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Subsurface utility mapping using multi frequency ground penetrating radar: A case study of road collapse

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Abstract: In Urban areas, non-invasive or non-destructive detection and mapping of various subsurface utilities is a major challenge. However, this is extremely important to detect any defects or damage in the pipelines or cables which can cause hurdles in various aspects. Traditional methods such as digging soil and roads without prior information about exact locations are destructive, time-consuming and labour intensive. Moreover, this activity only provides single point source information. In contrary, Ground Penetrating Radar (GPR) is an extremely useful geo-physical technique to image subsurface in non-destructive and faster way for extracting information about buried utilities such as electric and telephone cables, water and sewage pipes and other infrastructure in dense urban areas. In order to explore multi-frequency GPR capabilities, GPR profiles/signatures have been collected and analysed for various surface and subsurface utilities, like concrete road, peat road, underground pipes made of different materials, manholes and various cables have been brought out in this paper. Moreover, the present article also emphasizes on a case study carried out in Ahmedabad City, Gujarat, India to examine disturbances in the soil and road layers associated with the road collapse due to damages in the underground pipes. The results conclude that GPR technique is highly efficient in identifying most of the underground utilities made of different materials and also the deformation features in the road and soil layers.

Keywords: Ground Penetrating Radar, Subsurface Utilities, Road Collapse

1. Introduction

High-resolution subsurface mapping of the ground in rapid, economical and non-destructive way has always been a necessity in the field of subsurface exploration. However, until recently there were no effective methods that can meet the above requirements. Traditional methods such as digging soil and roads are destructive and time-consuming. In contrary, Ground-penetrating radar (GPR) is a non-destructive geo-physical technique which can image the subsurface with higher resolution in faster and cost effective manner. GPR detects electrical discontinuities in the shallow subsurface (typically < 50 m) by generation, transmission, propagation, reflection and reception of discrete pulses of high-frequency electromagnetic energy in the megahertz frequency range (Neal, 2004). It is used as near-surface remote sensing tool to detect buried objects and to characterize the subsurface structure and properties in a wide variety of applications such as mineral and groundwater exploration, geotechnical and archaeological investigations, as well as rock mechanics and mine development requirements, subsurface utility detection, road condition analysis etc. (Davis et al., 1989, Mellet, 1995; Annan, 2002; Lambot et al., 2004). Hence, to demonstrate the capabilities of GPR, a detailed study has been carried out over multiple sites in Ahmedabad, Gujarat for deducing signatures of various surface and subsurface utilities, like concrete road, asphalt road, underground pipes made of different materials, manholes and other utilities. The results obtained from the present study are showcased in the present paper.

2. GPR principle

Ground Penetrating Radar (GPR) is a geophysical sensor that uses high-frequency (e.g. 20 to 1,500 MHz) electromagnetic pulses to image the subsurface in non-destructive way. A GPR transmitter emits microwave pulses into the ground. When the energy encounters a buried object or interfaces between materials having different permittivity, it reflects or scatters back to the surface. A receiving antenna records the variations in the return signal (Figure 1). Reflecting interfaces may be soil horizons, the groundwater surface, soil/rock interfaces, man-made objects, or any other interface possessing a contrast in dielectric properties. However, dielectric properties of materials are not measured directly. The method is most useful for detecting anomalies and changes in the geometry of subsurface interfaces.

Two physical parameters of materials are important in subsurface wave propagation at GPR frequencies. One property is conductivity (σ), measured in mS/m (1/1000 Ωm). The other physical property is dielectric constant (ε), which is dimensionless. Good amount of energy of an EM field is consumed during interaction with water molecules or other polarizable materials. Thus, waves propagating through such material go slower and are subject to more attenuation (US EPA, 2016).

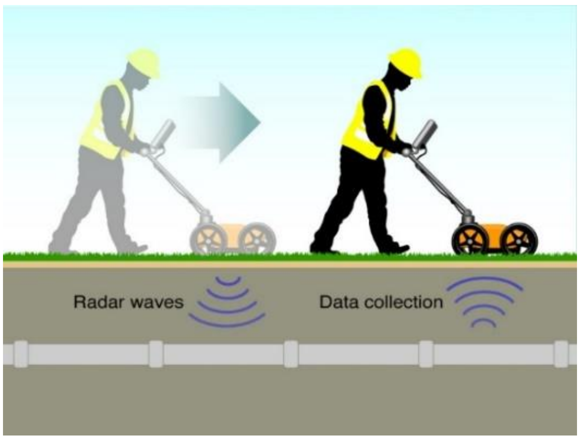


Figure 1: Schematic diagram representing GPR survey (http://saarit.in/gpr.php)

Velocity (V) of Radar wave in the medium:

$$V = (3\times10^{8})/\sqrt{\varepsilon}$$

Attenuation (A) of Radar wave in the medium:

$$A = 1.69\sigma/\sqrt{\varepsilon}$$

As the GPR signals are in the form of radar pulses, so, as the antenna moves across a point object the range of the object from the antenna changes. When, the antenna in just above the object the range is minimum. Hence, in the time-distance plot, radar image of a point object takes the form of a hyperbola (Figure 2). Amplitude of the reflected radar signal also depends on the material type. Reflection from the metallic objects are more than non-metallic objects. Therefore, hyperbolas appear from metallic objects are more prominent than non-metallic pipes (Amran et al., 2017, Narayana et al., 2018).

3. Experiment setup and study area

GPR can be operated in different modes such as common offset mode, common midpoint mode and WARR (Wide Area Refraction and Reflection) mode. In the present study, GPR is operated in the common-offset mode, where the transmitter and receiver are maintained at a fixed distance and moved along a profile line (Figure 3). A commercial GSSI based GPR with 100 MHz and 400 MHz antennas are used for subsurface mapping (Figure 4).

According to the prior information, the GPR experiments are conducted at SAC New Bopal Campus, SAC Main Campus, Bopal Cross Road (Near Vakil Saheb Bridge), Ranna Park and Jamalpur area of Ahmedabad, Gujarat. Based on the observations at these sites, the effective results are grouped into various themes and documented here for better understanding. The various object themes, location of the studied objects and the GPR antenna used to study are detailed in table 1.

Raw data from GPR profile was position corrected and processed with different filters for enhancing the subsurface reflections as part of post-processing using RADAN software. It was observed that after post-processing, all previously known underground objects are easily identifiable and their location (apparent) can also be retrieved from GPR 2D profiles.

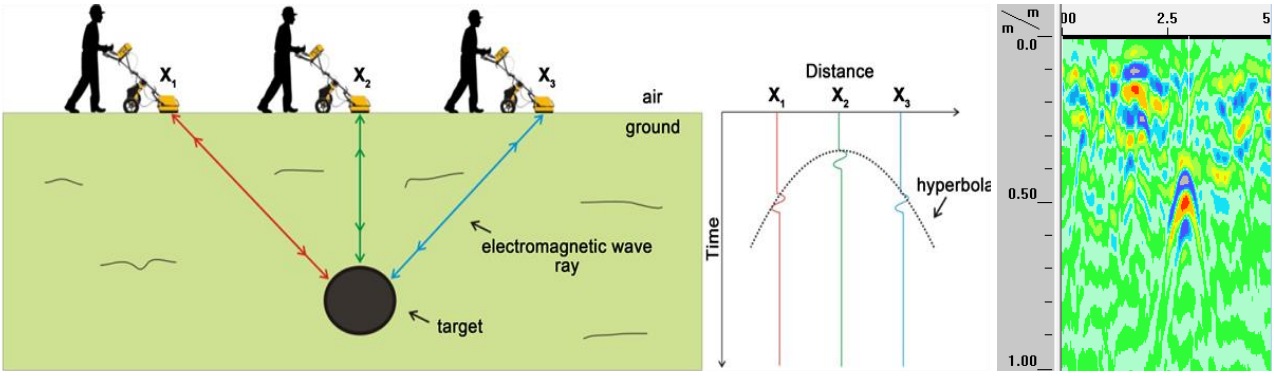


Figure 2: Inverted hyperbola formation from point object in GPR profiles (Poluha et al., 2017)

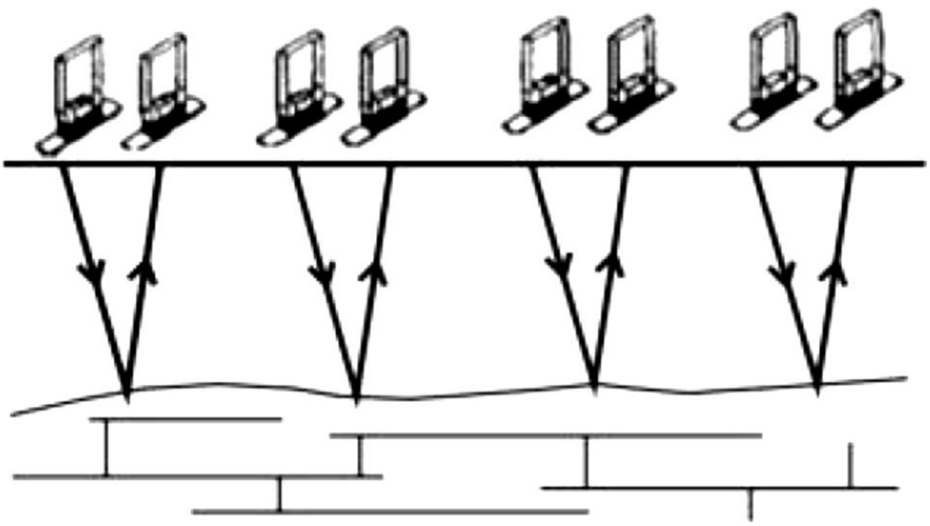


Figure 3: Common offset mode of GPR operation

Figure 4: GSSI 400 MHz GPR antenna (red) with control panel and carrier three-wheel cart. Left side HydraGo (blue) soil moisture instrument for measuring dielectric constant of soil.

Table 1: Various GPR experiments conducted in the present study

Sl. No.	Theme	Experiment Location	GPR Antenna used
1	Concrete Road	New Bopal SAC Campus	400 MHz
2	Asphalt/ Tar Road	All the sites	400 MHz
3	Manholes	New Bopal SAC Campus, Bopal Cross Road, Ranna Park and Jamalpur	400 MHz
4	Different Pipes and Utilities	All the sites	100 MHz, 400 MHz
5	Road and Subsurface soil profile	All the sites	400 MHz (Range 100 ns and 50 ns)
6	Road collapsed and cave-in situation	Ranna Park	400 MHz
7	Cave-in repaired sites	Bopal Cross Road	400 MHz
8	Subsurface water leakage	SAC Main Campus	400 MHz

4. Results and interpretations

4.1 Concrete road

Concrete structures reinforced by iron mesh or rebar are prominently identifiable using GPR study. Iron is a metallic substance, hence, presence of iron in the concrete give rise to high dielectric constant variation which leads to strong reflection of radar signals. Therefore, in GPR profiles the rebar or iron mesh appears very prominently with high reflected signal power.

In New Bopal SAC Campus, a GPR profile is collected using 400 MHz antenna. The rebar structure looks like densely populated small hyperbolas (Figure 5c, 5d) in a line due to strong reflection of the radar signals from iron mesh.

4.2 Asphalt / Tar road

Dielectric constant variation between asphalt layer and soil is low hence asphalt layer mostly remain transparent to radar signals. However, due to direct coupling, straight horizontal bands appear on top of the GPR profile. Direct coupling is a combination of the transmit pulse in air and surface reflection from the top of the material. So, the direct coupling carries information about the structure. Hence, if the asphalt layer is continuous, the top layer in the GPR profile becomes straight. Any disturbances in the road layer causes discrepancy in the top layers in GPR profile.

In all the investigated sites, GPR profiles have been collected mostly on the asphalt road. In figure 6, continuous asphalt road layers are visible as the top layer in the GPR profile. Below the asphalt road layer, parallel soil layers prepared for construction of road are also visible in the GPR profile (Figure 6).

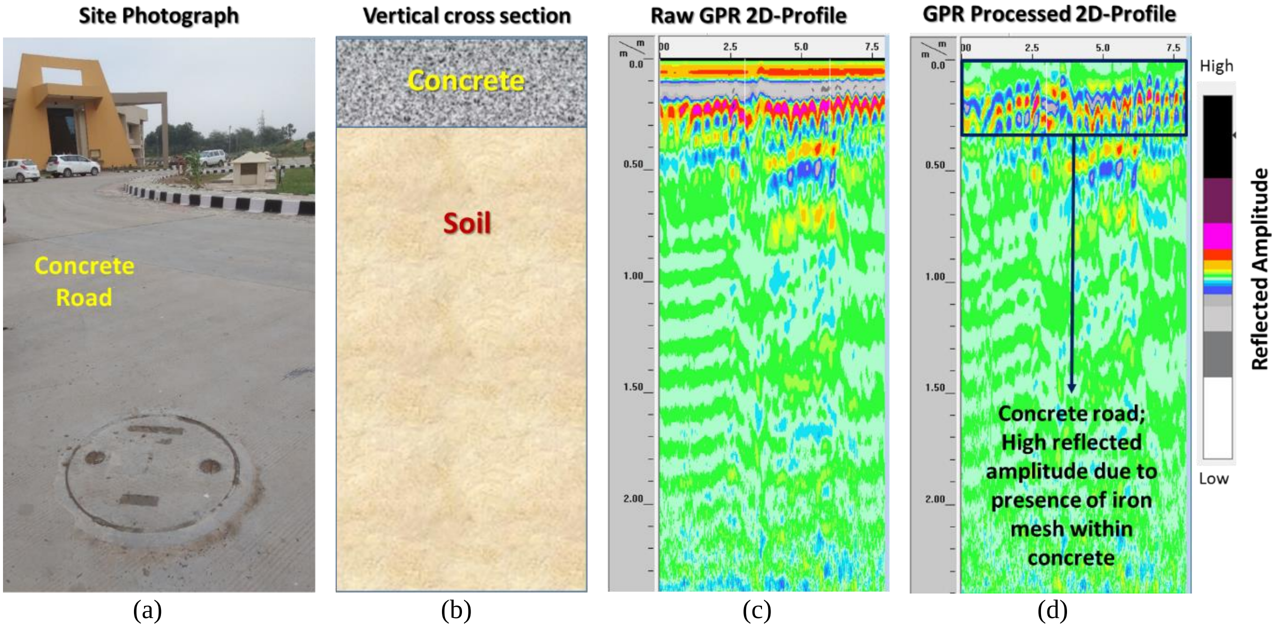


Figure 5: (a) Field Photograph where the GPR profile has been collected; (b) Cross-section of the profile based on prior information along which GPR signals are collected; (c) Position corrected GPR profile conducted on concrete road. Pink small densely populated hyperbolas are indicator of rebar in concrete road; (d) Background removed GPR profiles to highlight the rebar structure.

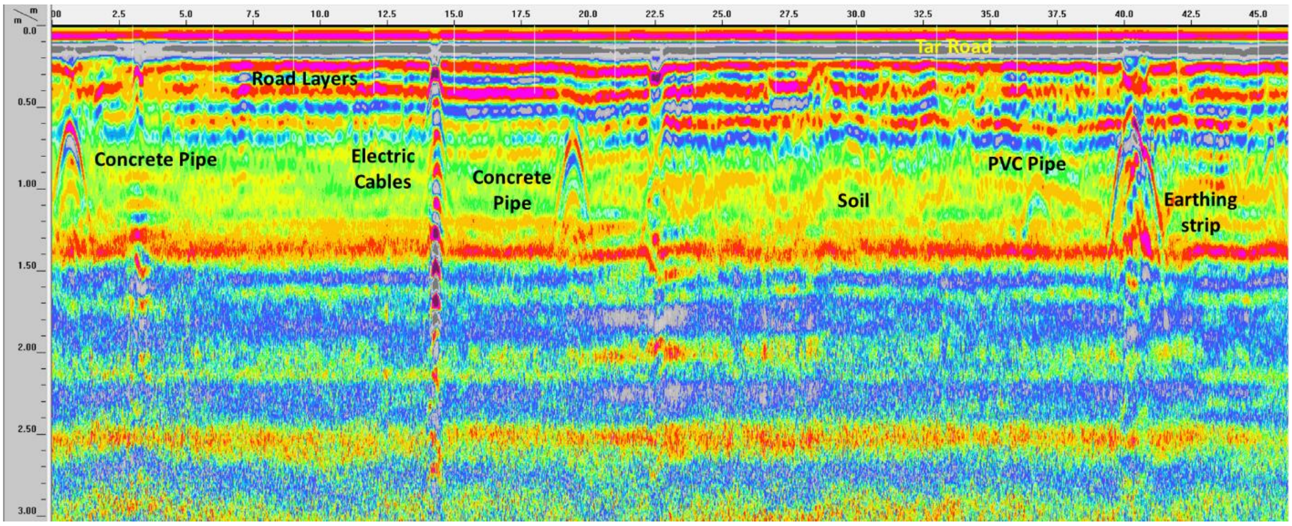
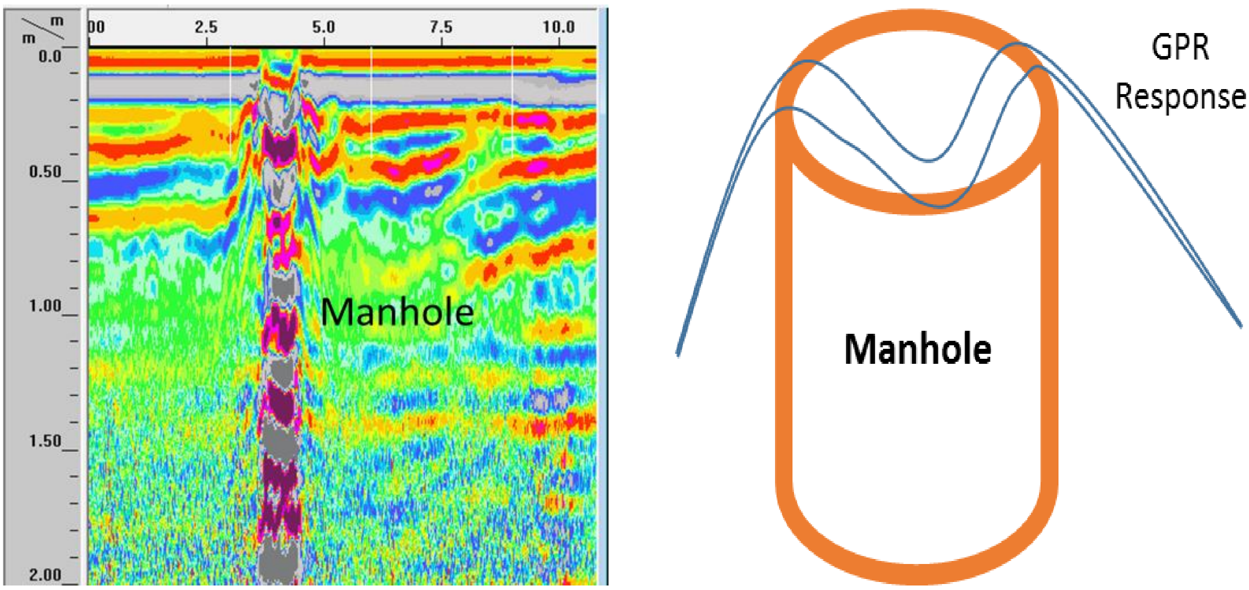


Figure 6: Continuous Asphalt layer as the top layer of the GPR profile.

4.3 Manholes

Manholes are vertical shafts filled with air, hence, act as air gaps. As air and surrounding soil has high dielectric contrast, hence, radar reflection from the manhole is strong (GSSI, 2018). Therefore, manholes appear as very prominent vertical structures in GPR profile (Figure 7a). Minute observation of the responses obtained from manhole reveals that the response is like 'M' shape and vertical stacks of 'M's give rise to the complete manhole structure. The 'M' shape is due to merging of two hyperbolas appearing from the walls of the manhole present either side of the air gap (Figure 7b).

For understanding responses from manhole structures, GPR profiles have been collected in New Bopal SAC campus, Ranna Park, Bopal Cross Road and Jamalpur area using 400 MHz antenna. The manhole structures are prominently decipherable in all the GPR profiles. However, in 100 MHz antenna due to long wavelength, manholes become transparent in the GPR profiles and not determinable. Thus, wavelength of the radar also plays very important role to decipher target object. If the object size is comparable with the wavelength it will appear in the GPR profile, else it will become invisible in the GPR profile. Figure 8 exhibit the series of manhole structures obtained in New Bopal SAC Campus.



(a) (b)

Figure 7: (a) GPR profile of a vertical manhole structure; (b) Reflected radar response from manhole structure

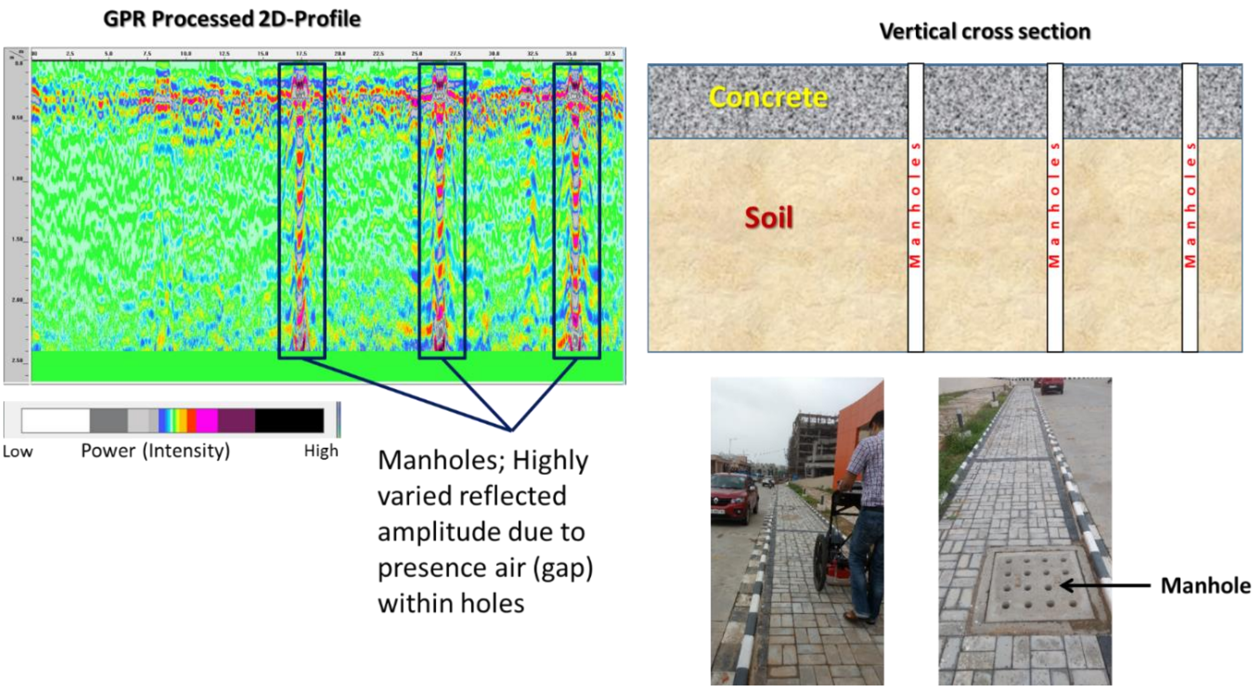


Figure 8: Series of manholes obtained from GPR profile in New Bopal SAC Campus

4.4 Different types of pipes and utilities

Underground utilities such as metallic and non-metallic pipes, electric cables and strips are successfully detectable using GPR survey. Underground utilities mostly act as a point object and their response mostly appear as hyperbolas. Metallic utilities have strong dielectric contrast with soil, so, strong radar reflection takes place leading to prominent appearance in the GPR profile. However, non-metallic utilities are less prominent. PVC pipes are mostly transparent, however, presence of air or water in the pipe helps to reflect radar signal from the pipe (GSSI, 2018). Hence, PVC pipes appear as weak hyperbola in the GPR profile. Figure 6 reveals various underground utilities like concrete pipes, electric cable, PVC pipe and Earthing strip obtained from GPR profile collected in SAC Main Campus using 400 MHz antenna. Here electric cable and earthing strip are metallic object, so, they have strong radar reflection. Concrete pipes are also appearing prominent in GPR profile. However, radar reflections from PVC pipes are feeble.

Along with the material property, GPR profiles also help to delineate the size of the underground utilities in relative manner. Figure 9 represents a GPR profile which is having subsurface pipes of various sizes. According to the size of the pipes, the size of the hyperbola also varies. The length of the crest part of the hyperbola is comparable with the perimeter of the semicircle of the pipe looked along in the GPR cross-section.

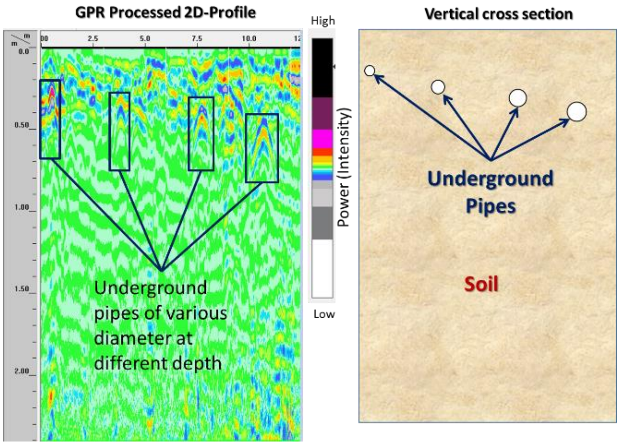


Figure 9: GPR profile showing subsurface pipes of different size present at different depth

If more than one pipes are present together, hyperbolas appeared form individual pipes in the GPR profiles will overlap with each other. Number of hyperbolas help to determine the number of pipes occurring together. However, if the distance between two pipes are less than the wavelength of the GPR signal, then GPR treat the two pipes as single object and only single hyperbola will appear in that case. As metallic objects act as strong reflector, GPR is not able to look below the metallic object. Hence, any pipe or object present below the metallic object is not decipherable in GPR profile. Figure 10, shows the occurrence of multiple pipes together in GPR profiles collected in SAC Main Campus. The depth of the object appeared in the GPR profiles are in apparent terms. The vertical depth accuracy of the object depends on the dielectric constant of the medium. More precise input of dielectric constant give rise to increased vertical accuracy. In SAC Main Campus, the dielectric constant of the soil measured with dielectric probe and using the value the pipes showed in figure 10 appeared in 40-45 cm below surface. Ground measurement reveals that exact depth of the pipes are 46 cm below ground level.

400 MHz antenna having capacity to penetrate shallow subsurface upto 3m below ground. However, for locating pipes present in greater depth, 100 MHz GPR antenna is useful which can penetrate upto 8-10m below surface. However, the object size should be comparable with the radar wavelength in 100 MHz, else, the object will not be visible in the GPR profile. As requested by AMC, a study is conducted at Jamalpur, Ahmedabad using 100 MHz GPR antenna to locate deep-seated underground pipeline. Figure 11 demonstrates the result of locating large diameter concrete pipes present at the depth of 4m below surface.

4.5 Road and subsurface soil profile

GPR technology proves its potential in imaging subsurface soil profiles which is useful for geological understanding. While surveying in all the sites, the soil morphology in the GPR profiles can be prominently delineated. The uniform soil body appears to be uniform in GPR profile due to absence of any contrast in dielectric properties. However, if any variation in the soil formation prevails then due to variability, the interfaces between the soil layers can be decipherable easily. Moreover, any deformation in the soil layer can also be understood from GPR profile.

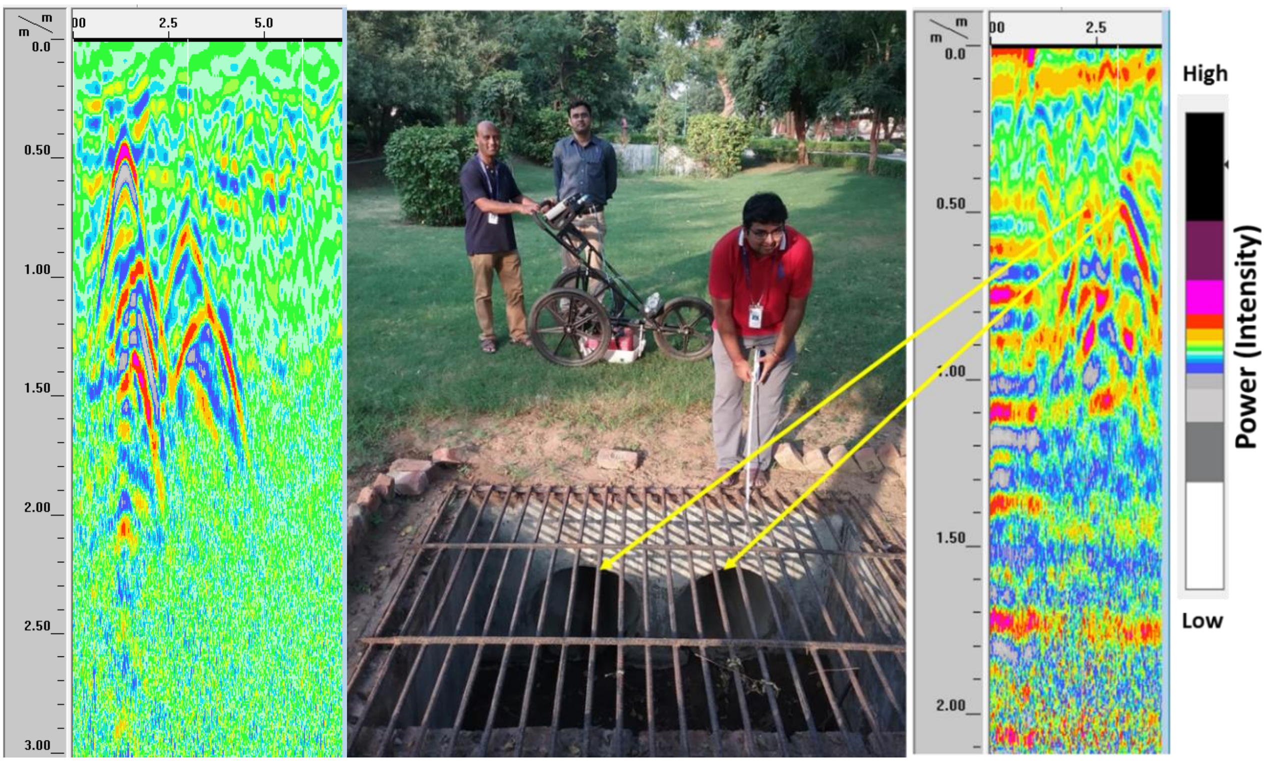


Figure 10: GPR profile showing occurrence of multiple pipes together

Figure 12 reveals the potential of GPR to identify uniform and layered soil profile present alongside. The survey is conducted at Ranna Park, Ahmedabad, with the help of officials of Ahmedabad Municipal Corporation (AMC), using 400 MHz GPR antenna with range value 50 ns and 100 ns. In 50 ns the penetration depth of the radar is upto 3m, however, in 100 ns GPR can image subsurface upto 6m. So, the profiles show that a uniform soil layer is existing upto greater depth and within that some part of the soil was excavated for installation of pipeline and the excavated pit was filled by various soil layers. Thus, while GPR survey it is important to conduct the survey in various range to understand the subsurface profile in overall details. Figure 13 also demonstrates the capacity of GPR to image both uniform and layered soil profile distinctly.

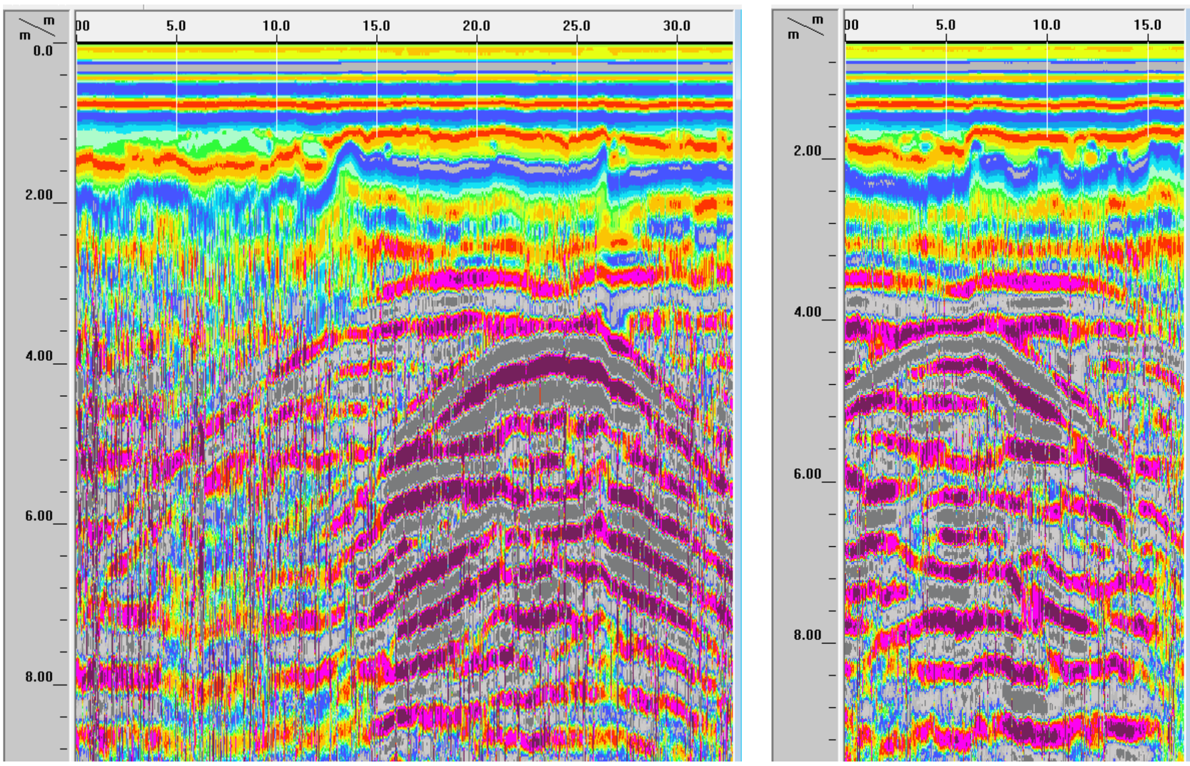


Figure 11: GPR profile showing deep-seated subsurface pipe using 100 MHz GPR antenna

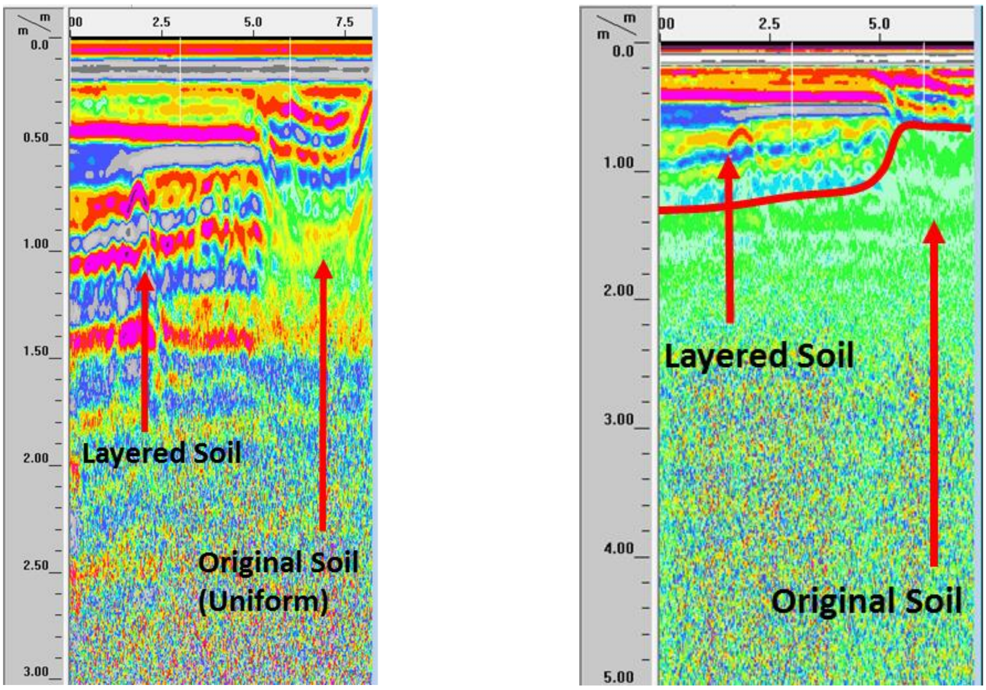


Figure 12: GPR profile showing uniform and layered subsurface soil profile using 400 MHz and in range value 50 ns (left) and 100 ns (right)

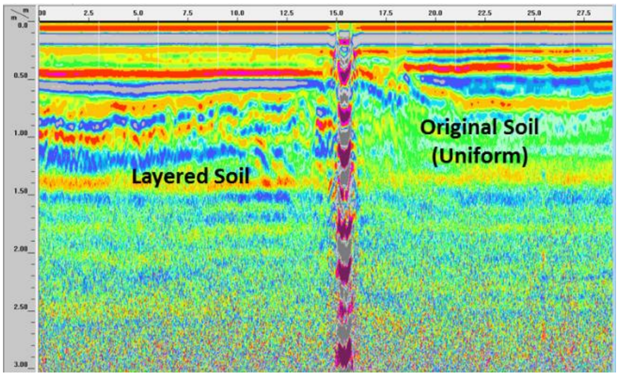


Figure 13: GPR profile showing uniform and layered subsurface soil profile.

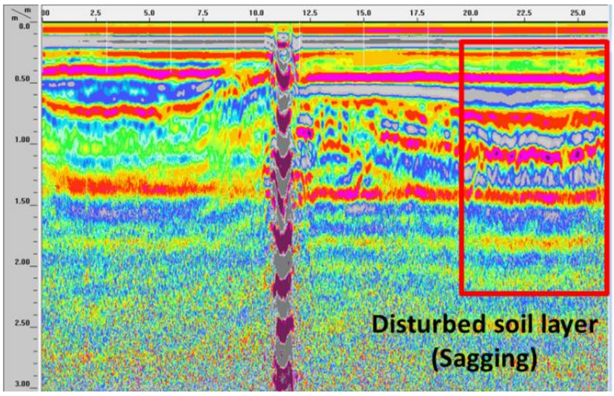


Figure 14: GPR profile showing deformation in the soil profile (sagging layers)

As GPR is able to exhibit the various soil layers, so, any deformation in the soil layers are easily distinguishable in the GPR profiles. Any bending, void formation and sagging of soil layers are understandable from GPR profiles. Figure 14 showing the GPR profiles collected in close vicinity of the cave-in area in Ranna Park, Ahmedabad using 400 MHz GPR antenna. The soil layers are sagged or deformed due to effect of cave-in. In another example from Jamalpur area, Ahmedabad, disturbed and undisturbed soil layers can be easily discriminated from GPR profiles collected using 400 MHz antenna (Figure 15). Thus GPR is useful is studying soil profiles and deformations occurring within it.

4.6 Road collapse and cave-in situation

In a case study, GPR survey has been conducted around cave-in area in Ranna Park, Ahmedabad with the help of Ahmedabad Municipal Corporation (AMC) officials and staffs. According to AMC officials, around 6m below the surface the concrete sewage pipe is placed in the area. The sewage pipe is having manholes which link the pipes with surface.

Due to presence of sewage material in the pipe, methane gas releases which accumulates in the roof of the pipe. The gas corrodes the concrete roof and reduces roof stability. When the roof of the pipe become unstable to resist overburden pressure, it fails and all the overburden soil then flows within the pipe to create a cave-in structure. This cave-in can extend upto the surface leading to road collapse (Figure 16).

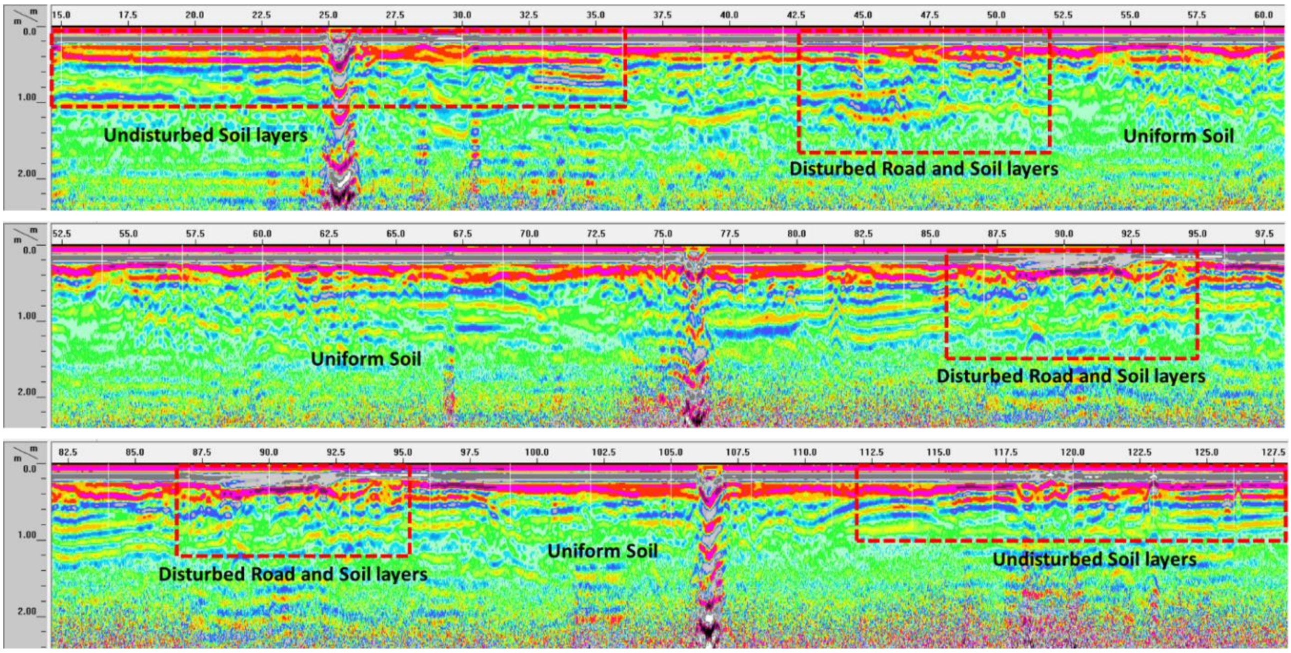


Figure 15: GPR profile showing undisturbed and disturbed soil profiles

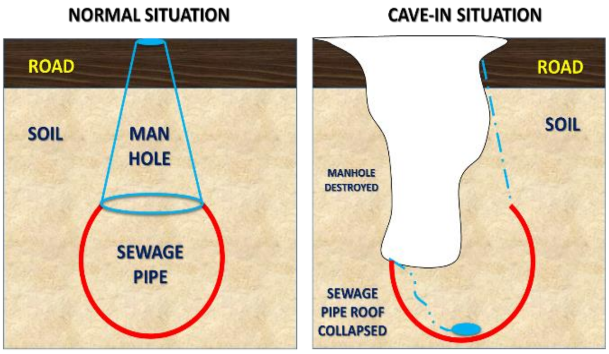
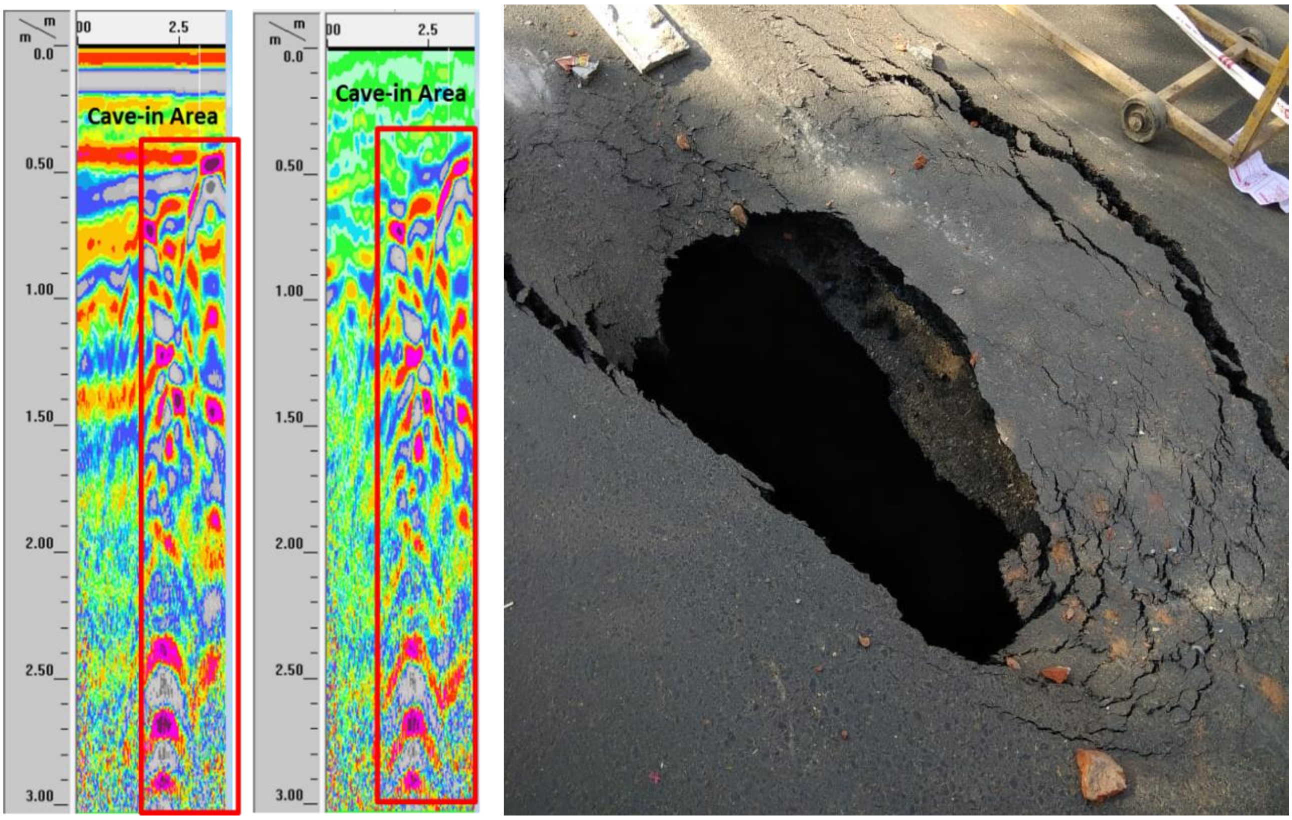


Figure 16: Occurrence of cave-in due to roof collapse of sewage pipe

In Ranna Park also similar road collapse associated with cave-in took place. A manhole connected to sewage pipe was present in that location, which got destroyed due to cave-in. Cave-in area is mainly a cavity structure filled with air. So, due to high dielectric constant variation in between soil and air, cave-in areas appear prominently in the GPR profiles (GSSI, 2018). In this area, road collapse has occurred in small extent, however, the subsurface cavity generated below the road has larger dimension. GPR profiles are collected above the road below which the underground cavity still persist. Figure 17a shows such GPR profile taken on subsurface cavity in Ranna Park, Ahmedabad. Figures 17a and 17b show position corrected GPR profile to locate the subsurface cavity and background removed GPR profile to delineate the extent of the cavity and the field photograph.

4.7 Cave-in repaired sites

The repaired cave-in sites appear to be different than the original layers prevailing in the area. A GPR survey has been conducted in a cave-in repaired site in Bopal Cross Road, Ahmedabad. The profiles show that the road and soil layers in the repaired site are random and not in continuity with the prevailing original layers. Hence, clearly the cave-in repaired sites can be decipherable using GPR study (Figure 18).



(a) (b)

Figure 17: (a) GPR profile just above the cave-in area, where left profile is position corrected and right profile is background removed to highlight only the cave-in area; (b) Field photograph of the road collapse associated with cave-in in Ranna Park, Ahmedabad

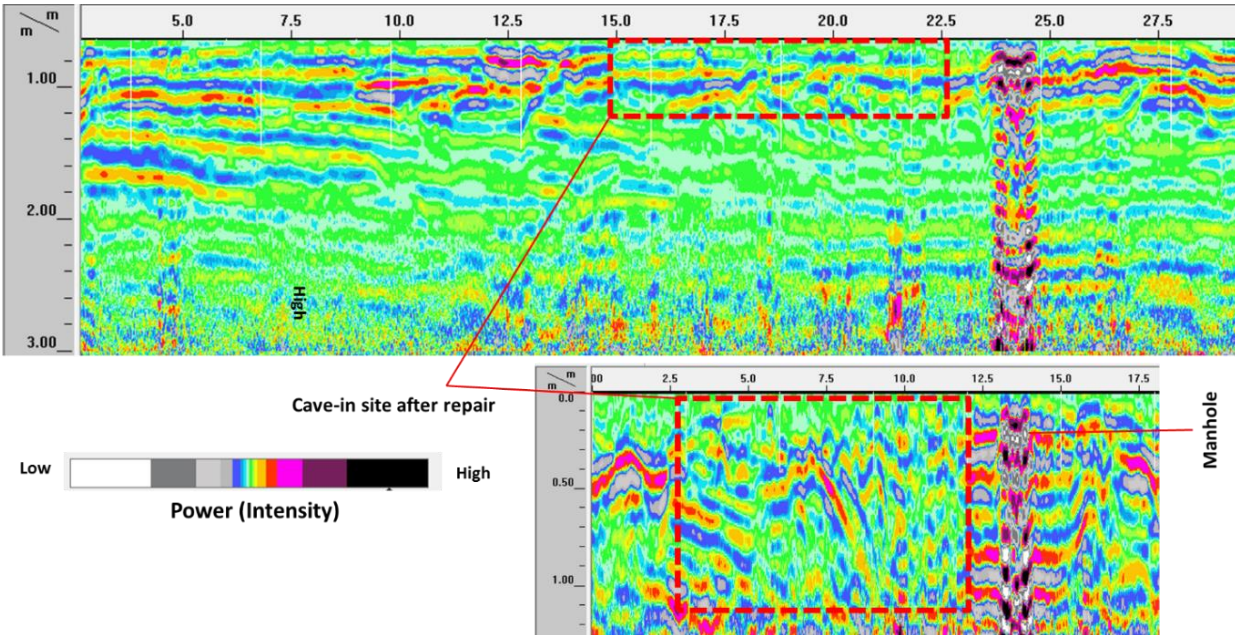


Figure 18: GPR of cave-in repaired site obtained using 400 MHz GPR antenna near Bopal Cross Road, Ahmedabad

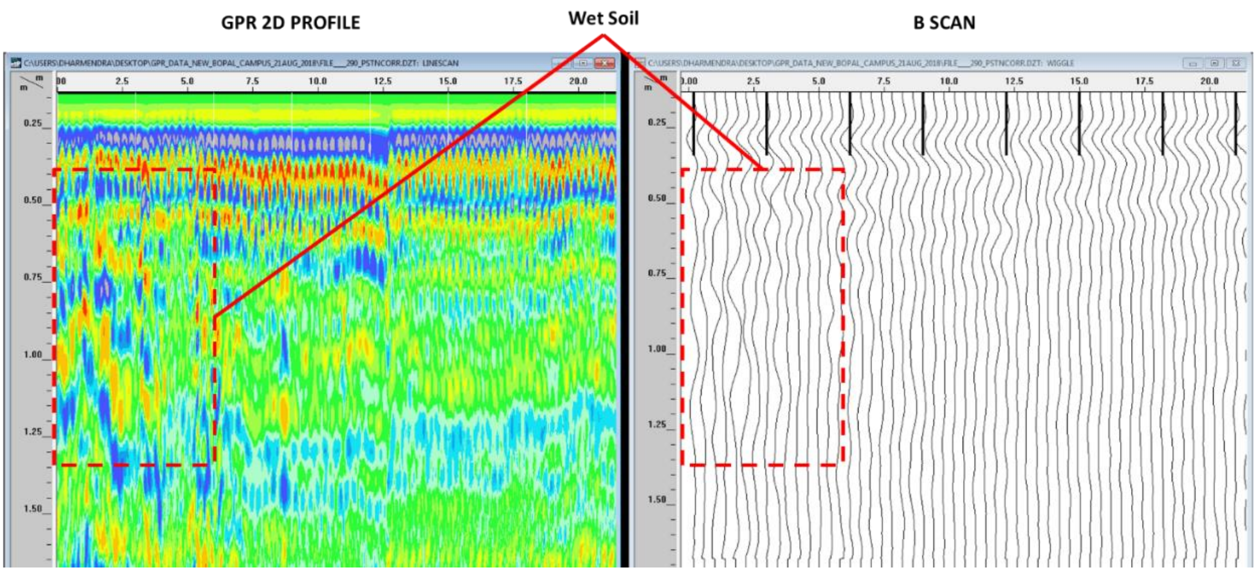
4.8 Subsurface water leakage

Another case study was conducted to understand the potential of GPR to detect subsurface water leakage in SAC Main campus, using 400 MHz GPR antenna. As water and soil having contrasting dielectric properties, so, radar reflection for the wet area in background of dry soil is high and appears prominently (GSSI, 2018). The zone having high radar reflection also delineates the extent of the wet soil.

Figure 19a reveals that the wet soil area shows high radar intensity compared to the surrounding dry soil. This phenomenon is more understandable in B Scan GPR profile (Figure 19b) where, individual A scans in the wet soil area showing strong positive radar reflectance compared to nearby dry soil, which helps to determine the extent of the water leakage.

5. Conclusion

The present study successfully explored the utilisation potential of GPR in detecting various underground pipes and utilities. The results show that GPR has greater proficiency of detecting concrete (rebar), manholes, metallic and concrete pipes compared to PVC pipe. Furthermore, GPR also has the ability to provide understanding about type of material and size of the pipe. In case of multiple occurrence of pipes, GPR is observed to locate the pipes depending on the distance between the pipes and the GPR wavelength.



(a) (b)

Figure 19: (a) GPR profile of the wet soil in background with dry soil; (b) GPR B scan of wet soil where individual A scan shows strong positive radar reflection compared to nearby dry soil

Further, the field survey also demonstrates the effectiveness of GPR technology in various subsurface road and soil layers. The survey also unveils its capability to detect subsurface deformations related to cave-in. GPR survey with lower frequency (100 MHz) antenna also effectively locates deep-seated utilities. Finally, GPR delineates efficiently presence of subsurface water.

Therefore, a significant amount of data collection has given an idea of the competency and efficiency of GPR, which led to understanding of extended application of GPR technology on mapping and determining various types of underground objects. Most importantly, this study allows the GPR frequency 100 MHz and 400 MHz to be used with confidence as a tool to detect underground pipes and utilities.

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