Use of Ground-Penetrating Radar (GPR) as an Effective Tool in Assessing Pavements—A Review

Ruchita Salvi, Ajinkya Ramdasi, Yashwant A. Kolekar and Lata V. Bhandarkar

Abstract In recent times, the road network in India is increasing rapidly and has become main route of transportation for goods and people. This has led to the boom in economic activities leading to greater tonnage being carried by the road. Further, this is assisted with the increase in road network by constructing new highways and increasing the traffic capacity of the existing highways/roads. The quality of roads and the thickness of each layer need to be designed properly to cater to this increased traffic movement and the tonnage too. GPR assists in quality assessment and interpretation of pavement conditions more precisely. With the use, the pavements generally tend to have problems, viz. cracking, roughness, rutting, and raveling over a period of time. To enhance the life of pavement, improve its riding quality, and minimize the maintenance requires thorough investigations of the existing pavements. Previously, investigations were carried out using visual observation of base course, core extraction, and its examination in the laboratory for which the core is extracted from the rutted section of roads. The methods used conventionally are time consuming, difficult to perform, and also not economical. So geophysical method such as ground-penetrating radar (GPR) is an alternative to the conventional methods, and being nondestructive, it is less difficult, time consuming, and also economical to use which gives detailed information about the

R. Salvi · A. Ramdasi · Y. A. Kolekar (✉)
Department of Civil Engineering, College of Engineering Pune, Pune, India
e-mail: yashwantkolekar@gmail.com

R. Salvi
e-mail: ruchitassalvi456@gmail.com

A. Ramdasi
e-mail: ramdasi.ajinkya@gmail.com

L. V. Bhandarkar
Department of Physics, College of Engineering Pune, Pune, India
e-mail: blv.physics@coep.ac.in

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pavement layer thickness, measurement of depth of rebar, dowel, etc., without much disturbance to the existing traffic movement. Thus, GPR can be used effectively in estimating total deteriorated sections and repair estimates.

Keyword Ground-penetrating radar (GPR)

1 Introduction

This paper describes the various studies carried out to understand the usage of GPR for assessing the quality of pavement and provide useful information to the engineer. The applications and problems discussed by various authors guide us to understand the recent developments in the GPR technique. This paper provides an insight into the applicability, limitations, and future scope for development of GPR as an effective tool in assessing the quality of the pavement and its improved understanding.

2 Ground-Penetrating Radar (GPR)

The ground-penetrating radar (GPR) is based on principle of radar where the source transmits electromagnetic (EM) waves with frequency varying from 10 MHz to 2.5 GHz into pavements. These EM waves reflect some of the waves through layer of material having different EM characteristics. EM waves which reflect back are received by receiver of GPR system which is shown as a plot of amplitude and time.

The passing speed of EM wave through a particular material is under the influence of its relative dielectric constant (ε_r). Surface reflection method is used for asphalt pavement materials, and relative dielectric constants are calculated.

The values of materials' relative dielectric constants are calculated, and the thickness of the particular layers (h_i) is found using equation:

$$h_i = \frac{c\Delta t_i}{\sqrt{\varepsilon_r}} \quad (1)$$

where c—speed of EM wave through vacuum

1. Δt_i—time between amplitudes A_i and A_{i+1}
2. ε_r—relative dielectric constant of the material.

EM signal can be sent up to 1000 scans/second.

3 GPR Principle

The reflected energy is collected and displayed as a waveform showing amplitudes and time elapsed between wave transmission and reflection (Fig. 1).

The determination of the pavement layer thickness is most successful application of the GPR. By "picking" the first peak of the reflected electromagnetic wave and knowing the layer dielectric constant (μ) and travel time (t) in nanoseconds, the thickness is determined (Al-Haddad and Abed 2013).

$$h(\text{in}) = 11.8 * t/\sqrt{\varepsilon} \tag{2}$$

Generally, the amplitude of the reflected pulses is used. With the help of the dielectric constant in air which is equal to (1), the subsurface layer dielectric constant can be calculated from

$$\sqrt{\varepsilon_1} = \frac{A_\text{m} + A_0}{A_\text{m} - A_0} \tag{3}$$

where

A_0 and A_m are the reflected amplitudes from the top of surface layer and the metal plate, respectively.

The dielectric constant of the subsequent layer is calculated from

$$\sqrt{\varepsilon_2} = \sqrt{\varepsilon_1}\frac{1 - \left(\frac{A_0}{A_\text{m}}\right)^2 + \frac{A_1}{A_\text{m}}}{1 - \left(\frac{A_0}{A_\text{m}}\right)^2 - \frac{A_1}{A_\text{m}}} \tag{4}$$

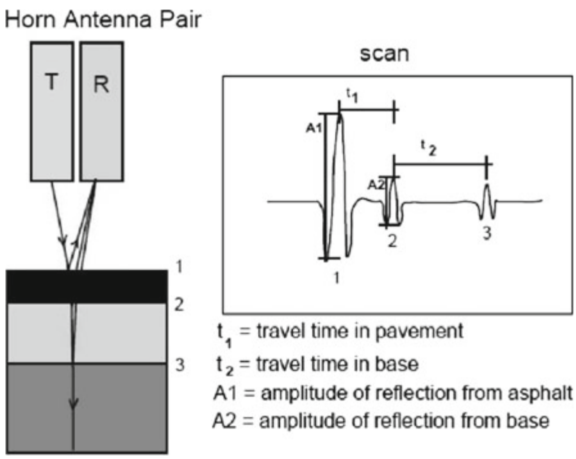

Fig. 1 Basic principle of GPR technique with horn antenna for pavement examination; T represents the transmitting antenna and R the receiver antenna. Interface 1 presents the air–asphalt interface, 2 presents the asphalt–base course interface, and 3 presents the base–sub-base interface (Al-Haddad and Abed 2013)

where A_1 is the reflected amplitude from the top of subsequent layer; moreover, a similar formula can be recursively obtained for the nth layer

$$\sqrt{\varepsilon_n} = \sqrt{\varepsilon_{n-1}} \frac{1 - \left(\frac{A_0}{A_\mathrm{m}}\right)^2 + \sum_{i=1}^{n-2} y_i * \frac{A_i}{A_\mathrm{m}} + \frac{A_{n-1}}{A_\mathrm{m}}}{1 - \left(\frac{A_0}{A_\mathrm{m}}\right)^2 - \sum_{i=1}^{n-2} y_i * \frac{A_i}{A_\mathrm{m}} + \frac{A_{n-1}}{A_\mathrm{m}}} \quad (5)$$

where

A_i is the reflected amplitude from the top of ith layer, and y_i is the reflection coefficient between the ith and $i + 1$th layers and can be calculated using the following equation:

$$y_i = \frac{\sqrt{\varepsilon_i} + \sqrt{\varepsilon_{i-1}}}{\sqrt{\varepsilon_i} - \sqrt{\varepsilon_{i-1}}} \quad (6)$$

The ranges of propagation velocities and dielectric constants for the pavement materials are given in Table 1.

4 Types of GPR

GPR is available in various types depending on the nature of work and application required. The principle of physics involved in GPR is based on the principles of propagation of electromagnetic waves, but different hardware and data processing

Table 1 Dielectric constants and propagation velocities for various pavement materials (Cao et. al 2011)

Material	Dielectric constant	Propagation velocities (m/ns)
Air	1	0.3
Ice (Frozen soil)	4	0.15
Granite	9	0.1
Limestone	6	0.12
Sandstone	4	0.15
Dry sand	4–6	0.12–0.15
Wet sand	30	0.055
Dry clay	8	0.11
Wet clay	33	0.052
Asphalt	3–6	0.12–0.17
Concrete	9–12	0.087–0.10
Water	81	0.033
Metal	∞	0

procedures are employed in different GPRs. The commercial and the most commonly used is “Impulse” GPR system, which transmits a short pulse of electromagnetic energy and records the time taken for reflections of the pulse to return to a receiver. Other varieties of GPR have different engineering applications, and these varieties are not suitable for assessing the quality of pavements.

Antennas are available in various ranges for GPR, and the most commonly used for impulse systems are “dipole” antenna which acquire data in time domain, requiring contact with the pavement surface (ground coupled) and “horn” antenna, are capable to operate while suspended at a short distance above the pavement surface (air coupled).

The greater depth of penetration (for a given signal frequency) is accomplished by the ground-coupled dipole antennas, whereas for higher data acquisition rates, air-coupled horn antennas facilitate higher speed surveys.

Horn antennas are more suitable, when the top layers of a pavement are to be evaluated for quality assessment, whereas ground-coupled dipole antennas are designed to be used near the surface so that the power radiated into the surface or medium is maximum possible and hence more suitable for thicker pavements (e.g., airports) or where information about the pavement foundation too is also required.

The purpose of this paper is to get data for land development, site selection, and other related activities using nondestructive modern sophisticated technology, in economical way. Greater accurate results in shorter time frame are achieved using these techniques.

The GPR type used in the field work is RAMAC GPR produced by MALA Company for geosciences as shown in Figs. 2 and 3.

Fig. 2 GPR setup

Fig. 3 Working of GPR

5 Methodology

- A grid will be generated on the ground manually at a suitable interval using paint/chalk.
- GPR antennas of different frequencies will be dragged on the grid lines by the GPR operator, who will be carrying the machine along with one laptop computer on his shoulder. Electromagnetic waves will be penetrated and received through the antenna. Acquired data will be stored in the laptop computer as soft files, and laptop will have a digital display of the GPR profile at the site itself.
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6 Application of the Technique (Evans et al. 2008)

Different types of information can be extracted using GPR depending upon techniques used. The site needs to be decided to work upon so that the engineer and the GPR specialist can think upon the methodologies to be incorporated to obtain the optimum information from the site. Although GPR is self-sufficient equipment to provide information regarding pavements, various pavement investigations such as FWD or coring of pavements are done along with GPR testing so that the data obtained at site by GPR and pavement investigations can complement each other.

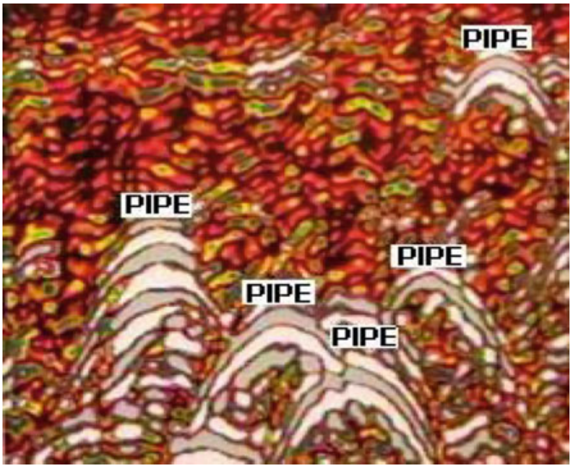

Fig. 4 Raw data showing signature of pipes by GPR (Geomodel)

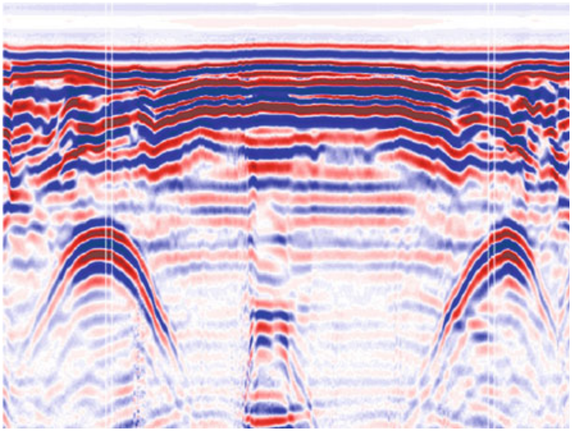

Fig. 5 Processed image of signature of pipes (Parsan)

6.1 To Find Underground Utilities

Deeper depths are reached using antennas with low frequencies from 25 to 200 MHz obtain subsurface reflections from (about 10–30 m or more), at the cost of low resolution. But with higher frequencies from 300 to 1000 MHz obtain shallow depths reflection (0 to about 30 feet), with have high resolution. These high-frequency antennas are used to investigate surface soils and to locate small or large, shallow buried objects in concrete (Figs. 4 and 5).

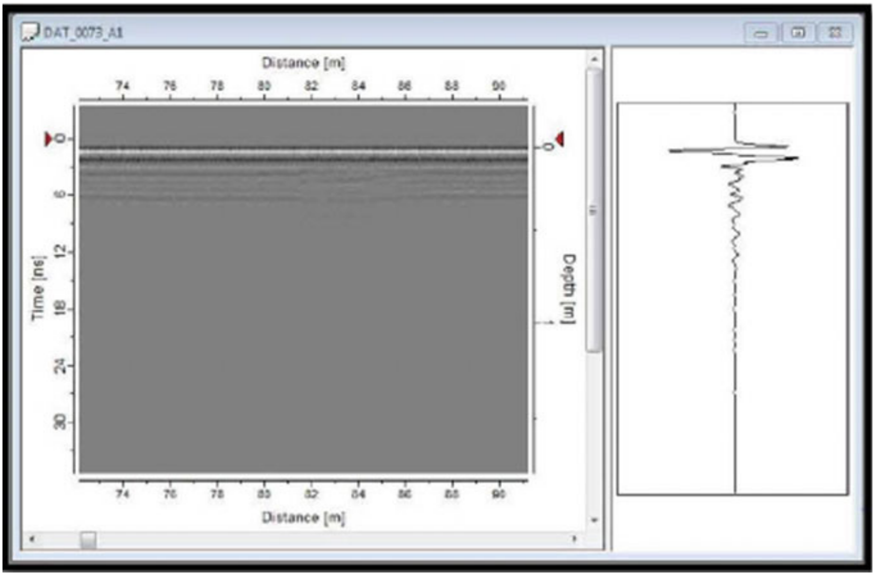

Fig. 6 Raw data of pavement (Al-Haddad and Abed 2013)

6.2 *Pavement Thicknesses*

GPR is used in calculating pavement thickness of a freshly laid pavement or an existing worn-out pavement. The different strata are identified based on the contrast in the dielectric properties at material interfaces. The interface between asphalt roads and subgrade is easily identified as compared to the interface between concrete pavement and subgrade; this is due to the similarity in the dielectric properties of the cement-bound material with the granular subgrade (Figs. 6 and 7).

6.3 *Quality Control*

GPR plays a vital role is assessing the quality of the newly laid pavement. They are used effectively to assess air-void content (i.e., percentage of air in the material mix), segregation of aggregates (which can be identified from the localized areas of low density material), which can be the result from poor mixing or unfair construction practices), and density of bound materials in addition to quality control of pavements that involves determination of layer thicknesses. The density and compaction of bituminous material are greatly affected by the presence of air voids, which is an important factor affecting the life and deformation properties of the pavements.

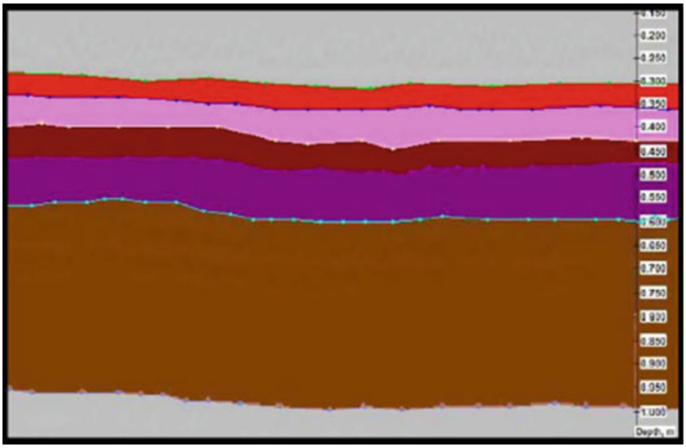

Fig. 7 Pavement profile after processing (Al-Haddad and Abed 2013)

6.4 Voids

GPR offers a useful tool for the detection of voids in the pavements of subgrade. The study shows the potential of a ground-coupled dipole antenna which is a relatively low-frequency (400 MHz) antenna used in GPR to locate voids as small as 50 mm in depth and locate other voids beneath reinforcement, although drilling and coring are recommended to determine the extent and depth of the void.

7 Accuracy and Limitation

(a) The accuracy of depth is normally within ±15%, while *X*–*Y* accuracy would be within ±5%. Accuracy in position can be improved by deploying positioning system.
(b) Georadar method cannot differentiate between a power cable (live or dead)/ telephone cable or OFC, metallic/nonmetallic/concrete utility. Hence, it is always essential to have all the background information like information on expected cables or pipes.
(c) It can give very tentative idea about the d out the diameter of the utility.
(d) The measurements of the Georadar are based on the returning signals reflected by a dielectric constant change. The signal penetration (maximum depth at which utility can be detected) depends on the dispersion of the signal in the soil. Hence, in clay, the depth of penetration would be least, while in sand it would be high.

(e) To detect larger objects, such as sewer lines, usually buried at greater depths, a low-frequency antenna (300 MHz) is used (depth range 2–10 m), while to detect smaller objects usually at lesser depths, a high-frequency antenna (500 MHz) is used (depth range 0.5–5 m).
(f) The minimum size that can be detected is related to antenna frequency and is limited to 1/8th of the signal wavelength. Hence, a 500-MHz antenna will detect objects larger than 30 mm dia. And a 100-MHz antenna will detect objects larger than 150 mm.
(g) While Georadar is the most efficient method for utility mapping, some objects can elude detection for various reasons, as mentioned below: Two objects very close to each other can be perceived as only one object.

  (i) An object located under another object/utility may not be seen.
  (ii) In a small boulder-type filling, a branch-off pipe or cable could be missed as confused with the surrounding rocks.
  (iii) A utility coming in and leaving the corridor between two survey lines could be missed, particularly if its presence is not expected.
  (iv) A highly conductive soil and or landfill areas could limit the penetration to the desired depths.

Similarly pavements covered with RCC slabs can also limit the signal penetration. A small corridor width under investigation could elude detection of a large diameter utility as confused with the soil bedrock interface.

8 Conclusion

As a part of geotechnical engineering, pavements have large number of uncertainties which could limit the use of nondestructive testing methods in respective field areas, but introduction of GPR has contributed to predict the uncertainties likes voids, thickness, and quality control analysis to ease and also to provide a solution more precisely. Though it is nondestructive, it yields more information and accurate data because of its precision which has helped to solve various problems of fields specifically related to pavements.

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