GROUND PENETRATING RADAR IN CIVIL ENGINEERING APPLICATION: CASE STUDY OF MULTISTOREY BUILDING FOUNDATION SITE TO MAPING SUBSURFACE FEATURES AT THE CENTER OF KARBALA GOVERNORATE, IRAQ

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ABSTRACT

The reconstruction of holy shrines and religious places in Iraq was developed after 2003. At the same time, some geotechnical problems are urgently waiting to be solved. Ground Penetrating Radar (GPR) is a noninvasive technology that has many applications including subsurface geology, archeology, engineering and environmental studies. It is very effective in solving some engineering and geological problems and detecting buried objects under the ground and helping to map subsurface geological structures, subsurface soil conditions and groundwater contaminants.

This paper demonstrates the utility of using GPR for mapping and locating subsurface features of multistorey building foundation site at the center Karbala district, Karbala governorate. A series of GPR profiles were acquired on a proposed multistory building site GPR survey has been carried out along fifteen profiles, ten longitudinal parallel profiles and the other profiles are transversal. In this study different antennas were chosen to conduct the survey, the antenna frequencies of 450 MHz and 750 MHz were used. The data were performed by using a commercial GPR system A MALÅ ProEx System™ from MALA Geoscience and we are using RadExplorer software for processing the data. The profiles reflect a lot of subsurface features. Most of the main subsurface features anomalies due to weak zones. These zones spreading in the front and especially in the center of a building starts from under the foundation to a depth of approximately six m. The water table depth at the site was defined from GPR radargrams at a depth of (2.7 and 3.5 m). Through years of practical experience with GPR surveys, we have summed up a suitable technique to solve various engineering and geotechnical engineering problems with GPR in Iraq.

Keywords: Ground Penetration Radar (GPR), Antennae, Soil investigation, Radargram, Weakness zones, Buried body
INTRODUCTION

Engineering geophysics is the application of geophysical methods to investigate of subsurface materials and features which are likely to have engineering implication. GPR is a safe, advanced, and non-invasive sensing technique that has several traditional and novel applications. GPR originally developed for high resolution imaging of the subsurface. Since its initial development during the mid-1920s, now is used routinely in condition evaluation of foundations, buildings, pavements, concrete slabs and walls and other constructions. GPR has become very popular for knowledge and defining what is underground such as subsurface geological features, particularly in engineering, environmental and archaeological applications (Reynolds, 1997 and Sharma, 1997).

GPR originally developed for military applications, provides an alternative. GPR has been used in fields as diverse as architecture, engineering, environmental management and mineral prospecting (Mellet, 1995 and Reynolds, 1997). It has aided examination of internal glacial structures (Murray et al., 2000) and is frequently used to study contaminants in groundwater and the nature of subsurface faulting (Benson, 1995 and Daniels et al., 1995), and the location and size of plastic or metal pipes (Peters et al., 1994) and other objects, particularly in archaeology (Conyers and Goodman, 1997). GPR has been used successfully to map soil and rock stratigraphy and bedrock topography (Olson and Doolittle, 1985; Davis and Annan, 1989, and Dominic et al., 1995), and the water table (Lapen et al., 1996). The technique has been shown to produce better near-surface resolution in the upper few meters of soil and bedrock than seismic refraction (Olson and Doolittle, 1985). It may detect the disturbed soil of the grave shaft, or a break in the natural stratigraphy or soil profile (Bevan, 1991). The major GPR strengths, on which its success in the civil engineering field is based, are related to the non-destructive and non-intrusive of the surveys, notably lower costs compared to traditional methods, high-speed data acquisition, reliability and representativeness of measurements. GPR provides significant, dense and accurate data; the resolution is higher, compared to competing geophysical technologies as seismic, transient electromagnetic, electrical and magnetic approaches. The main performance limitations occur in the presence of high-conductivity materials, such as clay or salt-contaminated soils, and in heterogeneous conditions causing complicated
electromagnetic-scattering phenomena. Considerable expertise is necessary to effectively design and conduct a survey; moreover, the interpretation of Radargrams is generally non-intuitive, thus specific competences are needed to enable measurements to be transformed into clear pictures and engineering decision making data. The electrical characterization of geological materials, as well as the relationships between electrical conductivity and dielectric polarization, were topics of great interest in the research community. In the civil engineering field, GPR is currently used for inspection, monitoring and design purposes. The detection of utilities and buried objects, as well as the surveying of road pavements, bridge decks, tunnels, and the measurement of moisture content in natural soils and man-made materials, are the main applications. In addition, interesting examples concerning the use of the GPR in structural, geotechnical and railway engineering have to be mentioned (Benedetto and Pajewski, 2015).

GPR method is based on the use of radio frequency electromagnetic (EM) waves. The frequency range utilized is from 30 to 3000 MHz. Inside of this frequency range, it is said that EM- waves can propagate in a low electrically conductive medium. Physical parameters affecting the wave are the medium’s conductivity, dielectricity and magnetic susceptibility. This method of transmitting pulsed electromagnetic (EM) radiation into the ground and recording the reflected signal has been utilized for a number of subsurface investigation applications. GPR has also proven to be a useful method in an appropriate near surface geological settings as a way to quickly, cost-effectively, and non-destructive analyze the shallow subsurface within engineering and environmental applications (Benson, 1995). These sorts of applications often directly affect the population that occupies the land and wishes to understand and utilize shallow subsurface environments. With the rise in population predicted during the 21st century, a more detailed understanding of the shallow subsurface will be required if humans desire to manage Earth’s limited resources (Neal, 2004), and utilize this knowledge within engineering and environmental applications. There is a wide acceptance of the radar method in certain areas of civil engineering, such as foundations, railway, road pavement evaluation, void and cavity detection and behind tunnel linings. There has also been an expanding role for the method in geological arid environmental applications, particularly in the rapid assessment of superficial deposits, location of shallow sinkholes in karstic areas, etc. Furthermore, in archaeological studies, GPR has
been used on many sites to identify potential excavation areas. As with seismic waves there is a trade-off between depth of penetration and resolution. For geological applications, where depth penetration tends to be more important than very thin resolution, antennae with frequencies ranging from 250 to 25 MHz are used for engineering applications, antennae with frequencies of 250 MHz and greater are used, typically as high as 900 MHz or 2 GHz (Casas et al., 2000).

The objective of this study is to utilize a GPR survey to identify near-surface features, buried bodies, walls, water table and geological features, such as joints, fractures, cavities voids, weak zones and collapse structures in the subsurface also sediments material within the foundation site of multistory building in the center Karbala district.

GEOLOGICAL AND TECTONIC SETTING OF STUDY AREA

The site of the survey is located in the center of Karbala district, Karbala province (central southern part of Iraq) 100 Km southern of Baghdad between longitudes (44° 01' 59.8'') and latitudes (32° 37' 13.0'') (Fig. 1), which is situated within the Mesopotamian Plain. The survey was conducted in a flat area covered by unconsolidated soil, which consists of silty sand. Tectonically, the site situated inside the Unstable Shelf, representing a part of Euphrates Sub Zone, that characterized by the existing of NW-SE structures and faults such as, Abu-Jir Fault, which trends parallel to the Euphrates river, the natural tectonic boundary between the Stable and the Unstable Shelves (Jassim and Goff, 2006). Abu Jir Fault Zone passes through the studied area and has a considerable effect on the topography of the area, particularly the configuration of the depressions and ridges as it was proved by (Hassan et al., 2000) in the neighboring areas. The Iraqi Southern Desert lies within the stable part of the Arabian Platform, where Cenozoic rock units are exposed and sloping gently East and Southeast, towards the unstable part of the Arabian Platform. The exposed formations in the studied area are (from older to younger): Euphrates, Fat'ha, Nfayil, Injana, Zahra and Dibdibba (Hassan et al., 2000; Hassan and Al-Khateeb, 2006). The study is covered by Quaternary sediments. The exposed Tertiary rocks are represented by Fat'ha Formation, consists of marl, claystone, limestone and gypsum, with rare siltstone and sandstone. Injana Formation consists mainly of sandstone, siltstone and claystone.
Dibdibba Formation consists mainly of sand, gravel and gravelly sandstone with lenses of clay, which is composed of compacted clay balls interfered with some sand and gypsum as cementing material. Quaternary sediments cover the underlying Tertiary formations; involve Pleistocene and Holocene sediments that include river terraces, gypcrete, flood plain sediments and Aeolian sediments; as constituents of almost all the soil of the studied area. Figure 1 show the geological map of Al-Hilla and Karbala region.

Fig. 1: Geological map of Al-Hilla and Karbala region modified from Barwary and Slewa (1995)
MATERIAL AND METHODS

GPR technique is similar in principle to sonar methods. The radar transmitter produces a short pulse of high frequency (30 – 3000 MHz) electromagnetic waves, which is transmitted into the ground through an antenna. Variations in the electrical impedance within the ground generate reflections that are detected at the ground surface by the same or another antenna attached to a receiver unit. Variations in electrical impedance are largely due to variations in the relative permittivity or dielectric constant of the ground. The reflection coefficient for a normal incident signal is:

\[ R = \frac{\sqrt{E_1} - \sqrt{E_2}}{\sqrt{E_1} + \sqrt{E_2}} \]

Where \( E_1 \) is the dielectric constant of medium 1 and \( E_2 \) is the dielectric constant of medium 2.

On the basis of the formula, the polarity of the reflection changes if \( E_1 \) is smaller than \( E_2 \), which is usually the default situation in road and soil structures (moisture content is getting higher when getting deeper). If \( E_1 \) is bigger than \( E_2 \), then the polarity of the reflected wave remains the same as the progressive wave’s polarity at the interface. In road radar measurements, however, it is common practice that the surface reflection is recorded as positive, even though the reflection coefficient is negative. Similarly, the other layers, where \( E \) (upper) < \( E \) (lower), are recorded as positive reflections. In the gray scale, they should be presented in such a way that the white reflection is in the middle (see Figure 2, \( E_1 < E_2 \)). Correspondingly, if the dielectric value of the lower layer is smaller than the upper, for instance, in the structure of Figure 2 \( \varepsilon_3 > \varepsilon_4 \), the reflection is so-called negative and then the black reflection is in the middle. GPR signal polarity, leaving the antenna and progressing in the medium, can be changed 180 degrees easily by changing the positions of the transmitter and receiver antenna, or when doing GPR data post processing by multiplying the signal by a factor (-1). The polarity information is not so critical in site investigations and still in many cases GPR site investigation data is presented in a way that does not show the sign of the polarity. Water has a dielectric constant of 80 (compared, for example, to 5 for dry soil and 8 for rock) and hence there are high reflection coefficients between dry and wet materials. In addition, the water table is a strong reflector (Saarenketo, 2008).
Achievable depth penetration with ground penetrating radar depends on what antenna frequency is used and therefore the signal wave length. The attenuation increases when GPR central frequency increases. The choosing a frequency for a GPR survey is quite critical. The Lower frequency with long wavelengths provide the deepest penetration, whereas high frequency with short wavelengths are only able to image shallow features. Higher frequency radar provides higher resolution than lower frequency radar (Conyers, 2004; Grealy, 2006; Neubauer et al., 2002, and Leckebusch, 2003). This is due to the shorter wavelengths of high frequency produce a narrower cone of transmission, which can focus on smaller areas and thereby resolve smaller features than the more spread out transmission cones produced by low frequencies and longer wavelengths (Conyers, 2004). The attenuation increases when GPR central frequency increases. A highly conductive medium results in an increase in the amount of energy scattering objects, when the wavelength gets shorter. Similarly, the penetration depth gets smaller as the frequency gets higher. On the other hand, the resolution gets better at the same time. The resolution also improves when dielectric value increases. In investigations site if target of the survey is to obtain information as deep as possible, then antenna central frequencies between 50 – 200 MHz should be used. If the target is closer to the surface, i.e. 3 – 6 m, then frequencies higher than 200 MHz can be used. Resolution refers to how close interfaces can be to one another and can still be identified as separate interfaces. This applies to both directions, horizontal and vertical (Saarenketo and Maijala, 2011).

GPR principles are similar to reflection principles in seismic methods. In contrast to seismic methods, radar instruments use electromagnetic waves (EM) instead of acoustic waves. EM-waves will not penetrate as deep as acoustic waves, but will result in much higher resolution maps. Targets with a contrast in electrical impedance to the surrounding media will be registered and detected. Therefore, surface radar instruments are primarily used for the detection and localization of metallic and non-metallic targets down to an approximate depth of 30 m. GPR instruments emit EM energy into the ground by transmitter (T_s), efficiently receive reflected signal (R_s), digitize the received signal, store the digital data, and display the output radargrams. Some of the systems, supplied with computers, allow for basic processing and the printing of hard copies. The general scheme of GPR system is depicted in Figure 2. Basically, GPR instrumentation
include: antennas providing for the emission and receiving of EM energy; a control unit governing all the parameters of radiated signal, timing, amplifier and filter settings, and digitization rate; a laptop computer for handling the parameters of control unit, data storage and visualization. Usually, the transmitter, amplifier and digitizer electronics are combined with the antennas in separate blocks to reduce the noise generated in connecting cables.

Fig. 2: General scheme of GPR system, the EM signal is emitted by the transmitter antenna (T_x), captured by the receiver antenna (R_x), amplified, digitized, and stored (Kovin, 2010)

Most of the GPR equipment used in site investigations utilize pulse radar principles as previously described. Equipment for site investigations consist of the following components: GPR antennas which consist of a transmitter, which transmits the pulse to the medium and a receiver that receives the reflected signals. The antennas are controlled by a control unit, where the wavelength and strength of the pulse are regulated. In digitizers, the received pulses are converted into digital format. A digitizer can be located in the antenna or in the control or central processing unit. The data collection setup is controlled with data collection software. Some setup parameters include scans per time or distance unit (for instance scan/sec, scan/m), measuring time window (ns), the number of the samples per scan (for instance 512, 1024 samples/scan) and the data format (for instance 16, 32 bit). Calibrated optical encoders (distance measuring instruments) are used to trigger the control unit as the system moves over a distance (Saarenketo and Maijala, 2011).
In this study a commercial GPR system: A MALA ProEx System TM from MALA Geoscience was used. It is composed of radar control unit with 12 v. battery. The control unit features a 32 bit processor, linked to a storage display device on one side and with an antenna on the other side. A special monitor is mounted to the control unit. Side of this monitor is a computer for data acquisition and preliminary analysis and filtering. The whole system is carried by a special cart, which is equipped with distance meter. Figure 3 shows GPR main equipments MALÅ ProEx System. One advantage of the MALA GPR system is the ability of using a wide range of antenna frequencies with the same control unit. The shielded and unshielded antennas with frequencies ranging from 25 to 2.7 GHz can be directly connected to the same control unit. Changing from one antenna to another can be done in the field in quite an easy way. In this study antennas (450 MHz and 750 MHz) are used.

Fig. 3: GPR main equipment MALÅ ProEx System

In this paper, the GPR survey inspected the uppermost 10 m of the area. The work requires designing of field procedure to fulfill the requirements that provide the best results. Fieldwork, including sixteen profiles have been investigated in the building site with dimensions of 30 x10 m (300 m²). There are eleven parallel longitudinal profiles, the space between profiles equals to 0.5 m extend from NW to SE and five transverse profiles, the space between these profiles is 3 m, it extend from NE to SW. The lengths of profiles are different depending on the area design. The length of profiles ranges between 8 – 31 m. Figure 4 shows the location map with satellite Image and GPR survey lines for building project.
The design of field survey provides a basis for survey planning, identifying the best conditions of the survey, and the more suitable operating parameters setting of the GPR instrument with antenna. Two types of antennas were used along these profiles (Gx 450 and GX 750) with two stages. The types of antenna and the lengths of profiles are listed in Table 1.

**Table 1: Antenna types, lengths and number of profiles of GPR survey**

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Profile number</th>
<th>Length (m)</th>
</tr>
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<tbody>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>1A – 1B</td>
<td>31</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>2A – 2B</td>
<td>31</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>3A – 3B</td>
<td>31</td>
</tr>
<tr>
<td>GX450MHz</td>
<td>4</td>
<td>31</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>5A – 5B</td>
<td>15</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>6A – 6B</td>
<td>15</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>7A – 7B</td>
<td>14 – 15</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>8A – 8B</td>
<td>8</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>9A – 9B</td>
<td>11</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>10A – 10B</td>
<td>11</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>11A – 11B</td>
<td>11</td>
</tr>
<tr>
<td>GX450MHz – GX750MHz</td>
<td>12A – 12B</td>
<td>11</td>
</tr>
<tr>
<td>GX450MHz</td>
<td>13</td>
<td>20 outside</td>
</tr>
</tbody>
</table>
The results of the survey can instantaneously be viewed on the laptop computer controlling the measurement. Ground Vision software allows real time filtering during measurement. Point reflectors will, due to spherical dispersion, be registered as hyperbolas, whilst plane reflectors will maintain their natural form. The lateral and vertical resolution of the results varies between 0.01 – 1.0 m depending on the choice of antenna frequency. The higher antenna frequency gives the higher resolution, but less penetration, and vice versa (GroundVision Manual, 2003).

**GPR DATA PROCESSING**

The GPR data processing was conducted using the RadExplorer™ software (version 1.2). Sixteen GPR data records were loaded into RadExplorer and a uniform set of processing routines were performed on each record to amplify the signal and to optimize the quality of the record. Several processing steps were applied to each record separately, such as background removal, band-pass filters, median filter, and automatic-gain control. The band-pass filter was applied in order to eliminate high-frequency components. The typical processing flow of GPR data is summarized in Figure 5. Data processing focuses on the purple highlighted areas: data editing, basic processing, advanced processing, and visualization/interpretation processing. Processing is usually an iterative activity in which the data will flow through the processing loop several times before it is finalized in the visualization step. Batch processing with limited interactive control may be applied to large datasets after initial testing on selected data samples have been performed. The basic processing steps are usually applied to the raw data (often automatically) and introduce minimal operator bias into the data without the need for additional subsurface information, typically in the form of trace editing, filtering or data correction (Harry, 2009). These procedures are in generally applicable to most collection modes. Processed files were saved in the proprietary format used by RadExplorer.
Fig. 5: Overview of GPR data processing flow
(Harry, 2009 and Annan, 1999)

INTERPRETATIONS AND RESULTS OF GPR PROFILES

There are fifteen radargrams were processed using the RadExplorer software (Figs. 6 through 9). Interpreting GPR data is a complex operation that can be subjective at times and relatively unambiguous at others. The depth of penetration is in the range of 4 to 7 m depending on antenna type. From the data of radargram and after processing, it was found the presence of an anomalous feature through the survey area. The first interface becomes much clearer, which may be attributed to a shallower interface and greater contrast between the loose and compacted soil layers. The profiles depicts topsoil strata starting at a depth range of 0.0 – 2.5 m along the profile, which represents fill materials. The water table was recognized at a depth range of 2.7 – 3.5 m. The red rectangular lines indicate many old remnant walls spreading along profiles at various depths. Although contrasts can be created by both geological and cultural differences in subsurface conditions, human made anomalies are apparent as they form geometric, architectural patterns in plan view, and have segmented sections of high amplitude (high contrast) floor features (Conyers, 2004). The set of black and white responses disappears, showing that this response must be caused by the boundary change between the topsoil and the subsoil. The next layer extends at different depth, it may indicate
saturated layer. Also we can notice distinct hyperbolic reflections (Yellow arc) due to discrete subsurface objects. Similarly, these hyperbolic reflections are mostly likely the old curving arcs or a remnant of the old building’s foundation. The GPR test can detect human burials in several ways. It may detect the soil distribution or breaks in the natural stratigraphy or soil profile.

Fig. 6: Radargrams of profiles 1 and 4, using antenna 750 MHz (left) and 450 MHz (right)
Fig. 7: Radargrams of profiles 5 and 7 using antennas 750 MHz (left) and 450 MHz (right). Profile (8–9) Antenna 750 MHz
Fig. 8: Radargrams of profiles (10 and 13). Antennas 750 MHz (left), 450 MHz (right)
Fig. 9: Radargram of profile 15 (outside area) with antenna of 750 MHz

CONCLUSIONS

GPR technique offers a number of advantages over other geophysical methods. There is a great need to evaluate subsurface parameters without disturbing the ground. It is essential that any technology used to detect, identify and locate such buried material be capable of scanning large surface areas rapidly and efficiently in the presence of disturbances. The primary reasons for the popularity of the radar method are its picture-like format of the anomalous features that allows an interpretation relatively forward if site conditions are simple and a strong dielectric contrast exists between the structure of interest and the surrounding material. From utilizing the GPR technique for shallow engineering investigations in the multistorey building foundation site, the following conclusions are achieved:

1. It has proved that GPR is a very simple tool to be used in delineation of the weak zones and subsidence on soil section.

2. The survey area contains a lot of subsurface features. Most of the main subsurface features anomalies are due to weak zones. These zones spread in the front and especially in the center of the building and starts beneath the foundation to a depth of approximately 6 m, it was expected to be caused by the drilling a well as a result of drag-and-dump of soil grains then soil under foundations lost its compaction.
3. There are clear collapse areas that a reference to weakness zone due to multiple stages of construction and at different time stages and at a depth about 6 m, in addition to the burial stages at interval times construction stages at the site.

4. An old building and old vault were appeared within building site which are buried in an irregular manner and is not compacted. Also a spreading arc system is recognized in the old building and the site is saturated with groundwater.

5. The existence of groundwater well, which is closed and not buried, causes weakness zone in this region. This well is located in the center of the site.

REFERENCES


