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Research Article

A Comparative Study of Subsurface Profile Using Bore Log Data and Geophysical Method at Mandideep Region, India

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Before beginning construction on any civil structure, it is imperative to conduct a soil investigation to determine the soil's parameters and to learn about the subsoil's behavior. A thorough analysis must be performed, taking into account the foundation's cost-effectiveness and any potential overdesign. In the early stages of a soil investigation, geophysical testing is used to find out about the subsurface. This is because geophysical tests are fast, easy to do, do not cause damage, and are cost-effective. In this study, subsurface profiling is performed using the inverse slope approach after resistivity tests are performed at numerous sites on varying terrain types. We generate a subsurface profile using inverse slope electrical resistivity testing and compare it with bore log data to identify any discrepancies. The results of the inverse slope method and the bore log data are comparable at different depths; further, the range of agreement of both results is determined by Bland–Altman analysis.

1. Introduction

1.1. General. An engineering structure's careful design is incomplete unless complete information about the type and condition of the substrate on which the structure is to be erected is available. Intelligent design for safe and economical construction requires thorough knowledge of subsurface conditions. As a result, knowledge about the subsurface condition is especially important in construction engineering, and it is obtained through geotechnical investigation. The investigation of soil mass sites is made more difficult by the fact that the sites are structurally heterogeneous and have an uneven topography. Subsurface assessment using two or more interactive geophysical techniques has become increasingly effective in recent years. These techniques are used to explore ground water [1]; assess ground profile using different integrated geophysical methods like GPR, ERT, and SRT [2, 3]; determine fluid flow near seafloor using bottom-simulating reflector [4], subsurface structure mapping [5], and interaction of hydrogen sulfide gas with basalt rock in volcanic areas using ERT and time domain-induced polarization [6]; assess feasible shale resources [7]; determine rock quality designation correlating with wave velocity [8]; study hydrogeological features to examine ground water salinization degradation [9]; analyze characteristics of tropical clayey sand [10]; determine diurnal radon temporal variation [11]; etc. A lot of studies [8, 12] developed a connection between geophysical and conventional mechanical parameters. Many geophysical methods, including electrical resistivity tomography (ERT) [13, 14], self-potential [15], magnetic [16], seismic [17], and induced polarization [18], are nondestructive and cost-effective for gathering important subsurface information. The depth and, to a lesser extent, the soil type can be detected when employing near-surface geophysical methods, such as electrical resistivity, because the inversion processes generate subsurface images. Electrical resistivity method assumed considerable importance in the field of subsurface exploration because of its very good resistivity contrasts among the lithological units. In the last few years, 2D and 3D ERT has been employed efficiently to assess the shallow stratigraphic conditions in numerous research, where fractured crystalline rock terrain [19], heterogenous sites [20], and waste disposal sites [21] have been explored. Apart from that, dynamic monitoring of water [22], investigation of fractured rock aquifers [23], and auriferous mineralization [24] have also been done. However, relying solely on geophysical

Figure 1: District map of Madhya Pradesh state.

techniques might lead to incorrect conclusions about the subsurface, as in the case of low electrical resistivity readings, which cannot reliably differentiate between the presence of water and that of clayey units. The present research concentrates on the subsurface identification through boring, i.e., the conventional method, and also through one of the geophysical methods, finally comparing both the results to understand the effectiveness, ease of operation, reliability, accuracy, and economy of the latter one.

1.2. Need of the Study. In conventional practice, soil boring tests are conducted at different locations to determine the subsurface condition. The conventional test provides information about the location at which the test is performed, and the subsurface profile is approximated by area-wide interpolation. Therefore, in this process, there is a chance of missing out on the thin soil layer with low capacity and fractures in the rock. Electrical resistivity, on the other hand, is a geophysical technique that may offer a continuous image of the subsurface and rapidly survey enormous areas. An effort is made to determine the degree of similarity between the two in this study, and the boundaries of consensus are established for the purpose of making a comparison.

2. Methodology

Multiple sites are taken into consideration, which include several locations in the Mandideep industrial area in the district of Raisen near Bhopal, the capital of Madhya Pradesh state. Figure 1 shows the state map with all districts shaded according to their soil type, along with the concerned district of Raisen marked under a red circle. The locations are such that it covers different parts of the industrial area of Mandideep. Figure 2 shows the map which depicts the present land usage of Mandideep area marking industrial as well as agricultural land; the map (1 : 16,000) is present in development scheme 2031 of Mandideep prepared by the Directorate of Town and Country Planning, Government of Madhya Pradesh.

The surface electrical resistivity soundings are standard techniques to delineate the weathered or fractured zone and assess its hydrogeological suitability. However, it has not been effective in delineating the deeper features, which occur as microlevel conductivity discontinuities in highly resistive host rock. Gradient resistivity profiling has been found to be effective in delineating them. However, the exact delineation of the fracture geometry cannot be asserted. The ratio of low resistivity to the background, the steepness of the profile, and the value of "low" are the important considerations. Because of the heterogeneous nature of the subsurface lithology, structures, and conductivity variation, the exact spatial disposition of the fracture and their hydrogeological characteristics may not be outlined from gradient data [25].

The standard procedure in the field is to perform at least one vertical electrical sounding (VES) on the low gradient resistivity to determine the resistivity of the weathered zone and to confirm the low's association with the underlying fracture. It is a property that is intrinsic to a substance and is not contingent on the size or shape of the substance. The resistivity is defined as the "resistance offered by a unit length

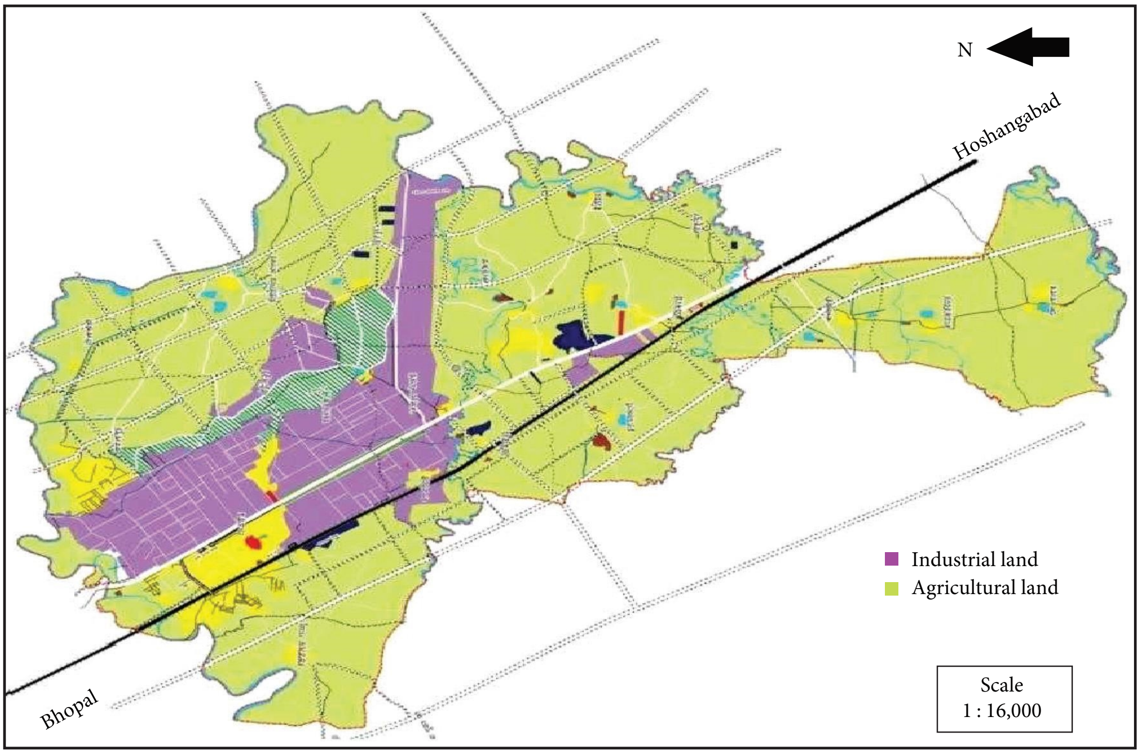

Figure 2: Map of Mandideep area.

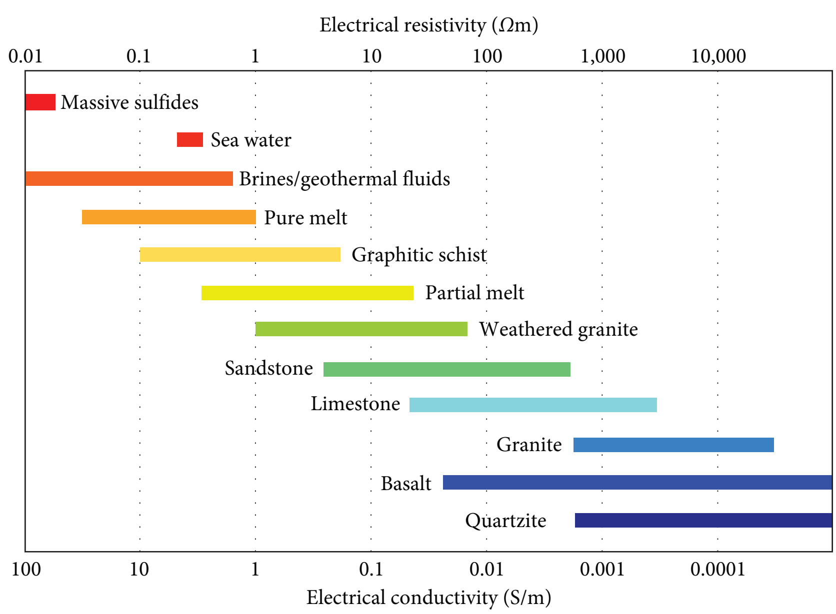

Figure 3: Resistivity range for different types of strata.

of a substance of a unit area to the flow of electric current when the voltage is applied at the opposite faces."

Electrical resistivity depends on particle size and surface charge density. Figure 3 shows the range of resistivity values for different types of soil strata, from 0.01 Ωm for sulfides to 10,000 Ωm for basalt [26]. Due to the size of the specific surface, the electric charge at the surface of clay makes it more electrically conductive than coarse-grained soils. Resistivity readings for the clay range from one to a few tens of Ωm. There is a tangential connection between resistivity and lithology in rocks that contain water.

Since the objective of the study is to compare the results of inverse slope method and the bore log data, the first step in this study was to decide the study area, so different terrain types were chosen to establish a good comparison. After deciding the study area, field investigation is carried out, and data acquisition is done. The acquired data are then used to generate the inverse slope. This subsurface profile

FIGURE 4: Satellite image with test location at Mandideep (scale 1 : 800).

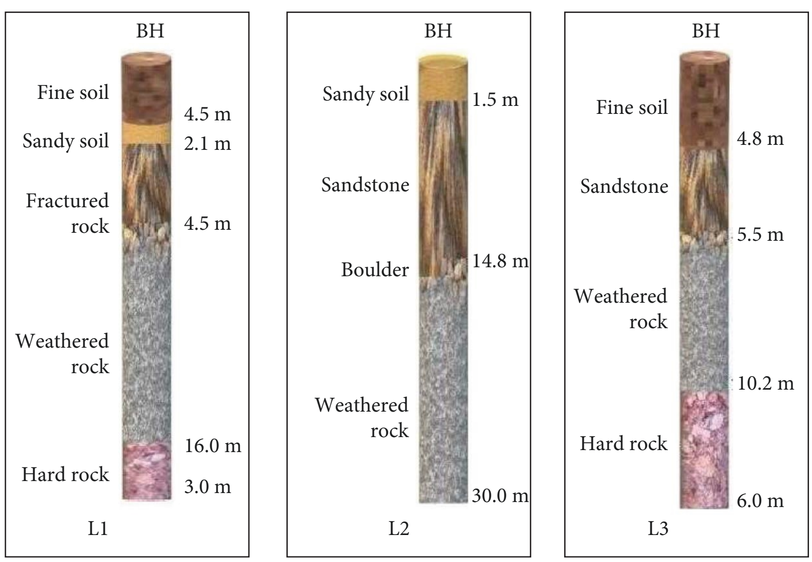

FIGURE 5: Bore log data for different locations (L1, L2, and L3).

generated by the inverse slope is then matched with the bore log data, a Bland–Altman plot is developed, and a comparison is done.

3. Field Investigation and Data Acquisition

3.1. General. Experimental work is done at three different site locations to find the subsurface profile of the regions. At these locations, electrical resistivity tests are performed in conjunction with bore log or core logging, and a comparison study is then performed between the subsurface profile generated by vertical electrical sounding and the bore log data.

3.2. Test Procedure. The Indian standard code (IS 2131 : 1981) specifies a standard procedure for conducting the standard penetration test for soils. The standard penetration is a time-consuming and destructive test used to determine the soil's geotechnical engineering properties. It helps determine the relative density, angle of shearing resistance, and unconfined compressive strength of cohesionless soil. Figure 4 depicts a satellite location plan of three Mandideep test locations (L1 at 23005′ 19″ N and 77031′ 06″ E, L2 at 23004′ 38″ N and 77031′ 37″ E, and L3 at 23005′ 27″ N and 77031′ 44″ E).

Soil retrieved through boring and SPT are presented in Figure 5. For bore log data for three different locations at

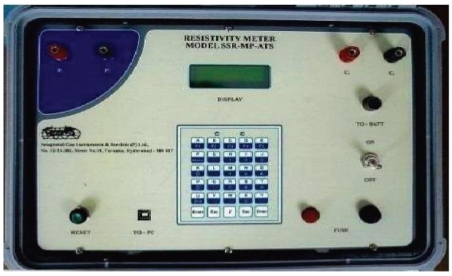

Figure 6: Signal stacking resistivity meter.

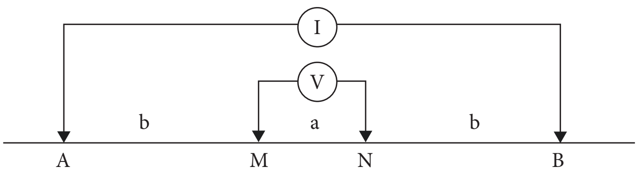

Figure 7: Schlumberger array arrangement.

different depths of 30, 47, and 26 m, respectively. At location "L1," there is fine soil at the early depths, followed by sandy soil and fractured and weathered rock deeper down the ground. Likewise, at location "L2," sandy soil is encountered at shallow depths and sandstone and weathered rock at greater depths. The stratification of the ground at location "L3" is very similar to that of "L1," with some variation in the depth of a particular soil layer.

Electrical resistivity survey is carried out deploying Resistivity Meter Model SSR-MP-ATS shown in Figure 6 for conducting gradient resistivity profile (GRP) and Schlumberger vertical electrical sounding at three locations. Vertical electrical sounding is performed at low GRP.

The way the electrodes are set up for a resistivity test is called a configuration or an array. Most of the time, the electrodes are set up in the Wenner, Schlumberger, or dipole configuration. In this study, Schlumberger setup is used as shown in Figure 7. In Schlumberger array configuration, four electrodes positioned in a linear arrangement with a common central point. The current electrodes, A and B, are positioned on the outside side, while the potential electrodes, M and N, are put in close alignment to each other. The Schlumberger array is considered to be the most advantageous approach for VES due to its practicality, mostly resulting from its notable reduction in labor requirements as compared to the Wenner array. In the field of VES, the Schlumberger array has a notable advantage due to the fact that, in most cases, only the outer electrodes A and B need relocation. In geophysical test carried out at the locations, a crew of three members were involved for VES operations, in which two individuals were responsible for manipulating the outside electrodes, while the instrument operator primarily handles the movement of the inner electrodes. The Schlumberger resistivity equation is shown as follows:

$$\rho = \frac{V}{I}\pi\frac{b^2}{a}. \tag{1}$$

Resistivity data are interpreted in two stages. In the first stage, data are processed to get the geoelectric parameters in terms of resistivity and depth/thickness. In the second stage, the nature of subsurface formations is inferred using the data and based on geological knowledge and correlative studies. The data generated from vertical electrical sounding are listed in Tables 1, 2, and 3 for locations L1, L2, and L3, respectively, and the inverse slope generated using the data is also listed in these tables. The values of the inverse slope are taken by $(AB/2)/\rho$.

4. Result and Discussion

4.1. General. According to the District Ground Water Information Booklet by Central Ground Water Board, Ministry of Water Resources, a rough estimate of the terrain type is made of all the locations, and then the sites are classified according to the terrain type in Table 4.

4.2. Collation of Two Methods. In Figure 8, the borehole data for location and inverse slope are compared. GPM data interpreted by the inverse slope mthod and BH represent bore hole data retrieved through boring the core at three specified locations. The comparison reveals that geophysical data are indicating change in strata in a very similar manner to that recovered from bore log data, with some amount of inaccuracy when considering depth. This is shown by the fact that the two sets of data are quite similar to one another. Table 5 shows the thickness of the stratified layers determined by both methods. Since boreholes and other traditional methods of exploration are costly and limited in their ability to cover a wide area, the acceptability of geophysical methods would be useful in the common practice of soil exploration.

4.3. Bland–Altman Analysis. As correlation and linear regression analysis is not suitable for comparative analysis, Bland–Altman analysis is an acceptable method to study the agreement between two measurements that are on a continuous scale and to detect the presence of a systematic difference between the measurements [27, 28, 29]. In Figure 9, a Bland–Altman plot is drawn to see the variation of results between the two methods used for subsurface exploration within a specified limit. The central line indicates the mean of the differences or bias, and the upper and lower lines indicate the upper and lower limits of agreement (LOA).

The plot shows that 11 out of 12 values fall within the expected range, with considerable volatility around the mean difference line. LOA are generated with a lower limit (LL) and an upper limit (UL). Lower limit and upper limit are calculated as:

$$\begin{aligned} \text{UL/LL} = {} & \text{Mean of difference} \\ & \pm (1.96 \times \text{Standard deviation of difference}). \end{aligned} \tag{2}$$

5. Discussion

The comparative examination of subsurface exploration using traditional bore log investigation and the inverse slope method

Table 1: Vertical electrical sounding data for location L1.

AB/2	MN/2	Resistance (R-ohms)	*K* factor (m)	Apparent resistivity (Ωm)	Depth (m)	Inverse slope
1.00	0.40	0.0788	3.30	0.26	0.67	3.92
2.00	0.40	0.0770	15.07	1.16	1.33	1.73
3.00	0.40	0.0063	34.70	0.22	2.00	13.90
4.00	0.40	0.0014	62.17	0.09	2.67	44.07
5.00	0.40	0.0035	97.50	0.34	3.33	14.70
6.00	2.00	0.0251	25.12	0.63	4.78	9.52
8.00	2.00	0.0845	47.10	3.98	5.33	2.01
10.00	2.00	0.0468	75.36	3.53	6.97	2.83
15.00	2.00	0.1054	173.49	18.28	10.60	0.82
20.00	2.00	0.0894	310.86	27.80	13.33	0.72
25.00	5.00	0.1617	188.40	30.47	16.67	0.82
30.00	5.00	0.0239	274.75	6.57	20.00	4.57
35.00	5.00	0.0202	376.80	7.60	23.33	4.61
40.00	10.00	0.0335	235.50	7.90	25.67	5.07
50.00	10.00	0.3610	376.80	136.01	30.33	0.36

Table 2: Vertical electrical sounding data for location L2.

AB/2	MN/2	Resistance (R-ohms)	*K* factor (m)	Apparent resistivity (Ωm)	Depth (m)	Inverse slope
1.50	0.50	0.3949	6.28	2.48	1.0	0.60
2.00	0.50	0.3314	11.77	3.90	1.3	0.51
3.00	0.50	0.3702	27.47	10.17	2.0	0.29
4.50	0.50	0.2084	62.80	13.09	3.00	0.34
10.0	0.50	0.0699	313.21	21.88	6.66	0.45
25.0	2.00	0.0591	487.48	28.83	15.66	0.86
30.0	5.00	0.0468	274.75	12.86	20.00	2.33
45.0	5.00	0.0098	628.00	6.16	30.00	7.30
50.0	5.00	0.0202	777.15	15.68	33.33	3.18
55.0	5.00	0.0190	942.00	17.91	36.66	3.07
60.0	10.00	0.0239	549.50	13.13	40.00	4.56
70.0	10.00	0.0202	753.60	15.19	46.66	4.60

Table 3: Vertical electrical sounding data for location L3.

AB/2	MN/2	Resistance (R-ohms)	*K* factor (m)	Apparent resistivity (Ωm)	Depth (m)	Inverse slope
1.00	0.40	0.1702	3.29	0.56	0.66	0.56
2.00	0.40	0.0531	15.07	0.80	1.33	1.50
6.00	2.00	0.0414	25.12	1.04	4.50	5.76
10.00	2.00	0.2179	75.36	16.42	6.66	0.60
15.00	2.00	0.1230	173.48	21.33	11.20	0.70
20.00	2.00	0.0077	310.86	2.38	13.33	8.40
25.00	5.00	0.0098	188.4	1.85	17.10	1.46
30.00	5.00	0.4660	274.75	128.02	20.00	0.23
35.00	5.00	0.3604	376.8	135.79	23.33	0.25
40.00	10.00	0.5046	235.5	118.84	25.96	0.33

Table 4: Soil profile for the three locations.

Site	Location	Soil profile
Mandideep	L1	Black soil and sandstone
Bhopal (MP)	L2	Sandstone
India	L3	Black soil and sandstone

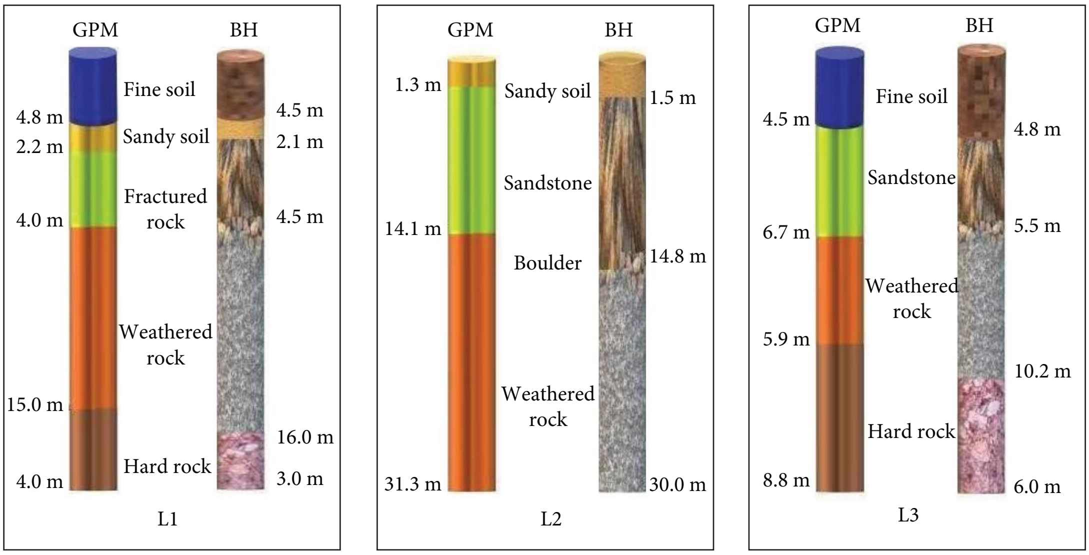

Figure 8: Bore log and Geophysical profile at locations (L1, L2, and L3).

Table 5: Thickness of strata by inverse slope and bore log data.

S. No.	Location	Strata thickness (inverse slope) in meter	Strata thickness (bore hole) in meter	Difference	Mean
1	L1	4.8	4.5	0.3	4.65
		2.2	2.1	0.1	2.15
		4.0	4.5	−0.5	4.25
		15.0	16.0	−1	15.5
		4.0	3.0	1	3.5
2	L2	1.3	1.5	−0.2	1.4
		14.1	14.8	−0.7	14.45
		31.3	30.0	1.3	30.65
3	L3	4.5	4.8	−0.3	4.65
		6.8	5.5	1.3	6.15
		5.9	10.2	−4.3	8.05
		8.8	6.0	2.8	7.4

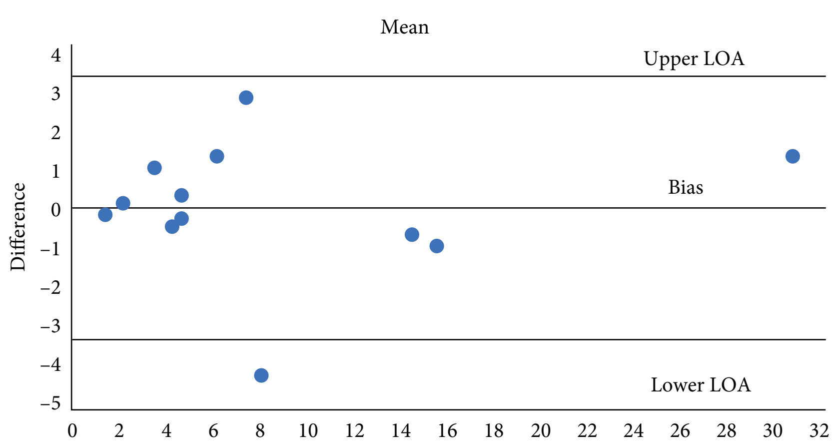

Figure 9: Bland–Altman plot.

of geophysical investigation provide significant insights into the precision and suitability of both approaches. The evaluation, supported by Bland–Altman analysis, highlights the concurrence between the methodologies, thus augmenting our comprehension of their individual merits and constraints.

The utilization of traditional bore log investigation has been a longstanding practice in the field of subsurface characterization, offering comprehensive insights into the composition and structure of soil and rock formations. The comprehensive scope of this approach, which is based on direct measurement, facilitates a comprehensive comprehension of the subsurface, thereby assisting in the development of engineering designs, formulation of construction plans, and evaluation of potential risks. Nevertheless, this approach may prove to be labor-intensive, costly, and constrained in scope, especially when dealing with large-scale endeavors.

On the other hand, the inverse slope method utilizes geophysical principles in order to make estimations about subsurface characteristics, providing a more economically viable and streamlined alternative. This method enables rapid assessments over extensive regions by extrapolating subsurface information through the analysis of slope variations in geophysical data. The technique's ease of implementation and minimal equipment requirements render it an appealing choice for expeditious preliminary evaluations.

The Bland–Altman analysis performed in this study serves as a pivotal link between these methodologies. The method's ability to exhibit strong concordance between the two approaches confirms the effectiveness of the inverse slope method in the field of subsurface exploration. The alignment of the plot with the bias/mean highlights the dependability of the geophysical technique in determining the characteristics of subsurface strata. The Bland–Altman plot is a powerful tool as it allows for the visualization of the agreement between the two methods and any systematic bias or random error.

The observed agreement between the conventional bore log investigation and the inverse slope method implies a wide range of possible applications. Bore log investigation is a reliable option in situations where the acquisition of precise and site-specific data is crucial. On the other hand, in the context of projects that require comprehensive coverage and cost-effectiveness, the utilization of the inverse slope method presents itself as a potentially effective approach.

The findings of this study have significant implications for the field of subsurface exploration, providing practitioners with a versatile approach to accommodate various project needs. By exploiting the advantages of each approach and capitalizing on their concurrence, decision-makers can attain a more comprehensive comprehension of subsurface dynamics. The incorporation of geophysical investigation techniques, such as the inverse slope technique, into existing methodologies presents novel opportunities for enhanced resource allocation, expedited project implementation, and well-informed decision-making.

6. Conclusion

In the present comparative study, we found the substrata profile generated by the inverse slope method and the bore log data. The following conclusions are made:

(1) The comparison of the subsurface profile generated by inverse slope and the bore log data is shown in Figure 8. The percentage variation in the thickness calculated through the inverse slope method and bore log data has been found to minimum variation is 0% and maximum variation is found 73%.

(2) Eleven out of 12 values of measurement are within the accepted limits in Figure 9 which reveals the suitability of comparative analysis.

(3) The Bland–Altman plot shows good agreement on either side of bias/mean, which reveals that inverse slope method (geophysical method) is a good tool to ascertain the change in strata deep down the ground, especially with low and less equipment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by Aman Tiwari and Suneet Kaur. The first draft of the manuscript was written by Nitin Dindorkar and Ankit Chakravarti. All authors read and approved the final manuscript.

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