymouth

Distance (m)	Depth (mm)	Description	Water content (%)
Southbound Lane - Left (inside) wheelpath			
75	0 - 30	Seal,	–
	30-100	sandy GRAVEL fine to coarse with silt and clay, dark grey (basecourse),	nm
	100-500	gravelly SAND fine to medium with silt and clay, dark grey,	nm
	500-740	silty CLAY with some sand, yellowish brown (volcanic ash).	nm
900	0 - 30	Seal,	–
	30-200	sandy GRAVEL fine to coarse with some clay and silt, dark grey (basecourse 2),	nm
	200-220	seal,	–
	220-450	fine to medium SAND, greyish brown (basecourse 1),	nm
	450-950	silty SAND fine to medium with some silt and clay, brownish grey.	nm

(continued p.A-75)

Distance (m)	Depth (mm)	Description	Water content (%)
SH3, New Plymouth (continued)			
Southbound Lane - Right (outside) wheelpath			
976	0 - 50	Seal,	–
	50-280	sandy GRAVEL fine to very coarse with silt and clay, dark grey (basecourse 2),	6.4
	280-300	seal,	–
	300-480	fine to medium SAND and fine to coarse GRAVEL (equally represented) with some silt and clay, dark grey (basecourse 1),	4.4
	480-970	silty CLAY, reddish brown (volcanic ash).	62
1201	0 - 50	Seal,	–
	50-120	sandy GRAVEL fine to coarse with some silt and clay, dark grey (basecourse 2),	6.3
	120-140	seal,	–
	120-210	sandy GRAVEL fine to very coarse with some silt and clay, brownish grey (basecourse 1),	3.6
	210-400	gravelly SAND fine to medium with silt and clay, dark grey,	nm
	400-700	silty CLAY with sand, yellowish brown (volcanic ash).	63
1900	0 - 30	Seal,	–
	30-150	sandy GRAVEL fine to coarse with silt and clay, dark grey (basecourse 2),	5.0
	150-170	seal,	–
	170-260	fine to coarse SAND and fine to coarse GRAVEL (equally represented) with silt and clay, brownish grey (basecourse 1),	4.7
	260-450	gravelly SAND fine to medium with silt and clay, dark grey,	nm
	450-1000	clayey SILT with sand, brownish yellow grey (volcanic ash).	nm

Distance is in metres from origin (0m)

nm not measured

– WC% of seal, concrete was not measured

Webb Street, Wellington City

Distance (m)	Depth (mm)	Description	Water content (%)
Eastbound Lane - Right (outside) wheelpath			
85	0 - 65	Seal,	–
	65-200	sandy GRAVEL fine to coarse with silt and clay, brown (basecourse),	2.9
	200-600	silty CLAY with find sand, orange mottled pale yellow and brown (fill),	29
	600-1500	silty CLAY with some fine sand, bright orange.	34
Westbound Lane - Right (outside) wheelpath (1 m from centreline)			
130	0 - 60	Seal,	–
	60-190	sandy GRAVEL fine to coarse with some silt and clay, dark brownish grey (basecourse),	3.6
	190-440	silty CLAY with fine sand, brown mottled orange grey and yellow,	20
	440-1200	silty CLAY with fine sand and some fine to coarse gravel, brown mottled orange grey yellow and black (includes pieces of brick).	23

Mulgrave Street, Wellington City

Distance (m)	Depth (mm)	Description	Water content (%)
Left Lane - Left (inside) wheelpath			
30	0 - 70	Seal,	–
	70-360	sandy GRAVEL fine to coarse with some silt and clay, brownish grey (basecourse),	6.8
	~360-510	CLAY with some silt, brownish grey mottled black and light grey,	22
	~510-1420	silty CLAY, greyish yellow brown mottled blackish brown,	20
	1420-1500	CLAY with some silt and sand, greyish green.	nm
Right Lane - Left (inside) wheelpath			
130	0 - 55	Seal,	–
	55-380	sandy GRAVEL fine to coarse with some silt and clay, greyish brown with grey (basecourse),	7.5
	380-1000	sandy GRAVEL fine to coarse with silt and clay, brown with grey,	11
	1000-1300	sandy GRAVEL fine with silt and clay, yellowish brown with grey,	8.2
	at 1300	hard pan layer.	nm

Distance is in metres from origin (0m)
nm not measured – WC% of seal, concrete was not measured

Lambton Quay, Wellington City

Distance (m)	Depth (mm)	Description	Water content (%)
Right Lane - Left (inside) wheelpath			
105	0 - 80	Seal,	–
	80-380	concrete,	–
	~380-1000	clayey SILT with sand and fine gravel, dark blue and grey mixed with pockets of clay, light grey mottled yellow, contains shells,	nm
	~1000-1350	SAND fine to medium with silt and clay, light grey with pockets of clayey silt, bluish grey mottled yellow and black,	nm
	1350-1400	clayey SAND with silt and some fine gravel, brownish black, contains shells.	nm
Left Lane - Left (inside) wheelpath			
160	0 - 70	Seal,	–
	70-360	concrete,	–
	~360-590	clayey GRAVEL fine to coarse with sand and silt, yellowish brown with grey,	nm
	~590-900	clayey SILT with sand and fine gravel, dark glue, bright blue and grey,	nm
	900-1470	silty CLAY with some sand and gravel, light brownish grey mottled yellow and orange.	nm

Featherston Street, Wellington City

Distance (m)	Depth (mm)	Description	Water content (%)
Right Lane - Left (inside) wheelpath			
10	0 - 120	Seal,	–
	120-365	reinforced concrete,	–
	365-570	GRAVEL fine to coarse and sand, silt and clay (basecourse),	nm
	570-1380	sandy GRAVEL fine with silt and clay.	11
Left Lane - Left (inside) wheelpath			
105	0-125	Seal,	–
	125-310	concrete,	–
	310-1500	GRAVEL fine to coarse with sand, silt and clay, yellowish brown with grey (basecourse).	8.0

Distance is in metres from origin (0m)
nm not measured
– WC% of seal, concrete was not measured

APPENDIX 7
LAYERS IDENTIFIED BY GPR AT CORE LOCATIONS

✓	indicates the layer thickness has been correctly identified by GPR
x	indicates the layer thickness has not been correctly identified by GPR
?	subgrade not reached during coring
– ✓	indicates the layer thickness reported by GB Geotechnics as a dashed line
–	indicates the pavement structure was not identified by GPR

An error band of ±50% has been allowed for the base of the seal and ±25% for other layers, in deciding whether or not the layer thickness has been correctly identified. Survey was carried out in April and May 1993

SH 2 Western Hutt Road - SH 58 Haywards Intersection
SH 56 Himatangi
SH 3 New Plymouth

Site	Location of cored holes	Layer identified by GPR at core locations		
		Base of seal layer	Boundaries within basecourse	Top of subgrade layer (gravel, sand, volcanic ash)
SH 2 (northbound lane)	45 m Left lane, LHWP	✓	x	?
	625 m Left lane, LHWP	✓	✓	x
	755 m Left lane, RHWP	✓	✓	?
	1550 m Left lane, RHWP	✓	x	?
SH 56 (eastbound lane)	675 m LHWP	✓	✓	x
	725 m LHWP	✓	✓	x
	1150 m RHWP	✓	✓	x
	1575 m RHWP	✓	✓	✓
	1900 m LHWP	✓	x	x
SH 3 (southbound lane)	75 m LHWP	x	x	✓
	900 m LHWP	✓	✓	?
	976 m RHWP	x	x	✓
	1201 m RHWP	✓	✓	x
	1900 m RHWP	✓	✓	x

Webb Street, Wellington City
Mulgrave Street, Wellington City

Site	Location of cored holes	Layer identified by GPR at core locations	
		Base of seal layer	Base of concrete layer
Webb Street	85 m Eastbound, RHWP	✓	✓
	130 m Westbound, RHWP	✓	–✓
Mulgrave Street	30 m Left lane, LHWP	–✓	–✓
	130 m Right lane, LHWP	–✓	–✓

Lambton Quay, Wellington City

Site	Location of cored holes	Layer identified by GPR at core locations		
		Base of seal layer	Base of concrete layer	Boundary within subgrade layer
Lambton Quay (right lane)	105 m LHWP	✓	✓	–
	160 m LHWP	✓	✓	✓

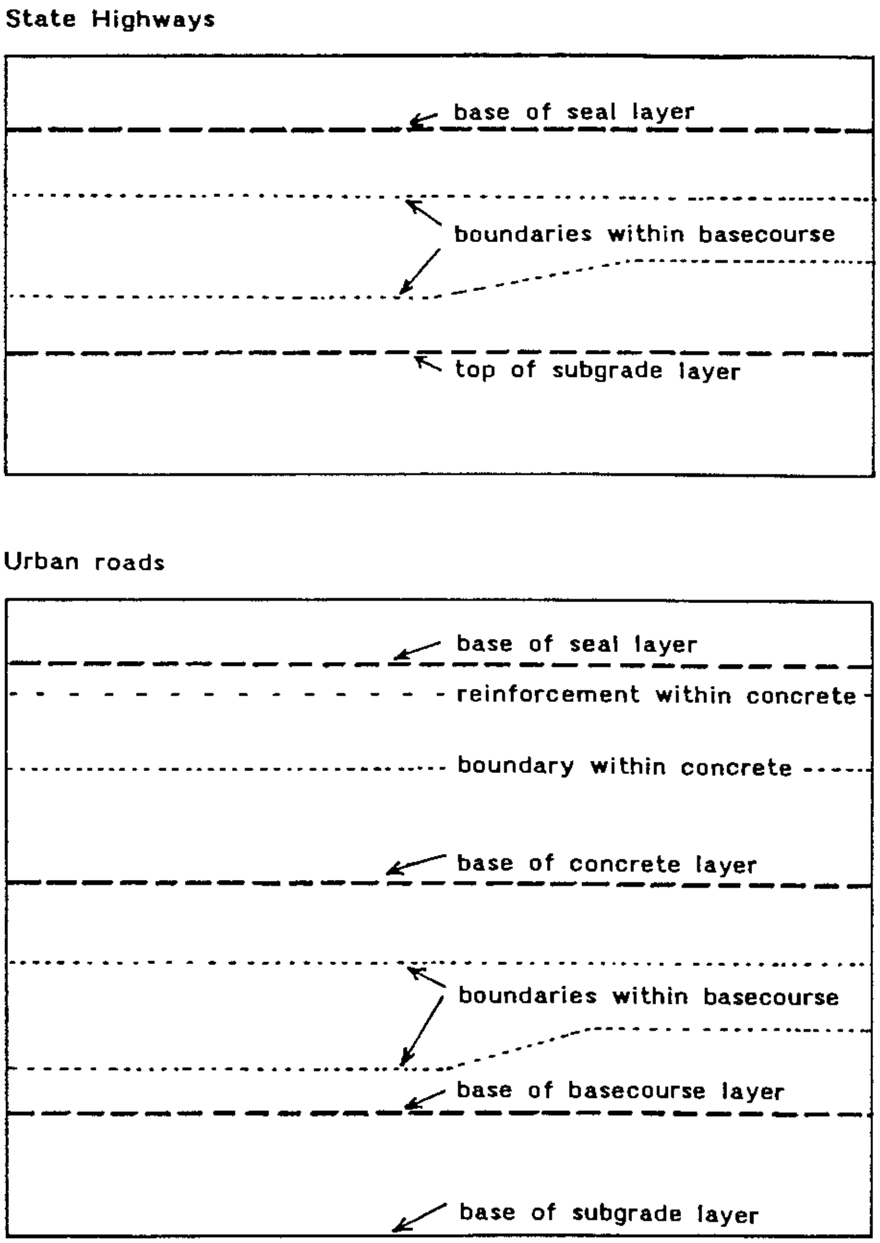
Featherston Street, Wellington City

Site	Location of cored holes	Layer identified by GPR at core locations		
		Base of seal layer	Base of concrete layer	Boundary within subgrade layer
Featherston Street	10 m Right lane, LHWP	✓	–✓	–
	105 m Left lane, LHWP	✓	–	–

APPENDIX 8
TERMINOLOGY USED FOR STRUCTURAL LAYERS AND BOUNDARIES

Figure A8.1 A diagrammatic representation of pavement construction layers and the terminology used by GB Geotechnics to describe the layers and boundaries.

Differences in terminology result from the different parameters being described. For example, descriptions of layers in core logs are made from direct observations, e.g. silty clay with fine sand, whereas descriptions of layers in a GPR survey are made by analysis of the GPR data, e.g. of changes in dielectric properties.



Repeated from Chapter 10, Part 2 of this report.

TERMINOLOGY USED FOR STRUCTURAL LAYERS AND BOUNDARIES

Site	Terminology used for structural layers and boundaries	
	WCL[1]	**GB Geotechnics[2]**
SH 2	Seal	Base of seal
	Sandy GRAVEL (basecourse)	Base of, or boundary within basecourse materials (sandy GRAVEL)
	GRAVEL - fine to coarse, silty, clayey	Top of subgrade or other material boundary
SH 56	Seal	Base of seal
	Sandy GRAVEL (basecourse)	Base of, or boundary within basecourse materials (sandy GRAVEL)
	Fine SAND	Top of subgrade or other material boundary
SH 3	Seal	Base of seal
	Sandy GRAVEL (basecourse)	Base of, or boundary within basecourse materials (sandy GRAVEL)
	Seal	
	SAND	Top of subgrade or other material boundary
	CLAY (volcanic ash)	

1 Terms used by WCL in their descriptions of core logs (Appendix 6)
2 Terms used by GB Geotechnics on their graphical presentations in their Report, reproduced in Appendix 5

Site	Terminology used for structural layers and boundaries	
	WCL[1]	GB Geotechnics[2]
Webb Street	Seal	Base of seal
	Sandy GRAVEL (basecourse)	Material boundary
		Base of basecourse (sandy GRAVEL)
	Silty CLAY	
Mulgrave Street	Seal	Base of seal
	Sandy GRAVEL (basecourse)	Material boundary
		Base of basecourse (sandy GRAVEL)
	CLAY/sandy GRAVEL	
Lambton Quay	Seal	Internal seal boundary
		Boundary between seal and reinforced concrete
	Concrete	Reinforcement
		Base of concrete
	Clayey GRAVEL	
	Clayey SILT	Subgrade boundary
	Silty CLAY	
Featherston Street	Seal	Internal seal boundary
		Boundary between seal and reinforced concrete
	Reinforced concrete/concrete	Reinforcement
		Base of concrete
	GRAVEL	
	Sandy GRAVEL	Top of sub-base

1 Terms used by WCL in their descriptions of core logs (Appendix 6)
2 Terms used by GB Geotechnics on their graphical presentations in their Report, reproduced in Appendix 5

APPENDIX 9
LOCATION OF SERVICES ALONG GPR SURVEY LINES

The tables in this Appendix have been constructed from plans and information given by the relevant authorities and companies responsible for the services, and from GPR data presented by GB Geotechnics. The tables allow correlation between these two sets of data.

Explanation of Conventions:

1912 A distance in a rural state highway survey that is underlined and in bold indicates a service is identified at this location by the GPR survey and on the plans of services (obtained from the relevant authorities and companies responsible for the services).

18? A distance in an urban road survey that is underlined and in bold with a query indicates that the GPR survey has identified a service to lie in one wheelpath only, or the location of the service identified by the GPR survey is more than 4m different to the location of a service indicated on the plans of services.

The method of counting services on Wellington City roads for the urban GPR surveys was as follows: four GPR runs were made at each site, i.e. one in each wheelpath, and the services located beneath wheelpaths of each lane were added together and presented as being in one lane. The service may occur just once or twice across a lane.

SH 2 Western Hutt Road - SH 58 Haywards Intersection

Distance along GPR survey line	Northbound LHWP					Northbound RHWP				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m			405		410*			405		410
					745†					745†
					860†					860†
					1010*					1010*
					1073*					1073*
					1100†					1100†
				1435	1435‡				1435	1435
			1500					1500		
			1675					1675		
2000 m			1912					1912		

* 33kV † 11kV ‡ Subway

SH 56, Himatangi

Distance along GPR survey line	Eastbound LWH					Eastbound RHW				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m										
				940					940	
2000 m										

SH 3, New Plymouth

Distance along GPR survey line	Southbound LHWP					Southbound RHWP				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m				150	125				150	125
		255					255			
					540					540
					560					560
				790					790	
				880					880	
				1000					1000	
				1200					1200	
				1220	1290				1220	1290
				1270					1270	
		1454					1454			
		1590					1590			
2000 m				1635					1635	

Webb Street, Wellington City

Distance along GPR survey line	Eastbound Left Lane					Westbound Right Lane				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m								2		
	17	18?		2-10?			18?	13?		
								54		
				60-66					60	60-70
				62				71	62	
								76-78?		
	93		96-97					90-92		
				97				97-98	97	
	138		133-136							
150 m			142							
Notes:	*	**	***	****	*****		**	†		††

*	Gas pipe runs along left wheelpath (LHWP).
**	Water pipes run the full length of the GPR survey line approximately down the centre of lane.
***	Drainage pipes run along the centreline of road.
****	Telecom cables run down right wheelpath (RHWP) from 0-2 m.
*****	Power cable runs down the centreline of road from 0-60 m.
†	Drainage pipes run along the centreline of the road for the full length of the GPR survey line and in this lane from Thompson Street (54 m) to 0 m.
††	Power cable runs down centreline of road from 0-60 m then crosses into this lane and continues to end of GPR line in left wheelpath.

Mulgrave Street, Wellington City

Distance along GPR survey line	Southbound Left Lane					Southbound Right Lane				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m										
	18	19				18?				
	24		21					22-24		
	37		38			37				
			49							
		58?								
				65	67				65	67
		101					101?			
	119				112?					112?
					127					127
150 m			150					150		
Notes:	*	**	***					****		

* Gas line runs the full length of GPR survey line.
** Water pipe runs the full length of GPR line approximately in the left wheelpath (LHWP).
*** Drainage pipes run adjacent to the centreline from 17-150 m.
**** Drainage pipes run adjacent to the footpath for the full length of the GPR survey line.

Lambton Quay, Wellington City

Distance along GPR survey line	Southbound Left Lane					Southbound Right Lane				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m		**9?**	**11?**							
			15?	14	**15?**			15	14	15
					23?					**23?**
		44-47?								
	52-54?		**57-62**	**53-56?**		48-52			51-53	
	64-66		**63-68?**			**66-68**		**63-67?**		
							78?	**69-73**		
		118?	**119?**		**116?**			**119?**		**116?**
			127	128-130						
					132				130-132	132
			144							
180 m					180					180
Notes:		*	**							

* Water mains run full length of surveyed section midway across width of southbound lanes.

** 0-11 m drainage runs along middle of left lane.
60-76 m runs obliquely across left lane.
127-144 m runs along left lane of LHWP.

Featherston Street, Wellington City

Distance along GPR survey line	Southbound Left Lane					Southbound Right Lane				
	Gas	Water	Drainage	Telecom	Power	Gas	Water	Drainage	Telecom	Power
0 m	3?				2?	3				2?
						7?		19-21		
						33		33		
					49					49
					54?	59-60			58-59?	54?
	67?	67?	68?	60-61?	75	67	67	68		75
		73	70		77	78		70		77
			72		79			72		79
			73							
	104?		95?			104		97-104		
						108				
	109?		107			109				
	115		108?			115				
130 m			113							
Notes:		*	**			***	****			

* Water pipe runs down centreline of left lane from 66-130 m.
** Two drainage pipes run along the centreline of the road, plus one down the centre of the left lane.
*** A gas line runs the full length of GPR survey line down the centreline of the right lane.
**** A water pipe runs adjacent to the gas from 0-66 m.

APPENDIX 10
IDENTIFICATION OF STRUCTURAL LAYERS AND BOUNDARIES USING GPR

Ratings used for describing continuity of the structural boundaries.

Symbol	Rating	% interface identified
VG	Very good	85-100
G	Good	60-85
S	Satisfactory	40-60
P	Poor	15-40
VP	Very poor	0-15

The ratings and corresponding "% interface identified" listed in this table have been determined from an evaluation of the information displayed in the graphic presentations in GB Geotechnics' report (Appendix 5 to this report).

Note: GB Geotechnics and WCL have used different terminologies to describe the layers. Tables relating the two terminologies are supplied in Appendix 8. Use the tables when comparing the core-log descriptions (described using WCL terminology, as in Appendix 6) with the structural layers identified by the GPR survey (using GB Geotechnics terminology, as in Chapter 10 in Part 2 and in Appendix 7).

Differences in terminology result from the different parameters being described. For example, descriptions of layers in core logs are made from direct observations, e.g. silty clay with fine sand, whereas descriptions of layers in a GPR survey are made by analysis of the GPR data, e.g. of changes in dielectric properties.

SH 2 Western Hutt Road - SH 58 Haywards Intersection

Lane	Length of road surveyed (m)	Wheelpath surveyed	Structural boundaries identified		
			Base of seal layer	Boundaries within basecourse material	Top of sub-grade layer
Northbound	0-1000	LHWP	VG	1 VG 2 G	P
		RHWP	VG	1 VG 2 G	S
	1000-2000	LHWP	VG	1 G 2 VG	S
		RHWP	VG	1 VG 2 VG	S

SH 56, Himatangi

Lane	Length of road surveyed (m)	Wheelpath surveyed	Structural boundaries identified		
			Base of seal layer	Boundaries within basecourse material	Top of sub-grade layer
Eastbound	0-1000	LHWP	VG	1 VG 2 G	P
		RHWP	VG	1 VG 2 G	VG
	1000-2000	LHWP	VG	1 G 2 VG	VG
		RHWP	VG	1 VG 2 G	S

SH 3, New Plymouth

Lane	Length of road surveyed (m)	Wheelpath surveyed	Structural boundaries identified		
			Base of seal layer	Boundaries within basecourse material	Top of sub-grade layer
Southbound	0-1000	LHWP	G	1 VG 2 G	VG
		RHWP	VG	1 G 2 S	VG
	1000-2000	LHWP	VG	1 G 2 G	VG
		RHWP	G	1 P 2 VG	VG

Webb Street, Wellington City

Direction of survey	Lane	Length of road surveyed (m)	Wheelpath surveyed	Structural layers and boundaries identified		
				Base of seal layer	Boundaries within basecourse material	Base of base-course layer
Eastbound	Left	0-150	LHWP	P	VP	G
			RHWP	G	VP	VG
Westbound	Left	150-0	LHWP	S	VP	VG
			RHWP	G	P	G

Mulgrave Street, Wellington City

Direction of survey	Lane	Length of road surveyed (m)	Wheelpath surveyed	Structural layers and boundaries identified		
				Base of seal layer	Boundaries within basecourse material	Base of base-course layer
Southbound	Left	0-150	LHWP	G	-	G
			RHWP	P	G	VP
Southbound	Right	0-150	LHWP	S	-	S
			RHWP	G	-	S

Lambton Quay, Wellington City

Direction of survey	**Lane**	**Length of road surveyed (m)**	**Wheelpath surveyed**	**Structural layers and boundaries identified**				
				Base of seal layer	**Reinforcement within concrete layer**	**Internal concrete boundary**	**Base of concrete layer**	**Base of subgrade layer**
Southbound	Left	0-180	LHWP	S	-	P	S	VP
			RHWP	VG	-	-	P	-
Southbound	Right	0-180	LHWP	P	-	VP	S	VP
			RHWP	VG	-	G	S	-

Featherston Street, Wellington City

Direction of survey	**Lane**	**Length of road surveyed (m)**	**Wheelpath surveyed**	**Structural layers and boundaries identified**				
				Base of seal layer	**Reinforcement within concrete layer**	**Internal concrete boundary**	**Base of concrete layer**	**Base of subgrade layer**
Southbound	Left	0-130	LHWP	VG	VG	VG	VP	-
			RHWP	S	VG	P	VP	VP
Southbound	Right	0-130	LHWP	VG	VG	VG	S	-
			RHWP	S	G	P	P	-

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