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INSTRUMENTATION FOR MONITORING PAVEMENT PERFORMANCE IN COLD REGIONS

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INSTRUMENTATION FOR MONITORING PAVEMENT PERFORMANCE IN COLD REGIONS

ABSTRACT

The Mechanistic-Empirical (ME) design guide developed under the National Cooperative Highway Research Program represents a true change in the approach to engineering road structures. Changes in material properties with seasonal variations in moisture and temperature condition, which influence the mechanical response of the materials and hence the structural response of road layers, forced reliance on empirical measures to predict performance. These empirical functions will require calibration to ensure the prediction model is responsive to local conditions including adopted construction practice.

The performance of pavements in cold regions clearly reveal the need to properly measure the distribution of stresses, strains, moisture, and thermal regimes, within road layers over a period of time. This paper presents the design, implementation, and use of a practical road instrumentation monitoring system capable of capturing all structural and environmental data for roadways. This proposed road installation scheme is simple yet effective in generating data that could be used to calibrate a host of design M-E and visco-elastic models including the new AASHTO design guide. Details include selection of sensors, data acquisition systems, data processing techniques and some actual data.

INTRODUCTION

In view of the substantial investments being made each year on maintenance and rehabilitation of roads, it is necessary to improve pavement analysis and design to produce durable cost effective pavement structures. One such improvement may target linking the pavement structure response, influenced by environmental, operating and service requirements as well as traffic loading, to the performance. Currently, pavement analysis, including the proposed M-E model, is based primarily on multilayered linear elastic analysis. Mechanistic characterization techniques of road materials represent one of the major improvements introduced in the M-E model. Therefore, it is important to account for the impact of seasonal variations in moisture and temperature condition on the mechanical behaviour of the material.

Construction standards involve placement of different structural layers above the undisturbed native soil, including asphalt concrete and/or portland cement concrete, dense-graded aggregate base, excavated material and in some cases, bedding materials used to protect buried utilities. The thickness of each layer is often determined using the elastic properties of its material components, determined from experiments conducted within the linear range of the response of the material. For example, the mechanical properties of asphalt materials are often measured at room temperature as required by American Association of State Highway and Transportation Officials (AASHTO design guide, 1993). However, the asphalt concrete road mat often experiences a wide range of thermal regimes during the different seasons, especially in temperate climate locations. It is well known that asphalt concrete becomes brittle and stiffer when subjected to a temperature lower than – 5 ^{o}C. On the other hand, temperatures more than +25 ^{o}C cause flow and fluidity of the asphalt cement that makes asphalt concrete softer and results in high permanent deformation leading to rutting even under low stress levels. These stresses are the results of applied traffic loadings and movements of the soil foundation layers.

The most common pavement surfaces in cold regions include traditional hot mix asphalt (HMA), cold mixes, bituminous surface treatments and gravel (Dore and Zubeck, 2009). HMA mixes are used on roads with high traffic volumes and usually contain about 95% aggregate, 5% asphalt, and additives such as anti-stripping agents, polymer modifiers and fillers. The mixture is prepared at 135 to 160°C. The thickness of the surface layer is between 50 and 150 mm. Cold mixes are prepared at room temperature (about 25°C) and these contain emulsifiers, lighter oil components and/or soft asphalt cements. Gravel roads are also common in cold regions because of the low capital cost, but their maintenance costs are higher.

Moisture content and temperature variations change the reislient response and properties of unbound materials including gravel materials, sand and clays. The moisture content of soil materials affect the load carrying capacity as well as the deformation response to applied loads. The new design guide (NCHRP, 2002) recommends the use of mechanical properties of unbound materials obtained from testing of compacted samples prepared for dry, wet and optimum moisture conditions. Unbound layers are often constructed using optimum moisture conditions of the material to ensure acheiving maximum dry density. However, the mositure content of the unbound layer within any given road structure will vary during service depending on the season, drainage, and the pervailing thawing/drying conditions. Therefore, the rate of permanent deformation and settlement of unbound layers varies from one season to another. This rate of deformation and subsequently the amount of permanenet deformation decrease year after year.

However, many North American municipilities still enforce weight restrictions for roads during thawing seasons in the spring of each year becuase of fear of reduced stiffness and load carrying capacity of unbound soil foundation layers. While the decision of imposing load restrictions is not due solely to higher stresses imposed on the unbound layers of the road, it reflects the lack of accurate knowledge of the stresses and strains imposed on these layers from traffic loadings. It also reflects lack of proper design and performance evaluation.

The leading discussions on the state of current practices of the new design guide (NCHRP, 2002) as well as decision making of road authorities, clearly reveal the need to properly measure the distribution of stresses, strains, moisture, and thermal regimes, within road layers over a period of 2-3 years.

ROAD INSTRUMENTATION DESIGN SCHEME

To design an effective and economical road monitoring system, one must consider both the structural and environmental data to be collected. Also, the type and arrangement of the layout of the different layers of the road should be considered in determining the type of instrumentation to be used. The adopted system should also be able to capture the impact of seasonal variations in moisture and temperature conditions on the mechanical properties and behaviour of road materials. The implemented system should utilize moisture gauges and thermocouples to establish changes in the gradients associated with the environmental parameters. The proposed instrumentation system also determined the frost depth of a given site using resistivity probes.

The selected sensors and data acquisition system should be capable for capturing the response of the pavement under dynamic loading conditions. It should also be capable of taking static readings associated with the buildup of permanent deformation with time and under the action of traffic loading. The design of the system of the current study used measurements of temperature and moisture conditions four times a day to conduct sensitivity analyses of changes in these parameters (i.e., the temperature sensitivity of the load response of the asphalt concrete and unbound soil materials at various moisture states). The structural response was measured and recorded on a daily basis.

Instrumenting a new road is ideal as the sensors can be installed during construction. However instrumenting existing roadways can be somewhat more difficult because it is typically done during road repair or utility repair and/or replacement. Precautions need to be taken to ensure that the performance of the instrumented section does not dramatically deviate from the surrounding or existing road structures.

SENSOR SELECTION

In implementing the proposed pavement monitoring system it is important to remember that the selection of sensors, their distribution within the different road layers, and the design of the data acquisition system should be based on the objectives of the proposed study and locally prevailing conditions. Site condition assessment information obtained prior to construction using general survey, cores and boreholes, or data collected from construction records proved useful in this study in the selection of sensors. The design of road instrumentation depends on the type of construction; whether it is new construction, repairs, or reconstruction. There are many factors that should be considered in the selection of sensors. Obviously, the sensor should be capable of capturing the intended property or response. Successful instrumentation design requires adequate knowledge of; (a) the type of sensor output (the majority of the sensors have voltage output), (b) the sensor measurement range, (c) the sensor's operating mechanism, necessary for determining its compatibility with the data acquisition system, (d) the life expectancy of the sensor, and (e) other limitations related to the surrounding magnetic environment. Finally, manufacturer's specifications related to output and capacity must be examined and considered in the selection process and respected during installation. Sensors selection and their manufacturers for this study are listed in Table 1.

SENSOR INSTALLATION PROCEDURE

In order to obtain effective road instrumentation system for a given application, pre-construction activities must be conducted in preparation for installation. The pre-construction activities involve taking non-destructive deflection basin measurements on the existing road structure, coring samples from the road and survey work. These activities establish the type of materials that exist within a road structure which play a major role in the road design as well as the selection of sensors for each road layer. Fig. 1 shows a block diagram of the master plan and communication links that should be prepared prior to the beginning of construction. The following describes the selection procedure for sensors suitable for the different road materials and provide the installation process of each sensor. In general, the sensors measure either the structural response (i.e., pressure and deformation) or the hydrothermal conditions (i.e., temperature, and moisture content) of road layers.

Structural sensors

Asphalt concrete strain

Asphalt strains were measured using Dynatest Past IIA strain gauges. Strain gauges were positioned within the asphalt concrete (AC) layer, to measure strain in the transverse and longitudinal directions with respect to the traffic flow. In this study, the gauges were installed close to the bottom of the lower AC layer. The Dynatest past strain gauge is an H shaped precision transducer specifically manufactured to measure strain in asphalt concrete. However, to ensure perfect results, the following steps were followed:

1. Apply a thin layer of bitumen primer (if not already done) within the area, where the transducer is to be placed and let it to cure.
2. Place a thin layer of 3 to 4 mm sand bitumen mix on the cured bitumen primer. Press the anchor bars of the transducers into the sand/bitumen mix, until contact between the strain gauge bar and the sand bitumen mix is established. Let it cure for at least one hour.
3. When possible, the sensor cable should be protected by burying it into the unbound materials to a depth of at least 40 mm.
4. Take some hot asphalt from the paver. Remove the biggest stones. Place a 20 to 30 mm thick layer on the transducer to cover it.
5. Compact the material by first applying a static pressure and a steel plate on the hot mix
6. Roll the hot asphalt in the direction of the anchor bars (rolling pin parallel to the transducer bar). Fig. 2 shows the position of asphalt strain gauges in x-y directions after the completion of compaction using a solid metal roller with 100 mm diameter and a width of 200 mm) (rolling pin type).
7. Place the asphalt with the paver and compact using a non-vibrating pneumatic tire roller.

Soil stress sensors

The soil pressure sensors model TP-101-9-9-S, manufactured by RST instruments, were installed directly beneath the asphalt layer. These sensors monitored the amount of pressure applied by traffic which was transmitted to each soil layer including the granular base and other unbound layers. This sensor has a transducer encased in a cylindrical tube attached to a flat pancake-type loading plate via a slender tube.

The loading plate should be in direct contact with the unbound material. To ensure this, a very thin layer of fine (silica) sand is spread over the area under the loading plate. The load plate area is then carefully seated by hand in the fine sand (slight twisting, with down ward pressure) until full contact is achieved. These sensors can also be placed directly on the crown of a buried utility (pipe) to find the exact amount of load applied by soil and traffic loading on the buried pipe. Finally, the connecting tube and transducer portion of the sensors is covered with base material to prevent direct contact with the asphalt slab.

EMU Soil deformation sensor (strain)

Sub-grade strain measurements were made with the ε-Measuring Unit (EMU) soil strain measuring system, an induction coil technology (Dawson, A.R., 1994) developed at Nottingham University which was later refined and enhanced (Dawson *et al.*, 1999) at the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers. An alternating current is passed through one coil, generating an electromagnetic field around it. Three receiving coils can detect this field. The strength of the detected electrical field is a function of the distance between the transmitting and receiving coils. Both dynamic (elastic) and permanent (plastic) strain can be measured by the coil system. The coils were installed in columnar stacks for the studied depth, starting at 150 mm below the asphalt layer, and the nominal center-to-center spacing was 150 mm. The strain measurements are made using the inductive coil system called EMU-CRREL system. These sets of 100 mm diameter coils sensors were manufactured by CRREL. Again, they measure vertical displacements in the vertical direction (designated as the Z direction) and in two perpendicular horizontal directions (X and Y directions). The Z direction coils are coaxial, which the X and Y direction coils are coplanar. The X direction is parallel to wheel path, and Y direction is perpendicular to it. It is recommended that the thickness of underlying compacted lift should be measured. This is because a small amount of trimming is necessary if the lift is too thick, and a small amount of shimming with soil is done if the lift is too thin. After the coil is aligned and levelled, it is covered with about 5cm of soil, which is lightly tamped. Sets of three 100 mm diameter EMU coils per layer are used to measure strain in the longitudinal, lateral and vertical directions. Measurements from two sets are necessary for determining vertical strain within an unbound pavement layer.

Plate soil deformation

Conventional settlement plates such as those manufactured by RST instruments, model EXF 0191A, were adopted in this study to quantify permanent deformations accumulating in the unbound road layers. These sensors contain a rod extensometer which monitors changes in the distance between one or more down hole anchors. Deformation of the unbound layers was determined by measuring the reference head. Any change in distance found by comparing the current measurement to the initial measurement indicates that movement has occurred. The rod extensometers are made of stainless steel with bottom and top caps which are the displacement surfaces with reference to the collar tube. The initial step in the installation of the extensometer is to stabilize the bottom cap on a rigid area, such as a block of concrete positioned in the subgrade material. The unbound materials are compacted around the bottom cap and backfilled up to the tube end, followed by screwing on the top cap. After these installation steps, the initial measurements are taken and used as the baseline data.

Environmental sensors

Temperature sensor

Copper-Constantan (Type T) thermocouple probes were used to determine the temperature profile of the soil layers and within the pavement structure. Type T thermocouples can measure temperatures in any condition with an accuracy of ± 0.5 °C. For this study, temperatures were measured at 3 or 4 different depths in the pavement surface, depending on the thickness of the asphalt layer. Temperature was measured every 100 mm in the other soil layers starting at 25 mm below the asphalt concrete layer. The thermocouple cable used in this study had twelve 20-gauge copper-constantan wire pairs, the sensor junction was formed at one end by: a) stripping the outer insulation at least 12 mm, b) twisting both ends together, c) soldering the twisted end, d) trimming the end, and e) covering the junction using heat-shrink tubing filed with silicon. A piece of wood was used to fix the thermocouple in place for particular position as shown in Fig. 3.

Moisture content sensor

Variations in moisture content through the depth of unbound layers were monitored using water content reflectometer sensors model CS615 or CS616, manufactured by Campbell Scientific INC. These water content reflectometers consisted of two stainless steel rods connected to a printed circuit board. In this study, the two rods were maintained at a constant distance apart by using a piece of wood in between to eliminate the effect of unparalleled and unequal distance between them, as shown in Fig. 4. The CS615 or CS616 sensors should be installed on a leveled surface and in the horizontal direction. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The CS615 and CS616 provide an indirect measurement of soil water content by using the effect of changing dielectric constant on applied electromagnetic waves. The probe rods act as a wave-guide and the material surrounding the rods (soil) varies in dielectric constant with the amount of water present in the material. Changes in the dielectric constant of the soil system can be attributed to changes in water content. The water content reflectometer sensors utilize the principles of time domain reflectometery (TDR) to measure the unfrozen volumetric water content present within the soil mass. The time domain reflectometery method of monitoring sub-grade water was introduced to pavement engineering by Neiber and Baker (1989). For this study, the reflectometers were connected to a Campbell Scientific CR10X and an AM416 relay multiplexer. The measured period of wave propagation was converted to volumetric water content using standard calibration values for a given soil material.

Resistivity probe sensor

The CRREL frost tube (Knuth, 2001), was used to monitor frost depths in the soil materials. These probes can be quite reliable when used in granular materials. The probe consists of 36 metal (rings) wire electrodes, spaced 51 mm apart, and mounted on a solid PVC rod (installation shown in Fig. 5). The resistivity probe measures the electrical resistance of the soil mass to identify points of change in the resistance field within the material. Such changes are induced by changes in the physical nature of the water contained in the soil as water undergoes phase change from the liquid stage to the solid stage within the soil. The CRREL frost tubes were found to be compatible with the data logger (Campbell Scientific CR10X) used in this study.

DATA ACQUISITION SYSTEM

The quality of the captured pavement response associated with traffic loading is influenced by the ability of the data acquisition system to match the vehicle speed. The pavement response is dynamic and necessitates the use of a high sampling rate at high vehicle speeds. The structural response starts to build up when a vehicle approaches the location of the sensor and diminishes after it passes that location. That location experiences an increase in vertical stress and strain until a peak is reached when the wheel is directly above it and then decreases as the vehicle moves away. This cause a bell shaped stress and strain pulse and necessitates acquiring a large number of readings to capture the peak response. Accordingly, a sampling rate representative of traffic speed on the road should be calculated in advance to guarantee capturing the necessary information. The stress pulse duration for a vehicle traveling at speed of 60 km/hr (Akram *et al.*, 1992) is 120 msec requiring a rate of 8 samples/sec to capture the peak. Attempt was made to combine sensors that were under the same vehicle pass. This was intended to read the strain corresponding to traffic induced stresses to facilitate quantification of the material elastic modulus. In this study, an initial attempt to measure the peak of the signal was missed at a sampling rate of 200 samples/sec when the capacity of the data loggers and the number of occupied channels were not considered in the design. Therefore, it is important to determine the rate after determining the combination of sensors involved in each reading and the capacity of the data logger. Experience gained in this study indicates that for a signal to capture the peak value, the rate should not be less than 1000 samples/second for any combination of sensors.

These details should be utilized in programming the data loggers. Major guidelines for designing a data acquisition system include:

1. Identify each sensor type and anticipated output range to determine whether it should be supported by either a slow or fast system.
2. Determine the reading frequency, i.e. how many times a day and for how long should the data retrieval mode be maintained.
3. Satisfy the objective of the investigation related to collection of dynamic response data to determine the optimum scanning intervals. As mentioned earlier, the number of sensors attached to the data logger and subsequent processing will limit the sampling rate per channel. Limited system capacity may force sampling different sensors for different events (vehicle passes). For pragmatic reasons, combinations of different sensors should be tested until the desired sampling rate is achieved.
4. Select data loggers and communication devices that are suitable to assemble a data acquisition system. In this study, in order to meet operational requirements of the system, two types of Campbell scientific data loggers were used;

   (a) Model CR10X was used to acquire (static) data. It is a durable and battery-operated programmable device that operates over a wide temperature range. The CR10X is equipped with a 3 or 4 AM416 multiplexer to accommodate all of the sensors. The rate of sampling of the CR10X is ideal to monitor thermocouples, full bridge strain gauges, and water content reflectometers.

   (b) Model CR9000 was used to record dynamic readings (traffic impact), as for monitoring stress and strain (εmu coil gauges). It is a faster data logger which is required to collect data for recording structural responses due to moving vehicles. The Campbell Scientific CR9000 is also a fast, durable, battery-operated, stand-alone and programmable data logger that operates over a wide temperature range. It can measure up to 100,000 samples per second and accommodate up to nine I/O modules.

INSTRUMENTATION BOX

The sensors, with different functions, were buried in the road structures to capture the structural and environmental response of the pavement. A data acquisition system was installed at the testing site to collect data from these sensors and these were remotely interrogated to download the data to a central laboratory. Accordingly, a system of conduits was required to connect the sensors in the testing site to the data loggers. A system for housing data loggers and communication devices was assembled to protect these devices throughout the life of the experiment. PVC pipes were used to protect wires not embedded in the pavement structure. Additional requirements at each site included 110VAC/60Hz power supply and two standard telephone lines for communication.

DATA CATEGORIES AND COLLECTION METHODOLOGIES

In road testing, the data to be collected can be broadly divided into two categories. The first type of data is obtained during the passage of a given heavy vehicle over the tested road section. This type of testing and monitoring was usually done once or twice per year. It is preferable to conduct this testing to measure such response during the freeze-thaw season and or after a major rain storm. We refer to this data as the dynamic data. The collection of this data requires the presence of the engineer or qualified personnel at the site and involves high speed data collection rates. The other data type is collected throughout the year and is called static data. The static data readings are associated with buildup of permanent deformation over time and under the cumulative action of traffic loading. It also involves measuring temperature and moisture conditions to conduct sensitivity analyses of changes in these parameters (i.e., the temperature sensitivity of the load response of the asphalt concrete and unbound soil materials at various moisture states).

Similar to other components of the monitoring system, data collection techniques should be designed to satisfy objectives of the experiments. Below is the procedure adopted to meet the objective set in this study.

1. Data should be collected frequently using a programmed data acquisition system and retrieved remotely via a modem on weekly basis. The communication system designed for this study was the CR10X data loggers, depicted in Fig. 6.
2. Collection of stresses and strains during the passage of test trucks requires the engineer to be present at the site. Any number of truck categories common to the specific road corridor may be examined depending on budget. Relationships established between the performance data and factors such as road geometry, construction quality and environmental condition, should be analyzed to guide the model calibration process. Data collected from multiple visits were needed to capture the impact of changes in the pavement materials related to aging of the binder and densification of unbound material.
3. The field instrumentation work should be complemented by other studies including non-destructive testing (NDT) and a laboratory investigation. The NDT data facilitates applications of lower levels of the mechanistic-empirical model. Temperature and moisture data were collected a number of times every day throughout the life of the experiment to support analysis.

4. The sampling rate was determined according to data category
5. Vehicles traveling at speeds as high as 60 kilometres per hour resulted in a loading period that was less than 1/100 of a second. This condition necessitates a high sampling rate. The CR9000 data acquisition system proved suitable for this high sampling rate (1000 to 2500 samples/sec.). Capturing environmental data at specified intervals do not require a high sampling rate and a CR10X system produced adequate data quality.

TYPICAL DATA RESULTS

Fig. 7 shows the details including the thicknesses of the layers of one of the road instrumentation systems built in Ottawa, Canada. The road layers thicknesses were selected based on experience and design of multi-layer pavement systems. A three-axel test truck, with axel weights of 43, 87 and 86 kN from the front to back, respectively, was operated immediately after construction (asphalt mat temperature was 50°C) revealing an extraordinarily high level of stresses that was transferred to the base and sub-base course as shown on Fig. 8. However, the pressures induced on the base and sub-base course materials were significantly lower when the temperature of asphalt concrete cooled to 21°C as shown in Fig. 9. Accumulation of permanent deformation was monitored daily by the EMU coil gauges as shown in Fig. 10. Capturing the impact of variations in temperature and moisture condition on the response of the different layers of the road structure was one of the elements included in the scope of this study. The temperature and moisture content gradient were monitored throughout the road depth. Figs. 11 and 12 show the temperature and moisture distribution respectively, measured for three layers of the road structure throughout a year. Fig. 12 shows that the maximum envelope of moisture content over one year ranged between 1.0 and 27.0 %.

Fig. 13 shows the typical data recorded by the resistivity probe of the unbound materials. Reference behaviour in the curve showed the unbound materials in an unfrozen state, while January behaviour in the curve showed change in the shape of the resistivity probe response, corresponding to the start of freezing at the top of the backfill. By repeating this process for every calendar day thereafter, the progress of the freezing front was determined and plotted versus depth as shown in Fig. 14.

CONCLUSIONS AND RECOMMENDATIONS

This paper describes a practical pavement instrumentation system that could be used as an effective tool for measuring the response of road layers to a host of applied environmental and traffic loadings. Road authorities may design the pavement monitoring system to address locally prevailing conditions and existing construction practices that influence the performance of their roads. The effectiveness of the system relies on appropriateness of the system design, which includes selection of hardware components (sensors and data loggers) and development of effective computer programs that will accurately execute the pavement monitoring plan.

The instrumentation system described in this paper was simple and may be replicated to produce the local data needed for calibrating critical components of the M-E model and improve its sensitivity to adopted construction practice and in-situ condition.

Positioning sensors in roadway structures is key in advancing knowledge and assisting in developing robust design methods of road structures. With these sensors located in the pavement structure, the road was smarter and provided excellent data, which lead to the development of an effective solution to the road design problem.

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387 Table 1 List of sensors

Sensor type	Measured response	Manufacturer
Pressure cells	Pressure	RST instruments LTD. British Columbia, Canada
PAST II Asphalt concrete strain gauges	Strain	Denmark
Water content reflectometer (TDR)	Volumetric water content	Campbell scientific Inc. Logan/Utah, USA
Thermocouple	Temperature	Thermo-electric wire& cable, LLC, Saddle Brook, NJ, USA
Extensometer	Unbound Settlement	RST instruments LTD. British Columbia, Canada
Emu coils (3 pairs each)	Unbound Settlement	US army corps of engineers
Resistivity probe	Frost depth	US army corps of engineers

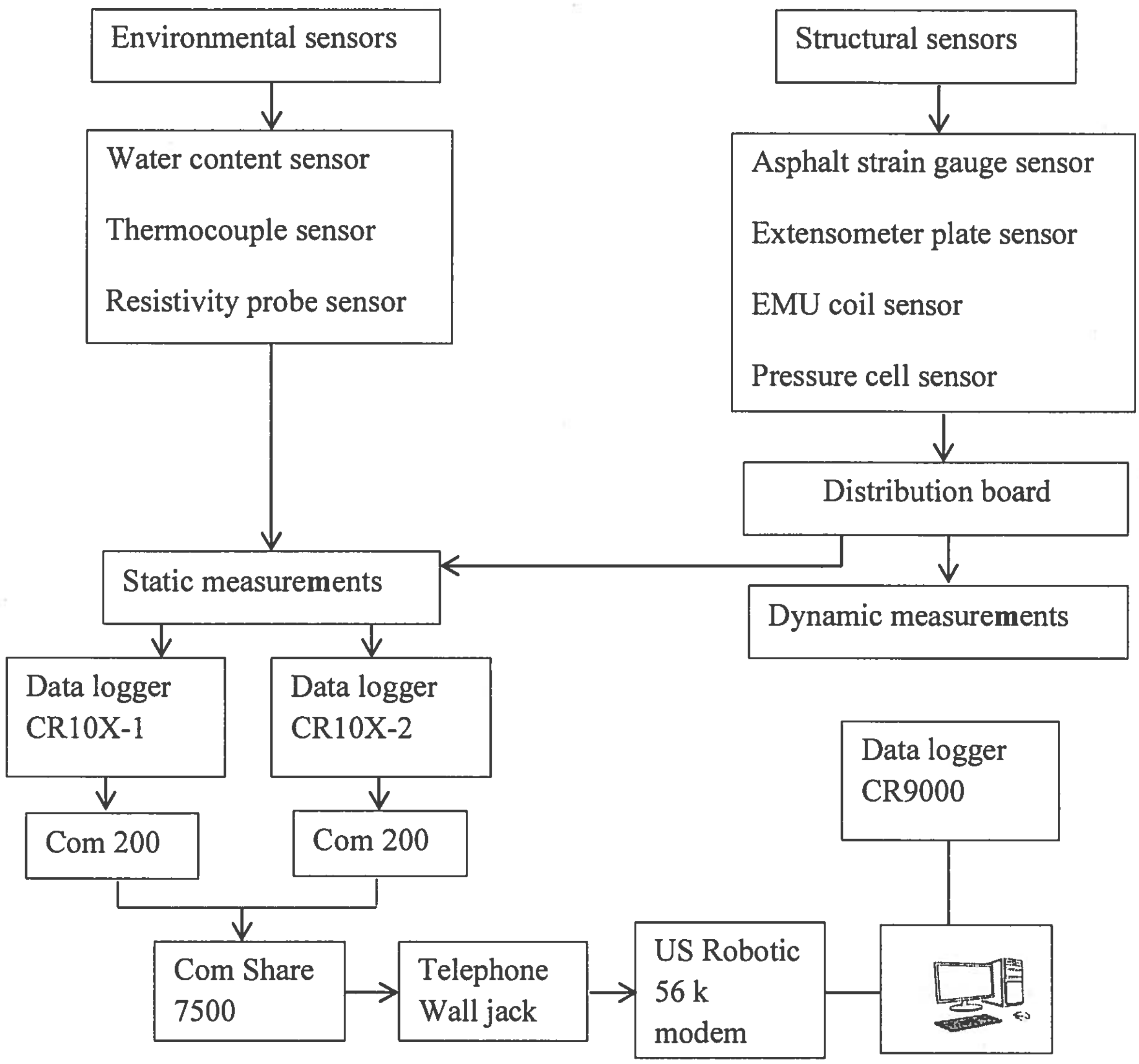


Fig 1. Typical instrumentation master plan

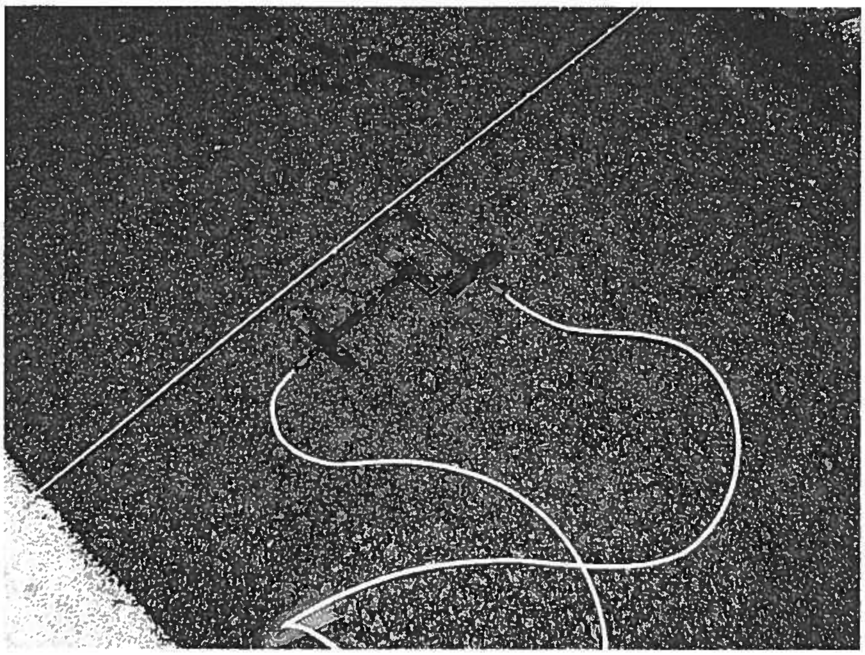
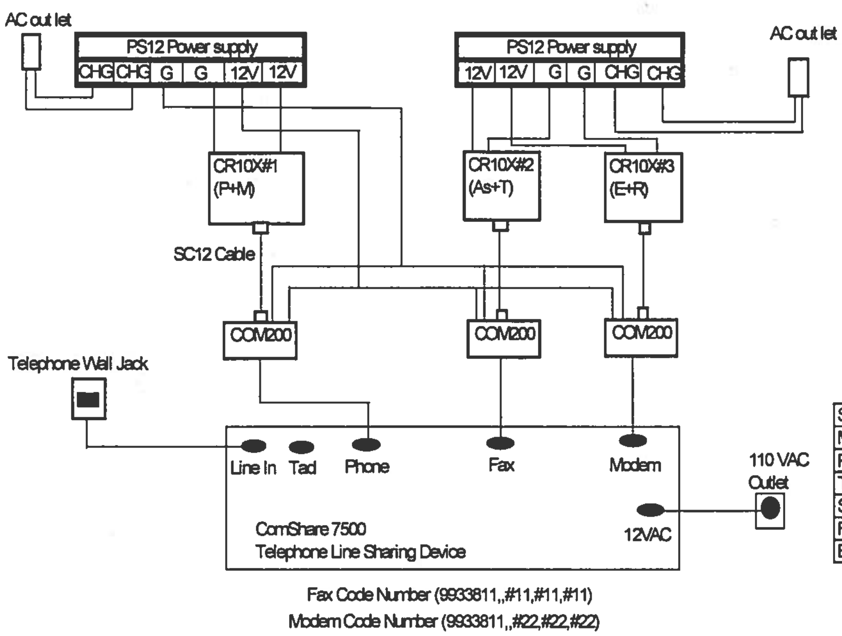


Fig 2. Installation of the AC strain gauges in the overlay in both directions

Fig 3. Typical installation of thermocouple

Fig 4. Installation of water content reflectometer

Fig 5. Installation of CRREL resistivity probe



Sympole	Sensor	# test point
M	Reflectometer	6
P	Pressure	6
T	Thermocouple	25
S	AC-Strain	4
F	Frost depth	48
E	EMU coil	14

Fig 6. CR10X communication set up

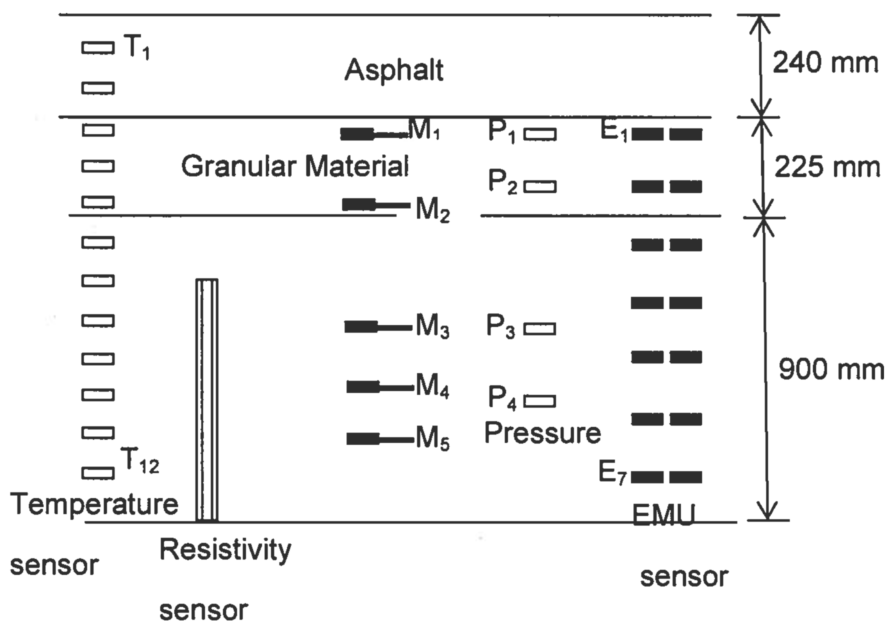


Fig 7. Road layers cross section and sensors distribution

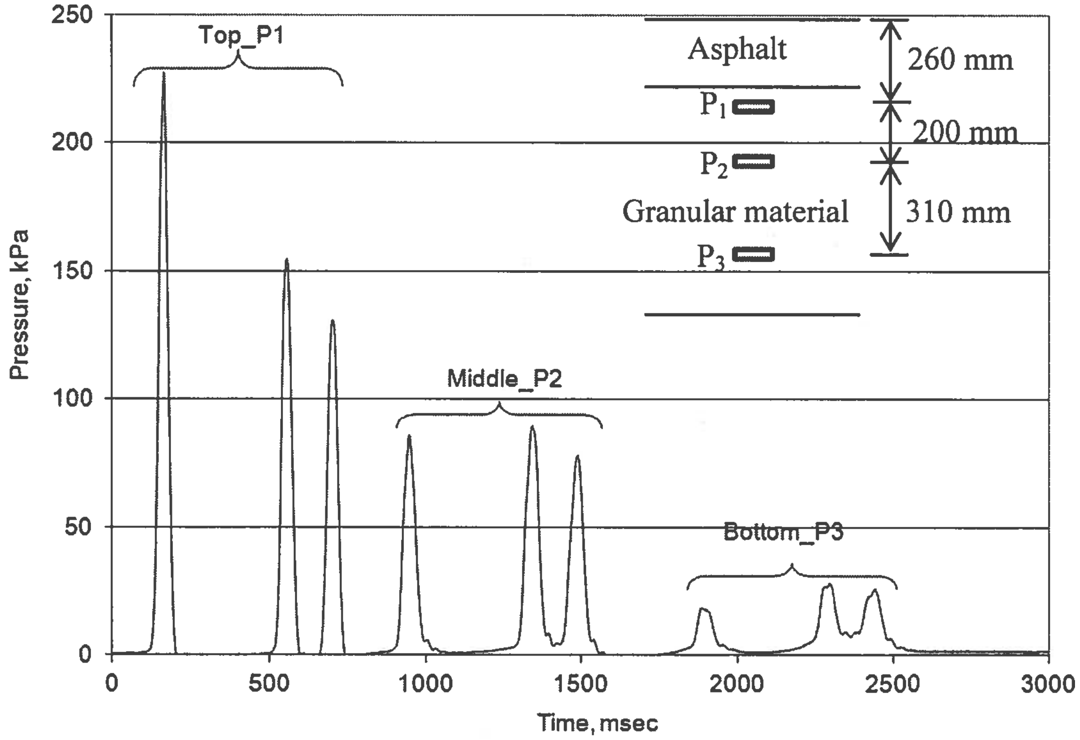


Fig 8. Typical pressure measurements after construction

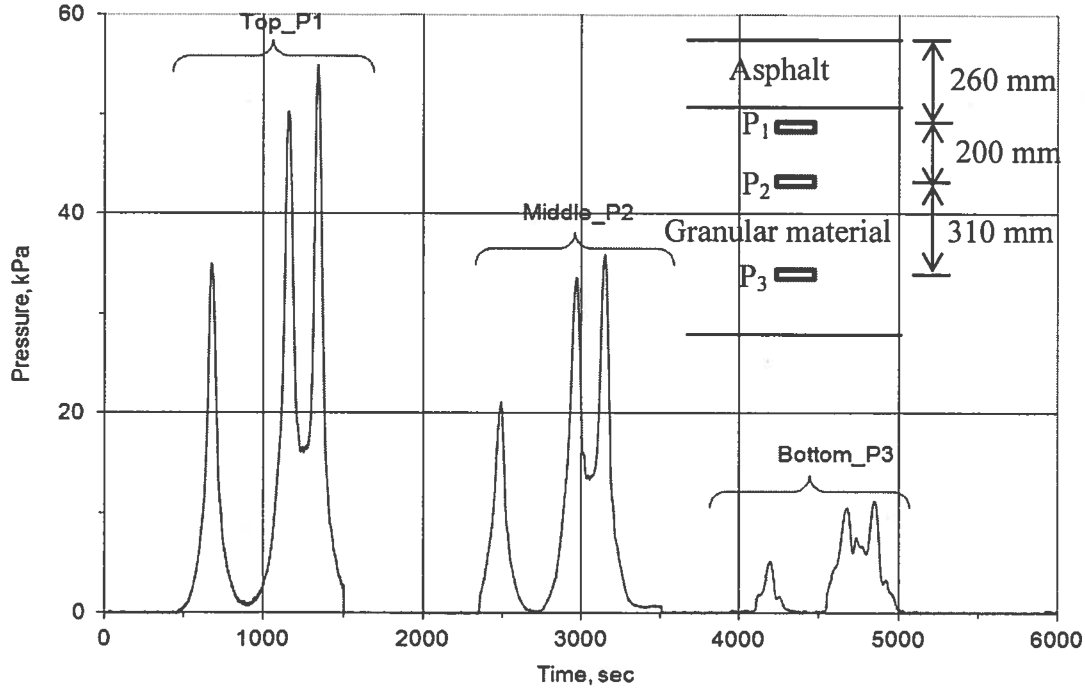


Fig 9. Typical pressure measurements during regular operation

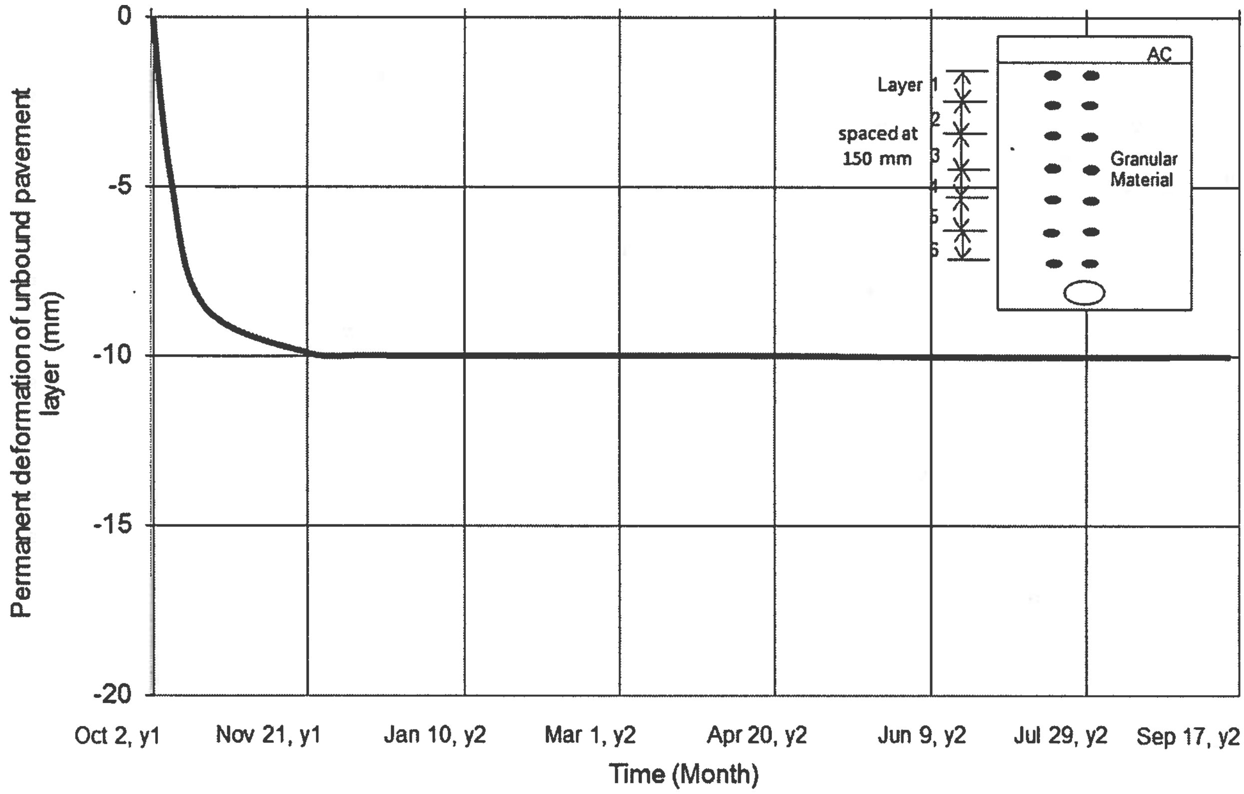


Fig 10. Typical deformation measurements during regular operation

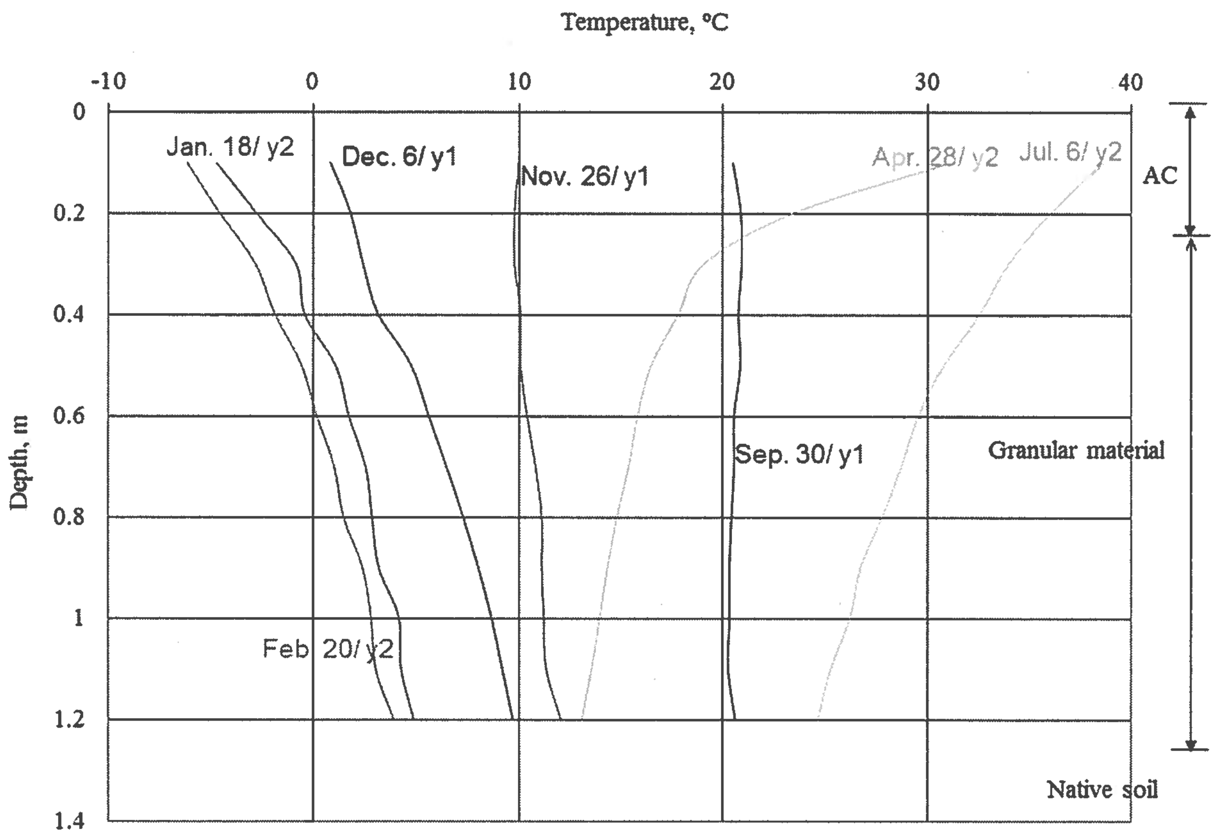


Fig 11. Temperature profile

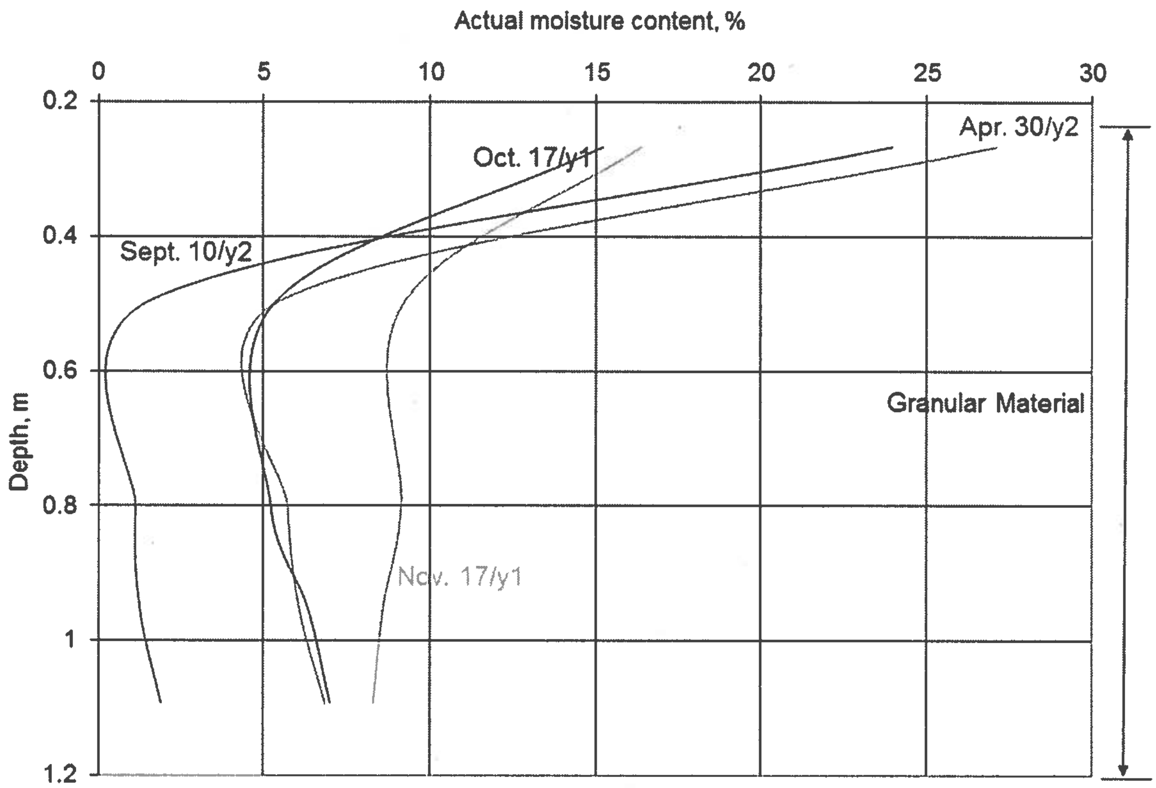


Fig 12. Moisture content profile

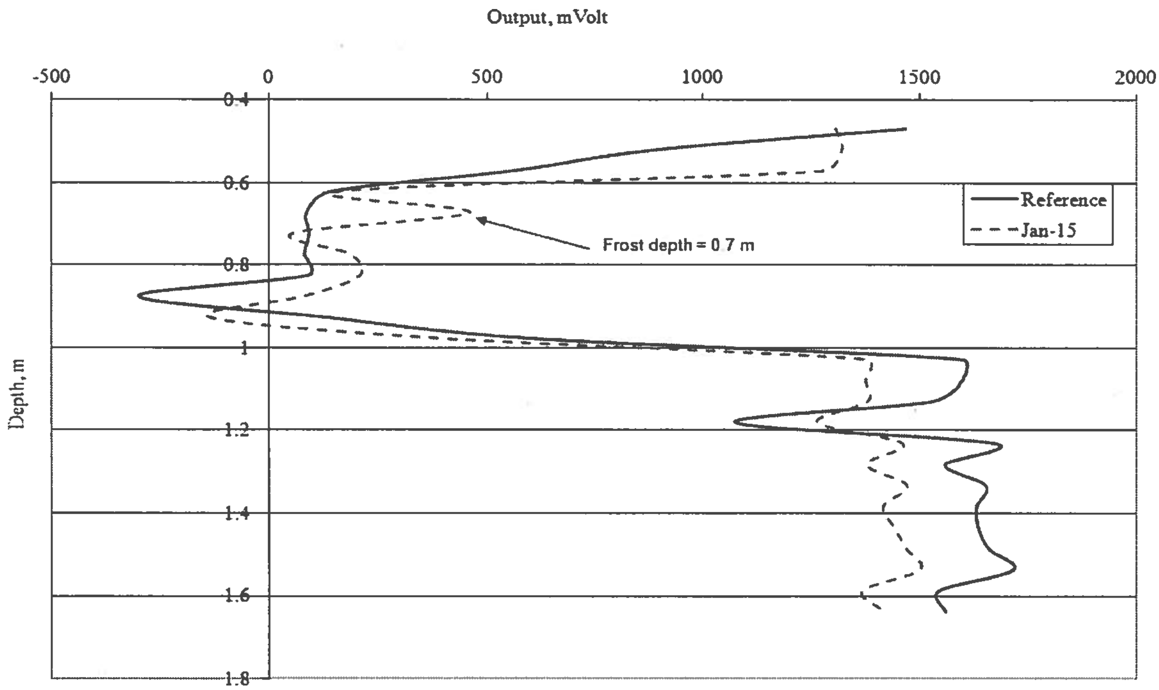


Fig 13. Resistivity data output

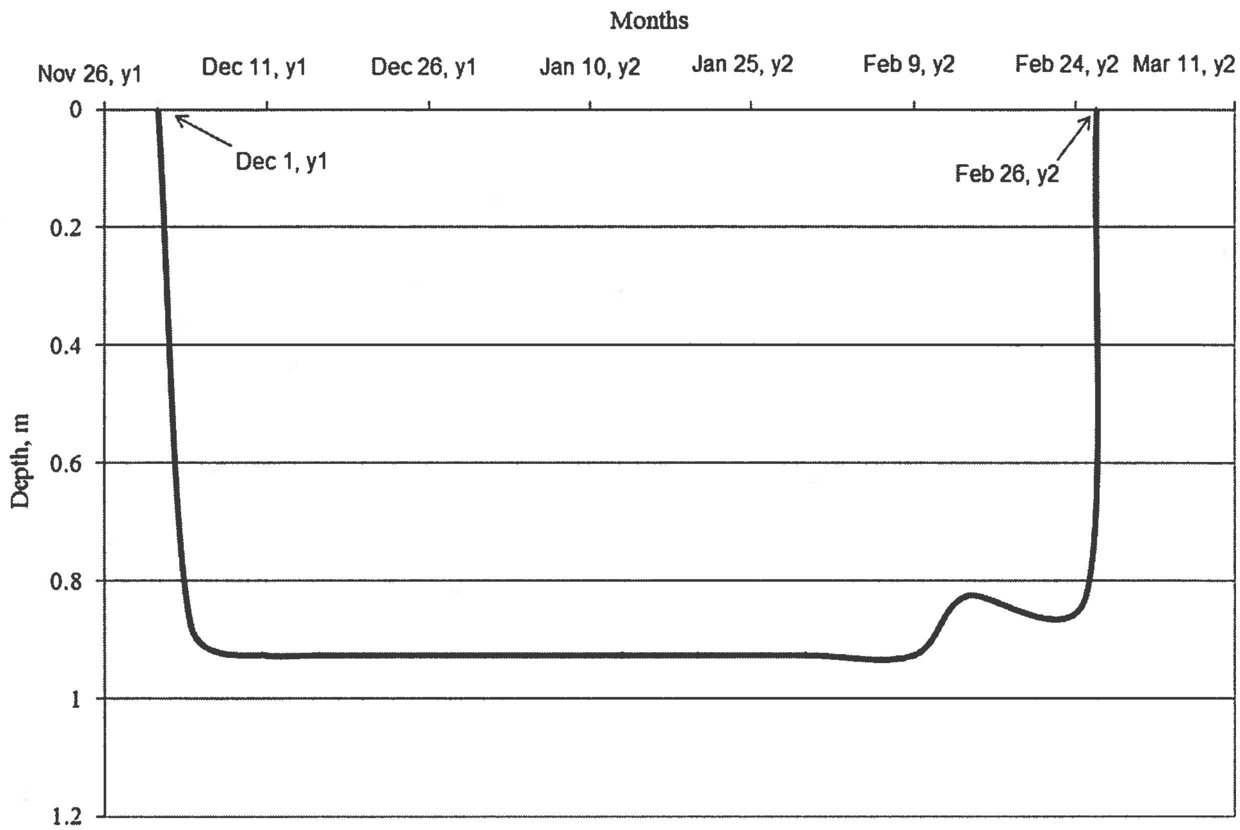


Fig 14. Typical freeze and thaw diagram