Soil exploration using ground penetrating radar

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Abstract. Geophysical methods are extensively utilized in the field of geology and in
gEotechnical engineering such as seismic, gravitational, magnetic and electromagnetic fields. 
These methods are used to locate or to understand conditions below the ground surface, and the
physical properties of subsurface. GPR also known as Radio Detecting and Ranging is based on
the electromagnetic waves. It is a specially designed radar unit for transmitting electromagnetic
pulses below the ground instead of air. In GPR the medium is soil which is heterogeneous and
has higher attenuation rate than air. This method is used to measure the length, depth or to locate
the soil layers and its deposits. GPR is one of the most versatile sensors; it provides high
resolution profiles for shallow depth. GPR has been used in diverse fields such as archaeology,
non-destructive testing, probing underground caves, detecting landmines, mapping pipes and
conduits, investigating the reinforcement and conditions of roads, bridges and airport runways, to
name a few. Use of this technique/method is being extensively adopted from recent years
because of its properties and vast applications. The main applications of GPR in subsurface
mapping are: mapping of subsurface utility structures, detection and mapping of unexploded
ordnance and mines, extraction of hazardous waste containers or unexploded ammunitions,
maintenance or repair of subsurface structures. This paper presents an understanding of the
concept or the need of GPR dedicated to civil engineering applications in general and in the field
of geotechnical engineering in particular.

Keywords: GPR, electromagnetic waves, sub-surface mapping, soil exploration, radio
detecting
1. Introduction

Soil investigations are essential components of geotechnical engineering used to characterize the subsurface conditions of the soil. Based on these investigations various parameters like soil classification, strength, stiffness and ground water conditions are determined (S. Muhammad 2020). Various soil exploration methods like open excavation, boring and sub-surface sounding methods are used when the depth of investigation is limited. In case of large exploration depths, geo physical method proves to be beneficiary. For the detection and representation of diverse near surface targets, typically for exploiting the contrasts in the subsurface distribution of a number of physical properties like density, electric conductivity, magnetic susceptibility etc. a variety of geophysical methods are used (A. D. Booth 2019). In this regard ground penetration radar is increasingly popular non-destructive tool especially suited for characterization and imaging.

Geophysical penetration radar (GPR hereafter) also known as surface penetrating radar is an active shallow geophysical method that relays electromagnetic signal into the ground. It is an advanced and non-invasive geophysical sensing technique that can be effectively used for subsurface investigation, 3 dimensional imaging of composite structures and diagnostics affecting the complete life cycle of works related to civil engineering. This method is used as an investigation tool for studying the underground behavior of soil up to a depth of 4 to 5 m(Y. Dong, F. Ansari 2011), sometimes deeper than that depending upon the ground conditions. This method is also used for looking through the walls (wall imaging) and also for soil characterization. When the topographic cover is smooth and material is fine grained subsurface imaging by radar is possible. GPR signal possesses a vast range of frequencies varying between 100MHz to 2GHz. For deep foundations, tunnels etc. the frequency ranges between 10 and 100MHz, while for road pavements, buried infrastructure it covers between 100 to 1000MHz [1]. This method is time scaled system i.e. the time elapsed between the generations of electromagnetic waves to its return is recorded which gives information about the distribution, orientation, thickness etc. of the soil stratum. This nondestructive test is becoming popular as it is moderate in weight, relatively low cost, high recording speed, reasonable budget and high versatility in terms of application[2]. The survey is conducted mainly on linear, isotropic and nonmagnetic materials. In contrast to other non-destructive methods like ultrasonic, microwave based techniques etc. this method is proving to be effective as it offers more penetrating power and can be used upto greater depths [3]. This method also has the finest resolution power a s compared to resistivity and seismic refraction methods [4].

The main applications of GPR is to find the whereabouts of buried conduits, detection of voids or cavities, locating water table, geotechnical foundation investigations etc. [5].

In principle GPR can be viewed as composed by a: control unit, which is used to record, store and display the reflected signals and serve as a time reference; a power system and antennas which consists of transmitter and a receiver. The basic assumption of GPR is same as that of conventional radar however as GPR usually has to locate static targets and in most cases the processing of the data is not requested in the real time. The practical applications of GPR in subsurface mapping are: mapping of subsurface utility structures, detection and mapping of unexploded ordnance and mines, extraction of hazardous waste containers or unexploded ammunitions, maintenance or repair of subsurface structures. This paper presents an understanding of the concept or the need of GPR dedicated to civil engineering applications in general and in the field of geotechnical engineering in particular.

2. GPR System Design

GPRs are designed to probe up to a few meters into the ground through non homogenous material. A GPR system comprises of four main elements: EM waves pulse generator, transmitting unit, receiving unit, and a power supply.

The function of transmitter is to produce a high voltage pulse with minimum duration. When the pulse is applied to the transmitting antenna it travels down the surface with some of the signals reflected back to
the surface which is received by the receiving antenna and then passed to the receiver as shown in figure 1. The main purpose of the receiver is to amplify the signals and format them for display by the control unit [6]. The antennae that are used for emitting and detecting the electromagnetic signal must have dimensions comparable to the wavelengths of the signal which finally defines the size of the GPR instrument [7].

![Elements of GPR system and process](image)

**Figure 1.** Elements of GPR system and process

Depending upon the method of acquiring data, two types of GPR can be classified: time domain and frequency domain. In time domain GPR short pulses are sent and their reflections are recorded as a function of time. A pulsed GPR system radiates and receives the echoes to electromagnetic pulses while as continuous wave is transmitted in frequency domain GPR in which frequency is increased step wise. In a stepped frequency GPR the electromagnetic pulse is first decomposed into its spectral components and sequentially radiated. As far as practicality is concerned, stepped frequency systems are generally claimed more performing (Noon 1996). However the pulse system is commonly used but nowadays frequency domain is used to synthesize the- responses from time domain by using inverse Fourier transformation [8].

**3. Mechanism**

GPR is based on the propagation of electromagnetic waves. A short pulse of high frequency electromagnetic energy is produced by radar (10 to 100MHz) which is transmitted in the ground. As the waves propagate into the ground, there is a decrease in power which is equal to the square of the distance [9]. The surface electrical properties are governed the propagation of radar waves. The velocity of the radar waves change when they transmit from surface antenna to the ground depending on the physical and chemical characteristics of the ground[10]. There is a significant change in the velocity as the waves propagate through various nonmagnetic materials. During the propagation of the waves, a part of them are scattered in the ground depending upon the ground conditions and some of them are reflected towards the surface where these get detected and recorded by receiving surface antenna as shown in figure 2. Mainly two types of antennas, dispersive and non-dispersive, are used. The time taken by a wave to travel down to an interface and return to the surface is called as travel time. This time determines the in situ propagation velocity of the subsurface material [11].

The wavelength of the radar signal is controlled mainly by two factors i.e. the frequency of the transmitted signal and the velocity of the signal travelling through the ground. Wavelength affects the resolution of the radar system. Longer wavelengths with low frequency have a greater penetration depth
but low resolution whereas shorter wavelengths with higher frequency signals have higher resolution but less penetration depth [12].

![GPR system working on ground](image)

**Figure 2.** GPR system working on ground

### 4. Electromagnetic Wave Propagation

The propagation of electromagnetic waves is governed by Maxwell’s equation, which mathematically describes the relationship between electric field, magnetic field, time, space material related equations [13].

The propagation of electromagnetic waves through a medium depends on the frequency. When frequencies less than that of material’s transition frequency is used then electromagnetic induction and energy diffusion takes place [11].

Velocity and attenuation (reduction of the amplitude of a signal) are the factors that describe the propagation of high frequency waves in the ground. These factors in turn depend on the properties of the material like dielectric constant and conductivity[6].

### 5. Data Processing

Processing of GPR data is much similar to that of the seismic processing. Main steps of processing are:

#### 5.1 Filtering

It is the basic step in post- acquisition data processing used to remove cultural or system noise and to enhance the visual quality of the data. There are different types of filters ranging from simple band-pass to sophisticated domain [14], though simple filters are commonly used because of their high efficiency in removing high/low frequency noise. In many cases the data can be prepared with filtering only [13] and the filters have to be applied either before or after the gains, a time variant scaling. If post gain filters are applied then the effect of amplitude and spectral content must be fully understood.

#### 5.2 Deconvolution
It is an analytical process which is designed to eliminate the effect of previous filtering operation from the recorded data and improve the resolutions of sections into a narrow, distinct form by compressing the recorded GPR wavelet [14]. Deconvolution also proves to be effective in the field of seismic exploration. The main purpose of this process is to improve the vertical resolution by shortening the pulse length[15] and is based on the assumption that the subsurface is uniform horizontal layer with intra layer velocities and the reflections do not scatter energy. In practical applications, Deconvolution method is limited as it is difficult to be applied in systematic profiles and does not give improved resolutions [15].

5.3 Background removal
Background removal, one of the most common operations, consists of replacing the current A-scan with difference between it and the average value of all the A-scan that compose the B-scan. With the help of this operation a cleaner image is produced by erasing all the flat interfaces preset in the data. This processing should not be used repeatedly because if there is a need to clarify image on daily basis it means that there is some problem with the equipment[16].

5.4 Migration
Migration, a spatial Deconvolution, is an inverse processing system which is used to correct the visuals of GPR in contrast to the survey geometry [8]. This operation requires good knowledge of the subsurface velocity. It is the final step in GPR processing but proved to be unsuccessful in complex, heterogeneous soils [14]. After this completion of this process topographical corrections are applied.

6. Data Collection
6.1 Common offset profiling
This is the most common survey technique carried out for surface and subsurface ground GPR surveys. With the help of this method large surveys are carried out in less time and with greater efficiency. In this method, as shown in figure 3, both the sending and receiving antennas are kept at a constant distance apart and are moved over the surface simultaneously[17]. The result is in form of a data set which is presented in a 2-D profile where measured travel time to the reflectors is displayed on Y-axis while on X-axis, the distance that antenna has traveled is noted down[18]. Two types of GPR systems, monostatic and bistatic units are used to collect the common offset data.
6.2 Common Midpoint Survey:
In this survey, the transmitter and the receiver antennae are moved away from each other in such a way that the distance between them remains fixed as shown in figure 4[18]. This method is helpful in determining the electromagnetic wave velocity by relating the wave velocity to the change in time travel, as a function of increasing offsets, between the two antennae.

7. GPR Applications
Ground Penetrating Radar has vast number of implementations which are mechanics of rocks, minerals and underground water analysis, geotechnical and archeological explorations, mapping bedrock depth, variation in different types of rocks, and fractures in bedrock, soil strata and water table in coarse grained
soil [2]. In the field of archeology GPR identifies the areas with alleged buried remains, monitoring of monuments and the state of preservation of these monuments and also provides information in order to address a restoration project properly. Demining is another important application of GPR. Another field of application of GPR is industrial agriculture where it is used to devise an intelligent exploitation and distribution of water. GPR is having a special application in the field of also civil engineering particularly to locate structural damages and is also used to get information about the structures which are beneath the surface.

Some of the applications of GPR in the field of civil engineering with their advantages are discussed below:

7.1 Identification of soil stratification and bedrock depth:

The evaluation of soil stratification can be done by using the antenna which is most suitable for the required depth of investigation. The antenna with frequency between 100 and 120 MHz proves to be finest with penetrating value of 15 to 20m or even deeper than that, especially in case of unsaturated soils[1].

A survey was conducted in which it was shown that the electromagnetic waves change when they pass through different soil layers because of the change in the dielectric and electrical permittivity constants[18].

7.2 Identification of buried utilities

Identification of underground objects is a very complex process especially in built-up areas. The location and depth of various buried utilities like gas pipes, sewers, energy cables, water drainage systems etc. must be properly determined. GPR serves as the best option not only for finding the position of the buried objects but also for mapping them [19,20]. The 3D imaging, formed with the help of grids, is the effective method of identifying the utilities because in 3D scan, series of parallel B scan is formed by continuous reflections from the hyperbolas which can be easily mapped and the location of utilities can be obtained[7].

7.3 Identification of water table

GPR is amongst the most favorable geophysical methodsthat are used to estimate the percentage of water present in the soil strata and also for locating water table [21–24]. When electromagnetic waves come in contact with the water content present in the soil, a slight difference in the dielectric properties of signal due to the strong dipole moment of the water and high sensitivity of GPR wave velocity is found[25].

8. Conclusion

Ground penetrating radar is extensively used for accessing the subsurface conditions. This method is software and data based. This system contains an antenna which transmits the signal to the said surface and gets reflected back, which helps in understanding the below surface atmosphere when perfectly transformed into visual images by a trained person. GPR is considered as one of the important tool in engineering for non-destructive testing.

9. Limitations and Scope for future studies

There are some of the conditions or properties of the surface soil where GPR cannot work as expected like:
1. Saline conditions, denser medium through which signal penetration is difficult.
2. It always needs a skilled person for the application of this instrument.
3. Loss of signal may occur when micro internal reflection takes place as these are of low energy.
4. Conductivity medium is also hard for GPR to work.
5. Wet clays can partially or completely absorb the signals.
6. Materials having similar dielectric properties will be difficult to get detected by GPR.

In future if the some of the above mentioned issues get resolved, it can be considered among top geophysical methods and can get adopted for all the physical investigations in geology or geotechnical fields, so it has a wide scope for future studies.

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