GPR geophysical method as a remediation tool to determine zones of high penetration resistance of soil

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Abstract. In this study, we demonstrated application of ground penetrating radar towards assessing zones of high penetration resistance (PR) within soil horizons with a view to characterize the subsurface media. Soil attributes changes both in time and space can be difficult to understand. This may be largely due to concealing nature of subsurface media and conventional methods of soil investigations that are usually restricted to observation at the surface and discrete points. Thus making interpolations, inferences and conclusions from such methods inadequate and less reliable. However, ground penetrating radar (GPR) – a geophysical method of investigation was used in this study in lieu of the traditional methods. Soil variability measured in its PR (strength) is related to its compactness- function of bulk density. GPR utilizes electromagnetic (EM) energy in the range of 10 MHz to 3GHz that propagates through the investigative materials. Analysis of the two-way travel time of EM wave gives information about the velocity of the travelling wave. Data were acquired on a loamy silty soil at a farmland in Krakow as a test site simulated with compaction by tractor passes to induce densification of the subsurface layers. Results of the test depicted distinguishing feature of the compacted zones which is reduction in (EM) waveform amplitude and rapid decay of the EM frequency spectra. The research outcome shows swift, cheap and less cumbersome method of soil investigation.

1. Introduction

There are so many factors that contribute to variability of soil which makes the uppermost layer of the lithosphere composites mixture. These factors include all conditions, processes, time and human reworking via various activities that culminated to soil formation. According to [1], soil is formed when rocks come in contact with air, water, and organism changing them into different composition. Thus, types of soil formed are a function of the parent material which is the rock. Soil densification is largely physical consolidations by impacted forces that degrades its both macro and micro structures, lower its porosity and hence causes reduction in water and air infiltration. Consequently, it results to increase in its penetration resistance [2]. Exposure of soil to vehicular traffic load, soil water contents, texture, structure and organic constituents have been reported to constitute the major influence of compactness of soil [3]. There is no doubt that such degradations are major environmental issues to contend with particularly professionals that depends on the soil attributes for their activities. Obtaining accurate information on the variabilities of the soil for optimum utilization and management is not so easy. This may be largely due to the concealing nature of the subsurface and the convensional approaches on which soil assessment is made which is based on surface observation, core sample analysis that are all at a
point. Moreover, these approaches are time consuming, laborious, invasive and expensive making the outcome of such investigation subjective and less reliable. [4] Singh et al 2015 highlighted the need to reduce impact of traffic on soil compaction via conservative agricultural practices and removal of hardpan within soil layers. Determination of bulk density and penetration resistance of soil using the emergency and early growth of planted crops was reported by [5]. The ripple effects of wet soil compaction due to tractors on physical properties of the soil with attendant decline in the chemical properties were given in the work of [6]. The report highlighted the extent of degradations that densification of soil could cause. Sustenance soil assessment cannot be overemphasised because continuous existence of life on earth apart from water and air, depend on it. [7] opined that knowledge of soil properties is important for forecasting the physical, chemical and biological processes that caused their formation. In the present study, we attempted to circumvent some of the conventional approaches by using geophysical method of investigation. Essentially, geophysical survey methods involve the use of principle of physics to understand the material properties that constitute the subsurface. It involves use of sensors to remotely obtain data from the subsurface that are translated into information through the data inversion or by use of several interpretation means. Ground penetrating radar is a method of geophysical survey that operates on electromagnetic in the radio wave band as a source of energy. The choice was informed by it non-invasive techniques thereby allowing absolute in-situ assessment of the subsurface. Furthermore the method is fast, requires few labour and its simplicity also enhances repeated measurement which allows temporal changes assessment. Estimated physical properties such as the dielectric permittivity and the corresponding depth values from field data analysis can be used to characterise soil physical properties [8]. Different tillage practices effects on soil physical properties have been investigated using integrated geophysical methods and outcomes found that the different practises created varying degrees of impacts on the soil physical characteristics [9]. Hardpan is a portion of the soil layer with very high bulk density with correspondent high penetration resistance was mapped using GPR and results correlate with other alternative means of assessment [10]. [11] also reported the simulation of the soil compaction response to GPR signals at a particular central frequency and found a good correlation of the results with field measurements. [12] interpreted soil compacted zone with strong reflection and non-compacted zone as weak reflection using the amplitude magnitude of the EM wave form. This may be accurate but the assertion may also subjective. Hence necessitated the integrated approaches of interpretation used in this study.

The focus of this study is the remote assessment of zones of high penetration resistance within soil horizons using ground penetrating radar (GPR) with a view to its characterization and associated variability it may have influenced in the subsurface media.

2. Method of study

Brief concept of the GPR method is discussed in this section. Details are found in literatures. Readers are refer to works of [13];[14];[15];[16];[17];[18]

2.1. Ground Penetrating radar

The method utilizes EM in the radio wave band as source of energy with central frequency range between 10 MHz and 3 GHz [19]. The components of the system unit comprise of the transmitting antenna that acts as a conduit through which pulse EM energy generated by the control processing unit (CPU) is emitted into the investigative media. At the encounter of contrasting dielectric materials within the propagating media, the propagated energy experience reflection, refraction or suppression (attenuation). Then the response is sensed by the receiving antenna for onward transfer to the CPU which converts it to signal that is display by a monitor usually laptop. Schematic illustration of a GPR system is as shown in figure 1. It is worth mentioning that captured response by the receiving antenna is dependent on the reflection coefficient. This is related to the reflected energy encountered at the interface between adjacent layers that is influenced by the contrasting dielectric properties of the traversing media according to equation (1) [15].
where $\varepsilon_1$ and $\varepsilon_2$ are dielectric constant of the different layers of the media and R is reflection coefficient. Evaluation of the two-way travel time of the propagated wave with other known parameter (depth) can be used to calculate its propagation velocity.

$$R = \sqrt{\frac{(\varepsilon_2)^{1/2}-(\varepsilon_1)^{1/2}}{(\varepsilon_2)^{1/2}+(\varepsilon_1)^{1/2}}}$$

(1)

Velocity of the EM wave within any identified horizon can also be known if there is information on the dielectric permittivity of the material and is related according to equation (2) [13].

$$V = \frac{C}{\sqrt{\varepsilon}}$$

(2)

where C is the velocity of light (~0.30m/ns) and $\varepsilon$ is the dielectric constant

There are so many factors that guide the choice of antenna frequency, site conditions when it is to be deployed and input parameters for field measurements of the GPR techniques. Details are found in literature.

2.2. Field Measurement

Field data were acquired on a loamy silty soil at a farmland in Krakow simulated with compaction by tractor passes to induce densification of the subsurface layers (figure 2). The test site is relative flat which enhances equal impacted force to influence the densification sought. ProEX model- a GPR complete system unit manufactured by MALA Geoscience Inc. Sweden (now ABEM/MALA) was deployed for the measurement with antennae of central frequency 800 MHz (shielded) which was informed by the wavelength that can give a better resolution at the target depth of investigation [12].
Readings were taken in the constant offset mode after the initial set up of the system and confirmation of signal response along pre-determined transects as shown in figure 2. The control system was mounted with a bag pack while holding the display monitor and the monostatic mode antenna was pulled at a walking speed. For velocity analysis of the EM wave for the purpose of depth conversion, three points wide angle reflection and refraction (WARR) readings were also taken. Few profiles were taken and processed for interpretation and subsequent deductions. Recorded data were subjected to editing, processing and enhancements to improve signal to noise ration and increase efficient interpretation. With the aid of the REFLEXW software developed by Sandmeier Inc, Germany, the following processing steps were carefully performed on the field data. Time zero correction was performed to give the start time specified in the file header of the recorded data [20] otherwise, depth estimate may be inaccurate. Processing that enhances signal-to noise ratio includes: Dewow- a filtering technique that suppresses the low frequency; Subtract DC-shift filter enhances proper alignment of the signal shift from the central axis due to equipment; Background removal- a 2D filtering process removes the elements of common environment to show clearly the anomaly present ; Time gain was also performed on the data to boost the energy of the signal that may have been attenuated with time as it travels deeper into the subsurface. Some penetration resistance values using penetrometer with the GPR transects were also taken for correlation with the GPR readings.

Non-stationary nature of the GPR EM wave allows its signals to have varying frequency components with time and hence makes the characterization of the embedded features of the signals’ locations and in the time frame usually unknown [21]; [22] Moreover, determination of the source of signal spectra from field data is hard due to interruptions of noise [23]. Therefore to minimise ambiguities that may arise from interpreting the data only in the time domain in which it was recorded, attribute computation that may aid subtle features delineation [24] and spectra estimations of the processed data were performed for the analysis of the frequency spectra components of the recorded signals.

3. Results

Results of the field data are presented in this section. Recorded data are presented in section (radagrams) which is the plot of the signal amplitude variations against the two-way travel time of the wave. Spectral estimations via decomposition are also presented in 2D and curves while the PR values were also plotted against trace amplitude values.

3.1. Ground penetrating radar (Radagram)

Compaction induced by the traffics are observable on the radagram (broken white cycles figure 3) showing the degree of effects with variation in depth. There is lateral discontinuity along the horizons within the subsurface materials pointing to distortion in the matrix of its composition. Thus resulting in
differential polarization effects as the GPR EM propagates across the investigating layers of the subsurface.

![Figure 3. A transect Radargram across the traffic zones](image)

Furthermore, penetration resistance values taken were plotted and correlates with the GPR trace amplitude reading (figure 4). Noticeable trend occurred in the two approaches. High penetrations resistance values shows reduction in amplitude on the GPR trace (figures 5 (a) and (b)) from depth of about 0.135m suggesting refraction occurrence in the EM wave as it encountered compacted zone perhaps due to the change in dielectric properties. The sudden change in the dielectric properties of the traffic zone may have caused the decline in the amplitude.

![Figure 4. Correlation of (a) Penetration resistance value and (b) GPR trace amplitude](image)

3.2. Spectral analysis results
Spectral analysis of the decomposition of signal at both the traffic zone and non-traffic enhances further the interpretation of the inherent distinguishing pattern at both scenarios. There is a visible significant decay of peak magnitude of the high frequency spectral at the traffic zone (figure 5a) but evolved over
a long time in the non-traffic zone (figure 5b) suggesting discrepancy in dielectric properties which gave rise to the signals. It can be inferred that the differential moisture contents at both the traffic and non-traffic zone which is influenced by the available void fractions may have been altered at the traffic zone causing its reduction. Moreover the amplitude magnitudes decreases sharply in the traffic zone than the non-traffic zone.

Figure 5. Time Frequency plot (a) Non-traffic zone and (b) Non-traffic zone

Power spectral density (PSD) is an estimation of signal's power content versus frequency. In a way, it is a means of characterizing the signal based on the average power of the signal sinusoid frequencies components variations. It actually describes the power present in a signal as a function of frequency, per unit frequency [25]. Estimated PSD for both the traffic and non-traffic zones is shown in figure 6.

Figure 6. PSD at both traffic and non-traffic zones

There are obvious significant reductions at the peaks of the spectral at the traffic zones compared with the non-traffic zone pointing to possible compactness of the zone which influences the interaction of the EM wave as it propagates within the subsurface media. The peaks also shift towards the lower frequency in the non-traffic (1.1GHz and 2.6MHz) than the traffic zone (1.25MHz and 2.9MHz) which may also point to the media constituent influence such as water. It is also worth to note that the spectrum bandwidth of the non-traffic zone reduces than traffic zone suggesting also variation in the water
contents. Frequency spectrum bandwidth of GPR diminishes while water contents increases [26](Rodés et al 2015).

**4. Conclusion**

Ground penetrating radar has been deployed for the assessment of soil strength variation at a test site based on certain attributes that make it a unique geophysical method that can complement soil investigations. Some of these attributes include non-invasiveness, fast, less labour intensive and continuous scanning of the traverse paths circumventing conventional methods point data interpolation. Zones of high penetration resistance are characterised by distortion in the waveform of the EM source of energy resulting in lower amplitude of the signals. The reduction in the signal amplitude is thought to be influenced by the alterations of the microstructures of soil horizons at the traffic zones which apparently control the volume fraction of fluid present. It was also found that region of high penetration resistance trends with lower signal amplitude values suggesting possible decline in the polarization potential of the zone which could be attributed to collapse in the soil matrix of the traffic zone.

We conclude that zones of high penetration resistance could be discerned from GPR scanning data and by extension, pockets of indurated (hardpan) zones which represent impervious layers within the soil layers may also be delineated. The non-invasiveness and swiftness makes this approach of soil investigation both alternative and complement to the traditional soil assessment methods.

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**References**

[1] Weil R R and Brady N C 2017 *The nature and properties of soils* Pearson Education Limited 52-99
[2] Wolkowski R and Lowery B 2008 *Soil compaction, causes, concerns and cures* University of Wisconsin-Extension
[3] Nawaz M F, Bourrie G, and Trolard F, 2013 *Agrono. for sus. Develop.* 33 291
[4] Singh J, Salaria A and Kaul, A, 2015 *Inter. J. of F. Agric. Vet. Sciences*, 5 23
[5] Mamman E, Ohu, J O and Crowther T 2007 *Inter. Agrophy.* 21 367
[6] Kuht J and Reintam E 2004 *Agrono. Resear.*, 2 187
[7] Bieganowski A, Witkowska-Walczac B, Glinski, J, Sokolowska Z, Slawinski C, Brzezinska M and Włodarczyk T 2013 *Inter. Agrophy.* 27 3
[8] Jonard F, Mahmouzadeh M, Roisin C, Weihermüller L, André, F, Minet, J, Vereecken, H and Lambot, S, 2013 *Geoderma* 207, 310
[9] Raper R L, Asmussen LE, and Powell J B 1990 *Transactions of the ASAE*, 33 41-0046
[10] André F, van Leeuwen C, Saussez S, Van Durmen R, Bogaert P, Moghadas D, de Rességuier L, Delvaux B, Vereecken H and Lambot S 2012 *J. of App. Geophy.* 78 113
[11] Akinsunmade A, Karczewski J, Pysz P, Tomecka-Suchoń S, and Uhl T 2019 *In IFToMM World Congress on Mechanism and Machine Science* 3741 Springer, Cham
[12] Annan P, 2003 *Sensors and software*, 278
[13] Annan A P, 2005 *In Hydrogeophysics* 185 Springer, Dordrecht
[14] Daniels D J 2004 *The Institution of Electrical Engineers, London*
[15] Jol H M, 2008 *Ground penetrating radar theory and applications* Elsevier
[16] Everett M E 2013 *Near-surface applied geophysics.* Cambridge University Press
[17] Utsi E C 2017 *Ground penetrating radar: theory and practice* Butterworth-Heinemann
[18] Forte E, Dossi M, Pipan M and Colucci R R2014 *Geophysical Journal International* 197 1471
[19] Sandmeier K J, 2012, *Reflexw version 7.0 software program manual*
[20] Ofuyah W, Orji O and Eze S 2015 *Geosciences* 5 86
[21] Othman A A, Fathy M and Maher A 2016 *Egyptian J. of Petrole.* **25** 45
[22] Bradford, J H, 2007 *Geophysics,* **72** J7-16
[23] Akinsunmade A, Tomecka-Suchon S and Pysz P 2019 *Geol. Geophy. and Environ.* **45** 257
[24] Jonard F, Bogena H, Caterina D, Gare S, Klotzsche A, Monerris A, Schwank M, and von Hebel C, 2018 *Observation and Measurement, Ecohydrology.* Springer-Verlag Berlin Heidelberg
[25] Maral, G., 2003. *VSAT Networks,* John Wiley & Sons
[26] Rodés J P, Perez-Gracia V and Martinez-Reguero A 2015 *Construction and Building Materials* **96** 181- 88