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Comprehensive Geophysical Assessment of Complex Geological Terrain in Kadapa Basin, India

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ABSTRACT

Traditional geotechnical investigation consisting of drilling many of boreholes, soil sampling and lab testing becomes uneconomical and time consuming for large and geologically intricate areas. In such cases, non-destructive geophysical surveys offer a time-efficient and economical solution, simultaneously providing an extensive areal coverage of subsurface profiling of geotechnical and geophysical properties. For the estimation of subsurface properties, three geophysical methods were employed in this study, which consisted of Ground Penetration Radar (GPR), Electrical Resistivity Tomography (ERT), and Multi-Channel Analysis of Surface Waves (MASW). Thus, the sub surface's shear wave velocity profiles and apparent resistivity profiles were obtained. In the shallow depths, discontinuities and fractures were studied using electromagnetic radargrams from GPR. These tests were complemented with borehole exploration at the site. Results obtained from surface-based methods were validated against bore log data and visual observation of surface terrain. Subsequently, bore logs were integrated with the geophysical survey results to construct an integrated subsurface profile. The integrated subsurface profiles presented a three-layer subsurface structure consisting of dense gravelly sand in the top 1m, followed by strong rock formations and, ultimately, very strong fractured rocks. The extent of fracture in the rocks was studied using samples obtained from boreholes and available trenches at the test location. These findings helped compare the three methods and their applicability in delineating different subsurface layers in this study. GPR proves to be effective at shallow depths, while ERT and MASW help investigate deeper layers better. Further, this study offers critical insights for site characterization and engineering decisions in complex geological environments, improving the knowledge base of efficient and reliable subsurface evaluation techniques.

Keywords: Integrated Subsurface Profile; Ground Penetration Radar (GPR); Electrical Resistivity Tomography (ERT); Multi-Channel Analysis of Surface Waves (MASW).

1. Introduction

Understanding the soil beneath the surface is one of the most critical steps in designing any structure. Two approaches are commonly employed to achieve this purpose: Geotechnical and Geophysical methods. The former involves drilling boreholes, collecting samples, transporting them to the laboratory, and evaluating their engineering properties. This method consumes time and provides points data, which requires several drillings in the complex subsurface and these are time-consuming processes and are uneconomical. However, it is used often due to accuracy in results, whereas the latter involves studying a larger area in a short interval without disturbing the soil profile. There are some instances where geophysical methods prove to be more effective than geotechnical methods. In Oran, Algeria, a residential and commercial complex area with a considerable cavity size that went unnoticed despite geotechnical investigation. However, it was discovered later due to a detailed geophysical investigation (Haydar Baker et al. (2015)). However, after several years, the area was affected by differential settlements and cracks. Geophysical tests revealed that the area was built on a landfill site, as per the case studies discussed by Haydar Baker et al. (2015). A similar kind of problem was resolved by Anbazhagan et al. (2017) when a new sewage line was planned to lay. In the project after executing 25% of the excavation work, they encountered weathered and hard rock, which caused the project cost to escalate drastically and delay. To overcome the problem, the authors used geophysical methods (Ground Penetrating Radar and Multi-Channel Analysis of Surface Waves), with the help of which they could delineate the soil profile and re-estimate the project cost.

According to Ibrahim Adewuyi et al. (2018), the geophysical method is a helpful technique in reducing time and cost when compared to drilling boreholes. The geophysical tests will also provide the dynamic properties of the soil such as Young's modulus, Shear modulus. However, to evaluate the engineering properties of the soil, the execution of geotechnical methods is a must, as conventional borehole drilling provides samples for detailed lab testing, and direct approximation of soil state in SPT and core recovery. Researchers globally used both methods to understand the soil profile under various circumstances. Lucas et al. (2017) were able to get essential information and validate the reason behind the deformation of the downstream slope of the Meretschibach Catchment, Swiss Alps, using

Electrical Resistivity Tomography (geophysical method) and monitoring of long-term geotechnical parameters like Soil temperature, suction as well as volumetric water content using Time Domain Reflectometry sensors. Sadegh Rezaei et al. (2018) estimated the geotechnical and geophysical parameters at the Narges Chal landslide in Iran. Further, they noticed a strong correlation between SPT-N value and electrical resistivity value and a very strong correlation between SPT-N value and shear wave velocity. Recently, researchers started performing geophysical tests and developing an integrated profile at various locations. Shaaban et al. (2013) used multi-channel analysis of surface wave (MASW), ground-penetrating radar (GPR), and 2-D electrical resistivity tomography (ERT) tests to detect the reasons behind the deterioration of various buildings located in the flood plain of the Nile River, Cairo. Similarly, Chandran et al. (2017) conducted GPR and MASW tests at two locations in Bangalore, India, developed an integrated profile, and compared it with borehole data. They observed that comparing geophysical and geotechnical techniques proves efficient, fast, and economical. Most of the study was limited to residual soil or filled-up soil areas, and very limited work is available for complex geological regions like Kadapa Basin.

In the present study, the subsurface investigation was conducted at a location proposed for the construction of an integrated steel plant in Kadapa district, Andhra Pradesh, India. Thus, a detailed investigation of the subsurface was desired using multiple geophysical and geotechnical methods. At two test locations in this geologically complex site, an integrated 2D subsurface profile is determined using Ground Penetrating Radar (GPR), 2D Multi-Channel Analysis of Surface Waves (MASW) and 2D Electrical Resistivity Tomography (ERT). Finally, the findings derived from geotechnical data are compared with the integrated profile.

2. Study Area

The study area is in Kadapa District, which is famous for the Cuddapah basin in Peninsular India (Fig. 1 and 2), which is considered as geologically complex (Saha (2002), Somasekhar et al.(2018)). The Cuddapah Basin dates to the Paleoproterozoic era. The site of interest comes under the geological formation of Gandikota Quartzite, which contains quartz with K-feldspar. The basin area was subjected to a few minor intraplate earthquakes of local magnitude 3 to 3.5 (Utpal and Rai, 2017). Roy Chowdhury and Hargraves (1981) clearly stated that the region is seismically active.

The study focuses on two specific locations, as shown in Fig 3. Geophysical tests, including Ground Penetration Radar (GPR), Electrical Resistivity Tomography (ERT), and Multi-Channel Analysis of Surface Waves (MASW), are conducted at both locations. At location 1, the tests covered a lateral spread of 400 m. In contrast, at location 2, the tests are constrained to a lateral spread of 100 m due to spatial limitations.

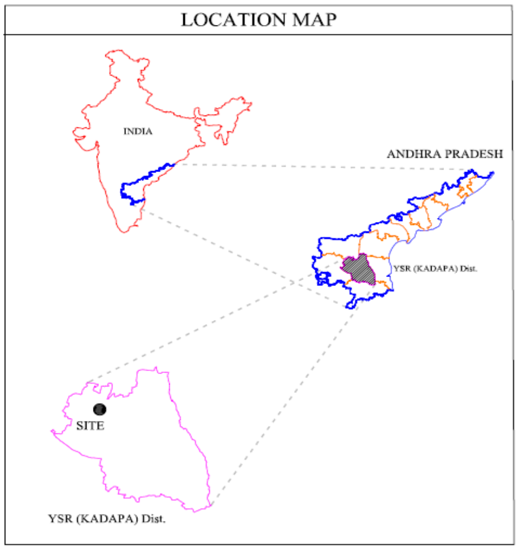


Figure 1. Location of the test site in India

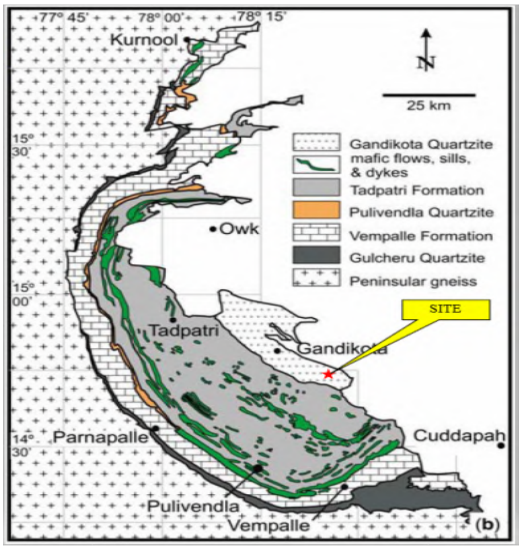


Figure 2. Geological Map of the Cuddapah Site

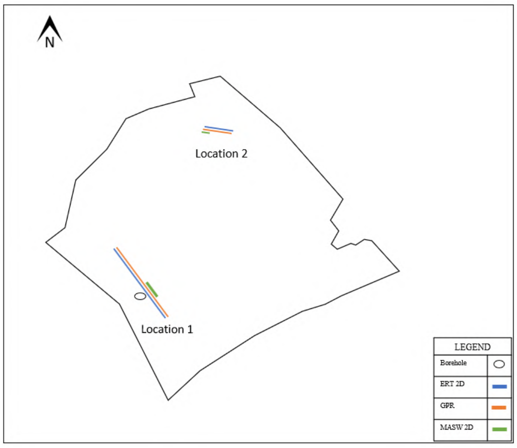


Figure 3. Study Area

3. Testing Methods

Many researchers like Roy Chowdhury and Hargraves (1981), Kumar et al. (2012), and Utpal and Rai (2017) clearly stated that the study area is seismically active and as per Anbazhagan et al. (2013), site-specific studies are needed to assess any hazards as the current seismic code IS 1893(2016) does not reflect the hazard values. The conventional borehole drilling and sampling method at this site may not be practical due to shallow near-surface bedrock. Hence, non-destructive geophysical tests GPR, ERT and MASW are used in the present study and at a later stage, the results are compared with the available bore log.

GPR is an Electromagnetic (EM) method used to detect Subsurface strata using dielectric contrasts. The GPR device consists of a transmitter which radiates EM waves, and then an in-house receiver detects the reflected waves from subsurface contrasts. The resulting radargram is processed for delineating layers. More details about GPR used in the study can be found in Anbazhagan et al (2018). Electrical Resistivity Tomography (ERT) assesses the electrical resistivity of subsurface layers by passing current through them and measuring potential differences. This process yields a 2D soil profile, showing the variation of resistance with depth. Multi-Channel Analysis of Surface Waves (MASW) is a surface wave test to capture dynamic soil properties. The procedure involves generating surface waves at a source and recording them with 24 geophones evenly spaced at 1m intervals, which act as receivers. The recorded data is then processed to create a site-specific dispersion curve. This dispersion curve is employed to ascertain the subsurface shear wave velocity profile through an iterative nonlinear inversion process.

Initially, at location 1, GPR, ERT, and MASW tests are conducted. A borehole is drilled near location 1, as depicted in Figure 3, to validate the results. Later, location 2 is chosen due to the exposed side of the terrain, facilitating more accessible validation of geophysical tests, as illustrated in later figures. The profiles generated from different tests are used to develop a single Integrated Subsurface Profile to obtain more reliable information (Chandran et al. 2017; 2020).

In the present study, the profiles derived from ERT, GPR and MASW are integrated to generate a subsurface profile at each location, and these profiles are compared with the borehole data and geologically exposed terrain of the sites.

4. Results and Discussion

4.1 Ground Penetrating Radar Survey

The GPR survey is conducted as per ASTM D6432-11 at two locations 1 and 2, as shown in figure 3. In the present study, antennas of 80 MHz/ 100 MHz is used for scanning deeper depths and antennas of 500 and 250 MHz for shallow depths. At location 1, the survey line extends for a distance of 400 m, whereas it is 100 m at location 2 due to site constraints. Figs. 4 and 5 shows the final processed radargrams obtained at locations 1 and 2 after applying filters. The following observations can be made from Fig 4. – Variation of soil thickness with lateral distance, the entire soil profile is delineated into three layers - the first layer ends at 1 m depth, layer 2 extends to a depth of 2.3 m, and layer 3 spans from 2.3 m to 18 m. The top layer seems to represent a dense material, layer 2 is a strongly fractured rock based on strong reflections, and the final layer signifies the presence of very strongly fractured rock due to consistent reflections in the radargram. Similarly, Fig. 5 represents the GPR radargram of location 2, and it shows the presence of three layers – the first layer extending up to 1m with dense kind of material, followed by strong rock, till 2.5 m noticed by strong reflections and finally, the last layer reaching till 20 m with fractured rock.

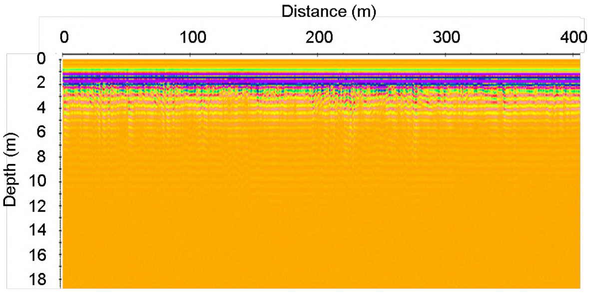


Figure 4. Radargram at Location 1

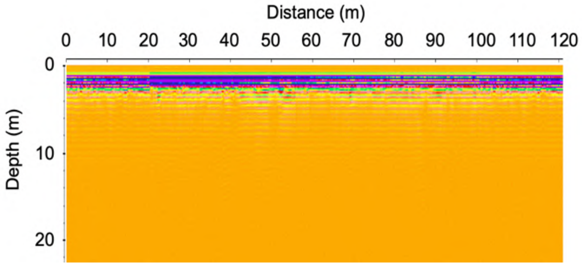


Figure 5. Radargram at Location 2

4.2 Electrical Resistivity Tomography Survey

The Electrical Resistivity survey is conducted as per ASTM D6431-99 and IS 15736:2007 at the exact locations as the GPR survey. The test results are processed using RES2DINV software, and the final 2D ERT profiles are shown in Figs. 6 and 7 for locations 1 and 2, respectively. The 2D ERT profile shows the variation of soil resistance with depth and lateral distance. Figure 6 shows that the stretch extends for a distance of 400 m and a depth of 60m. The delineation of Soil profile at location 1 is typical as it involves complex terrain. For a lateral distance of 130m, the soil profile is classified into 2 layers, considering the average resistivity values. The first layer, extending to a depth of 26m, comprising of dense soil with resistivity values ranging between 65-1000Ω-m. Following this, layer 2 primarily consists of Very strong fractured rock with resistivity values of 1000-1986Ω-m. Moving further along the lateral distance, from 130m to 400m, the soil profile is characterized into 3 layers. Layer 1 persists till 17m, predominantly consisting of Very strong fractured rock with pockets of hard rock and the resistivity value ranges from 1011-15047Ω-m. Layer 2 extends to a depth of 45m encompassing layers of dense soil and Strong rocks, with resistivity values lies in between 515-1986Ω-m. Finally, the last layer comprises of strong to very strong rocks due to resistivity values of 1011-3901Ω-m.

In the same way, Fig. 7 depicts the soil profile at location 2 for a distance of 100m and extends for a depth of 15m. From the profile, the subsurface can be delineated into three layers based on their resistivity values. Layer 1 extends for a depth of 8m with resistivity values varying from 996 – 1964Ω-m, indicating strong to very strong fractured rock with pockets of hard rock in between with a resistivity value of 7645Ω-m. Layer 2 extends for a depth of 12m with resistivity values ranging from 65.7-505Ω-m indicating dense soil presence and at a distance of 33m from the array, a pocket of low resistivity material can be noticed. Finally, layer 3 extends for 15m depth with a resistance value of 505-1964Ω-m, resembling very strong fractured rock.

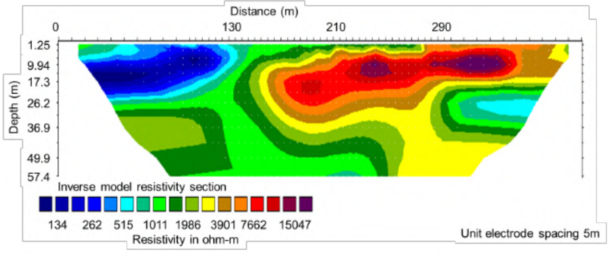


Figure 6. Electrical Resistivity Profile at Location 1

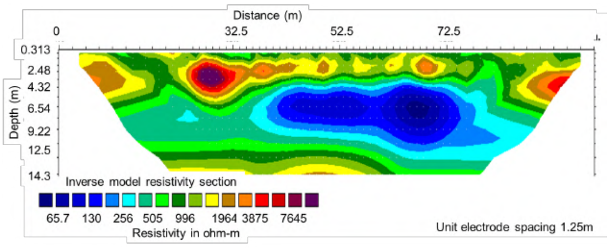


Figure 7. Electrical Resistivity Profile at Location 2

4.3 Multi Channel Analysis of Surface Waves Survey

This subsurface technique is generally used to map the variation of shear wave velocity with soil depth. These shear wave velocity profiles can then be used to determine seismic site class and amplification response of the region. The present study considers the exact locations of GPR and ERT. However, MASW at location 1 starts at a distance of 140m away from the other test lines and terminates at 180 m, covering a 20m distance on either side of the borehole, as shown in Fig. 3. For location 2, the MASW profile needs to be terminated at a distance of 40m from the array beginning due to spatial constraints. The data obtained from the tests are processed as discussed in section 3, and the final 2D inversion curve is shown in Fig. 8 and 9 for locations 1 and 2, respectively. Fig. 8 shows an increase in shear wave velocity with an increase in depth. The first layer terminates at an average depth of 5.5 m with a shear wave velocity of 400 m/s, resembling the presence of very dense soil, followed by another layer extending up to 14 m, representing strong fractured rock. Finally, the depth beyond 15 m is the beginning of hard rock as its average shear wave velocity starts from 1200 m/s. Similarly, Fig. 9 shows three layers at location 2 with abnormalities due to the complex nature of the site. The subsurface layers do not have uniform thickness. Layer 1 exhibits an average shear wave velocity of 400 m/s, showing the presence of very dense material, followed by layer 2, with an average shear wave velocity of 800 m/s, implying the presence of strong fractured rock. Finally, the third layer depicts the presence of very strong fractured rock with high shear wave velocity greater than 1000m/s.

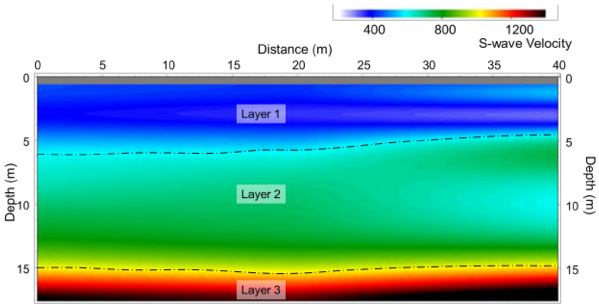


Figure 8. MASW 2D Profile at Location 1

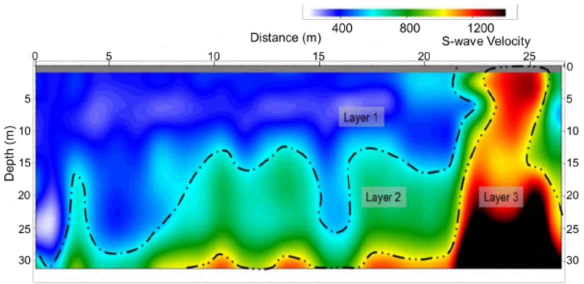


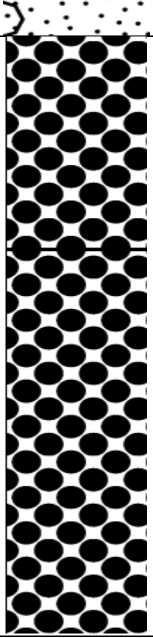
Figure 9. MASW 2D Profile at Location 2

4.4 Borehole Investigations

As described in section 3, to validate the results obtained from geophysical tests, a borehole is drilled at location 1, and for location 2, the subsurface itself is exposed in a trench nearby. Table 1 details the borehole, while Fig. 10 displays the exposed section of location 2. The following observations can be made from Table 1 - The soil exhibits a highly dense nature up to a depth of 1 m. Beyond this depth, the substrate transforms into strong to very strong fractured rock, impeding further drilling progress. Consequently, the borehole is terminated at a depth of 4.5 m.

Fig. 10 displays the intricate geological composition of the site, showcasing the exposed terrain at location 2. The soil profile, delineated by lines in the figure, reveals distinct layers. The uppermost layer signifies the presence of densely packed sand with a gravel composition (not visible in the picture). Subsequent layers consist of strong to very strong fractured rock, followed by very dense soil with weathered rock composition and fissured rocks. The profile concludes with the reappearance of very strong fractured rock.

Table 1. Bore log Datasheet at Location 1

Depth	Soil Profile	Stratum Pen (m)	Soil Description
1		1	Very Dense Gravelly Sand
2		2.3	Strong to Very Strong Fractured Rock
3		4.5	Very Strong Fractured Rock
4			End of Sample Borehole at 4.5m
5			

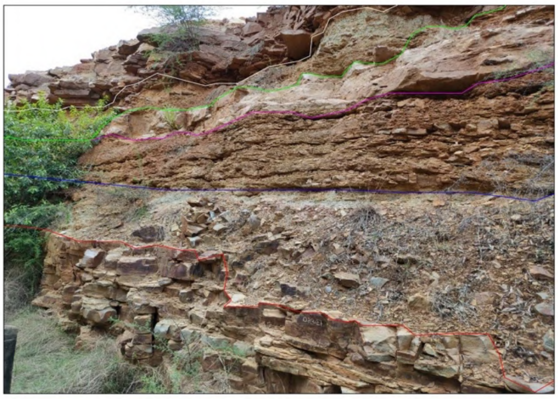


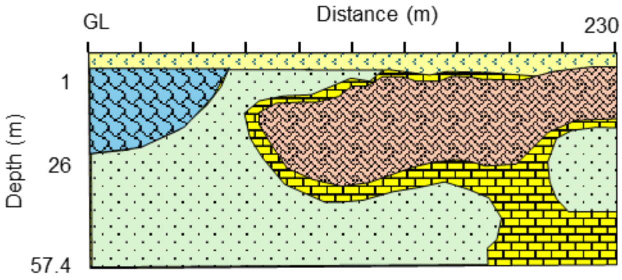
Figure 10. Exposed Soil Profile in a trench near Location 2

5 Integrated Subsurface Profile

The previous section describes the soil profiles obtained from individual geophysical and geotechnical methods, but a reliable soil profile can be obtained from integrated subsurface profiling using these test details results as per Anbazhagan et al. (2017; 2022).

5.1 Integrated Subsurface Profile at Location 1

At location 1, the survey lines of ERT and GPR extend for a distance of 400 m and MASW for 40 m, as shown in Fig. 3. The borehole is located at a distance of 160 m away from the survey lines of ERT and GPR, whereas MASW widens for 20 m on either side of the borehole. From Figs. 4, 6 and 8, the following observations can be made – GPR radargram shows a profile for a depth of 18 m, which is divided into 3 layers, 2D ERT profile extends for a depth of 60 m and shows the complex subsurface based on the resistivity values and MASW 2D profile shows subsurface for a depth of 18 m delineated into three layers. From the obtained profiles at location 1, it can be seen that very dense material exists for a depth of 1 m, confirmed by the borehole data, as shown in Table 1. For depths greater than 1 m, the GPR radargram shows strong to very strong fractured rocks, 2D ERT shows strong to very strong fractured rocks and hard rocks in detail, whereas MASW 2D profile shows the presence of very strong rock and hard rock. The bore log sheet shown in Table 1 provides the same for a depth of 4.5 m. As a result, a good coherence exists between the geophysical and geotechnical tests. So, the subsurface profiles generated from geophysical tests are used to generate an integrated subsurface profile, as shown in Fig. 11. It can be noticed that the 2D ERT test projects a detailed image of the site compared with other geophysical tests.



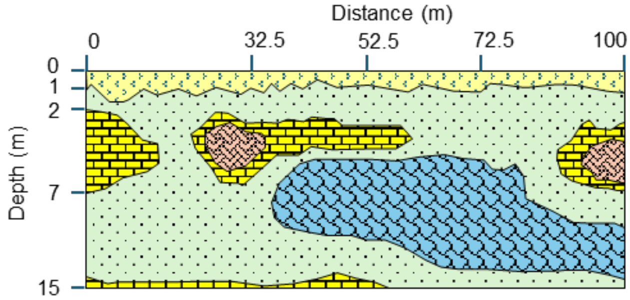
Legend	Subsurface properties
⁘	Very dense gravelly sand, Resistivity < 500 Ω-m, $(V_S)_{avg}$ = 440 m/s
▨	Dense sand with gravel, Resistivity: 134-515 Ω-m, $(V_S)_{avg}$ = 620 m/s
▩	Hard rock, Resistivity = 7662-15047 Ω-m, $(V_S)_{avg}$ = 650 m/s
░	Strong fractured rock, Resistivity = 1011-1986 Ω-m, $(V_S)_{avg}$ = 1866 m/s
▦	Very strong fractured rock, Resistivity = 1986-3901 Ω-m, $(V_S)_{avg}$ = 1345 m/s

Figure 11. Integrated Subsurface Profile at Location 1

5.2 Integrated Subsurface Profile at Location 2

GPR, ERT and MASW tests are performed at location 2, in which GPR and ERT extend for a distance of 100 m, whereas MASW needs to be terminated at a distance of 40 m from the array beginning, as shown in figure 3, due to site constraints. The subsurface profiles obtained from these geophysical tests are shown in Figs. 5,7 and 9. The profiles show that the GPR radargram shows a depth of 30 m, whereas ERT 2D represents the profile for a depth of 15 m, and MASW extends for 30 m depth. The GPR radargram delineates the profile into three layers –

Very dense material, strong rock and very strong fractured rock, as shown in Fig 5. In contrast, the ERT profile depicts various materials spread over the area, with the major composition of strong fractured rock with pockets of hard rock followed by very dense soil and, finally, strong fractured rock. In the case of the MASW profile, three layers can be easily noticed from Fig. 9, representing the presence of very dense material followed by very strong rock and hard rock. The geophysical profiles show that the ERT 2D profile shows a detailed image of the site compared to other profiles. The same profile seems valid with the existing exposed terrain, as shown in Fig. 10. From all the profiles, it can be seen that ERT 2D is an effective technique for deeper depths as it provides the location details in detail. So, considering all the profiles, an integrated subsurface profile is generated, as shown in Fig. 12.



Legend	Subsurface properties
🟨	Very dense gravelly sand, Resistivity < 500 Ω-m, $(V_S)_{avg} = 440$ m/s
🟦	Weathered rock, Resistivity: 60-350 Ω-m, $(V_S)_{avg} = 800$ m/s
🟫	Hard rock, Resistivity > 7000 Ω-m, $(V_S)_{avg} > 1200$ m/s
🟩	Strong fractured rock, Resistivity = 400-1000 Ω-m, $(V_S)_{avg} = 600$ m/s
▦	Very strong fractured rock, Resistivity = 1000-3500 Ω-m, $(V_S)_{avg} > 1000$ m/s

Figure 12. Integrated Subsurface Profile at Location 2

6 Summary & Conclusions

In the present study, a complex geological terrain was scattered over a large region in Sunnapurallapalle, Jammalamadugu Mandal, Kadapa District, Andhra Pradesh, India, and was selected to study the soil profile. Understanding such a complex subsurfaces using geotechnical methods is practically impossible as large number drilling is required, so geophysical methods are involved. In the study, two locations are selected at which Ground Penetrating Radar, 2D Electrical Resistivity Tomography and 2D Multi-channel Analysis of Surface Waves are performed. The subsurface profiles obtained from the geophysical tests are validated with the help of the borehole at location 1 and the presence of exposed terrain at location 2. The subsurface profiles obtained from the tests are in good coherence with the geotechnical data and geologically exposed terrain. For a detailed interpretation of the locations from geophysical tests, an integrated subsurface profile is generated.

The following observations can be made from the integrated profiles.

1. The subsurface profiles are very complex in nature as different materials are present at various depths and locations.
2. It may be difficult to profile variations of these subsurface complexes by drilling alone or geotechnical testing.
3. Integrating few boreholes and geophysical data from MASW & ERT are help to profile complex subsurface layers.
4. Further adding of MASW data helps to get the distribution of subsurface properties of Shear wave velocity, Young's modulus & Shear modulus, which is highly essential for further scope of work such as foundation design and site response analysis.

From the present study, the following observations are made – For shallow depths, GPR seems to be providing better results as it can be seen at both site locations that for depth up to 10 m, the image shown by GPR radargram is better. Moreover, for greater depths, ERT and MASW show a better portrait of the site. In this particular site, ERT 2D provides the subsurface profile in detail compared with MASW.

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