Project Report

Structural Assessment of Existing Road Pavement Using Field and Laboratory Experiments

by

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**Data Sheet**

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<td>Short Abstract (Maximum of 50 words)</td>
<td>In this study an attempt has been made to assess the thickness and structural characters of the existing road pavements using GPR antenna of 1.6 GHz and MASW of 24 channel geode seismograph with 4.5Hz geophones. Thirty one testing locations have been carefully selected in Bangalore by considering surface quality and type of roads. GPR and MASW survey has been carried out simultaneous in these locations. GPR gives electromagnetic wave velocity of subsurface layers, which are used to estimate pavement layer thickness. MASW gives shear wave velocity, which are used to estimate low strain dynamic properties of pavement layers. These results are compared with boreholes samples collected in the same locations. Comparison shows that these non destructive tests are effective in assessing thickness and quality (stiffness) with accuracy of more than 91% within short time.</td>
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Abstract

Determining flexible and rigid pavement layer thicknesses is important for pavement evaluation and for providing data to pavement management systems (PMS). Condition assessment of roads is a well known routine problem in transportation infrastructures maintenance. Many conventional methods practiced are time consuming and random testing. Ground Penetration Radar (GPR) is an electromagnetic method and Multichannel Analysis of Surface Wave (MASW) is seismic surface wave method, widely used to study many subsurface problems. In this study an attempt will be made to assess the existing pavement and substructures layers using GPR and MASW. Thirty one GPR and MASW surveys are carried out in different road conditions (good quality to bad quality) in and around Indian Institute of Science and the velocity and thickness of the pavement layers are estimated. In the same locations in-situ samples are extracted using core cutting machine. The in-situ samples are used to measure thickness, density, bitumen content and gradation of aggregates by carrying out laboratory tests. The shear wave velocity form MASW survey are combined with density from core samples and used to estimate low strain dynamic properties of pavement layer. The study shows that thickness of the pavement layers can be obtained from GPR with 91% accuracy. Visual classification and stiffness calculated are matching with respect to quality assessment.
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Chapter 1
Introduction

1.1 Introduction

India’s transport sector is largest and diverse; it caters to the needs of 1.1 billion people. In 2007, the sector contributed about 5.5 percent to the nation’s Gross Domestic Product (GDP), with road transportation contributing the lion’s share. Good physical connectivity in the urban and rural areas is essential for economic growth. Since the early 1990s, India's growing economy has witnessed a rise in demand for transport infrastructure and services. However, the sector has not been able to keep pace with rising demand and is proving to be a drag on the economy. Major improvements in the sector are required to support the country's continued economic growth and to reduce poverty (Worldbank, 2010).

Roads are the dominant mode of transportation in India today. They carry almost 90 percent of the country’s passenger traffic and 65 percent of its freight. The density of India’s highway network at 0.66 km of highway per square kilometer of land is similar to that of the United States (0.65) and much greater than China's (0.16) or Brazil's (0.20). However, most highways in India are narrow and congested with poor surface quality, and 40 percent of India’s villages do not have access to all-weather roads (Worldbank, 2010). Quality of road surface, stiffness and thickness of pavement layers are important parameters which influences the performance and efficiency of roads. Pavement evaluation plays a very important role in repair and rehabilitation of existing roads and quality control of new roads.
1.2 Motivation and Objectives

Determining flexible and rigid pavement layer thicknesses is important for pavement evaluation and for providing data to pavement management systems (PMS). Condition assessment of roads is a well known routine problem in transportation infrastructures maintenance. Knowledge of the structural condition of a pavement is required to make effective decisions on the type of maintenance or rehabilitation to be carried out on a pavement section. Reliable quantification of the structural condition is necessary for remedial work and which will also ensure the design life is achieved with maximum benefit/cost ratio. Pavement condition assessment is essential for the safe operation of vehicles and timely performance of pavement maintenance and repair (M&R). Condition assessment is performed conventionally based on pavement condition indicators which are determined based on measurement of pavement distress, structural capacity, friction and roughness. With the exception of roughness, all the other indicators are determined on a regular basis and the results are combined to determine M&R priorities and requirements. Roughness measurement is performed on an as-needed basis to help identify the source of roughness and the optimum method for eliminating roughness. Many conventional methods practiced are time consuming and random testing. Hence in this study, an attempt has been made to characterize existing pavement section by field and laboratory experiment and there by assessing the condition of the same, for better maintenance and repair work.

The main objective of this study is

(i) Condition assessment of selected pavements in Bangalore using conventional approach by calculating Pavement Condition Rating (PCR) based manual survey
(ii) Condition assessment of selected pavements in Bangalore using modern geophysical survey of Ground Penetration Radar and Surface wave

(iii) Thickness and Stiffness evaluation existing pavement layers and assess the quality

(iv) Collection of core samples by drilling and carrying out laboratory tests to determine thickness, bitumen content and particle size distribution to assess quality

(v) Compare pavement qualities and assess limitation and advantage of modern geophysical survey for pavement quality assessment.

1.3 Literature Review

Road pavement performance is a function of its relative ability to serve traffic over a period of time (Highway Research Board, 1962). Conventionally road pavement’s relative ability to serve traffic was determined quite subjectively by visual inspection and experience. However, experience is difficult to transfer from one person to another, and individual decisions made from similar data are often inconsistent. Recently many modern geophysical surveys are employed in road pavement evaluations. This section presents the literature of pavements evaluation, conventional and modern methods with technical terms.

1.3.1 Conventional Pavement Evaluation

In the late 1950s, systems of objective measurement (such as roughness meters, deflection and skid test equipment) began to appear that could quantify a pavement’s condition and performance. These systems, along with visual distress surveys, were used to aid in making maintenance and rehabilitation decisions, which, over the years have been refined and upgraded to provide rapid, objective means to (Hicks and Mahoney, 1981):
✓ **Establish maintenance priorities.** Condition data such as roughness, distress, and deflection are used to establish the projects most in need of maintenance and rehabilitation. Once identified, the projects in the poorest condition (low rating) will be more closely evaluated to determine repair strategies.

✓ **Determine maintenance and rehabilitation strategies.** Data from visual distress surveys are used to develop an action plan on a year-to-year basis; i.e., which strategy (patching, surface treatments, overlays, recycling, etc.) is most appropriate for a given pavement condition.

✓ **Predict pavement performance.** Data, such as ride, skid resistance, distress, or a combined rating are projected into the future to assist in preparing long-range budgets or to estimate the condition of the pavements in a network given a fixed budget.

Today, pavement performance is largely defined by evaluation in the following distress categories:

- Roughness (often called "smoothness")
- Surface distress
- Skid resistance
- Structural evaluation

**Roughness** - Pavement roughness is generally defined as an expression of irregularities in the pavement surface that adversely affect the ride quality of a vehicle (and thus the user). Roughness is an important pavement characteristic because it affects not only ride quality but also vehicle delay costs, fuel consumption and maintenance costs. The World Bank found road roughness to be a primary factor in the analyses and trade-offs involving
road quality vs. user cost (UMTRI, 1998). Roughness is also referred to as "smoothness" although both terms refer to the same pavement qualities (WSROT, 2010).

**Surface Distress** - Surface distress is "Any indication of poor or unfavorable pavement performance or signs of impending failure; any unsatisfactory performance of a pavement short of failure" (Highway Research Board, 1970). Surface distress modes can be broadly classified into the following three groups:

1. Fracture. This could be in the form of cracking (in flexible and rigid pavements) or spalling resulting from excessive loading, fatigue, thermal changes, moisture damage, slippage or contraction.

2. Distortion. This is in the form of deformation (e.g., rutting, corrugation and shoving), which can result from excessive loading, creep, densification, consolidation, swelling or frost action.

3. Disintegration. This is in the form of stripping, raveling or spalling which can result from loss of bonding, chemical reactivity, traffic abrasion, aggregate degradation, poor consolidation/compaction or binder aging.

Thus, surface distress will be somewhat related to roughness (the more cracks, distortion and disintegration - the rougher the pavement will be) as well as structural integrity (surface distress can be a sign of impending or current structural problems) (WSROT, 2010).

**Skid resistance** - Skid resistance is the force developed when a tire is prevented from rotating and slides along the pavement surface (Highway Research Board, 1972). Skid resistance is an important pavement evaluation parameter because:
- Inadequate skid resistance will lead to higher incidences of skid related accidents.

- Most agencies have an obligation to provide users with a roadway that is "reasonably" safe.

- Skid resistance measurements can be used to evaluate various types of materials and construction practices.

Skid resistance depends on microtexture and macrotexture of the pavement surface (Corley-Lay, 1998). Microtexture refers to the small-scale texture of the pavement aggregate component (which controls contact between the tire rubber and the pavement surface) while macrotexture refers to the large-scale texture of the pavement as a whole due to the aggregate particle arrangement (which controls the escape of water from under the tire and hence the loss of skid resistance with increased speed) (AASHTO, 1976).

Skid resistance changes over time. Typically it increases in the first two years following construction as the roadway is worn away by traffic and rough aggregate surfaces become exposed, and then decreases over the remaining pavement life as aggregates become more polished. Skid resistance is also typically higher during fall and winter and lower during spring and summer. This seasonal variation is quite significant and can severely skew skid resistance data if not compensated for (Jayawickrama and Thomas, 1998; WSROT, 2010).

**Structural evaluation**- Pavement surface deflection measurements are the primary means of evaluating a flexible pavement structure and rigid pavement load transfer. Although other measurements can be made that reflect (to some degree) a pavement's structural condition, surface deflection is an important pavement evaluation method because the magnitude and shape of pavement deflection is a function of traffic (type and volume),
pavement structural section, temperature affecting the pavement structure and moisture affecting the pavement structure. Deflection measurements are used in back calculation methods to determine pavement structural layer stiffness and the subgrade resilient modulus. Thus, many characteristics of a flexible pavement can be determined by measuring its deflection in response to load. Furthermore, pavement deflection measurements are non-destructive (WSROT, 2010).

Even though above four factors are responsible for pavement performance, which needs detailed survey and modern instruments to estimate. Hence conventionally performance of pavement or transportation network is assessed by quantifying Pavement Condition Rating (PCR) or Pavement Condition Index (PCI), which is a score that reflects their overall condition. This score, sometimes called a pavement condition rating, quantifies a pavement's overall performance and can be used to help manage pavement networks. By carefully choosing the rating scale (called the condition index), pavement condition scores can be used to (Deighton, 1998):

- **Trigger treatment.** For instance, once a pavement's condition rating reaches a certain level, it can be scheduled for maintenance or rehabilitation.

- **Determine the extent and cost of repair.** A pavement condition score is a numerical representation of a pavement's overall condition and can thus be used to estimate the extent of repair work and the likely cost.

- **Determine a network condition index.** By combining pavement condition scores for an entire road network, a single score can be obtained that gives a general idea of the network condition as a whole.
Allow equal comparison of different pavements. Since a pavement condition score accounts for all types of pavement performance measures it can be used to compare two or more pavements with different problems on an equal footing.

A pavement condition index is simply the scale or series of numbers used to describe a pavement condition. Typical pavement condition indices may be based on a scale of 0 to 5 or perhaps 0 to 100. The proper pavement condition index depends upon the objectives of whatever system is used to manage a particular pavement network (called Pavement Management System or PMS).

1.3.2 Pavement Condition Rating

Pavement Condition Rating (PCR) identifies various types of pavement distress for the pavement types and provides each distress overview and rating for pavement condition. The rating method used is based upon visual inspection of pavement. The rating method provides a procedure for uniformly identifying and describing, in terms of severity and extent of pavement distress. Although the relationship between pavement distress and performance is not well defined, there is general agreement that the ability of a pavement to sustain traffic loads in a safe and smooth manner is adversely affected by the occurrence of observable distress. The mathematical expression for Pavement Condition Rating (PCR) provides an index reflecting the composite effects of varying distress types, severity and extent on the overall condition of the pavement. The purpose of the PCR expression is to determine performance and the benefits associated with network condition improvements (such as roughness) for use in the benefit cost ratio (BCR) calculation for optimization (Rainsford, 2004). The PCR is a numerical rating on a scale of 0 to 100 that is determined based on measured distress types, quantities and severities.
Let distresses be called as D_1, D_2, D_3---D_N. Distress points (DP) are a function of weight factor (depends of distress type), severity and extent. DP for each distress will be estimated based on field survey and these are added to get summation value as below:

\[ \sum_{i=1}^{N} DP = DP_1 + DP_2 + DP_3 \ldots \ldots \ldots + DP_N . \]  

(1.1)

Where DP_i = (Weight for distress- D_i) (Weight for severity) (Weight for extent) and N is number of observable distresses. Distress weight is the maximum number of deductible points for each different distress type. The PCR is calculated by deducting total DP’s \( (\sum_{n=1}^{N} DP) \), the mathematical expression for PCR is as follows:

\[ PCR = 100 - \sum_{n=1}^{N} DP \]  

(1.2)

A PCR scale has been developed to describe the pavement condition using the PCR numbers calculated from the above equation. The scale has a range from 0 to 100; a PCR of 100 representing a perfect pavement with no observable distress and a PCR of 0 representing a pavement with all distress present at their “High” levels of severity and “Extensive” levels of extent. The PCR was developed to agree with the collective judgment of experienced pavement engineers as to the pavement structural integrity, surface operational condition, and needed level of maintenance and repair. Number distress depends on pavement types, for example distress of Faulting is used for Jointed Concrete pavements and Surface Deterioration is used for Jointed Concrete and Continuously Reinforced Concrete Pavements. Widely used distresses for Flexible Pavements and Composite Pavements are given in column 1 in Table 1.1. Weights for severity and extent of each distress are also given in Table 1.1.
### Table 1.1: Summary of PCR Distresses values

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<td>.8</td>
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<tr>
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<td>.3</td>
<td>.7</td>
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<tr>
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<td>.7</td>
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<td>.6</td>
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<td>Settlement (All Pavement Types)</td>
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<table>
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<tr>
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Flex  Flexible Pavement
Comp  Composite Pavement
1.3.3 Non-Destructive Tests for Pavement Evaluation

Numbers of non-destructive tests are used to test functional and structural properties of the pavement. This section presents review of non-destructive testing to evaluate pavement functional properties and structural properties. Pavements nondestructive tests can be broadly divided into several categories:

- Nuclear Equipment
- Deflection based Equipment
- Electromagnetic equipments and
- Seismic Equipments

Selection of particular nondestructive testing method is based on cost, time and availability of equipment.

**Nuclear Equipment** - A nuclear density gauge measures in-place HMA density using gamma radiation. Gauges usually contain a small gamma source (about 10 mCi) such as Cesium-137 on the end of a retractable rod. Gamma rays are emitted from the source and interact with electrons in the pavement through absorption, Compton scattering and photoelectric effect. A Geiger-Mueller detector (situated in the gauge opposite from the handle) counts gamma rays that reach it from the source. Pavement density is then correlated to the number of gamma rays received by the detector. Nuclear density gauges are typically operated in one of two modes, each of which uses a different correlation to determine pavement density

**Deflection Based Equipment**- Pavement surface deflections have been used in the past as an indicator of the pavement life. Pavement surface deflection measurements are the primary means of evaluating a flexible pavement structure and rigid pavement load
transfer. Although other measurements can be made that reflect (to some degree) a pavement's structural condition, surface deflection is an important pavement evaluation method because the magnitude and shape of pavement deflection is a function of traffic (type and volume), pavement structural section, temperature affecting the pavement structure and moisture affecting the pavement structure. Deflection measurements can be used in back calculation methods to determine pavement structural layer stiffness and the subgrade resilient modulus. Widely used deflection instruments are Benkelman beam and Falling Weight Deflectometer (FWD) or dynaflect.

**Benkelman Beam Test**

The Benkelman beam test procedure involves the measurement of pavement surface rebound with a cantilevered beam when a truck loaded to 8180 kg on its rear axle moves from rest. Measurements are made between the dual tires on the rear axle at specified intervals in the outer wheel path and are then corrected for temperature and seasonal variation. The corrected rebound values are used in a statistical manner to determine a most probable spring rebound (MPSR). The MPSR value, a specified design rebound and traffic number are used to enter a design chart (based on an accumulated experience on similar roads) to determine the overlay required to extend pavement life to 20 years. This test is fast, simple and inexpensive. However, it does not provide thickness information and must be accompanied by other tests that provide this information. In general, Benkelman beam tests are performed on an overlay is the preferred rehabilitation strategy.
**Falling Weight Deflectometer (FWD) or dynaflect.**

The dynaflect and Falling Weight Deflectometer are tools that measure surface deflection. In this technique, a number of geophones are used to determine the static deflection basin resulting from a vertical impact. A back-calculation procedure is then used to infer the thickness and resilient modulus of the constituent layers of the pavement structure. Due to the nature of the back-calculation algorithm, reliable layer thickness information is required to control the inversion process. Thus supplemental coring or road radar tests are required.

In this study, modern geophysical nondestructive tests of electromagnetic and seismic surface wave methods are used. Literatures of these two methods are given below:

### 1.3.4 Ground Penetration Radar (GPR)

GPR is an electromagnetic pulse reflection method based on physical principles similar to those of reflection seismic surveys. There are several synonyms and acronyms for this method like EMR (electromagnetic reflection), SIR (subsurface interface radar), georadar, subsurface penetrating radar and soil radar. GPR has been used since the 1960s with the term radio echo sounding (RES) for ice thickness measurements on polar ice sheets. The method has been increasingly applied for geological, engineering, environmental, and archaeological investigations since the 1980s.

Ground penetration Radar is an electromagnetic reflection method. Electromagnetic signal is emitted via an emitter built in antenna into the structure under inspection (Fig. 1.1). Emitted waves are reflected due to changes in material properties in substructures, which will be received by receiver inbuilt in antenna. This wave is recorded in control unit, displaced in monitor and further analyzed in computer. Frequency of emitted and
received electromagnetic waves plays important role in resolution and depth of
information. Commercially different antenna types (emitting and receiver unit) recording
different ranges of frequencies are available. Using high frequency antennas results in
high resolution data but reduces the depth of penetration. Low frequency antennas
provide greater depth of penetration at the expense of lower resolution. Electromagnetic
waves received from layers can be utilized to estimate dielectric properties of subsurface
layers, which is very important for different non-destructive evaluation techniques.
Dielectric properties are usually influenced by the volumetric properties of the subsurface
layers. The electric permittivity (dielectric constant) $\varepsilon$ and the electric conductivity $\sigma$ are
petrophysical parameters which determine the reflectivity of layer boundaries and
penetration depth. GPR is a well-established nondestructive method for investigating the
internal composition of many naturally occurring materials such as rocks, earth and
gravel, and man-made materials like concrete, brick and asphalt. It can also be used to
detect metallic and non-metallic pipes, sewers, cables, cable ducts, voids, foundations,
reinforcing rods in concrete, and a whole host of other buried objects (Fujie Zhou and
Tom Scullion, 2006).

![Fig. 1.1 – Radar Principle](image)
**Radar Principles**

Radar is short for **RA**dio **D**etection **A**nd **R**anging, so it's quite clear what it is all about: detection of a target and determination of its distance from the radar antenna. In general radar systems determine not only the distance but also the direction or location of the target. Both conventional radars and GPR use the same principle of traveling and reflected electromagnetic waves although the ways the waves are generated and treated are completely different.

![Fig. 1.2 - Basic principle of radar measurement](image)

A radar pulse emitted by the transmitter antenna is partly reflected and partly transmitted when it meets with an electrical discontinuity in the ground, that is, an interface at which there is a change in electromagnetic wave impedance or in other worlds a change in electrical properties. If the time for the pulse to go to the reflector and back again to the receiver antenna is measured, the location of the reflector in the ground can be decided, if
the velocity of the pulse is known. It can be seen from Figure 1.2 clearly the interfaces as layers result in a layer in the radargram, whereas objects form so called hyperbolas.

**COMPARISON OF GPR WITH OTHER NON DESTRUCTIVE METHODS**

**Seismic methods**

Comparisons are often done between seismic methods and GPR. Now what is the difference between these two methods? The resulting data looks very similar There are however a few fundamental things which distinguish the two techniques from each other:

- In seismic method, the reflection of the wave is caused by changes in the density of the material under investigation. In GPR the reflections are caused by changes in the electric properties, primarily in the dielectric constant $\varepsilon$.

- Seismic method requires a very good physical contact between the receiving/transmitting elements and the ground.

- Seismic method is at least 10 times more expensive than GPR per meter of profile.

- In GPR the velocity of the media usually never change more than 50% and that would be a rather extreme case, on a certain site. In seismic velocity contrasts can be much larger. This is because variations in density are much stronger than variations in the dielectric constant.

- GPR shows much more detail than seismic method, in other words, the resolution for GPR is higher.

- Seismic method works very well in clay where as GPR is almost useless. It also penetrates kilometers instead of meters as for GPR.
Ultrasonic methods

Much of what was said about seismic method is also true for ultrasonic since they are both acoustic methods, only the frequency differs. However the instrumentation is different and that makes a separate comparison valid:

- In ultrasonics the frequency is often high enough to make mm resolution possible e.g. in medicine.
- The contact with ground/media has to be so good that the sensors are often glued to the material one wants to investigate, or a contact gel is used.

Metal detectors/cover meters

Cover meters are types of instruments used for detection of rebar in concrete and metal detectors is probably familiar to everyone. Obviously these instruments only detect metal there are however, a few more distinguishing characteristics:

- Cover meters can never see through a wire mesh, anything below a first layer would be hidden. High-resolution radar sees trough a wire mesh and can detect both metallic and non-metallic objects under it.
- Cover meters are based on an assumption of a certain diameter of the rebars. This means that if two rebars are too close the instrument will become very uncertain.
- Metal detectors can be made very easy to use and also tuned to detect very small pieces of metal, smaller than GPR can resolve.

EM-locators

EM-locators are used to locate cables and metal pipes. They can be used both in active and passive mode, active meaning when the transmitter of the EM-locator is connected to the target. In practice the active mode is much preferred and people tend not
to use the passive mode when the active mode is possible. These instruments are easy to use and reliable. GPR is seldom used in these cases. Still there are many cases where GPR is more favorable:

- GPR detects both metallic and non-metallic targets, an EM-detector is only capable of locating the metal ones.
- The active mode requires the pipe, cable or tracer wire to be unbroken. For GPR this doesn’t matter.
- GPR can pinpoint many targets at one swat, when using an EM-locator you concentrate on one at a time, normally.

**X-ray**

No need to argue, X-ray is probably the most revealing NDT method. However it is very expensive, not only due to the complex security measures necessary during its application it's also quite slow and cumbersome.

**THE BASIC RADAR SYSTEM**

A radar system consist of

- **A control unit**, which generates the control signals for the receiver and transmitter antenna electronics, keeps track of the distance along the profile and buffers data from receiver.

- **Transmitter antenna** electronics, which generates impulses or steps, fed to the transmitting antenna.

- **Receiver antenna** electronics, which takes care of the incoming signals for digitisation and storage.
✓ **Transmitter and Receiver antenna elements**, bi-static. These can either be two separate units or mounted together in a box.

✓ **A recording facility** to store and display data. Most often this would be a laptop or a dedicated monitor.

✓ **An encoder to position and trigger the measurements**, most often a survey wheel or hip-chain or sometimes combined are used with GPS.

**GPR USED FOR**

As said before, only the imagination is setting the real limits for what can be done with GPR. In this section we're listing a few application areas in which GPR have been used previously. This list of assessments and analysis is not complete and new applications are added all the time.

<table>
<thead>
<tr>
<th>Archaeology</th>
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<td>Contaminated soil</td>
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<td>Soil classification</td>
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<td>Tunnel detection</td>
<td>Fault study</td>
</tr>
</tbody>
</table>

**GPR APPLICATIONS**

**Utility Locating**

To utility companies, buried services are assets that need to be protected, whilst to the construction industry they can represent a major hazard. Precise and reliable information
about the presence, location and depth of these utilities and other buried infrastructure is therefore essential. MALA Geoscience’s range of products offer the best imaging solution to reliably and non-destructively gather this important subsurface information accurately, efficiently and in real time, for both metallic and non-metallic targets (see Fig. 1.3).

**Key Advantages:** Locates metallic as well as non-metallic utilities - Easy user interface - Portable - Low cost GPR solution for the utility locating professionals - Fast - precise locating

**Solutions:** Subsurface Profiling & Object Location

**Products:**

* MALÅ MIRA (MALÅ Imaging Radar Array) System
* MALÅ Easy Locator System
* MALÅ X3M System

![Fig. 1.3 – GPR used Utility Mapping](image)

To locate and map utilities before any excavation begins is a concern to everyone involved. GPR is a beneficial tool due to its capability to locate both metallic and non-metallic utilities. When using GPR, both position and dept can be marked out on site and
later also visualized into 3D reports. Prior to new constructions or repair work it is important to locate existing underground utilities. If the utilities are of older age, the existing documentation is often non-existing or poor, which implies that accurate location becomes an important issue. This application will show some examples of GPR investigations where the aim has been to map different types of utilities.

**Key Advantages:** Locates metallic as well as non-metallic utilities - Fast - Easy user interface - Portable - precise locating - From low cost GPR solution with the Easy Locator for the utility locating professionals to more advanced solutions as the MALÅ MIRA –

**Products:**

* MALÅ MIRA (MALÅ Imaging Radar Array) System
* MALÅ Easy Locator System
* MALÅ X3M System
* MALÅ ProEx System

**Void Detection**
Buried voids are a hazard, both to engineers and the general public. They can impede construction operations, undermine building foundations and be the cause of destructive ground subsidence. Problems associated with hidden voids come in many forms such as naturally formed cavities and sinkholes in karstic limestone terrain, unknown basements, culverts, abandoned wells and mineshafts all of which present serious hazards.

**Key Advantages:** Locates metallic as well as non-metallic utilities - Easy user interface - Portable - Low cost GPR solution for the utility locate professionals - Fast - precise locating and non-destructive

**Solutions:** Subsurface Profiling & Object Location, Non-destructive Assessment & Testing

- Underground Storage Tank (UST) Location
- Septic System location
- Tunnel Assessment Surveys
- Rebar Location
- In-Slab Conduit Location
- Void Detection in Concrete

**Slab Thickness Measurement**
GPR can determine and record the slab thickness for both slab-on-grade and suspended slabs, determine rebar depth to measure concrete cover in slabs, beams and columns. GPR is a great tool for concrete evaluation and to determine concrete deterioration, slab thickness, rebar spacing, bar elevation, and amount of concrete cover over the rebar.

**Key Advantages:** GPR is a safer and less disruptive than X-Raying. GPR equipment is safe to use around people without any safety constraints or setup requirements. Because of these features, interruption of operations can be eliminated or minimized

**Application Area:** Infrastructure & Construction

**Products:**

* MALÅ CX (Concrete Imaging) System
* MALÅ ProEx System

**Road Evaluation**

Pavement engineers use ground penetrating radar to determine physical properties and characteristics of the pavement or subgrade. GPR helps engineers to determine the thickness of a pavement structure without resorting to excavation.
**Key Advantages:** A new breakthrough in GPR infrastructure technology for evaluating pavement, base and sub-base thicknesses. It is an extremely portable, user-friendly and cost-effective ground coupled platform that provides unmatched performance.

**Railway Ballast Evaluation**

Ground Penetrating Radar is an excellent non-destructive tool to inspect miles of Railroad track in a matter of minutes. It is capable of looking into the ground and quickly and accurately analyzing miles of data to determine where undercutting procedures should be focused.

Railway banks are often constructed with an insulating layer between the upper ballast material and the supporting layer below. The purpose of this insulating layer is to prevent fine material to reach the ballast. This investigation aimed to identify in which parts this insulating layer were installed, and in which parts it needed to be restored. The data was acquired with three antennas simultaneously, so the MALÅ CUII equipped with a multi channel MC-16 module was used, with shielded antennas, both 800MHz and 500MHz. Data acquisition was made with the MALÅ Ground Vision software and a laptop computer.
Runway Evaluation

Airport managers are now expending significant efforts to ensure that operating pavements are adequately engineered, or are reconstructed to cope with such demands. It is vital to detect at an early stage, defects such as sub-surface voids, rocking pavement slabs and de-bonding of materials and layers within the pavement and its sub-base. As increased traffic volumes and growth in aircraft movements restrict access to runways and other areas, rapid yet comprehensive survey techniques that avoid disturbing existing paved surfaces are becoming extremely valuable.

**Environmental Investigations:** Scientists and researchers use GPR for environmental assessment investigations in order to understand and examine the soil and potential contaminations.

**Mapping of Groundwater Resources:** GPR is used to map and examine groundwater resources

**Landfill Delineation:** GPR is used to locate landfill boundaries and contaminated soils.

**Contaminant Plume Profiling:** GPR is used for detecting and profiling contaminant plume from tank leaks, surface spills, piping leaks and landfills.
Site Assessment: As a non-invasive method, GPR is a perfect tool to locate and map the subsurface at a specific site.

Hazardous Material Delineation: GPR can be used to non-destructively examine areas of hazardous material.

Bedrock Profiling: GPR is successfully used by scientists and contractors to profile the bedrock and depth to bedrock.

River and Lake Bottom Profiling: GPR is used for investigating water depth, lake and river sediments and other underwater targets.

Peat Investigations: GPR is successfully used to identify the thickness and geometry of peat.

Ore Delineation: GPR can be used as a tool for locating ore from the background geology.

Archaeological Investigations: Ground penetrating radar is extremely useful in archaeology, where it can be used to inspect archaeological sites without being invasive. Ground penetrating radar saves a lot of time by allowing people to get an idea of the layout of the site and more specifically by identifying potential excavation sites before they start digging. It can also be used to gather information about culturally sensitive sites, or sites which might be damaged through excavation.

Snow and Ice Thickness Measurement: Researchers and others use GPR to measure the thickness of the snow. Measuring the thickness of the ice is of great importance in many situations. In the Northern regions it's of high priority to secure the quality of ice roads.
**Tree Trunk and Root assessment:** GPR can be used to rapidly estimate root biomass, dramatically reducing the number of soil cores that are usually needed and providing a much clearer picture of the lateral root system as it spreads out beneath the ground.

**Buried Objects Location (evidence, landmines, unexploded ordnance, IED, ammunition):**

![image of urban destruction](image)

Murder investigations require the locating of clandestine burials and a GPR reflection survey can be used to map the disturbances in soil profiles caused by excavating a site and also easily detects areas of backfill in otherwise homogeneous materials. Criminal evidence, weapons, human remains are often buried in shallow excavations and a GPR survey can readily detect these areas.

Preliminary results of layer thickness and spatial variations can be directly obtained in field by visual inspection of GPR radargram. The GPR radargram consist of captured reflected energy versus time many pulses, a typical plot one pulse is shown in Figure 4 as a graph of amplitude in volts versus arrival time in nanoseconds. This electromagnetic wave pulse can be used to estimate dielectric parameters and thickness of material wave passes. For example in the Figure 4, the reflection, A_1, is the energy reflected from the surface of the pavement, and A_2 and A_3 are reflections from the top of the base and subgrade, respectively. These are all illustrated as positive reflections, which indicate an
interface with a transition from a low to a high dielectric material. The amplitudes of reflection and the time delays between reflections are used to calculate both layer dielectrics and thickness.

![Diagram of radar antenna and pulse reflected energy versus time](image)

**Fig. 1.4 - A typical plot GPR pulse reflected energy versus time (after Scullion and Saarenketo, 2002)**

The dielectric constant of a material is an electrical property that is most influenced by moisture content and density. An increase in moisture will cause an increase in layer dielectric. In contrast, an increase in air void content will cause a decrease in layer dielectric. A range of typical dielectrics has been established for most paving materials. Pavement layers normally have a dielectric value between 3 and 6.5. Measured values dielectrics are significantly higher than this would indicate the presence of excessive moisture. Lower values could indicate a density problem or indicate that an unusual material, such as lightweight aggregate, has been used. The examples below illustrate
how changes in the pavement’s engineering properties would influence the typical GPR trace shown in Figure 4.

- If the thickness of the surface layer increases, then the time interval between A1 and A2 would increase.
- If the base layer becomes wetter, then the amplitude of reflection from the top of the base, A2, would increase.
- If there is a significant defect within the surface layer, then an additional reflection will be observed between A1 and A2.
- Large changes in the surface reflection, A1, would indicate changes in either the density or moisture content along the section.

**Layer Dielectrics Thickness Calculation**

Using the amplitudes (volts) and time delays (ns) from Figure 4, it is possible to calculate layer dielectrics and layer thickness. The equations used are summarized below:

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

(1.3)

Where

\[ \varepsilon_a = \text{the dielectric of the surfacing layer} \]

\[ A_1 = \text{the amplitude of surface reflection; and} \]

\[ A_m = \text{the amplitude of reflection from a large metal plate in volts (this represents the 100 percent reflection case).} \]

\[
h_i = \frac{c \times \Delta t_i}{\sqrt{\varepsilon_a}} 
\]

(1.4)

Where

\[ h_i = \text{the thickness of the top layer;} \]
\( c = \) speed of EM wave in air (150 mm/ns two-way travel); and

\( \Delta t_1 = \) the time delay between peaks, \( A1 \) and \( A2 \).

\[
\sqrt{\varepsilon_b} = \sqrt{\varepsilon_a} \left[ 1 - \left( \frac{A_1}{A_m} \right)^2 + \left( \frac{A_2}{A_m} \right)^2 \right] \left[ 1 - \left( \frac{A_1}{A_2} \right)^2 - \left( \frac{A_1}{A_m} \right)^2 \right]^{-1}
\]

(1.5)

Where

\( \varepsilon_b = \) the dielectric of base layer; and

\( A_2 = \) the amplitude of reflection from the top of the base layer.

\[
h_{\text{base}} = \frac{c \times \Delta t_2}{\sqrt{\varepsilon_b}}
\]

(1.6)

where:

\( h_{\text{base}} = \) thickness of base layer; and

\( \Delta t_2 = \) time delay between \( A_2 \) and \( A_3 \).

Using the above equations, one may calculate both layer thickness and dielectrics along the pavement. The use of the thickness information for either quality control of new construction or structural evaluation of existing structures is obvious to pavement engineers. However, the layer dielectric values and their variation along a highway are also of practical significance, as demonstrated by Saarenketo and Scullion (1995) and by Saarenketo (1997).

**Application of GPR on Existing Asphalt Pavements**

The biggest use of GPR is in the area of evaluating existing asphalt pavements for pavement rehabilitation. GPR testing is often used to determine layer thickness, detect changes in the pavement structure, and identify subsurface defects, particularly moisture
damage. This approach has proven to be highly effective in mature highway network and its focus on pavement rehabilitation. When dealing with older road networks where numerous sections have been widened and/or received partial rehabilitation, it is extremely difficult to maintain reliable layer thickness information (Scullion and Saarenketo, 2002). Pavements are evaluated using Air-coupled GPR most of cases in outside India, because of road geometry, less traffic noises, cost and facility. But in this study we have used Ground-coupled GPR for Indian roads. Few of case studies of pavement evaluation using GPR are given below:

Al-Quadi and Lahouar (2002) describes the identification of hot mix asphalt thickness using ground penetrating radar. Results show that GPR works well for some situations, but is not an appropriate tool for other situations. It is currently not used on a routine basis by the Departments of Transportation (DOTs) in the U.S. due mainly to difficulties encountered in data interpretation, as well as the expenses involved for conducting GPR surveys. Data interpretation difficulties are mainly attributed to the fact that images obtained from the reflected signals are dependent on the GPR frequency used and the dielectric properties of the structural materials. To calibrate GPR systems and to better interpret collected data (signals) from Virginia Smart Road in Southwest Virginia. These experimental sections provide a unique opportunity to explore the feasibility of using GPR to assess pavements and to verify its practicality. The GPR system cannot detect layer interfaces unless a significant contrast in the dielectric constants exists between the two considered layers. This requirement is more important for the deeper interfaces because of material loss that further attenuates the GPR electromagnetic signals. To overcome the inaccuracy in results from time domain analyses, a more sophisticated
technique is considered in this study. Preliminary results of analyzed data collected from interstate I-81 revealed an error of 6.8%, whereas the classic time domain technique showed an error of 12.7% for the same data.

Kenneth and Maser Study (1996) described the identification of pavement layer thickness data on the 40 Mn/ROAD research pavement sections. Since coring and other destructive testing was not acceptable, ground penetrating radar-(GPR) was selected for this purpose. Radar data for pavement layer thickness was collected at the Mn/ROAD research facility on July 7, 1994. The data was collected on all 40 test sections in the two outside wheel paths of each section. Two types of radar equipment were used: (a) air-coupled equipment normally operated at driving speeds, and (b) ground-coupled equipment normally operated at 5-10 mph. The data was analyzed using PAVLAYERO to determine layer thicknesses. The software is self-calibrating and the analysis was carried out without core data. Layer thickness results are presented as graphic pavement cross section plots, and in ASCII files. A report of first stage results was submitted on August 29, 1994 for comparison of computed asphalt and concrete thicknesses at 74 locations to available core data. The core data was subsequently provided by Mn/ROAD, and correlations between core and PAVLAYER data were carried out. A blind comparison between radar asphalt thickness data and cores has shown an R-squared of 0.98. For concrete thickness, the R-squared was 0.76. The average deviation between radar and core data was 0.24 inches for asphalt, and 0.53 inches for concrete. To improve the accuracy of the concrete data, a calibration factor based on this correlation was applied to the final analyzed data. Subsequent to the above analysis complete results have been obtained for asphalt and concrete layer thickness, for base and sub base thickness, and for.
the layer thicknesses of the four aggregate sections. Thicknesses have been reported at 10 foot intervals, and are presented in ASCII plots. This project has shown that for the Mn/ROAD pavement conditions: (a) accurate asphalt thickness data can be obtained using highway speed horn antenna ground penetrating radar equipment and automated analysis software; and (b) accurate thickness data can also be obtained for concrete and base thickness, but lower speed ground coupled equipment must also be used.

1.3.5 Multichannel analysis of surface waves (MASW)

Multichannel analysis of surface waves (MASW) method is one of the seismic survey methods evaluating the elastic condition (stiffness) of the ground for geotechnical engineering purposes. MASW first measures seismic surface waves generated from various types of seismic sources—such as sledge hammer—analyzes the propagation velocities of those surface waves, and then finally deduces shear-wave velocity (Vs) variations below the surveyed area that is most responsible for the analyzed propagation velocity pattern of surface waves. Shear-wave velocity (Vs) is one of the elastic constants and closely related to Young’s modulus. Under most circumstances, Vs is a direct indicator of the ground strength (stiffness) and is therefore commonly used to derive load-bearing capacity.

Advantages of the MASW Method

- Data acquisition is significantly more tolerant in parameter selection than any other seismic methods because of the highest signal-to-noise ratio (S/N) easily achieved. This most favourable S/N ratio is due to the fact that seismic surface waves are the strongest seismic waves generated that can travel much longer distance than body waves without suffering from noise contamination.
Because of an increased ability to discriminate useful signal from harmful noise, the MASW method assures an increased resolution when extracting signal in the midst of noise that can be anything from natural or cultural activities (wind, thunder, traffic, etc.) to other types of inherent seismic waves generated simultaneously (higher-mode surface waves, body waves, bounced waves, etc.)

In consequence, overall field procedure for data acquisition and subsequent data-processing step becomes highly effective and tolerant, rendering a non-expert method.

**Overall Procedure of MASW Survey**

The common procedure for (1-D, 2-D, and 3-D) MASW surveys usually consist of three steps (Figure 5)

1) **Data Acquisition**---acquiring multichannel field records (commonly called shot gathers in conventional seismic exploration)

2) **Dispersion Analysis**---extracting dispersion curves (one from each record)

3) **Inversion**---back-calculating shear-wave velocity (Vs) variation with depth (called 1-D Vs profile) that gives theoretical dispersion curves closest to the extracted curves (one 1-D Vs profile from each curve).
Fig. 1.5 - Common procedure for MASW surveys for 1-D, 2-D, and 3-D Vs mapping.

Park and Julian (2001) describe a feasibility test of the multichannel approach to seismic investigation of a pavement system. This test followed the procedure normally taken in the multichannel analysis of surface waves (MASW) method by using geophones and a light (8-oz) hammer source. Wave field transformations of recorded multichannel data
shows a strong fundamental-mode dispersion curve image in the frequency range of 30-600 Hz with normal (30-50 Hz) and reverse (50-600 Hz) trends. However, the transformation shows that this fundamental mode disappears quite abruptly and higher modes start to dominate in the higher frequencies up to 2000 Hz. Simultaneous recording of both vertical and horizontal components of seismic wavefields facilitates identification of seismic events. In order to record the horizontally travelling direct (or possibly guided) P-wave event in the uppermost layer, it seems critical to use horizontal phones with longitudinal orientation. Results of tests indicate that for an investigation focused into the uppermost layers of a pavement system it is essential to use a different acquisition system that can deal with much higher (> 2000 Hz) frequencies. In addition, complicated and unique elastic properties of pavement systems call for an inter-disciplinary study to develop an effective multichannel seismic method for this area of application.

Ryden and Park (2003) measured the multimodal Lamb wave dispersion curves and analyzed to obtain elastic stiffness parameters and thickness of concrete plate structures. With a simple and cost-effective field procedure and by utilizing the Multichannel Analysis of Surface Waves (MASW) processing technique, the characteristics of the different modes in experimental Lamb wave dispersion curves can be measured. Lamb waves are guided dispersive waves propagating in plate structures. By matching theoretical Lamb wave dispersion curves with experimental dispersion curves, Young’s modulus, Poisson’s ratio, and the thickness of the tested structure can be evaluated. A theoretical background with dispersion equations is given along with a practical guide to generate theoretical dispersion curves. Since these pure Lamb wave dispersion curves are
only dependent on the plate parameters, the frequency and the phase velocity can be normalized with respect to shear wave velocity and the thickness of the plate. This reduces the calculations during the matching procedure, and one only need to rescale the normalized axis of the dispersion curves to match theoretical and experimental dispersion curves. With a sensitivity analysis we give some recommendations on the matching procedure. The proposed analysis scheme is demonstrated using a case study on a concrete bridge support. Available reference data is in good agreement with the evaluated parameters from the presented analysis scheme.

1.4 Scope of the Project

Improving and maintenance of transportation infrastructures is a major task in any urban centre in India. These transportation facilities are playing a major role in infrastructure development, economical growth and people/industrial agglomerations. Most of the urban centers are improving transportation infrastructures, in particular, roads by better maintenance and augmentation, rather than new construction. In general, maintenance of road network in city/urban centre consumes almost 80% of cost in total transportation infrastructure expenditures. This may be due to the lack of scientific/technical knowledge for road condition assessment, maintenance and repairs. Road maintenance is a major issue in Indian cities, even in Bangalore, Karnataka, where most scientific research institutes and information technology companies are located.

In this study, an attempt has been made to characterize existing pavement section by field and laboratory experiment and there by assessing the condition for better maintenance and repair work. 36 different road conditions are selected in and around
IISc, these locations are inspected visually and PCR is evaluated as per conventional pavement condition assessment. In these 36 locations non destructive field experiment of GPR survey has been carried out. Dielectric parameters and thickness of these locations are estimated. In addition to this, in few selected locations seismic survey and wave survey using MASW has been carried out and shear wave velocity (SWV) of pavement layers are estimated using higher mode of surface wave and SWV of subsurface layers, below dense layer are estimated using fundamental mode of surface wave. In the same location, the undisturbed in situ samples are collected by core cutting. Density, bitumen content, gradation of aggregate are measured in the laboratory using in situ samples. SWV and density are combined and used to estimate shear modulus and Young’s modules at low strain level. These results are used to achieve the following:

- GPR data image bank for different roads condition
- Characterize the existing pavement using non destructive and laboratory tests
- These results are compared, combined and correlated to future applications; this can be used to evaluate other pavements and to identify problematic locations for pretreatments.
Chapter 2

Condition Assessment of Pavements using GPR, MASW and Core Samples

2.1 Introduction

Different types of road damages are found in Bangalore. They are mainly alligator cracking, strip failure and pot holes. These are mainly due to improper construction procedure, heavy traffic and weather conditions. Some of them are shown in Figure 2.1. Traditionally, pavement layer thicknesses have been determined by digging test-pits or by extracting cores from the pavement. This study is focussed on evaluation of pavement thickness and quality using Ground Penetrating Radar and compared with conventional boring and sampling. The detailed objectives are outlined in the previous section.

Alligator Cracking At Parking Lot

Ravelling Due To Segregation
Pavement failures are extensive and frequent in most of the Indian roads due to various reasons. But limited attempt has been made to study pavement condition rating before repair and rehabilitation of any pavement. Pavement condition assessment is mandatory steps in many countries before overlay and repairing. Many distinct research studies and reports are available on Pavement Condition Rating (PCR) and pavement evaluation using GPR, MASW and core drilling around the work. But limited attempt has been made to assess pavement condition using all these methods in single location. Hence this study estimate PCR, dielectric constant, thickness from GPR, shear wave velocity, thickness, bitumen content, aggregate gradation for different and compare the same. In this study the methodology is followed to achieve final objectives of the project.

- Preliminary survey and site selections
- Detailed distresses assessment and Pavement Condition Rating
- GPR survey and estimation of dielectric constant and thickness

**Fig.2.1. General types of pavement failures in Bangalore roads**
MASW survey and estimation of shear wave velocity

Core cutting and in situ sampling of pavement layers

Conducting laboratory test and measuring density, bitumen content and gradation of aggregate

Compare and correlation of results

2.2 Model Study for Validation

GPR is widely used in abroad, but it is new techniques for education institutes in India. In order to assess capability Model study has been carried out with known properties and dimensions. This study has been carryout in Geotechnical engineering laboratory in Indian Institute of Science, Bangalore to learn about GPR and Image interpretation. A model section of 3 m length, 1 m width and 0.3 m height has been constructed using Sand, Red soil, Concrete block and steel pipes. Dielectric properties of these materials are measured using GPR instrument of 500 MHz antenna by moving the antenna above the model section. Typical Model track with GPR 500 MHz antenna is shown in Figure 2.2.

Fig.2.2. Model section constructed in Geotechnical Engineering Lab
The concrete slap is buried at 1m from the section edge and close to surface with little soil cover. Later GPR survey has been carried out using 500 MHz antenna and electromagnetic signals are recorded. The standard correction is applied for DC removal, time zero adjustments and background noise removal. Figure 2.3 shows GPR image result. It can be clearly seen that strong signal reflection coming from the concrete slab after 1 m from edge. These results match very well with model track setup. GPR survey has been carried out on old drains covered by concrete slab and respective GPR image is shown in Figure 2.4. The dry and saturated sand can be easily identified in GPR survey. GPR survey image on dry and wet sand is shown in Figure 2.5.

![GPR radargram of the concrete block and soil](image1)

![GPR radargram of over old drain covered by concrete slab](image2)
2.3 Preliminary survey and Site Selections

Locations for study has been selected by detailed reconnaissance survey at Yeshwanthpur, Hebbal, Indian Institute of Science, RT Nagar, New BEL Road, Mallleswaram and Ring road between Yeswanthpur to Hebbal. Considering accessibility and traffic, four locations has been selected for survey i.e. IISc campus, Mathikere, New BEL road and Outer ring road. In these selected four location about 8 to 10 roads are selected based on the following criteria

- Pavement visual condition (maximum possible conditions are included)
- Type of roads
- Free from frequent traffic
Space for GPR and MASW survey

First day survey has been carried out at IISc in selected roads. Figure 2.6 shows the ten survey points in the IISc campus. GPR data and core samples were collected from these ten locations. Co–ordinates of each location, date of survey, core details and GPR file numbers are shown in the Table 2.1.

Fig 2.6 Testing locations in IISc campus, Bangalore

Table 2.1: Summary of tests carried out in IISc campus

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Co-ordinates</th>
<th>Visual Distress Survey</th>
<th>GPR (1.6GHz antenna)</th>
<th>MASW</th>
<th>Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>Genetic Engineering Block</td>
<td>13°00′56.42″N 77°34′07.96″E</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>yes</td>
</tr>
<tr>
<td>I2</td>
<td>Aerospace Engineering Block</td>
<td>13°01′01.81″N 77°34′16.10″E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>I3</td>
<td>Centre for Ecological Science</td>
<td>13°01′01.92″N 77°34′14.03″E</td>
<td>yes</td>
<td>yes</td>
<td>-</td>
<td>yes</td>
</tr>
</tbody>
</table>
Nine surveys have been carried out in the NEW BEL road next to Indian Institute of Science campus. Figure 2.7 shows survey points in NEW BEL road. GPR data and core samples were collected from these nine locations. Co–ordinates of each location, date of survey, core details and GPR file numbers are shown in the Table 2.2.
### Fig 2.7 Testing locations in New BEL road, Bangalore

#### Table 2.2 Summary of tests carried out in New BEL road

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Co-ordinates</th>
<th>Visual Distress Survey</th>
<th>GPR (1.6GHz antenna)</th>
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<th>Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₁</td>
<td>5ᵗʰ cross Radhakrishna ward no:18</td>
<td>13°01’49.77”N 77°34’31.69”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₂</td>
<td>Yedurappa road</td>
<td>13°01’40.90”N 77°34’21.52”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₃</td>
<td>Yedurappa road</td>
<td>13°01’40.90”N 77°34’21.52”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₄</td>
<td>New BEL Road-Ayyappa Temple</td>
<td>13°01’28.00”N 77°34’18.14”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₅</td>
<td>Near MSR Bus Stop</td>
<td>13°01’36.56”N 77°34’18.14”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₆</td>
<td>BEL Land</td>
<td>13°02’24.36”N 77°33’51.83”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₇</td>
<td>BEL Road Bridge</td>
<td>13°02’15.70”N 77°33’49.36”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>N₈</td>
<td>3rd Iron RMV 2nd Stage</td>
<td>13°02’15.70”N 77°34’08.56”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Nine surveys have been carried out in Mathikere next to Indian Institute of Science campus. Figure 2.8 shows survey points in Mathikere road. GPR data and core samples were collected from these nine locations. Co–ordinates of each location, date of survey, core details and GPR file numbers are shown in the Table 2.3.

Table 2.3 Summary of tests carried out in Mathikere

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Co-ordinates</th>
<th>Visual Distress Survey</th>
<th>GPR (1.6GHz antenna)</th>
<th>MASW</th>
<th>Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Vinuthan Kanchi silks</td>
<td>13°01’45.27”N 77°33’36.56”E</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>M2</td>
<td>Opposite to Vinuthan Kanchi silks</td>
<td>13°01’46.07”N 77°33’37.87”E</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>M3</td>
<td>Near south Indian bank</td>
<td>13°01’50.30”N 77°33’36.29”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Nine surveys have been carried out in the Outer Ring road next to Indian Institute of Science campus. Figure 2.9 shows survey points in Outer Ring road. GPR data and core samples were collected from these nine locations. Co–ordinates of each location, date of survey, core details and GPR file numbers are shown in the Table 2.4.

<table>
<thead>
<tr>
<th></th>
<th>Road Location</th>
<th>Co–ordinates</th>
<th>GPR Data</th>
<th>Core Details</th>
<th>File Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4</td>
<td>Road towards Yesvantpur</td>
<td>13°01’47.26”N 77°33’35.63”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>M5</td>
<td>Near to Bombay bazar</td>
<td>13°01’48.52”N 77°33’34.33”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>M6</td>
<td>Road opposite to Sri Ayyappa bakery</td>
<td>13°02’02.88”N 77°33’36.99”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>M7</td>
<td>8th main Mathikere</td>
<td>13°01’54.96”N 77°33’40.48”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>M8</td>
<td>10th main Mathikere</td>
<td>13°01’52.14”N 77°33’39.31”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>M9</td>
<td>Diwanara playo bustop</td>
<td>13°01’34.60”N 77°33’42.24”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

![Fig 2.9 Location of outer ring road - Hebbal](image)
Table 2.4 Summary of tests carried out in outer ring road - Hebbal

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Co-ordinates</th>
<th>Visual Distress Survey</th>
<th>GPR (1.6GHz antenna)</th>
<th>MASW</th>
<th>Drilling</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Vidyaranyapura road</td>
<td>13°02’48.17”N 77°33’24.64”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>R2</td>
<td>Vidyaranyapura road</td>
<td>13°03’05.68”N 77°33’25.45”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>Near to Vidyaranyapura</td>
<td>13°03’22.95”N 77°33’30.60”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>road</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>Opposite to Santi hair</td>
<td>13°03’42.01”N 77°33’31.91”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td></td>
<td>style</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>Rajarathnam circle</td>
<td>13°02’44.26”N 77°33’22.67”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>R6</td>
<td>Outer ring road</td>
<td>13°02’37.52”N 77°33’32.00”E</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>R7</td>
<td>Near to big bazaar</td>
<td>13°02’50.45”N 77°34’24.68”E</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>R8</td>
<td>Opposite to Big Bazar</td>
<td>13°02’49.66”N 77°34’24.83”E</td>
<td>yes</td>
<td>yes</td>
<td></td>
<td>yes</td>
</tr>
</tbody>
</table>

2.4 Pavement Condition Rating

Various pavement distresses and its severity and extent are important factors for accurate pavement surface condition assessment which affects the performance of pavement system. Various methods of pavement condition assessment have been developed over the years with varying degrees of accuracy and acceptance. Developed countries are
using digital photography to record pavement images and subsequent crack detection system. Pavement classification based on these modern facilities has undergone continuous improvements over the past decade. Important distresses and weights for type, severity and extent are presented in Table 2.5. Limited attempt has been made in India for detailed pavement condition assessment. In order to assess pavement condition of selected locations a detailed visual survey has been carried out with digital photography. Below subsections presents type of distress identified with severity and extent in selected location.

**Raveling**

Raveling is disintegration of the pavement from the surface downward due to the loss of aggregate particles. Raveling may occur as a result of asphalt binder aging, poor mixture quality, segregation, or insufficient compaction.

**Severity Level:**

*Low:* Very little coarse aggregate has worn away some loss of fine aggregate, coarse aggregate is exposed.

*Medium:* Surface has an open texture and is moderately rough with considerable loss of fine aggregate and some coarse aggregate removed.

*High:* Most of the surface aggregate has worn away or become dislodged. Surface is severely rough and pitted and may be completely removed in places.

**Extent Level:**

*Occasional:* Less than 20% of the surface area is raveling.

*Frequent:* Between 20% and 50% of the surface area is raveling.

*Extensive:* More than 50% of the surface area is raveling.
Bleeding

Bleeding or flushing is the presence of free asphalt binder on the pavement surface. Bleeding is caused by an excess amount of bituminous binder in the mixture and/or low air void content.

Severity Level

Medium: Both coarse aggregate and free bitumen are noticeable at the pavement surface.

High: Surface appears black with very little aggregate noticeable.

Extent:

Occasional: Less than 10% of the length exhibits bleeding.

Frequent: Between 10% and 30% of the length is bleeding.

Extensive: Bleeding occurs in more than 30% of the length.
Corrugations

Corrugations are a series of transverse ridges and valleys (or ripples) occurring at regular intervals along the pavement. Unstable bituminous mixture or poor base qualities are associated with this distress.

Severity Level:

Low: Noticeable effect on ride, but no significant reduction in comfort.

Medium: Moderate ride discomfort is noticeable, driver able to maintain vehicle control easily.

High: Vehicle vibration is severe, speed reduction is necessary for comfort and to maintain vehicle control.

Extent:

Occasional: Less than 10% of the section length is affected by this distress.

Frequent: Between 10% and 30% of the section length is affected by this distress.
**Extensive:** Greater than 30% of the section length is affected by this distress.

**Rutting**

Ruts are vertical deformations in the pavement surface along the wheel tracks. In severe cases pavement uplift may occur along the sides of the rut, but in most instances only a depression is noticeable. Rutting is caused by consolidation or lateral movement of any or all pavement layers, including subgrade, under traffic.

**Severity Level:** Rutting severity is based upon rut depth, as approximated visually.

**Low:** Barely noticeable, depth less than 6 mm (1/4 inch).

**Medium:** Readily noticeable, depth more than 6 mm (1/4 inch), less than 25 mm (1 inch).

**High:** Definite effect upon vehicle control, depth greater than 25 mm (1 inch).

**Extent:**

**Occasional:** Less than 20% of the section length is rutted.

**Frequent:** Between 20% & 50% of the section length is rutted.

**Extensive:** More than 50% of the section length is rutted.

**Potholes/Debonding**

Potholes are bowl-shaped voids or depressions in the pavement surface. Potholes are localized failure areas which are usually caused by weak base or subgrade layers.

Loss of surface by de-bonding is the removal of the asphaltic surface layer from the underlying layer. The problem is most common with thin asphalt surface layers [less than 50 mm (2 inches)] and is caused by freeze-thaw action or poor bonding of the two layers during construction.

**Severity Level:** Use the following table to determine the severity levels:

<table>
<thead>
<tr>
<th>Depth of De-bonded Area</th>
<th>De-bonded Area &lt;0.8 m²</th>
<th>De-bonded Area &gt;0.8 m²</th>
</tr>
</thead>
</table>

53
Regardless of depth, potholes less than 150 mm (6 inches) in diameter shall be considered to be of low severity.

**Extent:**

*Occasional*: < 5 potholes /1.6 km (per mile)

*Frequent*: 5 – 10 potholes/1.6 km (per mile)

*Extensive*: > 10 potholes/1.6 km (per mile)

**Patching**

Patching is either the placing of asphalt concrete (or other additional material) on the surface of the existing pavement or the replacement of the existing pavement in small isolated areas.

Deductions shall be made for all patches present in the pavement which are the result of deterioration and/or maintenance since the last construction project. For concrete pavements (JRC/JC or CRCP) deductions shall also be made for patches made with asphalt concrete material.

On flexible and composite pavements, large patches [greater than 12.5 m² (15 sq. yd.)] such as spot overlays or wedge courses shall be rated for condition as part of the existing pavement rather than as patches.

**Severity Level:**

*Low*: Patch size <0.1 m² (1 sq. ft.).

*Medium*: Patch size <0.8 m² (1 sq. yd.).

*High*: Patch size >0.8 m² (1 sq. yd.).

**Extent:**
Occasional: < 10 patches/1.6 km (per mile)

Frequent: 10 – 20 patches/1.6 km (per mile)

Extensive: > 20 patches/1.6 km (per mile)

Settlement

Settlement is a dip or depression in the longitudinal profile of the pavement surface. Settlement shall be considered as distress when it causes a noticeable effect upon riding quality. Settlement should not be confused with corrugation, which is another type of surface profile deficiency specific to flexible pavements.

Severity Level:

Severity is based upon the effect of the settlement on vehicle control when travelling along the roadway at 60 km/hour (40 MPH).

Low: Noticeable effect upon ride, driver able to maintain vehicle control easily.

Medium: Some discomfort to passengers, driver able to maintain control with slight corrective action.

High: Definite effect upon ride quality. Noticeable profile dips in settlement areas greater than 150 mm (6 inches). Poor ride corrective action needed.

Extent:

Occasional: Less than 2 settlements/1.6 km (per mile) of roadway.

Frequent: 2 to 4 settlements/1.6 km (per mile) of roadway.

Extensive: More than 4 settlements/1.6 km (per mile) of roadway.
Crack Sealing Deficiency

Crack sealing deficiency is crack sealing which is no longer effective in preventing intrusion of water or cracks which have never been sealed.

Severity Level:

Severity levels are not considered.

Extent:

Occasional: Less than 20% of the cracks along the pavement section are not effectively sealed.

Frequent: Between 20% and 50% of the cracks along the pavement section are not effectively sealed.

Extensive: More than 50% of the cracks along the pavement section are not effectively sealed.

Wheel Track Cracking

Cracks located within or near the wheel tracks. For evaluation purposes each wheel track shall be considered 1 m (3 feet) in width. Wheel track cracking usually starts as intermittent, single longitudinal cracks progressing to multiple longitudinal cracking, and eventually interconnected or alligator cracking. Wheel track cracking usually results from fatigue failure of the asphaltic layer.

Severity Level: Severity is based upon both crack width and multiplicity of the cracking. Both criteria must be satisfied when assigning the severity level.

Low: Single or intermittent multiple cracking with average crack width less than 6 mm (1/4 inch).
Medium: Single or multiple cracking (may also include regions of intermittent alligator cracking) with average crack width greater than 6 mm (1/4 inch) with little spalling or loose pieces.

High: Multiple cracking with extensive alligator cracking. Raveling is fairly common with average crack width greater than 6 mm (1/4 inch), and some alligator blocks are easily removed.

Extent:
Extent is based upon percentage of the wheel track length within the section which exhibits cracking.

Occasional: Less than 20%. Frequent: Between 20% and 50%. Extensive: More than 50%.

Longitudinal Joint Cracking
Deterioration or cracking of the longitudinal joints formed by separate passes of an asphalt paver, including shoulders and widening. Poor compaction along the longitudinal joint often results in the disintegration of material along the joint and may be accompanied by single or multiple cracking.

Severity Level:
Low: Deterioration <25 mm (1 inch) wide at the surface, or single crack < 6 mm (1/4 inch) and no raveling.

Medium: Deterioration 25 mm – 50 mm (1 inch – 2 inch) wide at the Surface and may extend down to the intermediate course, or single or multiple cracking 6 mm – 25 mm (1/4 inch - 1inch) with some raveling.
**High:** Deterioration > 50 mm (2 inches) wide at the surface and likely extending down to the intermediate course or lower, or multiple cracking > 25 mm (1 inch) wide with much raveling.

**Extent:** Based on the average linear feet of longitudinal cracking per 30 m (per station of 100 feet length).

**Occasional:** Less than 15 m/30 m (50 feet per station).

**Frequent:** Between 15 and 45 m/30 m (50 and 150 feet per station).

**Extensive:** More than 45 m/30 m (150 feet per station). Complete Longitudinal joint cracking along the pavement centerline and edge [60 linear m/30 m (200 linear feet per station)] is termed extensive.

**Longitudinal Cracking**

A crack or break approximately parallel to the pavement centerline. This type of cracking is usually associated with subgrade settlement or insufficient bearing support.

In a composite pavement, longitudinal joints and pavement edges of the underlying rigid base usually reflect through the asphalt surface as a result of thermal movement in the underlying slab. Poor paving lane joint construction can also result in a longitudinal crack (see longitudinal cracking of flexible pavements for description and images).

**Severity Level:**

**Low:** Crack width less than 6 mm (1/4 inch) with no spalling or distortion along crack edges.

**Medium:** Crack opened or spalled to a width between 6 mm and 25 mm (1/4 and 1 inch) over at least one half its lengths.
**High:** Crack opened or spalled to a width greater than 25 mm (1 inch) over at least one half its lengths.

**Extent (Composite):** Based upon the average linear feet of longitudinal cracking per 30 m (per station of 100 feet length).

**Occasional:** Less than 15 m/30 m (50 feet per station).

**Frequent:** Between 15 and 45 m/30 m (50 and 150 feet per station).

**Extensive:** More than 45 m/30 m (150 feet per station). Complete longitudinal joint cracking along the pavement centerline and edge [60 linear m/30 m (200 linear feet per station)] is termed extensive.

**Edge Cracking**

Edge cracks are longitudinal or crescent shaped cracks usually within 0.3 m (1 foot) of the pavement edge line.

**Severity Level:**

**Low:** Tight cracks, width less than 6 mm (1/4 inch) with no break up or raveling.

**Medium:** Crack width greater than 6 mm (1/4 inch) with some raveling.

**High:** Multiple cracking with moderate raveling and average crack width greater than 6 mm (1/4 inch).

**Extent:** Occasional: Cracking occurs along less than 20% of the pavement edge within the section.

**Frequent:** Cracking occurs along 20% to 50% of the pavement edge within the section.

**Extensive:** Cracking occurs along more than 50% of the pavement edge within the section.
Random Cracking

Random cracks are those cracks which are not categorized as wheel track, block, transverse, longitudinal joint, or edge.

Severity Level:

Low: Tight cracks, width less than 6 mm (1/4 inch) with no break up or raveling.

Medium: Crack width greater than 6 mm (1/4 inch) with some raveling.

High: Multiple cracking with moderate raveling and average crack width greater than 6 mm (1/4 inch).

Extent:

Occasional: Cracking occurs in less than 20% of the pavement section.

Frequent: Cracking occurs in 20% to 50% of the pavement section.

Extensive: Cracking occurs in more than 50% of the pavement section.

Block and Transverse Cracking

Block cracks are interconnected cracks which divide the pavement into large rectangular pieces or blocks. Block size may range from 1 m by 1 m (3 ft. by 3 ft.) upwards to 3 m by 3 m (10 ft. by 10 ft.).

Transverse cracking is cracks at approximately right angles to the pavement centerline. The occurrence of both block and or transverse cracking is usually related to thermal shrinkage of the asphalt binder. Binder age hardening is also related to formation of these crack types.

Severity Level:

Low: Average crack width less than 6 mm (1/4 inch) with no raveling or distortion along crack edges.
Medium: Average crack opened or raveled to a width between 6 mm to 25 mm (1/4 to 1 inch) along at least half its length.

High: Average crack opened or raveled to a width greater than 25 mm (1 inch) along at least half its length.

Extent:

Occasional: Less than 20% of the section length is affected by this distress.

Frequent: Between 20% and 50% of this section length is affected by this distress.

Extensive: More than 50% of this section length is affected by this distress.

Pumping

Pumping is the ejection of fine soil particles through pavement cracks, joints, or along pavement edges. Pumping can be identified by the presence of surface staining and base or subgrade material near joints or cracks. Shoulder disintegration at the pavement edge is often an indicator of pumping beneath the slab.

Severity Level:

Low: Some staining of the surface around cracks or joints is noted.

Medium: Same as Low.

High: Clear evidence that pumping exists. Excessive staining, medium severity or greater faulting, corner breaks or punchouts.

Extent:

Occasional: Less than 10 of the joints and cracks exhibit pumping.

Frequent: 10% to 25% of the joints and cracks exhibit pumping.

Extensive: More than 25% of the joints and cracks exhibit pumping.
Each location has been inspected for various possible distresses and estimated Distress points (DP) for each distress by considering distress type, severity and extent are given in Table 2.5. These are further used to estimate pavement condition rating (PCR) of each location as given in Equations 1.1 and 1.2 in the previous chapter. Typical calculation of PCR is given in Table 2.5 with weights for type of distress, severity and extent. Each location pavement has been classification using PCR scale given in Figure 2.12. Summary of PCR values and Pavement classification is presented in the next chapter.

![PCR Scale](image)

**Figure 2.12: PCR scale to classify pavement condition considering distress**
### Table 2.5: Typical PCR estimation for Bangalore road

<table>
<thead>
<tr>
<th>Distress Type</th>
<th>Distress Weight</th>
<th>Severity</th>
<th>Extent</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>Raveling</td>
<td>10</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>Corrugations</td>
<td>5</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Rutting</td>
<td>10</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Potholes/Debonding</td>
<td>10</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Edge Cracking</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Random Cracking</td>
<td>5</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 2.5 Flexible Pavement Study Using GPR

GPR survey has been carried out at selected 36 locations for length of about 6 m using Ground-coupled GPR. High frequency of Ground-antenna of 1600 MHz has been used, which is capable of recording high resolution data up to 0.5 m depth. GPR antenna is slowly moved along a survey line (Fig. 2.13) of the above proposed study of pavement section. Electromagnetic wave form data has been recorded by control unit. Using Rad Explorer software, the GPR data were processed by filtering to clear the sub surface features and to reduce the system noise. A depth profile was changed from the time profile by the wide angle measurement. Typical processed radargram is shown in Figure 2.14 for maximum surface reflection and Figure 2.15 shows for interface reflecion. Similarly other radargrams are given in Appendix A.
Electromagnetic wave form processed data was used to identify average single trace as shown in Figure 1.4 in previous chapter. Identified trace is further used to measure amplitudes and travel times to estimate dielectric constant and thickness. The pavement layer thicknesses and properties may be calculated using the amplitude and arrival times of the GPR waveform peaks corresponding to reflections from the interfaces between the layers. One may calculate the dielectric constant of a pavement layer relative to the previous layer by measuring the amplitude of the waveform peaks corresponding to reflections from the
Figure 2.14: Typical GPR Radargram using 1.6GHz antenna with trace details for maximum surface reflection

Figure 2.15: Maximum reflection at the interface of surface asphalt layer and base. Interfaces between the layers (Davis, 1994). The travel time of the transmit pulse within a layer in conjunction with its dielectric constant determines the layer thickness, as follows:

\[
\text{Thickness} = \text{velocity} \times \left(\frac{\text{time}}{2}\right)
\]  

(2.1)

Because the measured time between peaks represents the round-trip travel of the radar pulse, the thickness computation is based on time divided by 2. The radar velocity can be computed from the dielectric constant of the medium, \(\varepsilon\), as
Velocity = \( \left( \frac{3 \times 10^8}{\sqrt{\varepsilon}} \right) \) m/s \hspace{1cm} (2.2)

Where \( 3 \times 10^8 \) is the radar velocity in free space in m/s. Combining Equations 1 and 2, we get

\[
\text{Thickness} = \frac{3 \times 10^8 \times \left( \text{time/2} \right)}{\sqrt{\varepsilon}} \hspace{1cm} (2.3)
\]

Where time is measured in seconds and thickness is in meter.

The computation of thickness using equation 2.1 presumes that the layer in consideration is homogeneous and that its dielectric constant is known. Computation of the surface layer dielectric constant can be made by measuring the ratio of the radar reflection from the asphalt to the radar amplitude incident on the pavement. This ratio, called the reflection coefficient, can be expressed as follows:

\[
\text{Reflection coefficient (1-2)} = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \hspace{1cm} (2.4)
\]

Where, the subscripts 1 and 2 refer to the successive layers. The incident amplitude on the pavement can be determined by measuring the reflection from a metal plate (copper plate) on the pavement surface, because the metal plate reflects 100 percent. Typical incident amplitude on the pavement is measured as about 8326.85 milli volt. Using these parameters, dielectric constant and thickness at each location has been estimated and these values are presented in next section.
2.6 Flexible Pavement Study Using MASW

Surface wave method of MASW survey has been carried out at selected twelve locations (See Tables). Seismic wave from data has been collected using a geophone spacing of 0.25 m and a source distance of 0.5, 1 m and 1.5 m. Typical field set up of geophones and source with recording system is shown in Figure 2.16. Surface waves are generated using sledge hammer of 0.5 kg and these waves are captured by twelve geophones of 4.5 Hz frequency. Typical recorded surface waves are shown in Figure 2.17. Recorded waves are used to extract fundamental mode dispersion curve. Dispersion curve is extracted from 5 Hz to 600 Hz by dividing as low frequency part with normal trend (< 50Hz) and high frequency with reverse trend (>50Hz). Dispersion curve at low frequency part has been used to extract sub base, soil layer shear wave velocity and high frequency part has been used to extract pavement layers. Typical dispersion image from MASW test is shown in Figure 2.18.

![Fig 2.16 Data acquisition in MASW](image)
Figure 2.17: Typical field records using MASW 12 geophones

Fig.2.18: Typical dispersion curve lower and higher frequency of fundamental mode
Shear wave velocities are generated separately as low and high frequency dispersion curves. Typical shear wave velocity for high frequency part is given in Figure 2.19. Average shear wave velocity of pavement layers varies from 400 m/s to 1200 m/s based on density and bitumen content. Here we should note that most of the testing is carried out in nighttime where temperature variation is minimal. Variation of shear wave velocity with temperature of bitumen macadam is neglected. Typical combined shear wave velocity profile is given in Figure 2.20. More details of twelve shear wave velocity profiles are discussion and presented in the next section. Average shear wave velocity of pavement layer is estimated and used to obtain stiffness by considering in situ density measured. Measurement of in situ density is discussed in next section.

![Fig. 2.19: Typical shear wave velocity profile for high frequency wave in fundamental mode](image)
2.7 Drilling and testing of in situ samples

In the selected 36 locations drilling has been carried out by power rotary drilling and core samples are collected in order to compare and correlate PCR from visual distress survey, dielectric constant, thickness and shear wave velocity from non destructive testing. Figure 2.21 shows typical core drilling sample in the road. Drilled undisturbed samples are collected and used for further analysis. In situ core samples are analyzed visually, numbers of overlays are identified, and thickness of each overlay and the total thickness are measured. Typical core sample is shown in Figure 2.21, from the core it can be easily
noted that this location has 3 overlay layers of bituminous concrete. First and second layer consist of bituminous concrete of 4 cm each and third layer has thickness of 6 cm consist of bituminous concrete and sub base course. Total bituminous layer in this location is 14 cm. Summary of thickness of pavement layers in each location is discussed in the next chapter.

Figure 2.21: In situ core samples collected by drilling
**Bulk density of Bituminous Concrete**

In situ core samples collected in field is used to find bulk density. The bulk density of bituminous concrete is usually determined by water displacement method or measuring size and weigh of samples. These tests are widely used and it is not suitable for bulk density determinations on open-graded asphalt and is only suitable for dense, non-porous asphalt.

After cutting the core from the pavement, the material outside the layer is removed. Volume of sample is estimated by measuring size of core samples and combined with measured weight to estimate density. Bulk density has been determined for 31 bitumen concrete samples collected by drilling and coring. Bulk density values varied from 1.73 g/cc to 2.3g/cc. Bulk density values of in situ core samples in presented in the next chapter.

**Bitumen Extraction Procedure as per ASTM standards D 2172-05**

After determining bulk density samples air dried and used for to find bitumen content by carrying out Bitumen Extraction test as per ASTM D 2172-05 (2006). The paving mixture is extracted with trichloroethylene, normal Propyl Bromide, or methylene chloride using the extraction equipment. The bitumen content is calculated by difference from the mass of the extracted aggregate, moisture content, and mineral matter in the extract. The bitumen content is expressed as mass percent of moisture-free mixtures.

Bitumen content of 31 samples are determined and tabulated in next chapter.

**Aggregate gradation of the bituminous concrete core:**

After separating aggregate and bitumen, aggregated are used to find gradation of samples. Gradation of aggregate has been determined as per BS 812: Testing Aggregates: Part 103
- Method for determination of particle size distribution. Figure 2.21 shows typical gradation curve for aggregate extracted from Bitumen concrete. Aggregate grading is the term given to the percentages of the different size fractions, after sieving, that go to make up the whole material. Effective size (D10), uniformity coefficient (Cu) and coefficient of curvature (Cc) are determined and tabulated in next chapter.

Fig. 2.22: Gradation of aggregates extracted from the Bitumen concrete in situ core sample
Chapter 3
Summary and Conclusion

3.1 Introduction

Different types of road distress can be noticed in Bangalore roads, these are similar to Indian roads distress. The distresses are main factors which control pavement performance. Limited attempt has been made to assess the pavement condition scientifically to design overlay thickness and pavement maintenance. This chapter presents summary of four investigations discussed in previous chapter and compare the results. Visual inspections are carried out at 31 locations and different distresses are identified. Severity and extent of each distress has been assessed and used to estimate PCR values. Dielectric constant and thickness of pavement layers in each location has been estimated using GPR wave form data. Shear wave velocity of the pavement layers are estimated considering high frequency fundamental mode of surface wave. In these locations drilling has been carried out and in situ bitumen concrete sample are collected, which are used to measure pavement thickness. Bulk density, percentage of bitumen and aggregate gradation has been calculated in Laboratory using in situ core samples. These results are presented in the next section.

3.2 Results and Discussion

A conventional method for evaluation of pavement condition is Pavement Condition Rating (PCR). PCR and respective pavement quality for 31 locations are given in Table 3.1 column 2 and 3. Pavement performance is assessed based on PCR values, but it is purely based upon visual inspection of pavement distresses. It depends on surveyor and
no verification is possible. Selected Bangalore roads have PCR values of 50 to 100, which is representing poor quality to very good quality of roads.

GPR survey has been carried out in selected locations in Bangalore. Processed GPR Radargram images are used to create data bank of Radargram of GPR for Indian Roads (see Appendix A). Dielectric constant and thickness estimated from the wave form obtained from each Radargram are given in Table 3.1. It can be noticed that dielectric constant of pavement varies from 2.15 to 5.78. These values do not follow any trend with PCR and its classification, which may be attributed by PCR values. PCR values are qualitative and depend on surveyor. GPR test is fast and get reliable information of dielectric constants of pavement layers, which can be quantifiable at any time. Thickness of pavement layer has been estimated for 31 locations and is given in Table 3.1.

Shear wave velocity are measured at selected 12 locations by MASW experimental study and shown in Figure 3.1a and 3.1b. Shear wave velocity are estimated by extraction of high frequency fundamental mode surface wave. This shear wave velocity can be used to estimate shear modulus of pavement sections by knowing density.

Core samples are used to measure thickness, bitumen content and gradation parameters of effective size, uniformity coefficient (Cu) and coefficient of curvature (Cc) for 31 locations out of 36. Five in situ samples are damaged and hence not able to determine the bitumen content and gradation parameters. These parameters are tabulated in Table 3.1.

Thickness calculated from GPR is compared with thickness measured from in situ core sampling. Percentage of error is given in Table 3.1. Thickness estimated from GPR matches very well with core samples except for few locations where core samples
Figure 3.1a and b: Shear wave velocity at selected location using MASW
Table 3.1: Summary of results from visual condition assessment, non destructive testing and core samples

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<tr>
<th>ID</th>
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<th>$\varepsilon_a$</th>
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<th>Thickness (mm) from Core</th>
<th>Error (%)</th>
<th>Bulk Density (g/cc)</th>
<th>Bitumen Content (%)</th>
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thickness is less than GPR. In these locations error is more than 20%, which may be attributed by error manual measurement in the core samples. Average error of thickness estimation is about 8.95%. This study shows that thickness obtained from GPR matches very well with core sample with accuracy of 91%.

3.3 Conclusions

In this study an attempt has been made to assess pavement condition using non destructive testing and compare with in situ measurements. Conventional method of pavement condition rating has been attempted in selected roads by visual survey. Selected 31 locations are classified as per pavement condition rating scale. Non destructive tests of MASW and GPR have been carried out in selected locations and thickness, stiffness and dielectric constants are measured. In the selected locations in situ bitumen core samples are collected and thickness, bulk density, bitumen content and gradation parameters are measured. By comparing all the results the following conclusions are arrived from this study

- It was shown that a GPR can detect layer interfaces if a significant contrast in the dielectric constants exists between the two considered layers.
- Pavement thickness estimated by GPR is comparable with actual drilled borehole core samples. The time domain technique showed that thickness of pavement can be estimated with an error of about 9%.
- Borehole data gives accurate thickness of pavement if bitumen concrete is intact, but it is time consuming and costly when compared to GPR.
- MASW is an effective tool to measure the stiffness of pavement. Higher frequency fundamental mode of dispersion curves dominates at the shallowest depth range to locate asphalt and base layer.
GPR is an effective method to estimate thickness and heterogeneity in the bitumen concrete with short time.

Thickness can not be measured using MASW accurately and strength can not be measured in GPR. Combing both methods can help to assess pavement condition accurately.

Publications


References


9) Properties of Base Course Aggregates, Texas Transportation Institute, Report 0-1341-2, Texas Transportation Institute, College Station, TX,


Appendix –A
Data bank of GPR Radargrams

Figure A1: Radargram for location I_6

Figure A2: Radargram for location I_7
Figure A3: Radargram for location I₈

Figure A4: Radargram for location I₉
Figure A5: Radargram for location I\textsubscript{10}

Figure A6: Radargram for location M\textsubscript{1}
Figure A7: Radargram for location M₂

Figure A8: Radargram for location M₃
Figure A9: Radargram for location M_4

Figure A10: Radargram for location M_5
Figure A11: Radargram for location M₆

Figure A12: Radargram for location M₇
Figure A13: Radargram for location M₈

Figure A14: Radargram for location M₉
Figure A15: Radargram for location N₁

Figure A16: Radargram for location N₂
Figure A17: Radargram for location N₃

Figure A18: Radargram for location N₄
Figure A19: Radargram for location N5

Figure A20: Radargram for location N5
Figure A21: Radargram for location N₆

Figure A22: Radargram for location N₇
Figure A23: Radargram for location N8

Figure A24: Radargram for location N9
Figure A25: Radargram for location $R_1$

Figure A26: Radargram for location $R_2$
Figure A27: Radargram for location R₃

Figure A28: Radargram for location R₄
Figure A29: Radargram for location R₅

Figure A30: Typical Radargram for location R₆
Figure A31: Radargram for location $R_7$.

Figure A32: Radargram for location $R_8$. 