Ground penetrating radar and its applications in civil engineering

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Ground penetrating radar (GPR) is similar in its working principle to the radar used in air traffic control. It is a valuable device in locating defects and voids in concrete structures, and in determining embedded reinforcement and other sub-surface details. Masonry and earth structures can also be scanned to assess the condition of inner layers. The principles of the system, and its applications are discussed briefly in this paper along with typical images. Images of reinforcement details in a column and a bridge pier are presented along with a three-dimensional view of slab reinforcement. The quality of soil compaction can also be estimated by the sub-surface images.

Ground penetrating radar (GPR) is widely adopted for sub-surface imaging to assess the structural condition and to locate buried objects. The system comprises an antenna emitting electromagnetic energy, and receiving the reflected energy from the surfaces as well as that from the inner layers, besides a processor[1-3]. GPR emits electromagnetic energy that is projected in the form of radio frequency pulses into the structural element. The energy reflected depends upon the type and nature of the antenna, and the materials involved. The energy reflected is transformed into visual images, which provide extensive data on the sub-surface (inner) materials, when interpreted properly.

In principle, the working of GPR is similar to that of the radar used by air traffic controllers and vehicle speed surveillance systems used by traffic police[1]. In the case of air traffic control systems, the signal emitted by the antenna is reflected by the objects in the air, and is received by the same antenna and processed to locate the objects. GPR uses the same principle by processing the signal reflected from various depths of a structural element.

The system is helpful in locating the bars embedded in structural elements, sub-surface voids and delamination due to the changes in the electromagnetic properties of the medium of energy penetration. The system is useful not only in assessing structural concrete elements, but also in soils and masonry buildings, ancient monuments as well as locating buried pipes and ducts. Some of the applications of the GPR along with a brief discussion on the principles and image processing are presented in this paper.

GPR systems

Ground penetrating radar (GPR) is a technique of obtaining sub-surface images using electromagnetic radiation. The energy radiated by the antenna of the system penetrates the surface, and is either absorbed or reflected back at any discontinuities. GPR is valuable

Figure 1. A typical GPR system

in locating defects and voids in concrete structures, determining embedded reinforcement and other sub-surface details. Masonry and earth structures can also be scanned to assess the condition of inner layers.

The antenna housing comprises a transmitter and a receiver. The signal transmitted by the antenna is reflected at the interfaces of different materials (dielectric properties) and sensed by the receiver to create an image of reflections as the antenna is moved over the surface. The antenna dipoles create images of the reflected energy, which gives an indication of the sub-surface objects depending upon their electrical conductivity and dielectric constant.

Several GPR systems are available commercially with image processing software to help interpret the data obtained. The antenna comprises basically a transmitter

Table 1. Typical characteristics of antennae[3]

No.	Frequency, MHz	Pulse duration, ns	Penetration depth, m	Size, mm	Weight, kg
1	1500	0.6	~ 0.5	$40 \times 100 \times 165$	2.0
2	1000	1.0	0.75	$40 \times 100 \times 165$	2.0
3	900	1.1	2.0	$80 \times 200 \times 330$	3.4
4	400	2.5	5.0	$170 \times 300 \times 300$	6.4
5	200	5.0	9.0	$300 \times 600 \times 600$	17.7
6	80	12.0	20.0	1200	
7	40	25.0	40.0	2400	
8	20	50.0	150.0	4800	
9	15	60.0	200.0	6000	

and a receiver, and utilises electromagnetic energy to procure data on sub-surface conditions of a body. The technique relies on the transit time measurement of transmitted and reflected energy impulses to estimate the distance of penetration. Figure 1 shows a typical GPR system with antenna and processor. The person to the right is holding the 1.5 GHz antenna mounted on a cart for scanning. The person to the left is recording the images, while the 400 MHz antenna can be seen in the middle of the figure.

Antenna

Antenna is the most crucial element of the GPR system. The quality of data, range resolution and depth of penetration primarily depend upon the antenna characteristics. Antennae of various specifications are available for various applications. The most significant parameter for an antenna is the depth of penetration, which depends upon the conductivity of the material. The general features of a few typical antennae are indicated in Table 1.

It may be noted from Table 1 that higher the frequency of the antenna, the lower is the depth of penetration and smaller is the size and pulse duration. An antenna with 1,500 MHz frequency can penetrate only upto about half a metre generally, while a 15 MHz antenna can penetrate upto 200 m. However, deeper penetration of about twice the values indicated in Table 1 are possible depending upon the materials[3].

Similarly, the pulse duration of an antenna with 1,500 MHz frequency is 0.6 ns, while that of a 15 MHz antenna is 60 ns. The dimensions and weight of the antenna decrease with the increase in frequency. The configuration of antennae with frequency smaller than 100 MHz is different from that of high frequency antennae. The transmitter and receiver of high frequency antennae are encased in a strong housing, and can be dragged over the surfaces. Low frequency antennae (frequency less than 100 MHz) are generally mounted on a shaft while scanning. A typical 15 MHz antenna has two elements of 600 mm on each side of the small housing for electronic elements, while the transmitter and receiver are mounted on the telescopic antenna elements of about 2,400 mm with a distance of 3 m between them.

The antennae may be mounted on a wheeled cart to monitor the distance moved or may be dragged at a uniform rate over the required surfaces. The rugged antennae can be moved over vertical surfaces and even ceilings, if necessary. The antennae can also be mounted

Table 2. Typical material properties and velocity of propagation[3]

No.	Material	Dielectric constant	Velocity, mm/ns
1	Air	1	300
2	Water	81	33
3	Granite	5 – 8	134 - 106
4	Dry sand	3 – 6	173 – 122
5	Wet sand	25 – 30	60 – 55
6	Dry soil	3 – 5	173 – 134
7	Fresh concrete	11	90
8	Dry concrete	6 – 8	122 – 106
9	Asphalt	4	150

on a motor vehicle, and driven over the surfaces to be monitored, especially road and bridge surfaces.

Material properties

The depth of penetration depends upon several factors such as electrical conductivity of the medium and dielectric constant. The electro-magnetic energy penetrates deeper in resistive materials (dry sand, ice and dry concrete) than in conductive materials (wet concrete, salt water and wet soil). The energy is absorbed by the conductive materials and hence does not penetrate deep. The technique is eminently suitable to investigate materials with low electrical conductive materials such as concrete, sand, wood and asphalt.

Table 2 indicates the properties of a few common materials[3]. The dielectric constant of the material governs the velocity of the energy propagation, being inversely proportional to the square root of the dielectric constant. The velocity of radiation is 300 mm / ns in air with dielectric constant as unity and the velocity in water with a dielectric constant of 81 is one-ninth of the velocity in air. The values of penetration depth for various antenna frequencies listed in Table 1 are for a dielectric constant of 9. The depth of penetration will be more than that indicated in the table for materials of lower dielectric constant. Further, antennae of the same frequencies for deeper penetration are also available. The depth of penetration for high frequencies (> 100 MHz) could be nearly double the values indicated in Table 1 for specific configurations.

Image processing

Sub-surface features can be identified by the reflections at various depths of the scanned surface. The dielectric constant of the material and the estimated depth of penetration are selected for scanning. The material scanned may include layers of various dielectric constants, including air between the contact surfaces of the antenna and the structural element. However, all the layers are scanned for the dielectric constant selected. Since the velocity of propagation in air is much more than that in the material, the depth of air layer appears large for the high dielectric constant selected (usually 4 – 6).

The coupling of antenna with the surface due to possible air gap between the antenna and test surfaces causes a small initial error depending upon the distance between the antenna dipoles (transmitter- receiver offset). The larger the distance between antenna dipoles, the greater will be the coupling depth. A 1.5 GHz antenna has a dipole distance of about 60 mm, while a 400 MHz antenna has an offset of about 160 mm. The coupling distances between the images obtained by different antennae will be different and this has to be considered while estimating the depths of objects.

The images indicate the sub-surface details of the scanned objects, when interpreted by comparison with the data available. The penetration depth and resolution also depend upon the type and nature of the antenna adopted. The amount of energy reflected at an interface of dissimilar materials depends upon the dielectric properties of the materials and on the conductivity. Metal objects show a very bright reflection due to high conductivity. Consequently, reinforcement in a concrete element provides a strong reflection at the interface due to high contrast in dielectric properties, while concrete and soil provide only a weak reflection[4, 5].
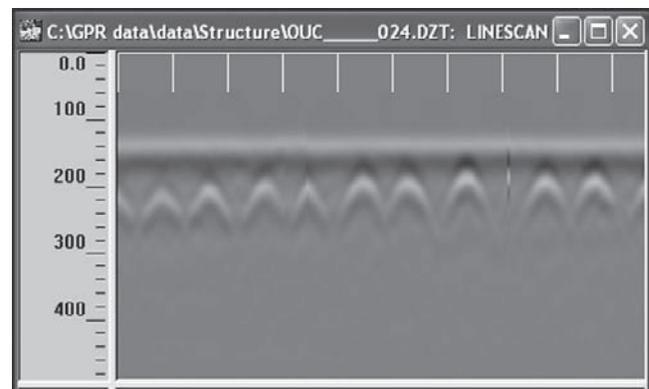

Figure 2. Transverse reinforcement in a column (1.5 GHz antenna)

Reinforcement in concrete elements

The images obtained depend upon the shape of the objects as well. A round object like reinforcing bar is marked by a hyperbolic profile as indicated in Figure 2. A reinforced concrete column was scanned by a 1.5 GHz antenna. The antenna, with a selected dielectric constant of 6 and penetration depth of 500 mm, was moved along the height of the column. The transverse reinforcement in the column is marked by the series of hyperbolic reflections, while the white band above the hyperbolas indicate the concrete surface. The antenna emits energy in the form of a cone, and is interrupted by the round object as the antenna is moved over the surface. Consequently, the energy is reflected continuously at the concrete - reinforcing bar interface as the antenna is moved over the bar, leading to the parabolic profile of the reflected energy[3].

It should also be noted that the profile offered by a reinforcing bar is circular when the dipoles (transmitter – receiver) are parallel to the bar, and results in a hyperbolic reflected image. If the bar is perpendicular to the dipoles, a continuous layer boundary is obtained. Figure 3 indicates the image obtained by moving the 1.5 GHz antenna along the width of a column. The three hyperbolic reflections indicate the three longitudinal bars in the middle region of the column width of 600 mm. The figure indicates only a part of the column because the antenna cannot cover the entire width.

The pier of a bridge shown in Figure 4 was scanned to locate the reinforcement details using a 1.5 GHz antenna. Figure 5 (a) indicates the images obtained when the antenna was moved horizontally along the pier width.
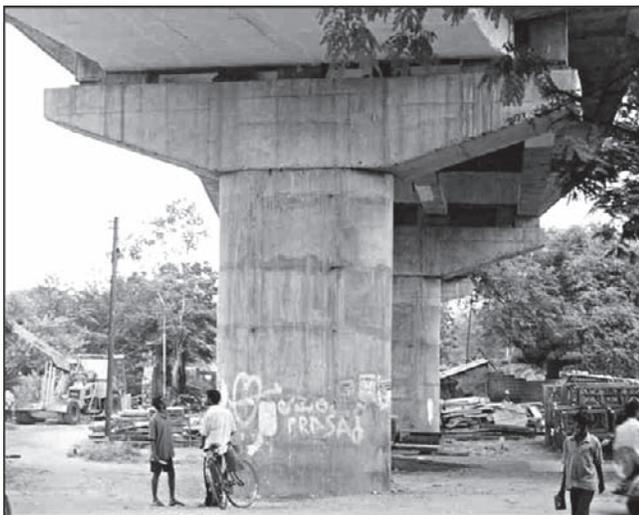

Figure 3. Longitudinal reinforcement in a column (1.5 GHz antenna)
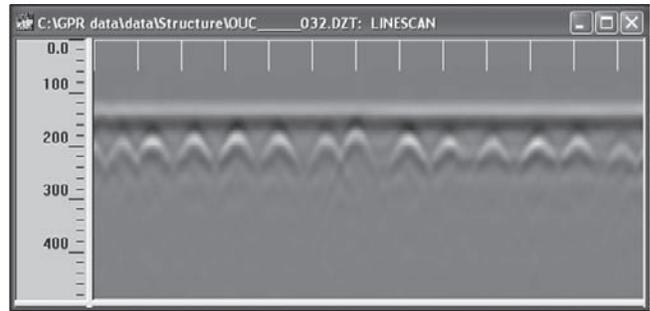
(a) Normal (grey) colour mode
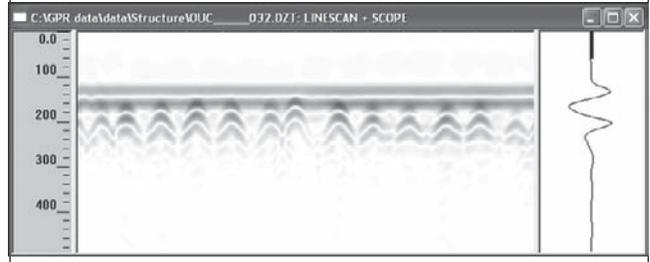
(b) Colour mode with a line scan

Figure 5. Longitudinal reinforcement in the bridge pier (1.5 GHz antenna)
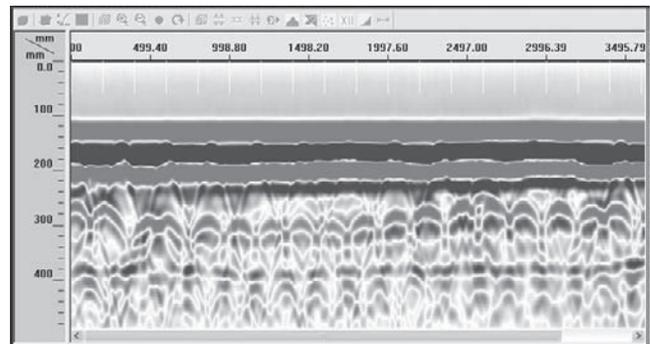

Figure 4. A bridge pier

Figure 6. Transverse reinforcement of the bridge pier (1.5 GHz antenna)
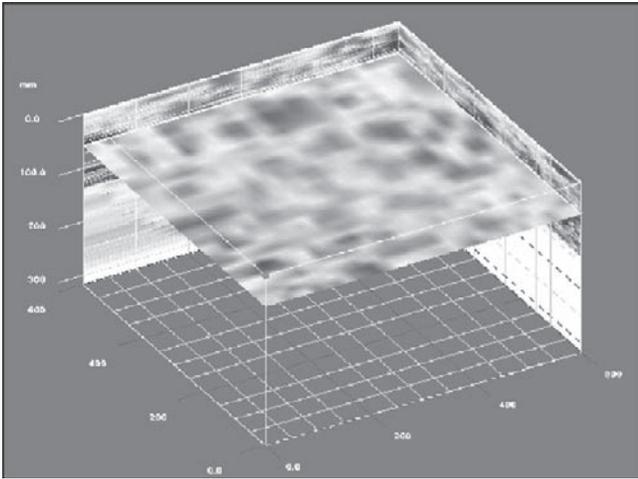
Figure 7. Three dimensional view of slab reinforcement (1.5 GHz antenna)

The location of the longitudinal bars is discernible in the figure. The image can be also viewed in different colour modes (Figure 5 (b)) to note the details. A line scan is also indicated in Figure 5 (b) to locate the concrete surface. The first kink (peak) in the line scan indicates the interface between concrete surface and air. The peak of the hyperbola locates the bars. The clear cover to the longitudinal bars of the pier can be estimated as 75 mm from the figure.

Figure 6 shows the image of the pier when scanned along its height over the narrow side (parallel to bridge axis) on a different colour palette. The reflections of the

(a) Normal image with a line scan

(b) Image in a different colour with a line scan

Figure 8. Well compacted soil layers (400 MHz antenna)

Figure 9. Image of a soil infill with poor compaction (400 MHz antenna)

transverse bars with a concrete cover of about 190 mm can be noticed in the figure along with a second layer of ties at a depth of about 290 mm from the concrete surface. The horizontal lines above the hyperbolas indicate different layers of concrete. The spacing of the ties at about 160 mm can also be noted from the horizontal distances marked in the figure. GPR is useful to locate bars at different levels below the surface.

GPR is supported by powerful software for image processing. Figure 7 shows a three dimensional sub-surface image of a slab. The slab was scanned over a grid of 12 lines spaced at 50 mm (an area of 600 mm x 600 mm). The images scanned in orthogonal directions are stored as grid data, and processed to form a three dimensional image. The 100 mm thick slab was reinforced with 8 mm bars spaced at 100 mm in orthogonal directions. The three dimensional image can be sliced where required to view the details.

Soil layers

The interfaces between compacted layers of soil provide weak reflections as indicated in Figure 8 and 9. The images were obtained using a 400 MHz antenna with a dielectric constant of 4.0. The soil layers were overlaid by a plain concrete slab of about 100 mm and a subgrade of about 100 mm thickness. The soil profile obtained in Figure 8 (a) indicates well compacted layers of concrete upto a depth of about 5 m below the surface layer. Figure 8 (b) indicates the same image in a different colour mode to note the layers more distinctly than in the grey image of Figure 8 (a). The line scan on the side of the images indicate full penetration depth. The firm lines zig zagging through the depth indicate the reflected energy of the signal received.

However, the signal at large depths is sometimes camouflaged by noise as the maximum deflection amplitude decreases to the level of system noise without yielding a usable signal. The sub-surface image of a soil
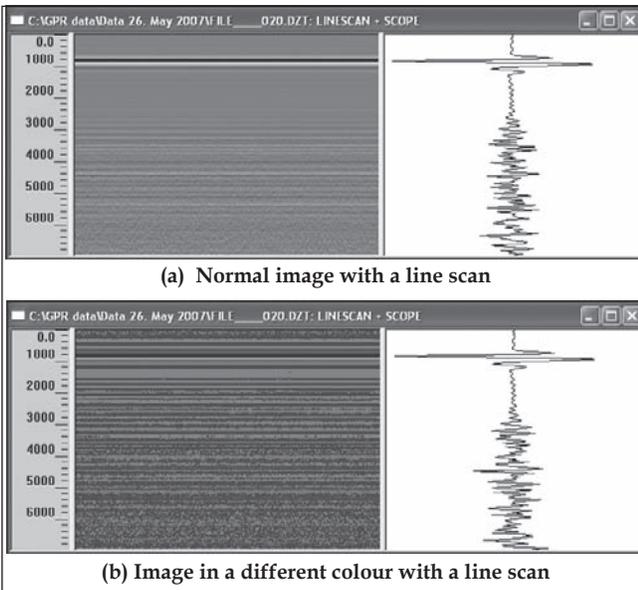
infill with poor compaction, using the same 400 MHz antenna, is indicated in Figure 9. It can be noted that the signal is unstable beyond a depth of about 2.0 m from the ground surface. The soil layers are below a concrete flooring of about 300 mm thickness in this case. The soil layers at a depth of 2.0 m below the flooring are not well compacted or are saturated with ground water. The wavy unstable signal does not indicate well compacted soil. GPR is also helpful in locating soil layers with poor compaction.

Summary

Ground penetrating radar (GPR) is widely adopted for sub-surface imaging to assess structural condition and also to locate buried objects. The system is backed by powerful software to obtain an insight into the sub-surface layers. A GPR system comprises of an antenna emitting electromagnetic energy, and receiving the reflected energy from the surfaces as well as that from the inner layers besides a processor. The energy reflected is transformed into visual images, which provide extensive data on the subsurface (inner) materials, when interpreted correctly.

The principles of GPR and interpretation of the data are discussed briefly along with a few typical examples (reinforced column, bridge pier and sub-surface soil layers). Three-dimensional image of a slab is also presented.

GPR is yet another valuable tool in the repertoire of civil engineers for non-destructive testing and quality control.

Acknowledgement

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