Ground Penetrating Radar and its Applications in Civil Engineering

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1.0 Introduction

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.

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.

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. 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.

2.0 Principle of 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. The principle of radar surveying is shown in a schematic diagram in Fig. 1.

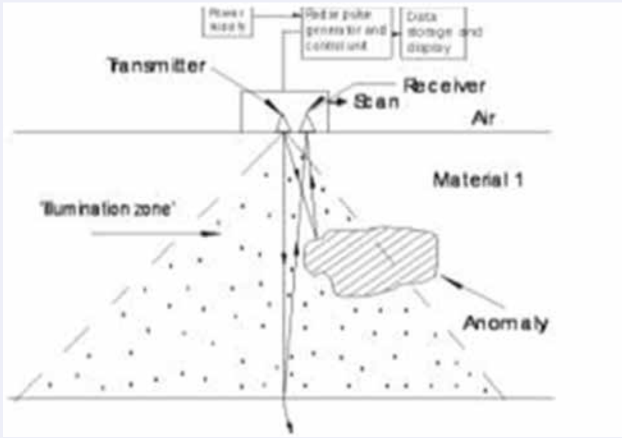

Fig. 1: Principle of radar surveying

GPR equipment contains three basic units such as:

- Antennas
- Control units
- Recorder and display unit

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.

Electromagnetic pulses of frequency 500MHZ to 3000 MHZ from radar transmitter are directed into the material having a pulse duration of ≤ 1 ns (nano seconds). The waves propagate through the material until a boundary of different electrical characteristics is encountered, reflected at interface of different layer and reinforcement along its travel path (Fig. 1).

The signal recorded is usually referred to as a scan or trace. They are referred as B scans and C scans. B scans normally give sectional view, whereas C scans give plane view. C scans are obtained by a combination of B & D scans. The scan is in the form of 3D images.

Although 3D GPR images have been successful in showing orientation and location of embedded targets internal voids identification is difficult to be identified

Several GPR systems are available commercially with image processing software to help interpret the data obtained. The antenna comprises basically a transmitter and a receiver, and utilizes 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. Fig. 2 shows a typical GPR system with antenna mounted on a cart and processor for scanning. Fig. 3 shows a latest model of GPR for scanning.

Fig. 2: A GPR survey for concrete structures

2.1 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. Antennas 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 antennas are indicated in Table 1.

Table 1. Typical characteristics of antenna

Fre-quency MHz	Pulse duration, ns	Pen-etration depth, m	Size, mm	Weight, kg
1500	0.6	0.5	40 x 100 x 165	2.0
1000	1.0	0.75	40 x 100 x 165	2.0
900	1.1	2.0	80 x 200 x 330	3.4
400	2.5	5.0	170 x 300 x 300	6.4
200	5.0	9.0	300 x 600 x 600	17.7
80	12.0	20.0	1200	
40	25.0	40.0	2400	
20	50.0	150.0	4800	
15	60.0	200.0	6000	

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 up to about half a meter generally, while a 15 MHz antenna can penetrate up to 200 m. However, deeper penetration of about twice the values indicated in Table 1 is possible depending upon the materials.

Fig. 3: Latest Model of GPR

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 decreases with the increase in frequency. The configuration of antenna with frequency smaller than 100 MHz is different from that of high frequency antenna. The transmitter and receiver of high frequency antenna are encased in a strong housing, and can be dragged over the surfaces. Low frequency antennas (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 antenna 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 antenna can be moved over vertical surfaces and even ceilings, if necessary. The antenna can also be mounted on a motor vehicle, and driven over the surfaces to be monitored, especially road and bridge surfaces.

2.2 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. 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 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, antennas of the same frequencies for deeper penetration are also available.

Table 2. Typical material properties and velocity of propagation

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

3.0 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 antennas 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.

4.0 Reinforcement Scanning in Concrete Elements

The images obtained depend upon the shape of the objects as well. The longitudinal and transverse reinforcing bars are marked by a profile taken by a GPR survey as shown in Fig. 4.

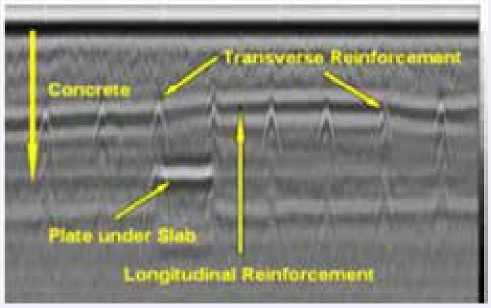

Fig. 4: Longitudinal and transverse reinforcing bars profiling during a GPR survey

Similarly the reinforced concrete column can be scanned by a 1.5 GHz antenna. The antenna, with a selected dielectric constant of 6 and penetration depth o f 500 mm, should be moved along the height of the column.

The transverse reinforcement in the column is usually marked by the series of hyperbolic reflections, while the band above the hyperbolas indicates 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.

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.

A roof slab was scanned to locate the reinforcement details using a 1.5 GHz antenna and shown in Fig. 5.

The image can be also viewed in different colour modes to note the details. With an Ekko mapper software the images are sliced into 4 parts (0 to 30 mm depth, 30 to 60 mm depth, 60 to 90 mm depth and 90 to 120 mm dept for detail analysis as shown in Fig. 6.

The reflections of the transverse bars with a concrete cover spalling of concrete reinforcement corrosion can be seen at 90-120 mm depth of concrete surface in

Fig. 6. The spacing of the ties can also be noted from the horizontal distances marked in the figure in 0 to 30 mm depth. GPR is useful to locate bars at different levels below the surface.

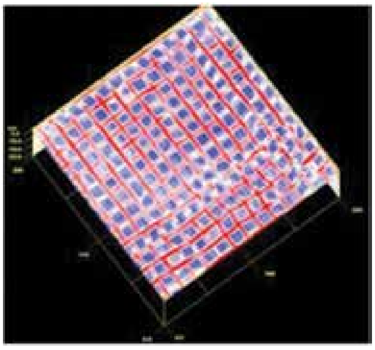

Fig. 5: C-scan – Reinforcements in a Slab

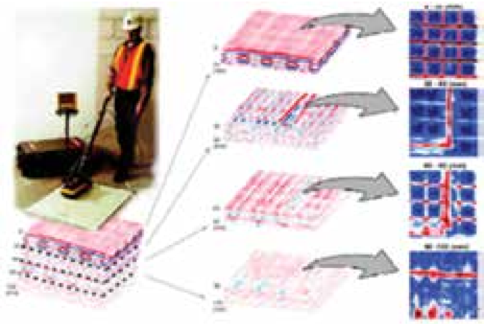

Fig. 6: Ekko Mapper software

Similarly one of the deck slab of a bridge was scanned to check the voids which were also cross checked with extracted core samples as shown in Fig. 7. The GPR images at location 1, 2, 3(left side image) are correlated with the core samples (right side image) at same place. It was observed exactly similar nature of voids in core samples as being observed in GPR survey.

GPR is supported by powerful software for image processing as shown in Fig. 8. The images scanned in orthogonal directions are stored as grid data, and processed to form a three dimensional image for detail analysis and interpretations of results.

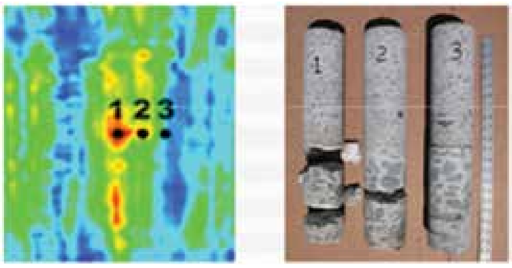

Fig. 7: Verification of concrete deterioration by GPR and core samples

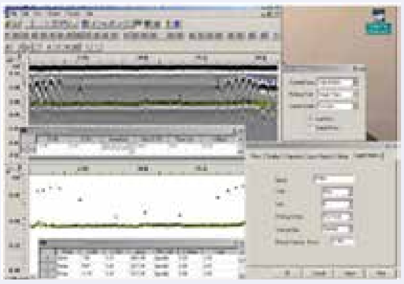

Fig. 8: Processed data from one scan line

5.0 Outcomes of GPR Survey and Reporting

A GPR survey report should normally describe in the following:

- Outline of the survey objectives.
- Description of survey method used.
- Type of GPR equipment used, including antenna frequencies and recording time range.
- Data processing routines applied.
- Survey results including location map
- Interpretation
- Classification or coding of results (if required).
- Conclusions and recommendations (if appropriate).

A site plan showing the location of the survey lines and the raw GPR profiles are normally the minimum outputs required. Map scales, the compass direction and relevant geographical site features should be marked on the plans and radargrams to assist interpretation. Where nontechnical persons may use the outcomes of the report, it may appropriate to include a cautionary warning that GPR profiles show the intensity of electromagnetic waves reflected from objects both under the survey lines and also possibly from above the ground. Therefore some spurious features appearing on the radargrams may not always appear to be consistent with subsurface structures.

6.0 Conclusion

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 subsurface 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.

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

Ground Penetrating Radar Applications

[Excerpts from http://www.malags.com/home and Application of Ground Penetrating Radar to Civil and Geotechnical Engineering" by Richard J. Yelf, http://www.emph.com.ua/18/pdf/yelf_01.pdf]

1.0 Introduction

Ground Penetrating Radar (GPR) is a safe, non-destructive and non-invasive imaging technique that can be effectively used for advanced inspection of composite structures and for diagnostics affecting the whole life-cycle of civil engineering works.

GPR provides high resolution images of structures and subsurface through wide-band electromagnetic waves.

2.0 Application

GPR is an effective tool for subsurface inspection and quality control on engineering construction projects. The numerous applications of GPR include the following:

- Mapping pipes (including PVC pipes), cables and other buried objects.
- Continuous inspection of layers in road pavements and airport runways. Due to the rapid data acquisition rates, it can be used at highway speeds to monitor changes in subgrade and asphalt pavement layers.
- Mapping cavities or voids beneath road pavements, runways or behind tunnel linings.
- To monitor the condition of railway ballast, and detect zones of clay fouling leading to track instability.
- Detailed inspection of concrete structures, location of steel reinforcing bars and pre- and post-tensioned stressing ducts. GPR can be used in 3-D mode to map multiple layers of steel in buildings, in order to avoid damage when drilling through such structures.
- Inspection and quality control of pre-cast concrete structures, such as bridge deck beams.
- Detection of zones of honeycombing, voiding and chloride attack in concrete.
- Mapping zones of deterioration and delamination on bridge decks.

Besides these applications it can be employed for geotechnical foundation investigations, mapping geological information, hydrogeological studies, investigation of active geological fault zones, archaeological studies, forensic studies, as well as for several other purposes.

The key advantages in subsurface investigations: Locates metallic as well as non-metallic utilities – Easy user interface – Portable – Low cost GPR solution for the utility locate professionals – Fast – precise locating.

Some of these applications in civil engineering field along with their specific advantages have been discussed briefly:

2.1 Utility Locating

The utility 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 metallic and non-metallic utilities and other buried infrastructure is therefore essential and can be easily located by a GPR survey (Fig. 1).

Fig. 1: GPR survey for locating utility services on a road

2.2 Utility Mapping

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 depth can be marked out on site and later also visualized into 3D reports (Fig. 2).

Fig. 2: GPR survey for utility mapping and their location mapping (bottom drawing) along with their 3D view of the location (top right)

2.3 Buried 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. Naturally formed cavities and sinkholes in karstic limestone terrain, unknown basements and culverts, abandoned wells and mineshafts, all of which present possesses serious hazards can be detected by a GPR survey (Fig. 3).

Fig. 3: GPR survey for detecting buried voids below the ground surface

2.4 Underground Storage Tank (UST) Location

GPR can locate Underground Storage Tanks (UST) and any associated underground piping. This non-destructive inspection and geophysical survey can determine the location and depth of a UST or provide the location of a former tank vault (Fig.4).

Fig. 4: GPR survey for detecting underground storage tank

2.5 Tunnel Assessment Surveys

To investigate possible quality deterioration within and above tunnels, GPR has proven to be an effective tool. When using GPR the condition of lining, location of hidden construction shafts, voids and delamination (Fig. 5) can be made both safe and cost-effective.

The key advantages such as: Ground penetrating radar is the most well-established technique because of its rapid data acquisition and versatility.

Fig. 5: GPR survey for detecting defects in a tunnel

2.6 Post- Pre-tension Cable Location

The imaging system allows scanning concrete structure simply and safely and presents data clearly for real-time and in-the-box data acquisition, display and analysis.

Key advantages: GPR is a real-time NDT technique that quickly locates the position of post tension cables (Fig.6), rebar, and electrical conduits embedded in concrete, eliminating dangers associated with cutting or drilling and the high costs required for their repair if cut or damaged.

Fig. 6: GPR survey for locating post-pre- tension cables

2.7 Rebar Location

Ground Penetrating Radar is an effective tool for detection of embedded rebar in concrete (Fig. 7) floors and walls. GPR can detect the depth and orientation of electrical conduit, utility cables and water lines.

Key advantages: Ground Penetrating Radar (GPR) is a valuable tool in commercial construction. It's a safe, non-destructive method for detecting hidden elements in concrete.

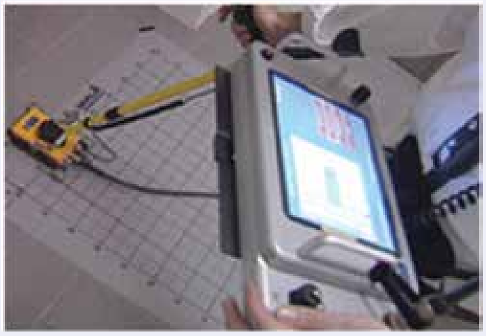

Fig. 7: GPR survey for locating embedded rebars in concrete

2.8 In-Slab Conduit Location

GPR is used to locate electrical conduits embedded in or below slabs (Fig. 8) prior to saw cutting or core drilling, thereby minimizing the risk of electrocution to the operator and reducing the risk of building systems shutdowns.

Key advantages: Accurate target location within a concrete slab on-grade, wall, or supported slab can be achieved more quickly, safely, and economically with GPR instead of other existing techniques.

Fig. 8: GPR survey for locating embedded electrical conduits in concrete

2.9 Void Detection in Concrete

The presence of voids in concrete which impacts the structural stability can be detected by a GPR survey (Fig.9). Key advantages such as: GPR is superior to radiography (X-Ray—the only other NDT technique capable of "seeing" through a structure) in speed, efficiency, and cost-effectiveness.

Fig. 9: GPR survey for detecting voids inside concrete

2.10 Slab Thickness Measurement

GPR can determine and record the slab thickness (Fig.10) for both slab-on-grade and suspended slabs, determine rebar depth to measure concrete cover in slabs, beams, and columns.

Fig. 10: GPR survey being used for measuring the depth of RCC slab

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.

2.11 Concrete Evaluation

GPR is a great tool for concrete evaluation and to determine concrete deterioration (Fig.11), slab thickness, rebar spacing, bar elevation, and amount of concrete cover over the rebar.

The key advantages such as: – A fully integrated GPR solution for concrete imaging, – Collecting data three different measurement modes, – Providing the highest resolution and detail of data, – Combines both GPR and EM technology simultaneously, – Multiple antenna frequencies.

Fig. 11: GPR survey being used to evaluate the deterioration of RCC slab

2.12 Road Evaluation

Pavement engineers use ground penetrating radar to determine physical properties and characteristics of the pavement (Fig.12) or subgrade. GPR helps engineers to determine the thickness of a pavement structure without resorting to excavation. A test method and the procedure are given in ASTM D 4748 for the non-destructive determination of thickness of bound pavement layers using short-pulse radar. This test method permits accurate and non-destructive thickness determination of bound pavement layers. This test method is widely applicable as a pavement system assessment technique.

Fig. 12: GPR survey being used to evaluate the characteristics of road pavement

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.

2.13 Bridge Deck Evaluation

The GPR technology can be used without the costly removal of the asphalt overlay in bridge deck (Fig.13). Quantitative data results can be compared from one year to the next. In addition construction companies that have been contracted to repair bridges can also use GPR to identify specific areas in need of repair. This allows companies to repair specific problem areas with bridges. Ease of repair will help in the problematic funding issues currently plaguing many DOT's.

Fig. 13: GPR survey can be used to evaluate the condition of bridge deck

2.14 Railway Ballast Evaluation

Ground Penetrating Radar is an excellent non-destructive tool to inspect miles of railroad track (Fig.14) 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.

Fig. 14: GPR survey being used to evaluate the railway ballast

2.15 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.

GPR survey can be used to evaluate the condition of runway pavement of an airport (Fig. 15).

Fig. 15: GPR survey being used to evaluate the runway pavement of airport

3.0 Types of GPR Products

IDS GPR products and services for the Civil Engineering industry are based on two different kinds of technologies that meet the varying needs and necessities of the customers. The first category is on-contact application such as Aladdin, RIS Hi-BrigHT, RIS One & RIS Plus where these GPR systems can use the combination of multiple frequency antennas to provide faster and more accurate inspections. The 2nd category is remote based application known as Interferometric Radar solution such as IBIS-FL and IBIS-FS and these radars can be operated remotely and there is no need for direct contact with the target being monitored. This technology allows the remote monitoring of movements of structures such as dams, bridges, towers, buildings with sub-millimeter accuracy.

4.0 Limitations

- GPR does not work well in saline conditions, in high-conductivity media and through dense clays which limit signal penetration.
- Highly trained personnel needed for application of this instrument.
- The detail calibration procedures have not been standardized.

5.0 Conclusion

GPR is a powerful diagnostic tool for civil and geotechnical engineering. To obtain the best results it must be applied correctly by properly trained personnel, who are familiar, both with the physical principles of the method and also of its limitations. The resultant data should be interpreted carefully, combining the relevant information of above ground and subsurface features. Calibration of the results using boreholes or test pits or concrete sample as applicable must be recommended.