Integrated geophysical subsurface investigation for effective completion of the sewage pipeline project in the shallow bedrock region

This paper presents a case study depicting the importance of geophysical investigation prior to cost estimation and execution of an excavation work by the experience of the ongoing project.The project for laying of a new sewerage pipeline in the shallow bedrock region of Bangalore with an estimated cost of about Rs.50.00 lakh, which was started after formal approval and tendering. After executing 25% of excavation work, weathered and hard rock was found along the alignment at an average depth of around 2.5 m, which increasedthe cost of excavation and project period. The contractors topped the work due to unidentified tender item (rock excavation) which caused cost escalation above estimation and required additional time and machinery excavation. A scientific investigation using integrated geophysical survey techniques has been carried out to profile the subsurface lithology, estimate precise soil and rock volumeforestimation ofincreased cost of excavation due to presence of rockand time required for completion of the project. Detailed integrated subsurface profiling has been carried out using Ground Penetrating Radar and Multichannel Analysis of Surface Wave to find out the thickness of soil and rock. A 2-D subsurface profile has been generated from both investigation and used to map the soil and rock layers. An estimate of soil and rock volume has been prepared from the survey results and compared with the prior estimate to assess differences observed in the cost of excavation. In comparison, it has been found that the estimate obtained from survey result is 2.17 times higher than the presumed estimate for a typical section. This study helped to re-estimate project cost, effective planning of the project and thereby timely completion.

Keywords: Ground-penetrating Radar, Cost Estimation, Excavation, Geophysical Investigation.

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1 Introduction

Preliminary geophysical investigation of subsurface strata is important prior to tendering or execution of excavation work in a construction project. Such investigations help in proper planning, cost estimation and time bound project execution. The data from the investigation helps in identifying the types of geologic materials with engineering properties, their porosity, thickness, weathering condition for the design and planning of the project. These investigations predominantly help in a pipeline project to plan alignment (orientation and direction) of excavation, to find out the volume of excavation material, to find out the type of material need to be excavated and also to estimate project cost. This also helps to prepare Program Evaluation Review Technique (PERT) chart for project management and timely completion of the project. Inadequate, imprecise survey information can substantially impact the accuracy of estimation or a bid analogous with a certain excavation project (Stump, 2004). Also such unexpected costs can weaken the financial viability of the contractor's business.

Ground penetrating radar (GPR) has been widely used for profiling shallow subsurface strata as well as mapping bedrock. It provides high resolution stratigraphic images of subsurface geology, buried anomalies, moisture content, soil pollutants/contaminants. GPR also provides subsurface data with good precision identifying the boundary between different types of geologic materials along with formations like synclines and anticlines. In favourable conditions GPR has been more accuracy in determining the soil depth as well as a 3D depiction of soil volumeas compared to other conventional methods (Sucre *et al*., 2011). The quality of GPR data is dependent on electrical conductivity of the soil, which is further dependent on its mineralogy, its water retention capacity and cation exchange capacity (CEC) (Doolittle and Collins, 1995). As the higher the CEC, decreases the electrical resistivity of the soil, which in turn increases the signal attenuation and reduction in penetration depth as well as resolution of the data (Saarenketo, 1998).The application of GPR requires less extensive field work as well as processing than other geophysical methods (Binder *et al*., 2009). Arcone *et al*. (1988) have successfully demonstrated the use of low frequency GPR for profiling the permafrost and the bedrock depth in Alaska. A 400 MHz GPR was successfully utilized to collect the subsurface data to plan the excavations for buried structures at an archeological site in Petra, Jordan (Conyers *et al*., 2002). The GPR technique has been used in the past to determine peat thickness, peat volume and estimate carbon pool in a boreal peatland in Canada by Dallaire and Garneau, (2008). It was found from the study that the GPR thickness data are significantly similar to manual measurements. Benson, (1995) demonstrated the application of GPR in assessing natural or man-made geologic hazards like contaminant plume in ground water/soil, cavities and shallow subsurface faulting with 100 MHz antenna. He observed that GPR was highly efficient in detecting shallow cavities if the host strata has comparatively low electromagnetic wave attenuation factor. GPR can not only be used for preliminary survey, but can also be used for quality management and condition assessment of constructed structures. Rey *et al.* (2015) used GPR with three (100, 250 and 800 MHz) center frequencies for preliminary characterization of ornamental stones (Macael Marble, CremaMarfil and Red Travertine). They found that GPR was a very effective tool in determining the intactness of stone blocks, quality and locating anisotropies which further helped in the determination of the orientation of cutting process. Stump (2004) devised a portable subsurface imaging system using GPR which would provide real time geological, geophysical and geographical position data for a particular excavation site. Ligas and Palomba, (2006) demonstrated the use of very low frequency electromagnetic geophysical method for estimating the clay content in a mineral deposit for profitable exploration. GPR provided the actual thickness of a floor slab which was assumed to much thinner as per the architect for cost estimation of demolition of a building (Mellet, 1995). GPR is helpful in identification of subsurface utilities prior to excavation process which helps in avoiding accidental utility damage and hence cost saving against the damage (Lew, 1997). In general, geophysical survey techniques are rapid and cheap mode of subsurface profiling, which cover a larger area in less time also they provide continuous information of the sub-surface profile unlike other point testing methods.Though the use of GPR for project planning and estimation has not yet taken place, it has been successively used in estimating bauxite ore content in a mine field before starting the mining process. Sucre *et al*. (2011) observed that the soil depth estimated by point testing methods like augers was 40% less against the actual depth and GPR acted as an effective tool in soil depth as well as volume estimation.

In past decades, the geotechnical site characterization using the shear wave velocity (Vs) obtained from multichannel analysis of surface waves (MASW) has been widely used in site characterization and bedrock mapping. The Vs is directly related to the density and rigidity of a material helps in identification of soil and rock layers separately as both have different density and rigidity (Anbazhagan *et al*, 2016). Anbazhagan and Sitharam (2009) have used shear wave velocity for determining the spatial variability of weathered as well as engineering bedrock at depths ranging from 1 to 50 m. The MASW method can be successfully used for identifying sinkholes, top of bedrock and zones of weathered bedrock (Schokker *et al*., 2008). Also MASW data can be optimally used for monitoring the ground improvement (compaction) process of a site after 3D conversion of the adjacently placed survey lines (Suto and Scott, 2009).Though GPR and MASW are widely used for geophysical investigation, a very limited attempt was made to integrate both data for obtaining volume of the subsurface layers for effective excavation. Hence, in this study an attempt has been made to create subsurface profiling to estimate quantity of the excavation and project planning.

2 Problem Statement

The study was conducted in order to investigate the issue related to a stalled excavation work of the pipeline project in Bengaluru city area. The project was aimed at laying a 450 mm diameter reinforced cement concrete pipeline to transport sewage to a sewage treatment plant. The total length of the pipeline is 820 m designed for gravity flow. The issue in the case was pertaining to cost and pricing of the excavation work which was estimated without performing preliminary subsurface investigation along the proposed alignment of the project. As the cost was estimated on the assumption that only soft or hard soil exits along the excavation route, but while excavation it was found that at an average depth of 2.5 to 4 m weathered rock or granite existed (Figure 1) along a major portion of the excavation where the average depth of excavation was about 6m.

The unpredicted encountering of hard rock during excavation created hurdles as hard rock requires different kind of machinery and equipment for excavation. Also the standard rates for excavation of hard rock are higher than that for soft or hard soil, which in-turn increases the overall project cost. The increase in project cost was a main

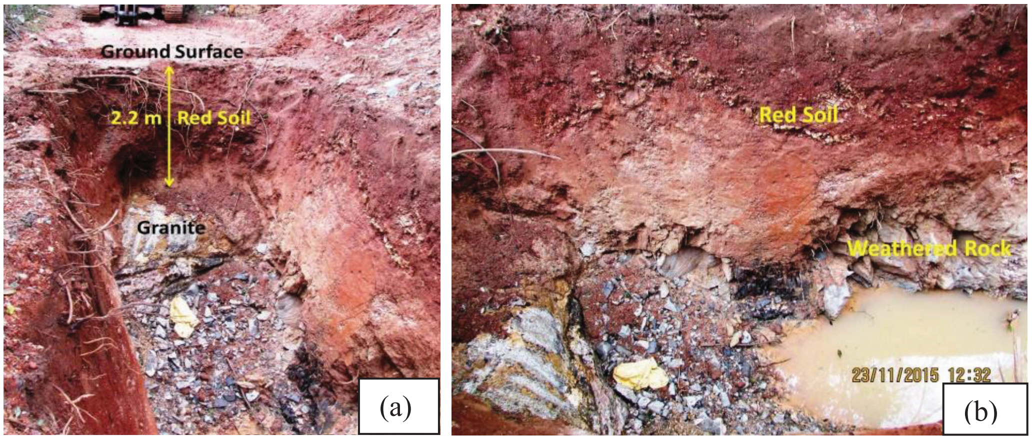

Fig. 1: (a) and (b) Weathered rock observed below the red soil layer at the site

issue due to which the project was stalled in between.The authors of the paper were involved in investigation of alternate alignment, quantification of soil and rock excavation and estimation of cost escalation for the project.

3 Study area and geology

The study area is situated in the west block of Bruhat Bengaluru Mahanagara Palike (BBMP) area (Figure 2). Bengaluru is located at latitude of 12°58′ N and longitude of the 77° 36′ E with an average altitude of 910 m above mean sea level in Karnataka state in peninsular India. Bengaluru is financial, executive as well as administrative capital of Karnataka. It is one of the eight metropolitan regions of India with the booming infrastructure sector. It is also known as the Information Technology (IT) capital of the country as well as it is a major centre for the scientific intellect of our country as many institutes of strategic importance and research laboratories are based in the city.

Though the major part of the region is mainly flat, the western part is a bit hilly. Peninsular Gneissic Complex (PGC) is the major rock type found in Bengaluru whose formation is caused due to granitization of aged sedimentary rocks like migmatites, gneisses and granites while the dominant soil type comprises of red laterite and loamy to clayey soils (Anbazhagan and Sitharam, 2009). The formation of these Gneiss basements dates back to Archean era that is around 2.5 Ga - 3.5Ga (Ga- Geological ages). Anbazhagan and Sitharam, (2009) conducted seismic surveys using multichannel analysis of surface wave (MASW) method in the Bengaluru metropolitan area for determining the spatial variability of bedrock depth, in which the rocks were categorized based on the shear wave velocity. The characterization was done in two categories one being weathered rock or soft rock ($V_s = 330 \pm 30$ m/s) and another one is engineering rock or hard rock ($V_s = 760 \pm 60$ m/s). It was concluded from the study that the depth of weathered rock in the western region (study area) of BBMP was shallow and within 5 m from the surface i.e. shallow bedrock region. The weathered rock in this case is referred as granite, which was found in the study area. Also, many rock outcrops can be found in the western region of the metropolitan area. It is also recommended to go for detailed subsurface profiling in the shallow bedrock region for any civil engineering project, which involves excavation to save cost and time. We understand from the tendering document and site work execution that the project estimation and also work was commenced without the proper Geotechnical investigation and interpretation. A typical excavated section with pipeline laid and shallow bedrock in the site is shown in Figure 3.

Fig. 2: Shallow Bedrock Region in the Bengaluru Map (source: http://wgbis.ces.iisc.ernet.in/) (map not to scale).

4 Field Survey and Testing

Geotechnical field survey and subsurface profiling plays an important role by providing suitable information for project planning and

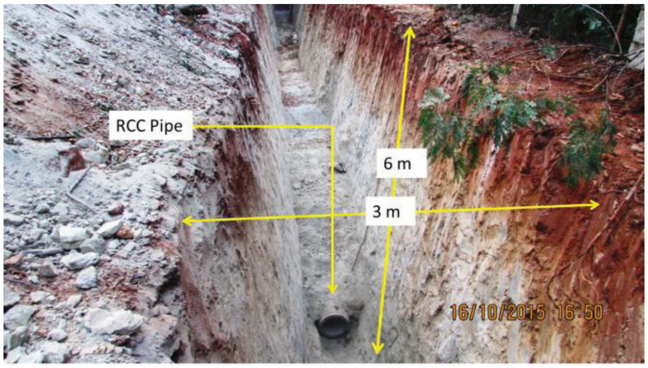

Fig. 3: Typical Excavated Trench Section of the Pipeline Project

design. In this study, an electromagnetic method of GPR and the seismic method of MASW with excavated cross section has been used to generate subsurface profiling of the different alignment.

4.1 Ground Penetrating Radar (GPR)

Ground penetrating radar is a low cost non-destructive geophysical investigation technique. It utilizes propagation of electromagnetic waves which identifies the change in the electromagnetic properties of the soil, which depends on the mineral content of ground material, moisture content and bulk density (ASTM D6432-11, 2011). It can precisely map the spatial domain of shallow subsurface objects and ground geology. It consists of four principal components, namely; display unit, control unit, receiver and transmitter. A wideband of electromagnetic waves with known centre frequencies is transmitted into the ground through a transmitter; the waves on encountering a change in electric conductivity or dielectric permittivity get reflected and they are received by the receiver and recorded as a function of time and stored for further processing. The interface at which the waves get reflected is considered to be the boundary between two geological layers/materials. Lower the centre frequency of the antenna greater will be the penetration depth, but with higher frequency comes higher resolution. GPR comes with varying frequencies that is from 10 MHz to 3 GHz. The current study was performed using Mala GeoSciences 25 MHz rough terrain antenna (RTA) (Figure 4a) and a Pro-Ex model 100 MHz ground coupled, bi-static and shielded ground penetrating radar antenna. The distance between the transmitter and receiver in 25 MHz RTA is 4 m and in 100 MHz is 0.5 m.

A small unexcavated section of the pipeline was selected for the survey as shown in the Figure 5. Two survey lines (Line I and II) each of different radar frequencies were selected for the

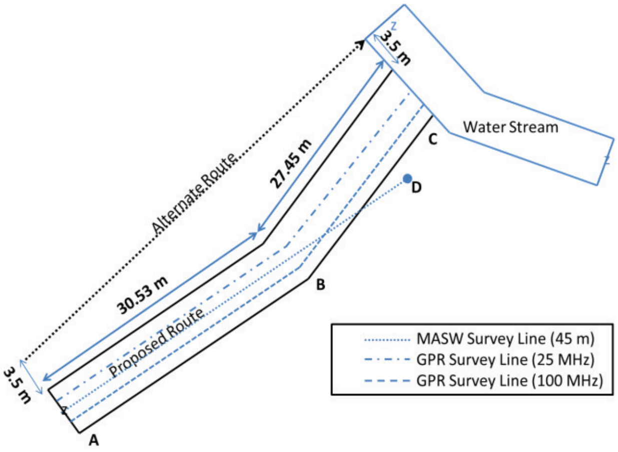

Fig. 5: Orientation of Geophysical Survey Lines, Line I (100) MHz, Line II (25) MHz GPR and Line III MASW survey lines at the site location

Fig. 4: (a) Field data acquisition using 25 MHz RTA on the site and (b) Typical field set for MASW survey

geophysical study. The geophysical survey was conducted in a small unexcavated stretch. As the width of the excavation was confined to 3 m, and since the area was surrounded by bushes a single run by both 25 MHz and 100 MHz antennas was performed. The profile length was measured using standard acquisition wheel for 100 MHz antenna whereas for 25 MHz RTA it was done through the hip chain. The survey lines started from the point 'A' where the excavation was stalled and it was conducted till a water stream (point C) over which the pipeline would pass. The survey, with 100 MHz antenna was done in two parts as there was a turn in the orientation of pipeline at point B. The emitting wave velocity for the survey was experimentally estimated by running a trial survey over a known buried anomaly (concrete pipe) in the study area and thesampling rate waskept about ten times the centre frequency of antennas for better resolution. The data acquired was then processed by Rad Explorer 1.41 software packages. The raw data was processed in a stepwise manner as follows: (1) D C Removal which removes the constant component of the signal (2) Time zero adjustment to adjust the vertical time scale in order to set the actual emitting time of wave from the antenna (3) Background removal to remove the background noise due to instrument clutter (4) Bandpass filter to increase the signal to noise ratio, (5) Amplitude correction to apply automatic gain control to the signal and (6) Hilbert transform to convert radar trace in instantaneous amplitude. Subsurface profiles and comparison of results with excavated location is discussed in the next section.

4.2 Multichannel Analysis of Surface Wave (MASW)

MASW, an in-situ non-destructive method uses frequency dependent properties of horizontally travelling surface waves (Rayleigh) for visualization and characterization of sub-surface lithology (Park et.al., 1999). In this study an MASW setup consisting of 4.5 Hz, 12 geophones and a 24-channel geode seismograph has been used to obtain a 2D Vs profile of the section of unexcavated trench. The seismic waves at the site were created by an active source by impounding a 15 pound sledge hammeron a 300 mm × 300 mm mild steel plate of 1 inch thickness. A stack length of 10 shots or hits were taken for recording the data set. The geophone spacing was kept at 1 m and the shot location was kept at 5 m from the last geophoneto obtain the best achievable signal-to-noise ratio. The survey was repeated in the forward direction to get 2-D shear wave velocity profile across the length. The linear orientation of the MASW survey line can be seen in Figure 4b and Figure 5 (section A - D). The wave data, thus recorded by vertical geophones were then processed by SurfSeis software to obtain a 2-D shear wave velocity profile across the length in three simple steps as follows: 1) Application of Fourier transformation to convert the wave signal from time to frequency domain. 2) Dispersion-curve analysis and 3) Inversi

5 Subsurface Profiling and Discussion

5.1 Line I (100 MHz antenna)

The line I was conducted in two parts, first part from point A to B of 30.5 m and the second part from point B to C ranging 27.5 m. The final radargram for a survey line from point A to B is given in Figure 6 (a) - (b) in which (a) represents the radar image in distance versus depth plot and (b) shows the reflection strength/ signal strength envelope for the radargram. Figure 7 (a) and (b) depicts the lithology of the section A – B after partial and full excavation which in confirmation with the radargram in Figure 6 (a) and (b). Figures 8 (a) and (b)represent the radargram and reflection strength profile for section B – C for line I respectively.The reflection strength is obtained by performing Hilbert transform over the radar trace. The reflection strength is typically the variation of instantaneous amplitude of the radar wave over the distance and depth. The instantaneous amplitude helps in identifying and differentiating soil lithology through higher and lower values of signal amplitude as the amplitude

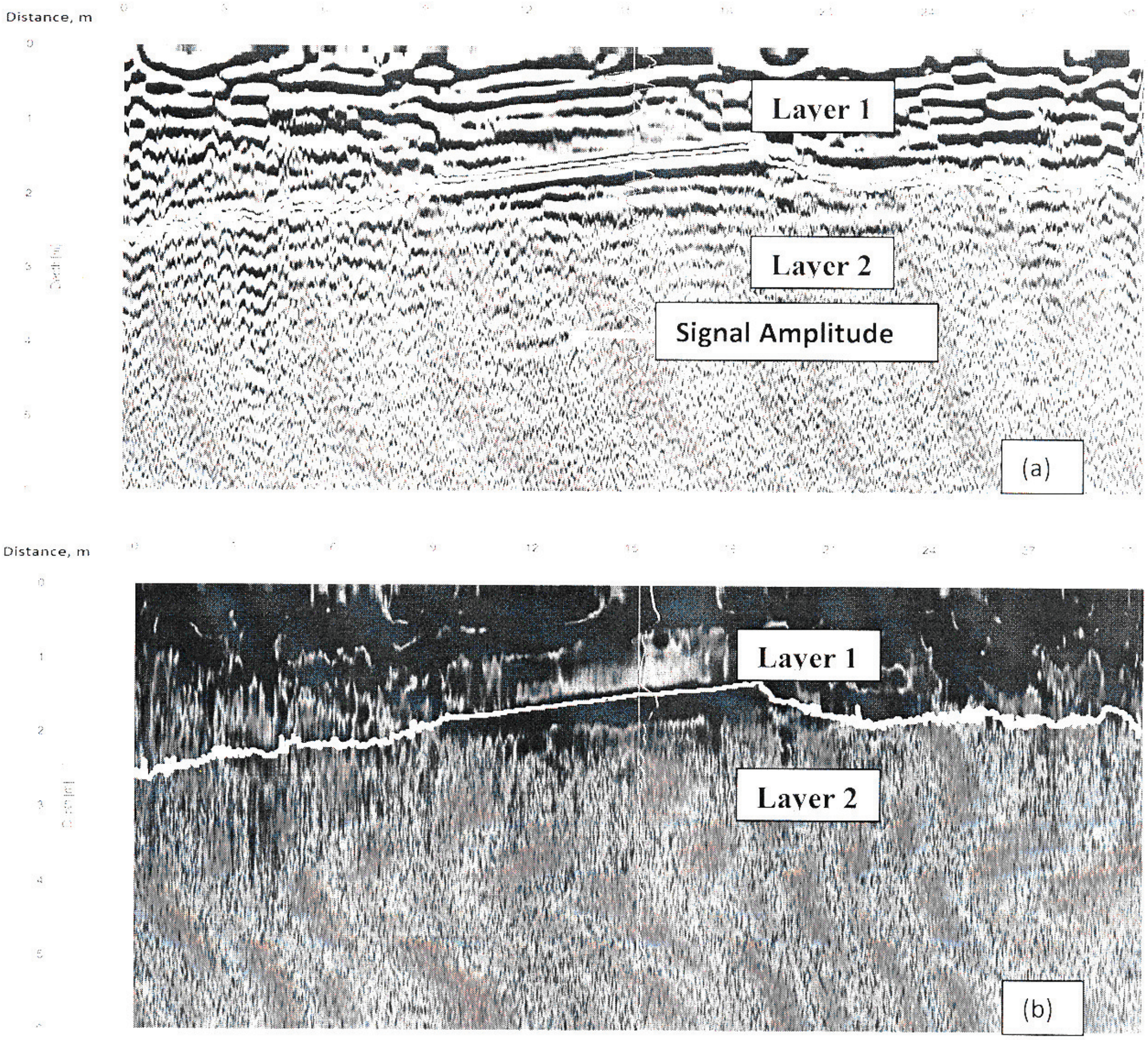

Fig. 6 (a): 2D radargram of line I from point A to B depicting distance (x-axis) v/s time (y-axis) scale with identification of layers, and (b) 2D GPR section of line I showing separate layers on the basis of reflection strength

of electromagnetic wavesare higher in porous or softer media as compared to dense media like rocks.In Figures 6 (a) and 8 (a) it can be observed that there is a strong reflection in the signal trace at the soil and rock interface. Similarly, in Figures 6 (b) and 8 (b) a peak is observed in the trace amplitude for signal strength. The first peak in both the traces is observed due to interaction from air to ground, whereas the second peak is due to the interaction of the wave at the soil and rock interface. Hence, this way the layers of soil and rock can be identified. In section A – B from Figure 6 (a) and (b) two layers are observed where layer 1 has a thickness varying from 1.5 m to 2.5 m which is identified as red soil below which layer 2 exits and is assumed to be hard rock up to the depth of excavation i.e., 6 m. Similarly, in Figure 8 (a) and (b) two layers are identified with layer 1 having an average thickness of 2.5 m from the surface below which layer 2 exits which is hard or weathered rock. Also an average signal penetration depth of 4 m is observed in both the sections for 100 MHz radar, which may be due to the presence of clay content in the red soil which is mainly present in the study area. As clayey soil has the ability to trap water, which attenuates the electromagnetic signals and reduces the penetration depth.

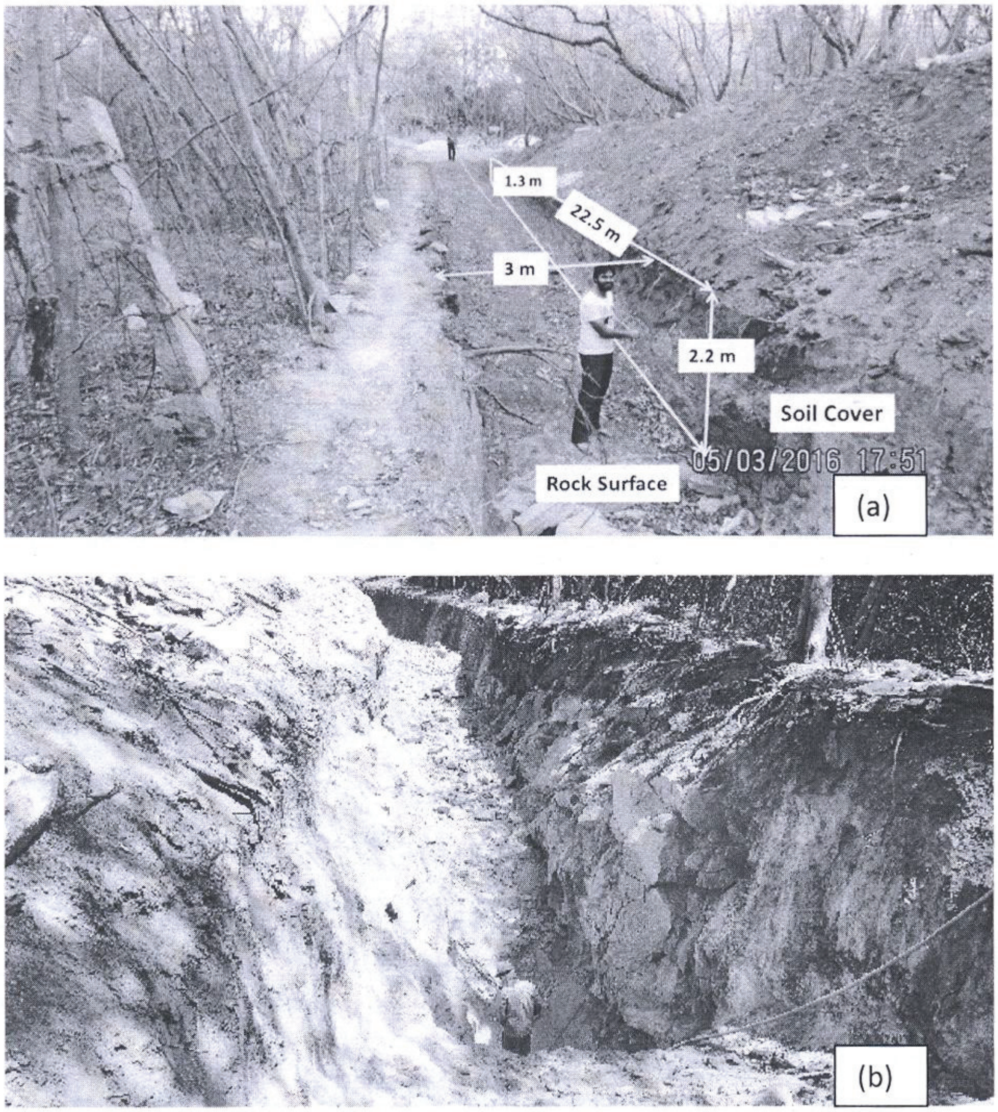

Fig. 7: (a) On-site actual cut-section from point A to B after removal of overburden and (b) Lithomeric section A-B post excavation

Further, in Figure 8 (a) the hyperbolic signature observed at the top and at 2.5 m depth in the centre of the radargram is due to small underground conduit. This identification helps in planning, preventive steps during excavation over the region so that the buried structure is not damaged. In both the section of line 1 two typical layers were observed, whichwere found in close context with the actual lithological situation on excavation.

5.2 Line II (25 MHz RTA)

Line II was surveyed by 25 MHz RTA in a continuous run from point A to C and was measured around 52 m. The difference in length of line I and II is due to high unevenness of ground surface. The final GPR radargram of line II is shown in Figure 9 (a) which depicts the subsurface profile through a 25 MHz RTA. Two typical layers can be ascertained from the radargram namely layer 1 and 2 on the basis of strong reflection at the interface. Figure 9 (b) represents the reflection strength of the radargram which is obtained by performing Hilbert transform over the radar trace. Here layer 1 has a thickness varying from 4 m to 6.5 m below which layer 2 exits which is weathered granite and is found up to the depth of excavation that is up to 6m from the surface. It can be observed from the

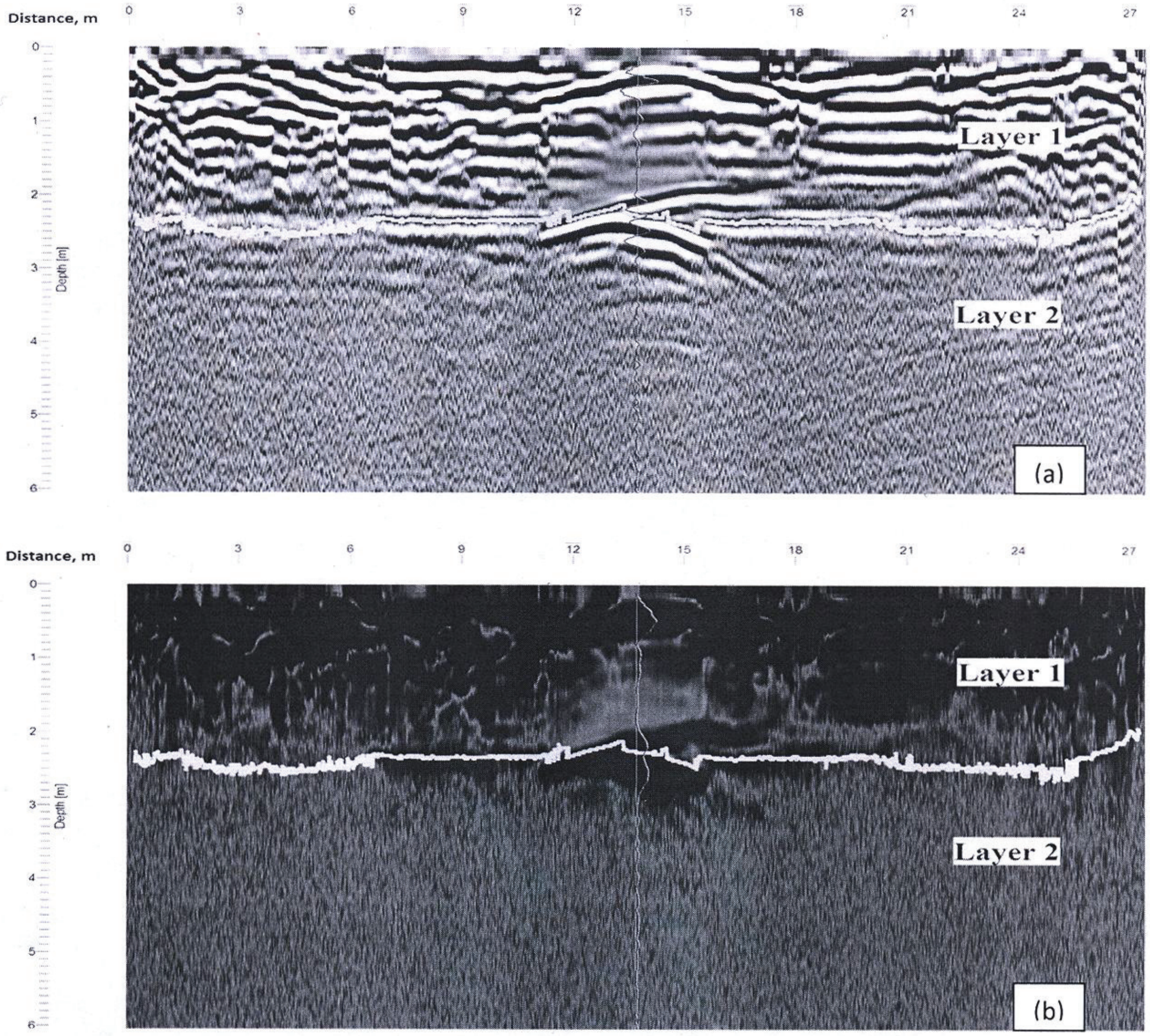

Fig. 8 (a): 2D radargram of line I from point B to C depicting distance (x-axis) v/s time (y-axis) scale; (b) 2D radargram of line I from point B to C depicting showing separate layers on the basis of reflection strength

radar images that thin and shallow lithological boundaries cannot be identified precisely with low frequency radar antenna (25 MHz) as compared to higher frequency radar antenna (100 MHz) hence much lithological detail cannot be obtained from the radargram.Also the presence of ditch at shallow depth is not observed in the radargram which is clearly identified by the higher frequency antenna.

5.3 2-D MASW Profile

The MASW survey was performed along the survey line A – D using multiple shifts to obtain a 2D Vs profile of 45 m length. The curves were obtained by performing dispersion analysis over a fixed range of 10-50 Hz. On integration and inversion of all the curves a 2D shear wave velocity versus depth profile for 45 m length and10m depth was obtained as shown in Figure 10. The section is further divided into a2-layered structure by black dotted line based on the shear wave velocity ranges. These boundaries have been delineated based onthe range of Vs values considered by Anbazhagan and Sitharam (2009) based on Bengaluru data. According to the study done by Anbazhagan and Sitharam (2009)

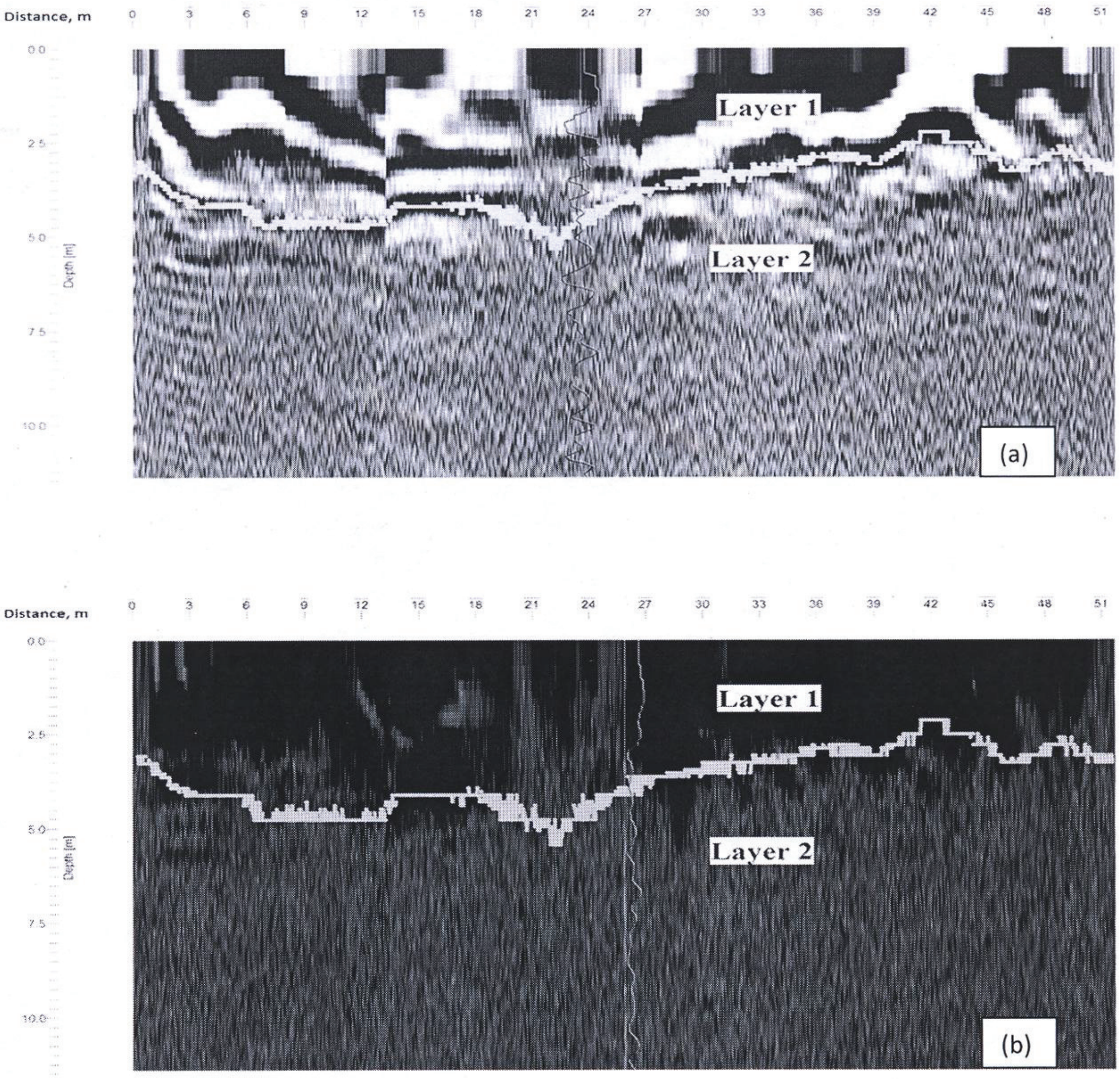

Fig. 9 (a): 2D radargram of line II for section A-C depicting distance (x-axis) v/s depth (y-axis) scalewith identification of layers and (b) 2D GPR section of line II representing showing separate layers on the basis of reflection strength

Vs values for the overburden red soil is less than 360±30 m/s, for weathered and hard rock is above 360± 30 m/s. Based on these values, the top layer, i.e. layer I 1.5 – 2.3 m thick can be classified as the red soiland layer below this can be called as layer II withVs values of 330 to1800 m/s which represents weathered rock and hard rock. Also, it can be observed from Figure 10 that at a depth of 8 m below a more dense or rigid material is present confirming to the much higher shear wave velocity at higher depths.

Also the depth to bed rock obtained from the current study is in conjunction with bedrock map given by Anbazhaganand Sitharam (2009), which provides a confirmation of shallow bedrock in the proposed project area.In this study on comparing the GPR and MASW images it is found that the Vs profile is in much conjunction with the radar images.Though the boundaries between the layers and volume of earthen material cannot be determined during MASW data accurately, but the shear wave velocity of the region gives an

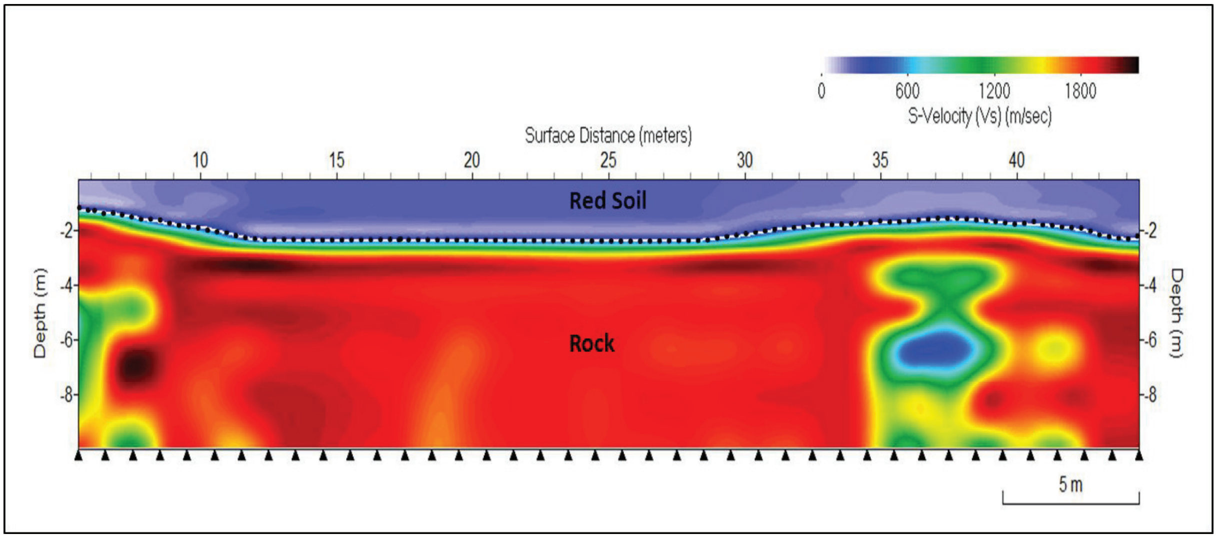

Fig. 10: 2-D shear wave velocity profile along the survey length

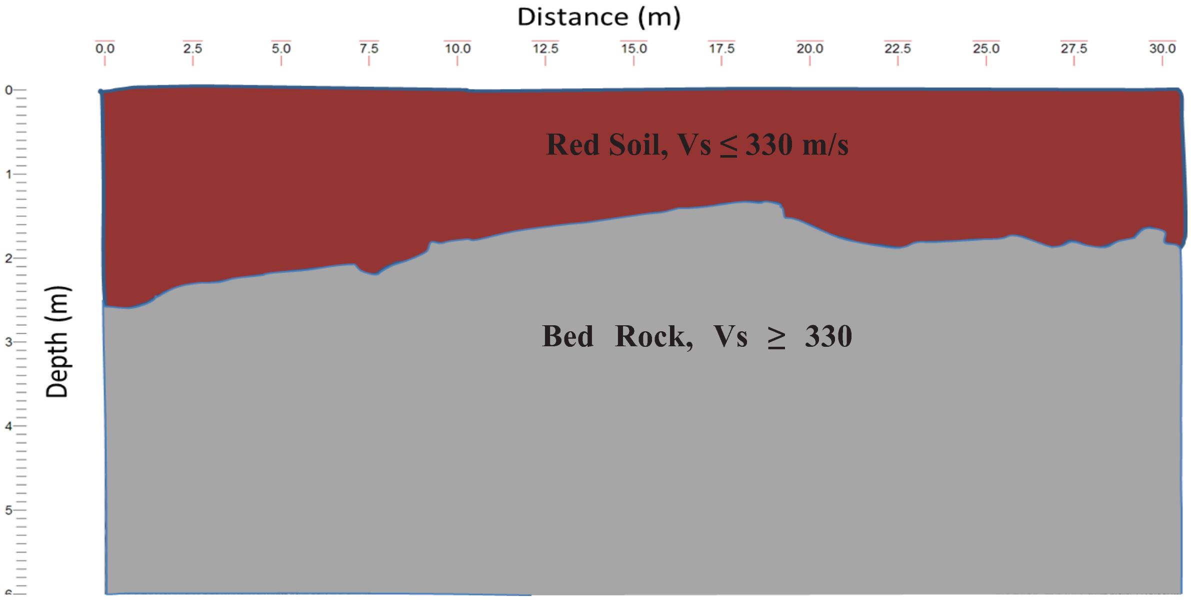

Fig. 11: Integrated subsurface profile for Line I for cost estimation

idea about the density, rigidity and the type of material which cannot be ascertained from the radar results. This demonstrates the credibility of using more than one or integrated geophysical technique for subsurface characterization.

Similarly GPR and MASW survey was carried outin alternate alignments, so that alternate route with lesser or deeper rock presence can be proposed to save excavation cost. In this study it was observed that the soil depth kept reducing on the right side of proposed alignment and slightly /no variation in the left side of proposed alignment. By considering gravitational flow, slight alteration is given in the proposed alignment and cost estimation of old proposed and newly proposed alignmentis almost similar.

6 Subsurface Profile and Cost estimate

The results obtained from geophysical surveys are integrated to generate a final subsurface profile of the proposed alignments (Figure 11). It has

Table 1: Calculation of percentage escalation of actual cost from the estimated cost.

Case	Description				Amount Rs. Ps.
	Earthwork excavation for foundation of buildings, water supply, sanitary lines and electrical conduits either in pits or in trenches 1.5 m and above in width, in **hard soil**.		Excavation 1.5 m and above in width in **hard rock** by chiseling and/ or wedging where blasting is prohibited for foundation of buildings, sanitary lines and conduits either in pits or in trenches.		
	Quantity (cum)	Rate Rs. Ps.	Quantity (cum)	Rate Rs. Ps.	
Actual based on this study	151.875	245.00	253.125	1096.00	3,14,634.375
Old Estimated	405	245.00	0	-	99,225.00
	Percentage escalation from estimated cost				**217.09 %**

been found that the actual subsurface condition is in contrast to the one assumed for estimation of the excavation work. Hence, to validate the benefits of performing a preliminary geophysical survey before executingthe excavation work, the section obtained from Figure 11 is considered and the cost of excavation as per the assumed lithology and observed lithology is estimated. The volume is calculated for a trench of 22.5 m long x 3 m width x 6 m height. From Figure 11 the depth of soil at origin point is 2.5 m, whereas at the termination point it is 2.0 m. The volume is estimated as per 2-D section in Figure 2 with constant width.

The unit rates for excavation are taken from the government prescribed Karnataka Schedule of Rates for Building Works (KSRB) for typical cases of excavation in soil, hard soil, soft rock and rock. As per the schedule it cost **Rs. 245.00** per cubic metre of earthwork excavation, including dressing the bottom and sides of pits and trenches, stacking the excavated soil clear from the edges of the excavation for foundation of buildings, water supply, sanitary lines and electrical conduits in **hard soil, whereas** for performing the above mentioned work in **hard rock** by chiseling and/or wedging it costs Rs. 1,096.00 per cubic metre, which is almost five times higher. From Table 1 it can be observed that a **217.09 %** hike in the cost of execution of the excavation work occurred due to lack of geotechnical data and improper planning. The comparisons prove the importance of conducting preliminary geotechnical and geophysical investigations prior to the planning and execution of any civil construction work. This study shows that project executed without proper subsurface exploration in shallow bedrock region lead into problem of additional cost and delay. Time and cost required for integrated subsurface investigation are less than the cost associated with delay of the project. Similar studies are widely used in most countries; however, these tools and methods are not widely utilized and available in India.

7 Conclusions

The growing importance of integrated subsurface investigation prior to the planning and execution of civil construction work has been presented with typical case study for the sewage pipeline project in the shallow bedrock region. The study has been carriedout at a site of a stalled sewage pipeline project. The project was stalled due to presence of rock during excavation work, which was not specified in the tender document and planned estimate. The geophysical survey was carried out using ground penetrating radar (GPR) and multichannel analysis of surface waves (MASW) at unexcavated sections of alignment to profile the subsurface soil and rock layers and estimate the precise soil and the rock volume for excavation to assess the cost of excavation and provide an alternate route for alignment if any. The results from the survey were compared with the actual ground results and 2-D subsurface profile was generated by integrating GPR and MASW 2-D profile. A volume of soil and rock to be excavated was calculated and compared with the old estimated cost. The cost of excavation was obtained from integrated subsurface profile and compared with the tendered or estimated cost. In comparison, it was found that the actual cost of excavation exceeded the estimated cost by 217.09%, which is more than twice the original estimated cost. From the results it can be concluded that performing integrated subsurface prior to planning or executing a project, provides knowledge of the geophysical or geotechnical properties of the site area which helps in estimating the exact cost of excavation, planning the orientation of the alignment and efficient use of time, manpower and machine also accidental damage to subsurface utilities as well as excavation machinery can be avoided. More accuracy in volume calculation can be obtained by performing GPR surveys in grid patterns for 3D visualisation.

References

1 Alvin K. Benson, 1995, “Applications of Ground Penetrating Radar in Assessing Some Geological Hazards: Examples of Groundwater Contamination, Faults, Cavities, *Journal of Applied Geophysics,* 33: 177-193.

2 Anbazhagan P. and Sitharam T. G., 2009, “Spatial Variability of the Depth of Weathered and Engineering Bedrock using Multichannel Analysis of Surface Wave Method”, *Pure and Applied Geophysics*, 166: 409–428.

3 Anbazhagan P, Anjali U, Sayed SR Moustafa and Nassir S.N. Al-Arifi (2016) "Correlation of Densities with Shear Wave Velocities & SPT N Values" *Journal of Geophysics and Engineering*, 13, 320–341. doi:10.1088/1742-2132/13/3/320.

4 ASTM D6432-11,“Standard Guide for Using the Surface Ground Penetrating Radar Method for Subsurface Investigation”, ASTM International, West Conshohocken, PA, 2011.

5 Binder D., Brückl E., Roch K. H., Behm M., Schöner W., Hynek B., 2009, “Determination of Total Ice Volume And Ice-Thickness Distribution of Two Glaciers in the Hohe Tauern Region, Eastern Alps, From GPR Data”, *Annals of Glaciology* 50(51).

6 Choon B. Park, Richard D. Miller, and Jianghai Xia, 1999, “Multichannel Analysis of Surface Waves”, *Geophysics*, Vol. 64, No: 800-808, 7 FIGS.

7 Doolittle, J.A., and M.E. Collins. 1995. “Use of Soil Information to Determine Application of Ground Penetrating Radar”, *Journal of Applied Geophysics*. 33:101–108.

8 Eric B. Sucre, John W. Tuttle, and Thomas R. Fox, 2011, “The Use of Ground-Penetrating Radar to Accurately Estimate Soil Depth in Rocky Forest Soils”, *Forest Science*, 57(1).

9 Greg Stump, 2004, “Subsurface Imaging System and Method”, *United States Patent*, Patent No. US 6701647B2.

10 Jeffrey J. Lew, 1997,“Subsurface Utility Engineering: An Initial Step in Project Development”, *Journal of Construction Education*,Vol. 2: 109 – 118.

11 James S. Mellett, 1995, “Ground Penetrating Radar Applications in Engineering, Environmental Management, and Geology”, *Journal of Applied Geophysics*, 33: 157-166.

12 Koya Suto and Brendon Scott, 2009, “3d Treatment of MASW Data for Monitoring Ground Improvement at Uncontrolled Fill Sites”, *Proceedings of the 9th SEGJ International Symposium*, Sapporo, Japan.

13 Lawrence B Conyers, Eileen G. Ernenwein, and LeighannBedal, 2002, “Ground Penetrating Radar (GPR) Mapping as a Method for Planning Excavation Strategies, Petra, Jordan”, *Society for American Archaeology,* e-tiquity Number 1, ISSN 1541-5465.

14 Ligas P., Palomba M., 2006, “An Integrated Application of Geological–Geophysical Methodologies as a Cost-efficient Tool in Improving the Estimation of Clay Deposit Potential: Case study from South-Central Sardinia (Italy)”, Ore Geology Reviews 29: 162–175.

15 Pierre-Luc Dallaire and Michelle Garneau, 2008, “The Use of a Ground-Penetrating Radar (GPR) to Characterize Peat Stratigraphy and Estimate the Carbon Pool in a Boreal Peatland, Eastmain Region, James Bay, Québec, *Canada”,12th International Conference on Ground Penetrating Radar*, Birmingham, UK.

16 Rey J., Martínez J., Vera P., Ruiz N., Cañadas F. and MontielV., 2015, “Ground-Penetrating Radar Method Used for the Characterisation of Ornamental Stone Quarries”, *Construction and Building Materials*, 77: 439–447.

17 Saarenketo, T. 1998. “Electrical Properties of Water in Clay and SiltySoils” *Journal of Applied Geophysics*, 40:73–88.

18 Schokker A. J., Laman J. A. and Srivistava A., 2008, “Sinkhole Void Grout Treatment”, Final Report, The Thomas D. Larson Transportation Institute, The Pennsylvania State University.

19 Steven A. Arcone, Daniel E. Lawson, Allan J. Delaney, Jeffrey C. Strasser, and Jodie D. Strasser, 1998, “Ground-Penetrating Radar Reflection Profiling of Ground Water and Bedrock in an Area of Discontinuous Permafrost”, *Geophysics*, Vol. 63, No. 5: 1573-1584, 13 FIGS.