

Remote Sensing of Land

Editor-in-Chief: **Dr. Suresh Kumar**

EISSN: 2582-3019

DOI: <https://doi.org/10.21523/gcj1>

Applicability of Ground Penetrating Radar for Soil Profile Studies – An Investigation in Piedmont Plain in Parts of Saharanpur District, Uttar Pradesh

Justin George Kalambukattu^{1*}, Suresh Kumar²

1. Agriculture and Soils Department, Indian Institute of Remote Sensing, Indian Space Research Organisation, Dehradun, Uttarakhand, India - 248001.
2. Agriculture, Forestry and Ecology Group, Indian Institute of Remote Sensing, Indian Space Research Organisation, Dehradun, Uttarakhand, India - 248001.

To cite this article

Kalambukattu, J. G. and Kumar, S., 2024. Applicability of Ground Penetrating Radar for Soil Profile Studies -An Investigation in Piedmont Plain in Parts of Saharanpur District, Uttar Pradesh. *Remote Sensing of Land*, 8(1), 22-29.

DOI: <https://doi.org/10.21523/gcj1.2024080102>

TERMS AND CODITIONS FOR THE ARTICLE

Please visit this link for full terms and conditions for use of this article:

https://gathacognition.com/site/term_condition/term-condition

This article may be used for academic purposes including research, teaching and private studies.

However, any reproduction, redistribution, reselling, loan, other licening, etc. in any form are forbidden.



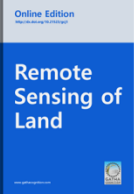
GATHA COGNITION

<https://gathacognition.com>



Remote Sensing of Land

Homepage: www.gathacognition.com/journal/gcj1
<http://dx.doi.org/10.21523/gcj1>



Original Research Paper

Applicability of Ground Penetrating Radar for Soil Profile Studies – An Investigation in Piedmont Plain in Parts of Saharanpur District, Uttar Pradesh



Justin George Kalambukattu^{1*}, Suresh Kumar²

1. Agriculture and Soils Department, Indian Institute of Remote Sensing, Indian Space Research Organization, Dehradun, Uttarakhand, India - 248001.
2. Agriculture, Forestry and Ecology Group, Indian Institute of Remote Sensing, Indian Space Research Organization, Dehradun, Uttarakhand, India - 248001.

Abstract

Soil profile studies especially identification of different soil layers is a vital component in soil survey. The present study was undertaken to assess the applicability of ground penetrating radar (GPR), a widely adopted geophysical technique and instrument for soil profile studies under different landforms (piedmont and alluvial plain) located in the Indo-Gangetic Plain region in Saharanpur district of Uttar Pradesh. GPR survey was conducted using dual frequency antennas (200 and 600 Mhz) at specific locations corresponding to landforms of piedmont and alluvial plain along transect. The radargrams generated by standard processing of ground scan data showed widely varying patterns in both the landforms, corresponding to the variations in soil layer distribution. From the radargrams generated, a clear distinction could be made between the soils of piedmont as well as alluvial plain. The radargram of alluvial plain showed very smooth transition between soil layers whereas in case of piedmont plain, the profile appears to be discontinuous as well as irregular. The soils of alluvial plain showed clear/distinct soil layer distribution till nearly 75cm depth in contrast to the piedmont soils which exhibited parabola patterns in radargram indicating the presence of stones/boulders within very short depth from the surface. The results regarding identification of contrasting soil layers using GPR were validated and found to be in agreement with standard soil profile information of the sampling sites in different landforms. GPR being a non-destructive technique could help in acquiring large number of such observations in much lesser time providing vital information for land use planning as well as soil mapping activities.

© 2024 GATHA COGNITION® All rights reserved

Article History

Received: 06 July 2023
 Revised: 25 January 2024
 Accepted: 27 January 2024

Keywords

Alluvial Plain;
 GPR;
 Piedmont;
 Radargram;
 Soil Layers;
 Soil Profile;
 Texture.

Editor(s)

K. V. Suryabagavan

1 INTRODUCTION

Ground penetrating radar (GPR) is a useful geophysical instrument and technique to identify various geological features (Ercoli *et al.*, 2013; Imposa *et al.*, 2015), lithological contacts (Pratt and Miall, 1993; Bristow and Jol, 2003), fault identification (Gross *et al.*, 2004; Arora *et al.*, 2019; Kannaujiya *et al.* 2021), soil studies (Doolittle and Collins, 1995; Gómez-Ortiz *et al.*, 2010), groundwater depth estimation (Menezes Travassos and Luiz Menezes, 2004; Doolittle *et al.*, 2006) etc. Several

studies have used GPR to characterize various aspects of soils, including soil horizon/layer detection/stratigraphy (Nováková *et al.*, 2013; Simeoni *et al.*, 2009; Zhang *et al.*, 2014), assessing variations in soil clay content (Gómez-Ortiz, 2010; Tosti *et al.*, 2013), compaction (Freeland *et al.*, 2008; Muñoz *et al.*, 2016), soil moisture content (Huisman *et al.*, 2003; Grote *et al.*, 2010), determining depth to subsurface horizons, peat stratigraphy (Plado *et al.*, 2011; Sass *et al.*, 2010) etc.

* Author address for correspondence

Agriculture and Soils Department, Indian Institute of Remote Sensing, Indian Space Research Organization, Dehradun, Uttarakhand, India - 248001.

Tel.: +91 8171291318

Emails justinagri@gmail.com (J. G. Kalambukattu -Corresponding author), suresh_kumar@iirs.gov.in (S. Kumar).

<https://doi.org/10.21523/gcj1.2024080102>

© 2024 GATHA COGNITION® All rights reserved

A much detailed review of GPR based methods applied in soil studies has been given by Zajčová and Chuman (2019). GPR application predominantly depends on variations in electrical impedance of the media being studied. The electrical impedance is mainly determined by dielectric and conductive properties, magnetic permeability, as well as the physical properties of the material (Daniels, 2004). For most soils in natural environment, variations in water content is the major factor influencing GPR reflections, as the dielectric constant of water is around 80 while the value is between 3 and 5 in case of dry soil (Topp *et al.*, 1980). Such wide variation between the values of water and dry soil assist in detecting the changes in GPR signals corresponding to water content variations, mainly at the boundaries of various soil layers resulting in moisture distribution which is highly contrasting. The GPR based studies helps in rapid and inexpensive collection of large amount of georeferenced data, which aids in detailed characterization of the spatial soil property variations in comparison to conventional sampling techniques. GPR technique was employed for mapping the distribution of limiting soil layer, which helped to understand the pathway of subsurface flow, by combining with soil moisture data (Gish *et al.*, 2002). GPR was used to identify subsurface layer with known depth and used this information to estimate soil moisture content with considerable accuracy in comparison to conventional techniques such as TDR and neutron probe (Lunt *et al.*, 2005).

GPR sent short pulses of electromagnetic waves/signals from a transmitter (with frequencies ranging from 25 Mhz-600 Mhz), enters to the ground and comes in contact with different soil horizons, objects/bodies or subsurface strata having variations in electrical conductivity, magnetic permeability as well as dielectric constant values. A part of this transmitted energy gets reflected back and is recorded by a receiver antenna of the GPR, whereas the residual energy continues to travel into the deeper layers of the ground and gets reflected further, until it finally scatters and dissipates with depth. Depth of penetration and vertical resolution is dependent on soil conditions, input signal characteristics (especially frequency) as well as configuration of the transmitter-receiver assembly. When the attenuation of EM waves is high due to less resistive subsurface features (substances with high dielectric constant) then penetration depth decreases while the more resistive subsurface features allows less attenuation and hence EM waves can penetrate more deeper. EM waves with high frequency generally have high resolution with less penetration depth while the low frequency waves shows more penetration with lower resolutions (Rial *et al.*, 2007). The more conductive subsurface causes quick conversion of electromagnetic energy into heat hence less signal strength at depth.

The propagation of EM waves during a GPR survey is measured as per the equation:

$$v = \frac{c}{\sqrt{\epsilon}} \quad (1)$$

where v = propagation velocity of wave in medium, c = velocity of EM wave in vacuum (3×10^8 m/s) and ϵ = dielectric constant (relative permittivity) of the medium. The dielectric constant relates the ability of a material to carry alternating current to that of vacuum. It not only determines the velocity of EM waves but also governs the reflection characteristics of the boundaries according to the equation

$$r = \frac{\sqrt{\epsilon_U} - \sqrt{\epsilon_L}}{\sqrt{\epsilon_U} + \sqrt{\epsilon_L}} \quad (2)$$

where, r = Reflection coefficient, wave propagating from media (U) to (L), ϵ_U and ϵ_L are the dielectric constants of the respective media (i.e., upper and lower soil layers). R value > 0 , indicates a difference in dielectric property between the two media and results in reflection of waves at the interface (Venkateswarlu and Tewari, 2014). i.e., the strength of GPR reflection is a function of the contrast in dielectric constant across a reflecting boundary. These reflections or refractions are recorded by the receiver and the series of signals received during this continuous process results in soil subsurface profile sections. Reflection coefficient, indicating the contrast between two adjacent layers, has a range between 1 to -1. Positive sign indicates a higher dielectric constant in the upper soil horizon and negative sign indicates a lower dielectric constant in the upper horizon. A higher absolute value of reflection coefficient indicates a higher contrast between two adjacent soil layers and an easier detection of the interface by GPR. This helps in better identification of subsurface horizons.

The GPR helps in identification of different soil layers due to change in dielectric constant, which can be attributed mainly to the textural variations. The time delay gives depth information, whereas the amplitude (measured in volts) gives dielectric property if changes are there in layer composition and the resultant electrical properties. However no such work has been reported from India regarding the use of GPR for soil survey related studies. Therefore, the present study was undertaken to assess the applicability of GPR for soil profile studies under different landforms in piedmont plain (foot hills) and alluvial plains.

2 MATERIALS AND METHODS

2.1 Study Area

The study was conducted in part of Saharanpur district of UP, which falls in the Indo-Gangetic Plain. A transect comprising piedmont regions lying in the foothills of outer Shivalik hills and alluvial plains near Saharanpur was chosen for conducting the study. The sampling locations pertaining to piedmont plain and alluvial plain are located in two different sub-districts/tehsils of Saharanpur district. GPR survey as well as soil profile location corresponding to piedmont plain (PP) and alluvial plain (AP) regions were located in the Behat

tehsil as well as Saharanpur tehsils, respectively (Figure 1). The area lies in between latitudes $29^{\circ}58'57.91''$ to $30^{\circ}18'52.039''$ and longitudes $77^{\circ}27'51.064''$ to $77^{\circ}50'3.152''$, with elevation values varying between 216 to 367 metres. The case study areas (piedmont plain and alluvial plain) were identified on the basis of their representativeness of different geomorphic units, exhibiting contrasting soils having specific pedogenic processes and specific land use types. The sites showed uniformity with respect to landform/slope/land use characteristics. The sites were also selected based on their undisturbed nature as well as accessibility characteristics.

The piedmont plain represents the soils formed mainly due to colluvial processes and are characterized by increased amount of coarse fragments. This results in predominantly drier soils for most part of the year, resulting in the adoption of rainfed agricultural practices with most areas following maize-wheat cropping system. Similarly, significant amount of area is under

orchards of various fruits like mango, guava, litchi, etc. especially towards the foothills and higher elevation regions of piedmont plain. Whereas, the alluvial plain represents the soils mainly formed by depositions associated with alluvial processes. These areas are characterized by increased amount of clay constituents, resulting in soils remaining moist during most part of the year. The increased water availability also facilitates the adoption of irrigated agriculture, with adoption of rice-wheat cropping system as well as widespread cultivation of sugarcane crop in the area. The exact locations for GPR survey within the two landform types (PP and AP) were determined based on the availability of detailed soil survey information of the area. Detailed soil survey report along with profile descriptions and horizon wise physicochemical analysis results of the area generated by the authors few years ago was used to select typical soil profiles representing the distinct landforms and land use types in the area, for conducting GPR survey.

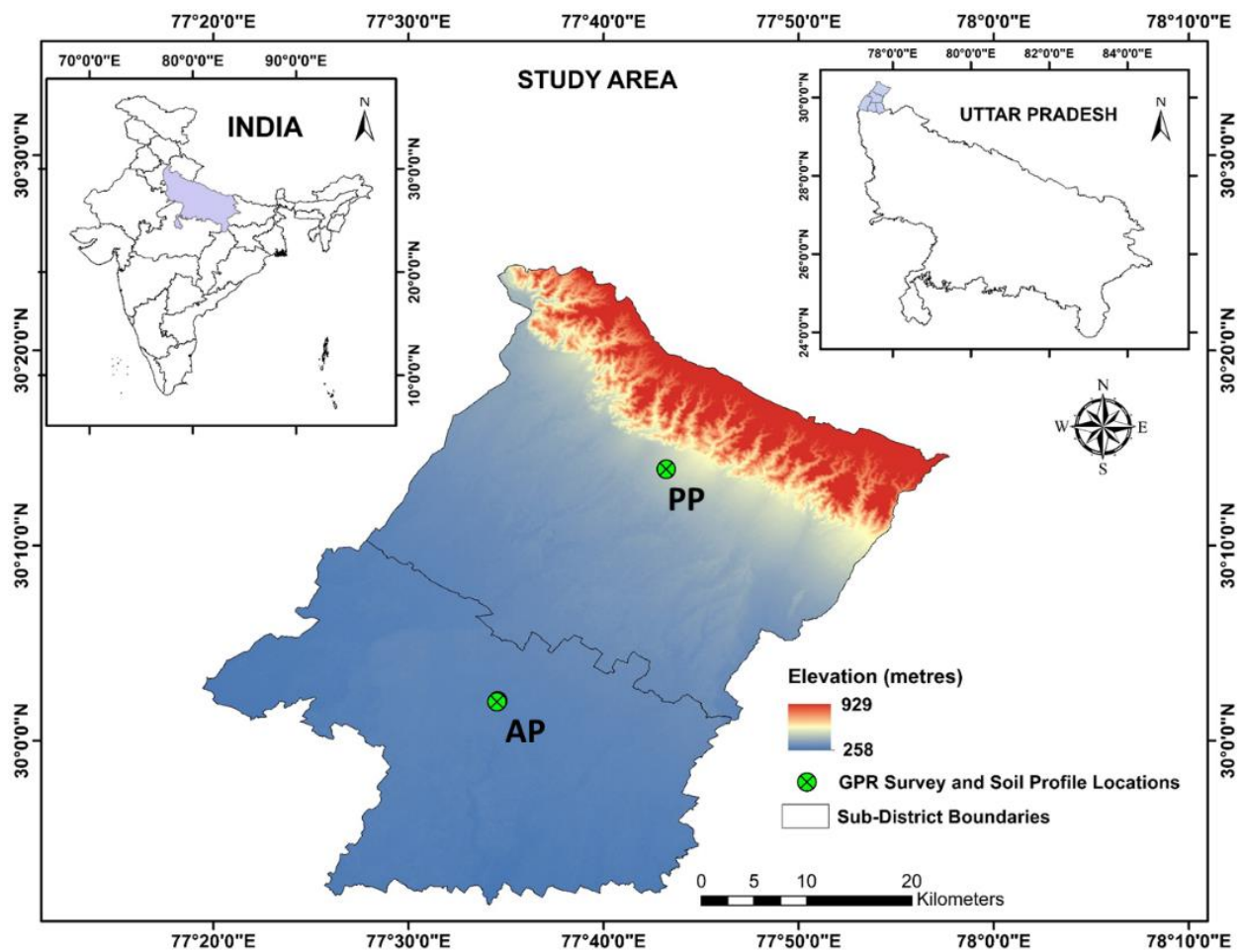


Figure 1. Location map of the study area: Piedmont plain (PP) and Alluvial plain (AP) study locations overlaid on elevation variation and sub-district boundaries. Position of Uttar Pradesh within the Indian subcontinent and Saharanpur within the Uttar Pradesh state is indicated in the inset maps. (Source: Elevation data from SRTM DEM)

2.2 Field Data Collection

GPR survey was conducted at specific locations corresponding to landforms of piedmont and alluvial plain along the transect (Figure 1). The selection of survey locations was done as discussed in the previous section. The overall methodology adopted in the study is depicted in Figure 2.

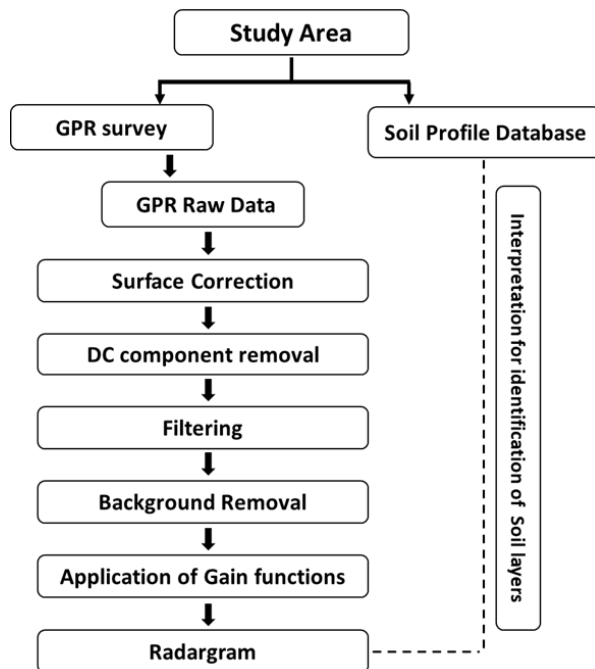


Figure 2. Overall methodology

The GPR survey locations representing the respective landforms as decided based on previous soil survey records were visited for GPR data collection and correlated with soil profile data. Recently irrigated, wet or waterlogged fields were excluded from GPR survey to avoid excess signal attenuation which may adversely affect the objectives of the study. Care was taken to choose fields/areas with considerable uninterrupted length to get sufficient linear distance for GPR measurement. GPR survey for obtaining soil profile information was carried out using IDS RIS plus system equipped with dual frequency (200 and 600 MHz) antennas (Figure 3a) and GRED 3D viewer during February 2016. The transmitter-receiver antenna assembly was slide on the ground surface along the pre-decided measuring line in the field (Figure 3b). The EM wave pulses were continuously recorded by the receiver antenna along the scanning distance resulting in the generation of subsurface soil profile.

2.3 GPR Data Processing

The field collected GPR scan data was processed using GRED HD software, which is widely used for GPR High Definition Data Post Processing. The raw data collected during field scans comprised of two data files for each location corresponding to the two different frequency antennas. Among these two, the higher frequency (600MHz) antenna has less penetration depth

and thus provides us with more resolution. So we processed the data generated using 600 MHz frequency only. The methodological steps adopted for the generation of radargram as well as interpretation for identification of different soil layers is given in Figure 2. The various processing steps finally yielded a radargram showing the amplitude of radar signals caused due to reflection from soil particles and their variations.

3 RESULTS AND DISCUSSION

The radargrams obtained from the two landforms showed widely varying patterns, corresponding to the variations in soil layer distribution (Figure 4). From the radargrams generated, a clear distinction could be made between the soils of piedmont as well as alluvial plain. The radargram of alluvial plain (Figure 4b) showed very smooth transition between soil layers whereas in case of piedmont plain (Figure 4a) the profile appears to be discontinuous as well as irregular. The soils of alluvial plain showed clear/distinct soil layer distribution till nearly 75cm depth indicated by smooth horizontal lines and further the signal strength got minimized mainly due to the presence of increased moisture content. Whereas in case of piedmont soils, the radargram showed irregular patterns where smooth layers were observed near to the surface (up to about 20cm) layer. Beyond the surface layers, parabola patterns are visible which indicates the presence of stones/boulders after shallow depth from the surface.

The presence of coarse fragments (granules/boulders) causes the EM waves to reflect from surface without any penetration and results in the generation of parabola features in the radargram. In piedmont, the chances of occurrence of coarse fragments within very shallow depths are quite common due to the various geological and erosive processes of colluvial action. Whereas the alluvial plain is mainly a flood plain, where the finer material are deposited by action of flowing water. In piedmont plain the signal attenuation was observed at increased depths mainly after 1.5m, whereas in case of alluvial plain the attenuation starts approximately at 60 cm. This is attributed to the higher moisture content in soil profiles of alluvial plain starting from a depth of 75cm, due to compact arrangement of much finer soil particles. In case of piedmont plain soil profiles, the particles are much coarser in comparison to alluvial plains and also the presence of large number of coarse fragments/stones causes increased percolation as well as drainage into much deeper layers.

The results regarding contrasting soil layers identified using GPR were compared/validated with standard soil profile information of the sampling sites in different landforms of the area (Table 1). First, we selected the largest peaks in the radargrams to identify the boundaries of layers. In case of alluvial plain three distinct layers were identified from radargram namely A_p , A_1 and B layers corresponding to depth intervals of

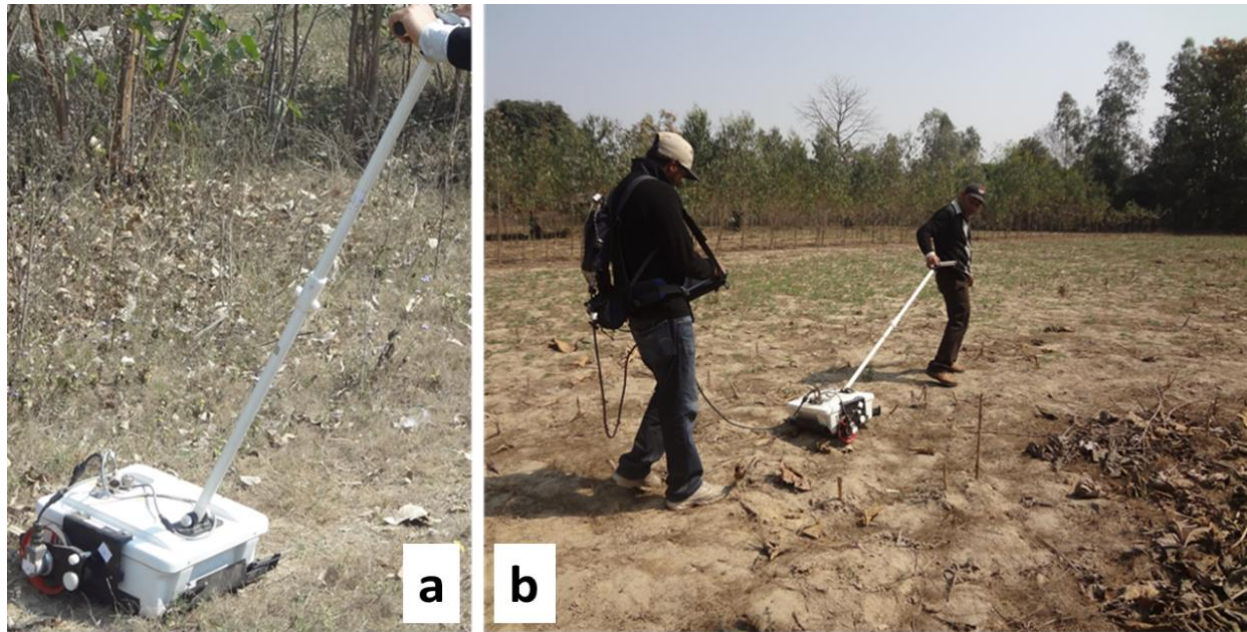


Figure 3. Photographs showing (a), GPR instrument (b) field data collection during GPR survey

Table 1. Soil profile information of sampling sites in different landforms

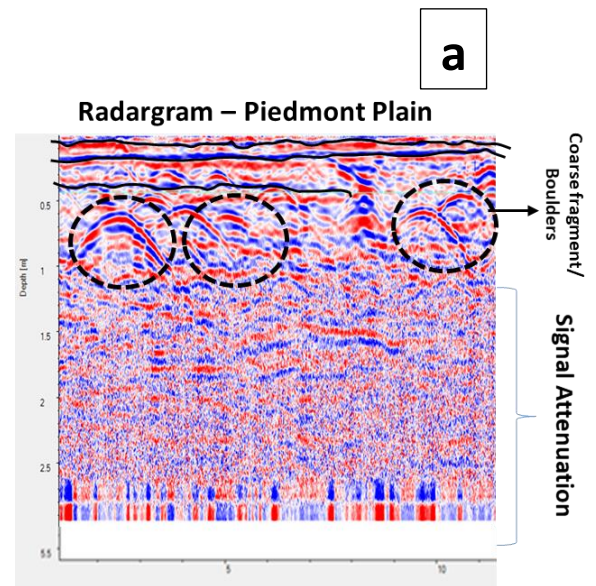
Horizon	Soil depth	O.C*	Sand (%)	Silt (%)	Clay (%)	Texture	Coarse fragments (%)
Alluvial Plain							
A _p	00-21	0.6	39.2	46	14.8	Loam	Nil
A ₁	21-32	0.15	35.2	38	26.8	Loam	Nil
AB	32-66	0.6	32.2	28	39.8	Clay loam	Nil
B	66-90	0.37	35.2	26	38.8	Clay loam	Nil
C	90-140	0.15	49.2	26	24.8	Sandy clay loam	<5
Piedmont Plain							
A _p	00-10	0.37	67.2	22	10.8	Sandy loam	5 - 10
A ₁	10-28	0.07	55.2	32	12.8	Sandy loam	15-20
A ₂	28-58	0.06	52.2	35	12.8	Sandy loam	30-40
AC	58-88	0.06	47.2	40	12.8	Loam	50 - 60
C	88-148	0.3	42.2	44	14.8	Loam	60-70

*Organic carbon (%), A_p- ploughed A horizon, AB- transition horizon between A and B with predominance of A, B- subsoil mineral horizon, C- Parent material, AC- transition horizon between A and C with predominance of C

0-15, 15-28 and 28-45, respectively. The soil profile of the same area revealed the presence of similar layers at depth intervals of 0-21, 21-32 as well as 32-66, respectively. The textural information of these layers also revealed significant variations in clay content ranging 14.8% in A_p, 26.8% in A₁ and 39.8% in B₁ layers.

The textural class of A_p as well as A₁ were found to be loam (l), whereas B₁ belonged to clay loam (cl). The increased signal attenuation beyond 60cm may be attributed to the higher moisture content associated with higher clay content (39.8%) as evident from the soil profile description.

Horizon	Depth	Description
A _p	0-10	10YR 4/3 (dry), sandy loam, weak very fine sub angular blocky, very friable consistence, common medium pores, common fine roots, no effervescence, gradual smooth boundary, , 5-10% coarse fragments.
A ₁	10-28	10YR 4/3 (dry), sandy loam, weak very fine sub angular blocky, very friable consistence, common very fine pores, few fine roots, no effervescence, gradual smooth boundary, 15-20% coarse fragments.
A ₂	28-58	10YR 5/3 (dry), sandy loam, weak very fine sub angular blocky, very friable consistence, common very fine pores, few fine mottles, very few fine roots, no effervescence, and clear smooth boundary, 30-40 % coarse fragments.
AC	58-88	10 YR 6/2 (dry), loam, single grain, very friable consistence, common medium pores, no roots, no effervescence, clear smooth boundary, 50-60% coarse fragments.
C	88-148	10 YR 6/4 (dry), loam, single grain, very friable consistence, common medium pores, no roots, no effervescence, gradual boundary, 60-70% coarse fragments.



Horizon	Depth	Description
A _p	0 - 21	10YR 5/4(dry), loamy, moderate medium to sub angular blocky, hard firm to slightly plastic consistence, common medium pores, common moderate roots, no effervescence, clear smooth boundary, no coarse fragments
A ₁	21 - 32	10YR 6/4 (dry), loamy, moderate medium to sub angular blocky, slightly hard friable and no plastic consistence, common fine pores, coarse medium roots, no effervescence, clear smooth boundary, no coarse fragments.
AB	32 - 66	10YR 5/4 (dry), clay loam, strong coarse angular blocky, firm consistence, few fine pores, few fine mottles, common coarse roots, no effervescence, and clear smooth boundary, no coarse fragments.
B	66 - 90	10 YR 5/2 (dry), clay loam, moderate medium sub angular blocky, firm slightly plastic consistence, few fine pores, no roots, no effervescence, clear smooth boundary, no coarse fragments.
C	90 -140	10 YR 5/4 (dry), sandy clay loam, weak medium sub angular blocky, firm slightly plastic consistence, few fine pores, no roots, no effervescence, gradual boundary, < 5% coarse fragments.

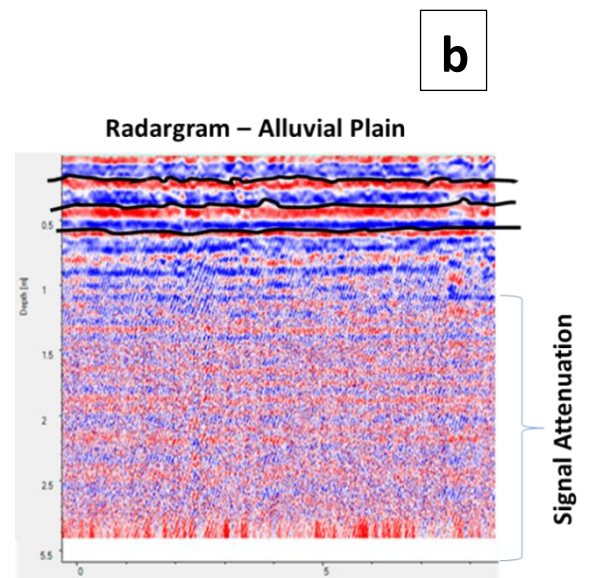


Figure 4. Radargram showing soil layer distribution at different landforms Piedmont plain (a) and Alluvial plain (b) along with the soil profile descriptions of the corresponding survey site.

4 CONCLUSION

The GPR being a non-destructive technique provides us valuable information regarding the presence or absence of boulders, depth of its occurrence, etc. thus helps in differentiation of various landforms such as piedmonts/foothills as well as a flood plains/alluvial landforms. The technique could be useful for detailed soil mapping in small areas at very detailed scale such as 1:5000, where the main focus will be on assessing soil depth characteristics for detailed planning. The approach could be very beneficial for commercial farm layout planning where plots for different crops needs to be prepared taking into account the soil depth as well as crop rooting/growth characteristics. This being a non-destructive technique could be much useful in various land use planning activities. This technique can play significant role in establishing and confirming various landform units. GPR could be used as a tool for establishing/mapping areas of soil series which normally requires checking the series boundaries by observing soil profile/pits at close intervals. GPR, due to its non-destructive nature could help in taking higher number of such observations at close intervals in the field, at comparatively much lesser time and cost.

Even though, GPR technique was found to be useful for identification of soil layers as well as coarse fragments in the present study, the technique has got certain limitations too. The applicability of this technique in heavy textured clayey soils is limited, owing to the increased attenuation of GPR signals. The presence of high moisture contents in soils also decrease the depth of signal penetration, thus affecting the wide spread applicability of this technique. Hence the moisture content /irrigation status of the area needs to be seriously considered before conducting GPR surveys for collection of soil information. Similarly, presence of hard impermeable layers as well as larger boulders/stones results in the scattering and dissipation of signals thus reducing the overall penetration depth as well as resolution.

ABBREVIATIONS

AP: Alluvial plain; **EM:** Electromagnetic; **GPR:** Ground Penetrating Radar; **PP:** Piedmont Plain; **SRTM:** Shuttle Radar Topography Mission; **TDR:** Time Domain Reflectometry; **UP:** Uttar Pradesh.

ACKNOWLEDGEMENTS

The authors sincerely thank Indian Space Research Organization (ISRO) for providing financial support under "Technology Development Plan" project. Authors place their sincere gratitude to all the anonymous reviewers for their valuable comments and suggestions that improved the quality of this manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Arora, S., Malik, J. N. and Sahoo, S., 2019. Paleoseismic evidence of a major earthquake event (s) along the hinterland faults: Pinjore Garden Fault (PGF) and Jhajra Fault (JF) in northwest Himalaya, India. *Tectonophysics* 757, 108-122. DOI: <https://doi.org/10.1016/j.tecto.2019.01.001>
- Bristow, C. S. and Jol, H. M., 2003. Ground penetrating radar: Applications in sediments. *211 Geol. Soc. London Sp. Pub.*, 338.
- Gómez-Ortiz, D., Martín-Crespo, T., Martín-Velázquez, S., Martínez-Pagán, P., Higuera, H., and Manzano, M., 2010. Application of ground penetrating radar (GPR) to delineate clay layers in wetlands- A case study in the Soto Grande and Soto Chico watercourses, Doñana (SW Spain). *Journal of Applied Geophysics*, 72(2), 107-113. DOI: <https://doi.org/10.1016/j.jappgeo.2010.07.007>
- Daniels, D. J., 2004. Ground Penetrating Radar, Ed. 2nd, The Institute of Electrical Engineers, London, United Kingdom. DOI: <https://doi.org/10.1049/PBRA015E>
- Doolittle, J. A. and Collins, M. E., 1995. Use of soil information to determine application of ground penetrating radar. *Journal of Applied Geophysics* 33, 101-108. DOI: [https://doi.org/10.1016/0926-9851\(95\)90033-0](https://doi.org/10.1016/0926-9851(95)90033-0)
- Doolittle, J. A., Jenkinson, B., Hopkins, D., Ulmer, M. and Tuttle, W., 2006. Hydrogeological investigations with ground-penetrating radar (GPR): Estimating water table depths and local ground-water flow pattern in areas of coarse-textured soils. *Geoderma* 131, 317-329. DOI: <https://doi.org/10.1016/j.geoderma.2005.03.027>
- Ercoli, M., Pauselli, C., Frigeri, A., Forte, E. and Federico, C., 2013. Geophysical paleoseismology through high resolution GPR data: a case of shallow faulting imaging in Central Italy. *J. Appl. Geophys.* 90, 27-40. DOI: <https://doi.org/10.1016/j.jappgeo.2012.12.001>
- Freeland, R., Sorochan, J., Goddard, M. and McElroy, S., 2008. Using ground-penetrating radar to evaluate soil compaction of Athletic Turfgrass fields. *Applied Engineering in Agriculture*. 24, 509-514. DOI: <https://doi.org/10.13031/2013.25136>
- Gish, T. J., Dualaney, W. P., Kung, K.-J. S., Daughtry, C. S. T., Doolittle, J. A. and Miller, P. T., 2002. Evaluating use of ground-penetrating radar for identifying subsurface flow. *Soil Sci. Soc. Am. J.* 66, 1620-1629. DOI: <https://doi.org/10.2136/sssaj2002.1620>
- Gross, R., Green, A. G., Horstmeier, H. and Begg, J. H., 2004. Location and geometry of the Wellington Fault (New Zealand) defined by detailed three-dimensional georadar data. *Journal of Geophysical Research* 109, B05401. DOI: <https://doi.org/10.1029/2003JB002615>
- Grote, K., Crist, T. and Nickel, C., 2010. Experimental estimation of the GPR groundwave sampling depth. *Water Resour. Res.*, 46, W10520. DOI: <https://doi.org/10.1029/2009WR008403>
- Huisman, J. A., Hubbard, S. S., Redman, J. D. and Annan, A. P., 2003. Measuring soil water content with ground penetrating radar a review. *Vadose Zone J.* 2, 476-491. DOI: <https://doi.org/10.2136/vzj2003.4760>
- Imposa, S., De Guidi, G., Grassi, S., Scudero, S., Barreca, G., Patti, G. and Boso, D., 2015. Applying geophysical

- techniques to investigate a segment of a creeping fault in the urban area of San Gregorio di Catania, southern flank of Mt. Etna (Sicily-Italy). *J. Appl. Geophys.* 123, 153-163. DOI: <https://doi.org/10.1016/j.jappgeo.2015.10.008>
- Kannaujya, S., Philip, G., Champati Ray, P. K. and Pal, S. K. 2021. Integrated geophysical techniques for subsurface imaging of active deformation across the himalayan frontal thrust in Singhauli, Kala Amb, India. *Quaternary International*, 575-576, 72-84. DOI: <https://doi.org/10.1016/j.quaint.2020.05.003>
- Lunt, I. A., Hubbard, S. S. and Rubin, Y., 2005. Soil moisture content estimation using ground penetrating radar reflection data. *J. Hydrol.* 307, 254-269. DOI: <https://doi.org/10.1016/j.jhydrol.2004.10.014>
- Menezes Travassos, J. and Luiz Menezes, P., 2004. GPR exploration for groundwater in a crystalline rock terrain. *Journal of Applied Geophysics* 55, 239-248. DOI: <https://doi.org/10.1016/j.jappgeo.2004.01.001>
- Muñiz, E., Shaw, R. K., Gimenez, D., Williams, C. A. and Kenny, L., 2016. Use of Ground-Penetrating Radar to Determine Depth to Compacted Layer in Soils Under Pasture. In: Hartemink A., Minasny B. (eds) *Digital Soil Morphometrics. Progress in Soil Science*. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-28295-4_26
- Nováková, E., Karous, M., Zajíček, A. and Karousová, M. 2013. Evaluation of ground penetrating radar and vertical electrical sounding methods to determine soil horizons and bedrock at the Locality Dehtáře. *Soil And Water Research*, 8(3), 105-112. DOI: <https://doi.org/10.17221/6/2012-SWR>
- Plado, J., Sibul, I., Mustasaar, M. and Jõelett, A., 2011. Ground-penetrating radar study of the Rahivere peat bog, eastern Estonia. *Est. J. Earth Sci.* 60, 31. DOI: <https://doi.org/10.3176/earth.2011.1.03>
- Pratt, B. R. and Miall, A. D., 1993. Anatomy of a bioclastic grainstone megashoal (Middle Silurian, southern Ontario) revealed by ground-penetrating radar. *Geology* 21, 223-226. DOI: [https://doi.org/10.1130/0091-7613\(1993\)021%3C0223:AOABGM%3E2.3.CO;2](https://doi.org/10.1130/0091-7613(1993)021%3C0223:AOABGM%3E2.3.CO;2)
- Rial, F. I., Pereira, M., Lorenzo, H., Arias, P. and Novo, A., 2007. Vertical and horizontal resolution of GPR bow-tie antennas. *4th International Workshop on, Advanced Ground Penetrating Radar*. DOI: <https://doi.org/10.1109/AGPR.2007.386549>
- Sass, O., Friedmann, A., Haselwanter, G. and Wetzel, K. F., 2010. Investigating thickness and internal structure of alpine mires using conventional and geophysical techniques. *Catena* 80, 195-203. DOI: <https://doi.org/10.1016/j.catena.2009.11.006>
- Simeoni, M., Galloway, P., O'Neil, A. and Gilkes, R., 2009. A procedure for mapping the depth to the texture contrast horizon of duplex soils in south-western Australia using ground penetrating radar, GPS and kriging. *Aust. J. Soil Res.* 47, 613-621. DOI: <https://doi.org/10.1071/SR08241>
- Topp, G. C., Davis, J. L. and Annan, A. P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resour. Res.* 16, 574-582. DOI: <https://doi.org/10.1029/WR016i003p00574>
- Tosti, F., Patriarca, C., Slob, E., Benedetto, A. and Lambot, S., 2013. Clay content evaluation in soils through GPR signal processing. *J. Appl. Geophys.* 97, 69-80. DOI: <https://doi.org/10.1016/j.jappgeo.2013.04.006>
- Venkateswarlu, B. and Tewari, V., 2014. Geotechnical Applications of Ground Penetrating Radar (GPR). *Journal Indian Geological Congress, Roorkee, India.* 6. 35-46.
- Zajícová, K. and Chuman, T. 2019. Application of ground penetrating radar methods in soil studies: A review. *Geoderma*, 343, 116-129. DOI: <https://doi.org/10.1016/j.geoderma.2019.02.024>
- Zhang, J., Lin, H. and Doolittle, J. 2014. Soil layering and preferential flow impacts on seasonal changes of GPR signals in two contrasting soils. *Geoderma*, 213, 560-569. DOI: <https://doi.org/10.1016/j.geoderma.2013.08.035>
