Electrical Resistivity Investigation for Dam Site

D. S. Aswar, P. B. Ullagaddi, and S. D. Ambadkar

Abstract The resistivity surveys give the variation of electrical resistivity with the depth. The vertical electrical resistivity sounding (VES) was carried out at Bhama Askhed dam site approximately aligned with the dam alignment on downstream to generate additional data to complement existing geological data. The VES interpretations carried out using resistivity inversion (IR) and inverse slope method (ISM) to generate resistivity interpretations for part of modelled area. The field resistivity data is interpreted to obtain the true resistivity and the thickness of the ground layers. The electrical resistivity (ER) cross sections showing the variation of resistivity with the depth are also prepared. The findings of resistivity survey have complemented the available exploration data. The study has also helped to identify the occurrence of low-resistivity zones, which was missed earlier due to inadequate depth of geological investigation. Low-density of dam foundation substratum towards spillway area where the high seepage has occurred leading to EDA failure has been investigated.

Keywords Geophysical survey · Vertical electrical sounding · Resistivity cross sections · Resistivity inversion · Inverse slope method

1 Introduction

Geophysical methods may be used as complementary tool for site investigation. The resistivity method is used to study the horizontal and vertical variations in the subsurface electrical properties. It can also contribute as a tool to optimize extent of

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investigation required by identifying the locations of anomalies for further investigations. The electrical anomaly of substratum is mainly because of variations in the rock resistivity. The verified results of geophysical survey can be extended to areas of spare geological data. Geophysical methods have been extensively used in dam investigations, as well as in the assessment of existing dam structures.

2   Study Area Bhama Askhed Irrigation Project

The Bhama Askhed Irrigation Project (18° 15′N, 73° 43′E), is situated on the River Bhama, a right-bank tributary of River Bhima (Krishna Basin), at village Waki, Taluka- Khed, Pune, Maharashtra (India). The project consists of 51.125 m high and 1425 m long earthen dam with gross storage capacity at FRL of 230.47 MCM and 55.5 m long ogee side spillway. During 2005, heavy seepage accompanied with the dynamic spillway discharge forces, uplifted and displaces, thirteen concrete panels ($7 \times 11 \times 0.30$ m each) of flip bucket type, energy dissipating assembly (EDA). The structural failure of the EDA portion has occurred due to excessive seepage and associated uplift pressure [1, 2]. The discussions here are mostly confined here to analyse and interpret geological conditions leading to EDA failure.

3   Vertical Electrical Sounding

Proportion of current flowing beneath subsurface depth is a function of current electrode separation AB. High electrode separations is, however, limited by difficulty of working with lengthy cable and space availability on site [3]. The sounding locations were chosen considering the availability nearly horizontal, workable space for electrode spreading. The site topography has limited the depth of geophysical exploration due to limited scope of electrode separation. The tail channel area is with rocky outcrop and deep-water gullies making it difficult for establishing electrode contact points. The main purpose of vertical electrical sounding is to deduce the electrical resistivity variation with depth and thus to interpret the geological subsurface characteristics. Considering the advantages and the suitability, the Wenner array was selected for VES [4]. The electrical resistivity survey was carried out with the standard Wenner electrode array with current electrodes (AB) spacing varying from 1.5 to 200 m. The maximum current electrode separation used was AB = 200 m, with AB/3 = 65 m. Electrical resistivity survey was carried out along four geoelectric traverses based on available space, as geoelectric profile-I, profile-II, profile-III and profile-IV to obtain a possible coverage of the study area. Table 1 presents details of geoelectric traverses conducted during the field survey.

VES was conducted at 25 VES stations (VES_1 to VES_25) distributed along these traverses (Fig. 1). The profiles were orientation approximately parallel to dam alignment on downstream, with combined length of 1450 m.

Traverse lines	VES stations	Fore bearing	Length (m)
Profile-I	VES_1 to VES_4	33° 30′	250
Profile-II	VES_5 to VES_14	12°	550
Profile-III	VES_15 to VES_20	9° 30′	350
Profile-IV	VES_21 to VES_25	9° 30′	300

Table 1 Details of geoelectric traverses
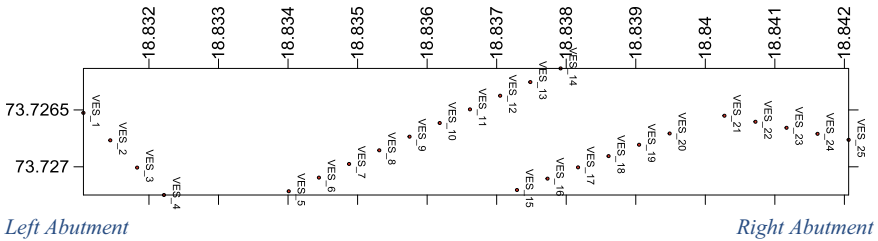
Fig. 1 VES stations and geoelectric traverse location

The spacing between the VES stations was 50 m. Number of profiles and number of VES stations in each profile were selected based on available working space, accessibility and field conditions.

3.1 Interpretation Methods

VES data yields apparent resistivity for various electrode separations. This data is used to find true resistivity and depths of subsurface formations. The interpretation of resistivity sounding data can be done in two stages,

1. Processing the data to get the geoelectric parameters in terms of resistivities and depths/thicknesses of formations.
2. Geoelectric parameters interpretation for the nature of subsurface formations based on geological understanding and correlative studies [5].

Qualitative Interpretation. A qualitative method indirectly displays the information of the geological structure and the geological variations over the study area. The qualitative resistivity interpretation carried out for study consists of observation of the field sounding curve, isoapparent electrical resistivity maps, apparent resistivity profiles, pseudo sections and resistivity cross sections.

Quantitative Interpretation. Field resistivity data was interpreted using inverse slope method (direct method) [5] and automatic iterative inversion approach [6] to obtain the geoelectrical section parameters, i.e. layer thickness and resistivity values. The geoelectrical section parameters are obtained by plotting the sounding curves on natural scale in inverse slope method (ISM). Whereas, the sounding curves are plotted

on double logarithmic scale in resistivity inversion technique (IR). The true resistivity obtained was used to generate iso-resistivity contour, thickness map and resistivity profiles using SURFER software. The results are interpreted by correlating layer resistivity and corresponding formation thickness with the nearest borehole data.

Resistivity Interpretation by Resistivity Inversion (IR) Method. The vertical electrical resistivity soundings were interpreted using inversion techniques to obtain true subsurface resistivity, using computer-based inversion using software such as IPI2Win and EarthImager [7]. The inversion method minimizes the difference between the modelled and measured apparent resistivity. IPI2Win utilizes the geological concepts and data along with the resistivity observations, instead of only direct sounding curves inversion. Thus, providing equivalent resistivity solutions better suited to both geophysical data (i.e. the least-fitting error) and geology. Output consist of, resistivity curve, resistivity-depth table, pseudo cross-section and resistivity cross-section. The IPI2Win software suggests a best-fitting model for the initial interpretation for input sounding point data. The degree of uncertainty of the computed model parameters and its fit with standard curve are expressed in terms of fitting root mean square (RMS) error. A number of inversions reproduce the layer resistivity and the corresponding layer thickness until the model parameters of the VES curve are resolved with the fitting error. Model trial involves altering the number of layers by means of splitting or joining them and changing the properties of the layers. Layer boundary elevations are shown and calculated relative to surface elevations. Fix flags allow the user to fix parameters for the inversion calculations. The nature and distribution of different lithologic layers evidence by depth wise variation of resistivity values. The simulated results of the 25 VES stations have disclosed the existence of 4–6 geoelectric layers.

Resistivity Interpretations by Inverse Slope Method (ISM). ISM was used for quantitative interpretation of the vertical electrical sounding using Wenner configuration. It gives reasonably dependable depth calculations under most of the conditions [5, 8]. The inverse of apparent resistance obtained $(1/R)$ is plotted against the Wenner electrode separation '$a = AB/3$' on a natural graph to detect layers at locations under consideration. Near surface, very thin layers are suppressed in inverse slope method; on the other hand, the effect of thinner deep layer is brought out clearly with ISM. With the adequate data density, ISM is able to use linear plotting to trace even thin layers buried at great depths. The ISM has enabled to distinguish distinct sublayers. A single lithological layer identified using the inversion technique could be separated into two or more sub layers by the ISM. This provided an additional advantage to use ISM in this case study.

Fig. 2 Resistivity sounding curves (Profile-IV)
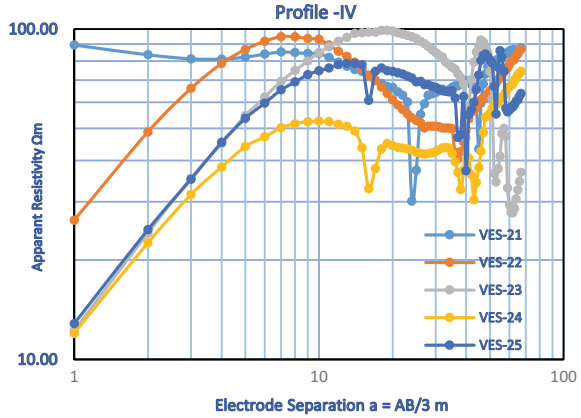
3.2 Geophysical Investigation Analysis—Sounding Curves Interpretations

The apparent resistivity, 'ρa' values were plotted against the electrode spacing ($a = AB/3$) on a double-logarithmic scale to obtain the resistivity sounding curve [9]. Fig. 2 represents such resistivity sounding curves for geoelectric traverse line along Profile-IV.

Observations from these sounding curves reveals that the profile-IV showing resistivity anomalies with depth. These low-resistivity zones in profile-IV towards spillway section around 40 m may be corresponding to low-density formations. The continuous rise in the sounding curve towards high-resistivity values indicates presence of a massive hard rock. However, the resistivity values decrease around 40 m for Profile-I and for Profile-IV and at 30 m for Profile-II and for Profile-III. These descends in resistivity values correspond to low-resistivity weaker zones at respective approximate depths. However, all the profiles marked increase in apparent resistivity values towards the end.

3.3 Isoapparent Resistivity Map

The qualitative interpretation involved isoapparent electrical resistivity maps and geoelectrical pseudo sections. The apparent resistivity value ($\rho1$, $\rho2$, $\rho3$) of the individual layer was used for the preparation of isoapparent resistivity maps using Surfer software. These maps reflect the lateral variation of apparent resistivity over a horizontal plane at a depth of interest. Assuming the ideal depth of investigation for the Wenner configuration is approximately equal to the electrode spacing "a" or 1/3 of current electrode spacing (AB), the isoapparent electric resistivity maps were constructed at $AB = 102, 117, 135, 150, 168, 183$ and 201 m. These maps reflected the

lateral variations of the electric resistivity at an approximate depth of about 30, 35, 40, 45, 50, 55 and 60 m as shown in Fig. 3. The right and left abutment (bank) directions are assumed as looking towards the dam upstream, i.e. from downstream to upstream. Typically, all the isoapparent electric resistivity map at approximate depth up to 60 m showing the consistent low-resistivity values even with the increasing depth towards the northern area (around VES_23 and VES_24) towards the right bank spillway section. However, the resistivity slightly improves towards extreme Northern area after the depth of 55 m. These indicates the presence of uniform bedrock towards the left bank, i.e. Southern part. The apparent resistivity profile, Fig. 4, shows the
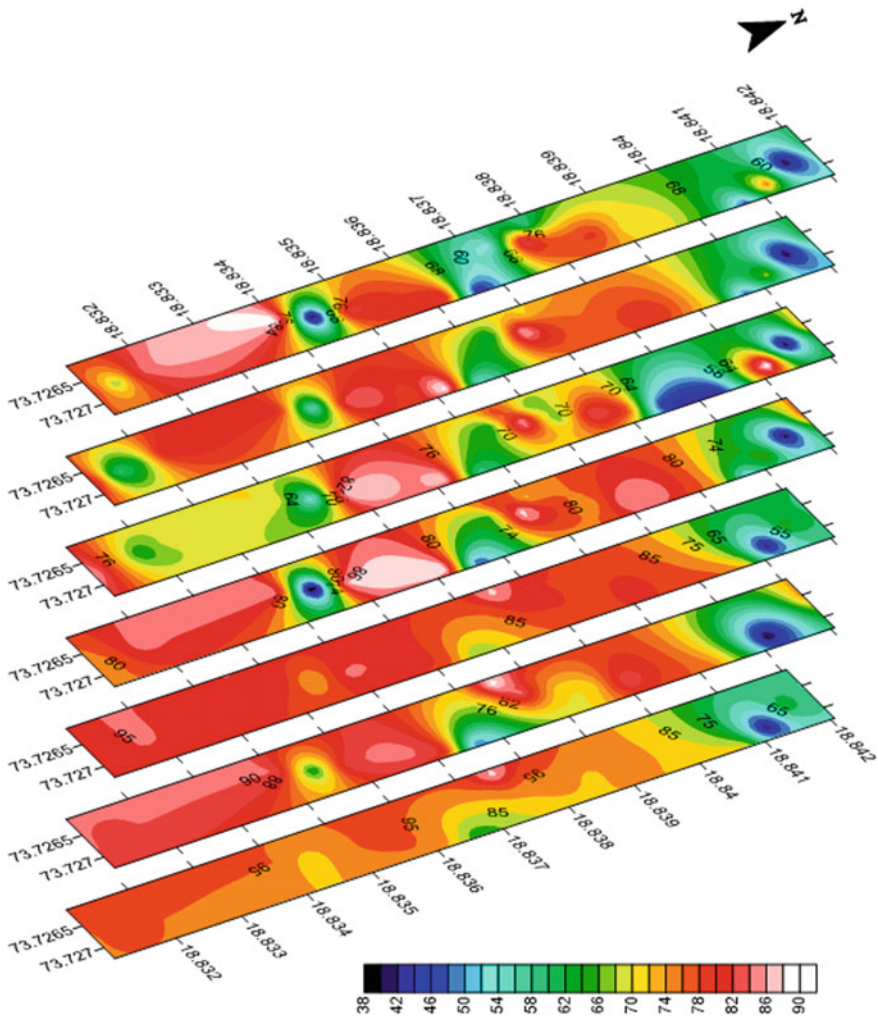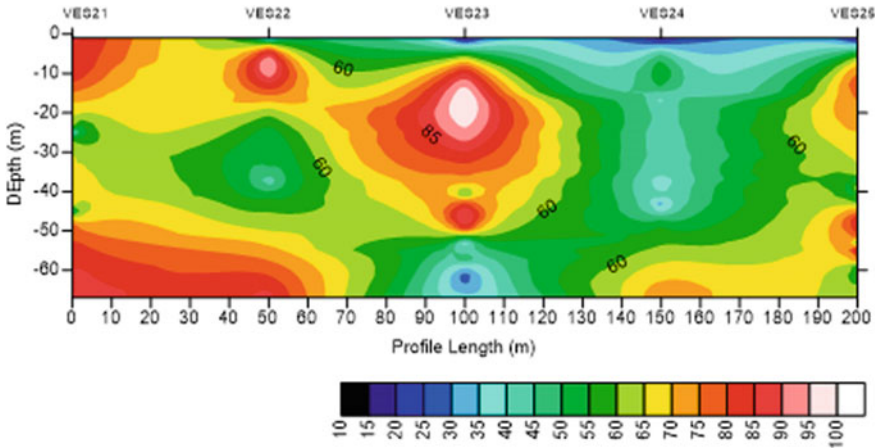

Fig. 3 Stacked isoapparent resistivity map

Fig. 4 Apparent resistivity Profile-VI (VES_21_25)

variation of apparent resistivity over the depth of substratum; the results are similar to pseudo resistivity cross sections obtained in inversion resistivity method. These apparent resistivity profiles are qualitatively easy to interpret compared to pseudo resistivity sections. Based on apparent resistivity, variation over the depth different lithological zones has been identified. The apparent resistivity profiles along the VES traverse were plotted to reflect qualitative geologic setting, along these profiles using Kriging data interpolation.

The obtained apparent resistivity values are low (40–50 Ω m) at the depth around 35–40 m (VES_22), 55–60 m depth (VES_23) and at depth 35–40 m (VES_24 and VES_25), at the Northern soundings towards spillway areas. These sounding stations show consistent low-density, saturated zones at the greater depths preceded by initial high density, high-resistivity area. Profile-IV is indicating the likely low-density trends towards spillway area where the high seepage has occurred leading to EDA failure.

3.4 Interpretations of the Inversion Method

2D electrical resistivity pseudo cross section (apparent resistivity) and resistivity cross section (true resistivity) were constructed based on VES data (VES_1 to VES_25) along Profile-I, Profile-II, Profile-III and Profile-IV (Fig. 5.)

These provided a simple image, for qualitative interpretation with spatial variation of apparent (pseudo cross section) and true subsurface resistivity information [10].

The detected layers at VES stations show a wide range of resistivity values with the last (deepest) layer showing very high resistivity normally for all the sounding points. However, VES stations VES_8 (29.8 Ω m), VES_9 (37.9 Ω m), VES_10
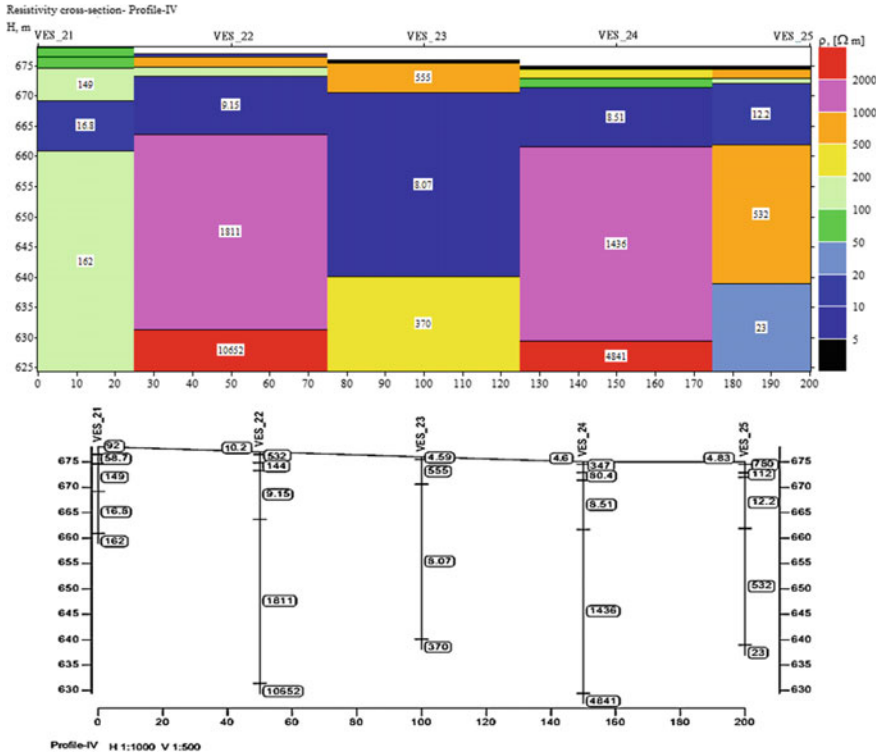
Fig. 5 2D electrical resistivity and geoelectric cross sections along the profiles III and IV

(17.4 Ω m), VES_19 (7.06 Ω m), VES_20 (44.7 Ω m) and VES_25 (23 Ω m) are terminating into low-resistivity layers and needs further investigation for verification of bedrock condition.

3.5 Inverse Slope Method Interpretations

Inverse slope method has enabled in distinguishing the sub layers, which correlate well with bore logs. The resistivity data was analysed, and ISM interpretations were carried out for all VES station (VES_1 to VES_25). Both IR and ISM interpretations, based on their methodological approaches, have given slightly variable results.

4 Result Comparison for IR and ISM

A. Layer thickness comparison for IR and ISM—In general, there was no specific trend regarding obtained layer thickness for VES stations using IR and ISM, however, for most of the cases, ISM is giving greater thickness for top layers compared to IR method. In IR method, the lower layers get compressed on logarithmic scale. In general, IR method shows a greater number of high resistivity low-thickness layers, which is the limitation of this method. On the natural scale ISM, decompress the layers at greater depth, identifying the better layer resistivity variation at greater depth as compared to IR method. Thus, giving a greater number of layers at greater depth.

B. Absolute Resistivity Comparison for IR and ISM—In general, ISM and IR layer resistivity values show good agreement for top layer. VES_1, VES_18 compares well for both ISM and IR, whereas VES_2, VES_4, VES_6, VES_7, VES_13, VES_16, VES_17, VES_19, VES_20, VES_21 show appreciable correlation for top layers. IR method in general is giving very high-resistivity value for the last layer with infinite thickness. The resistivity results show good trend correlation for almost for all VES. The ISM for VES locations showing a greater number of layers that there is larger variation in resistivity values for stations, VES_11, VES_14, VES_15, VES_22, VES_23 and VES_25.

4.1 Correlation of Subsurface Resistivity with Existing Borehole Data

There is a considerable overlap of resistivity values between different rock types. In addition, the resistivity of rocks depends on degree of weathering, fracturing, porosity, saturation, clay content and resistivity of pore water and the concentration of dissolved salts. The given rock type can exhibit a large range of resistivity. Identification of a rock type is difficult based on only resistivity data. Since the resistivity ranges of different earth materials have overlapping values, the calculated resistivity values cannot be directly applied to the soil or subsurface rock without correlating that with the subsurface formations. Correlation studies of resistivity and well data in nearby area is essential to identify the formation. The interpreted results of the VES are correlated with the available litholog of the exploratory boreholes to establish the correlation between resistivity and available lithological formations [11]. The interpreted geoelectrical parameters from both IR and ISM results are correlated with the nearest deepest borehole (Drill Hole -DH) as shown in Fig. 6.

The geoelectrical results obtained by the ISM are in good agreement with the available descriptive lithological logs (ground truths). The subsurface model derived by inverse slope method is more comparable with borehole data compared to conventional curve matching-based inversion method. However, the reasonable correlation was not observed for all the boreholes. The reasons may be due to insufficient depth of these boreholes and the considerable distance from the VES stations. The average
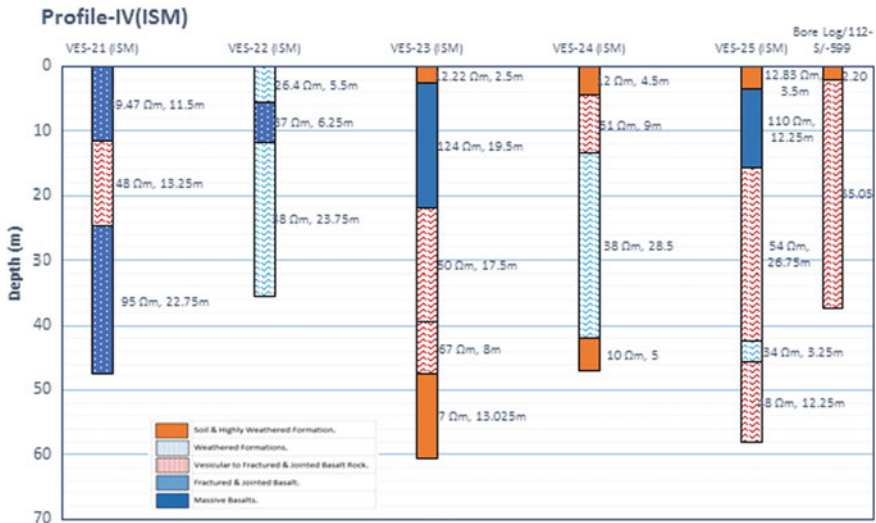
Fig. 6 Inferred geoelectric and geological sections, Profile-IV (ISM)

distance of the VES stations from boreholes were 285 m, 210 m, 200 m and 77 m for profiles I, II, III and IV, respectively. It is very likely that the geology may show changes over such considerable distance separation. Another possible reason may be difference of ground elevation between boreholes and VES locations due to topographic relief. The VES locations are on the downstream of the dam alignments and are on depressed floor elevation particularly for profile-I and profile-II. The difference between the average elevation of Profile-I, Profile-II and corresponding borehole location was more than 16.25 m and 8.5 m, respectively.

The ISM results show better correlations with borehole lithologs. Inverse slope method is found to be more suitable for identifying the deeply located formations. Hence, interpreted resistivity and thickness values by inverse slope method were adopted for layer geoelectric properties correlation. The obtained absolute resistivity from ISM was compared with known resistivity and associated lithology correlation for Deccan Trap formation [12]. Table 2 represents the correlation of absolute resistivity for the VES-25 with the drill hole DH-112S (CH-599 m) for identifying possible lithology.

4.2 Isopach and Isoresistivity Distribution

The resistivity values for the individual layer have been used to prepare isoresistivity maps showing distribution of electrical resistivity for each layer. The thickness isopach map for each layer is also constructed showing individual layer thickness

Table 2 Correlation of VES-25 with DH-112S/chainage CH-599 m

Borehole Data DH-112-S/-599			Geoelectric interpretation VES-25				
Formation	Tk. (m)	Depth up to (m)	No. of layer	Tk. (m)	Depth up to (m)	ρ (Ω m)	Formation
Overburden	2.20	2.20	1	3.5	3.5	12.83	Highly weathered
Chlorophaeitic compact porphyritic basalt with plagioclase phenocrysts	35.05	37.25	2	12.25	15.75	110	Jointed rock
			3	26.75	42.5	54	Vesicular, fracture and jointed rock
			4	3.25	45.75	34	Slightly weathered
			5	12.25	58	48	Vesicular, fracture jointed rock

variation. The layer thickness and layer resistivity contours are shown with colour variation for each layer (Figs. 7 and 8).

True resistivity values for resistivity inversion (IR) and inverse slope method (ISM). Both the methods have demonstrated high resistivity values for deeper layers. The resistivity profiles plotted with these high magnitude values for isoresistivity maps and resistivity profiles suppress and hinder the low-resistivity zones. Also, for the Deccan Trap, higher resistivity value above 300 Ωm indicates hard massive basaltic bedrock.

Considering these aspects, only for representation purpose (in Fig. 9), the high resistivity values are rationalized to 300 Ω m and infinite thickness of the deepest layer rounded to 100 m without losing their significance. These figures have helped to locate the low-resistivity formations in substratum. Figure 9 shows low-density formations around 30 m towards spillway section which may be a potential cause for seepage problem.

4.3 Depth to Competent Bedrock at VES Stations

The resistivity of formation depends upon the characteristic of the element constituting the given geologic medium. Rock resistivity is affected by the degree of fractures, weathering, porosity and saturation. The resistivity data obtained for both IR and ISM method was interpreted in terms of bedrock availability. The comparison of resistivity profiles showing variation of true resistivity with depth for both IR and ISM. The respective profiles show considerable qualitative agreement. The respective profiles depict the similar trend of high true resistivity contour closer and their approximate locations. However, there is quantitative difference for the absolute
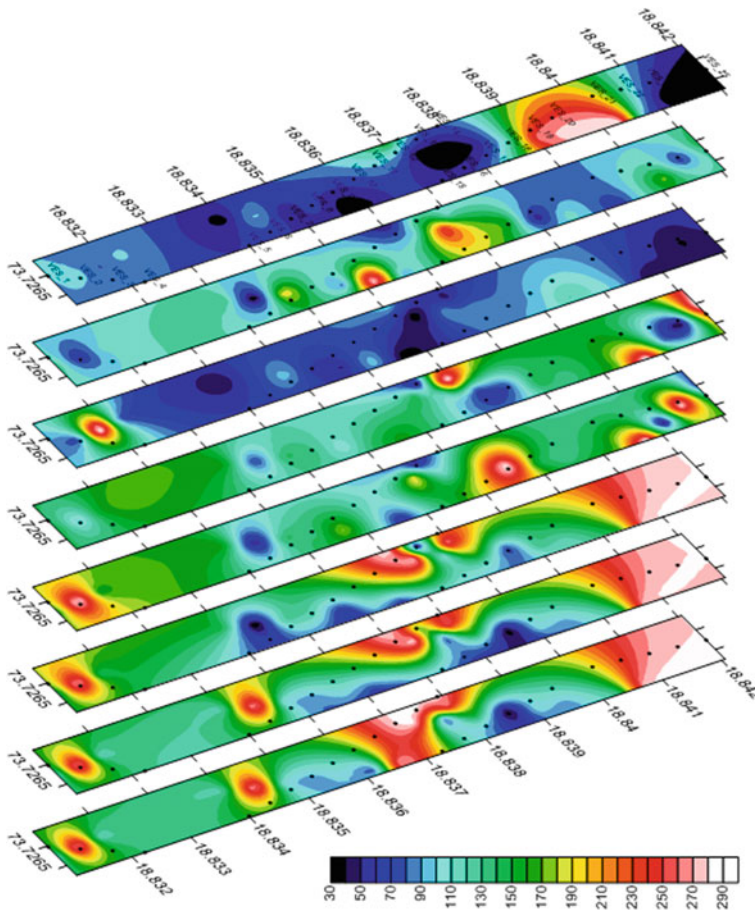
Fig. 7 Stacked layer absolute resistivity contour map (ISM)

layer resistivity and thickness. The differences are mainly due to the high range of the resistivity values obtained for IR method.

The VES results revealed heterogeneous nature of the subsurface geological sequence. The geologic sequence beneath the study area is composed of highly weathered formation, slightly weathered soft rock formations, vesicular, fracture and jointed rock, fracture and jointed rock, thick jointed rock, massive basalt rock and highly massive basalt basement. It is also concluded from the study that the depth to the competent bedrock is relatively variable by both resistivity inversion and inverse slope method as shown in Fig. 10.

The depth to bedrock by IR method is in the range of 13–67 m and for ISM is about 30–58 m. The ISM giving approximately 20–21% higher average depth to the bedrock for left abutment and approximately 145% higher depth for right abutment. For the right abutment (VES_21 to VES_25), resistivity inversion method has given the less
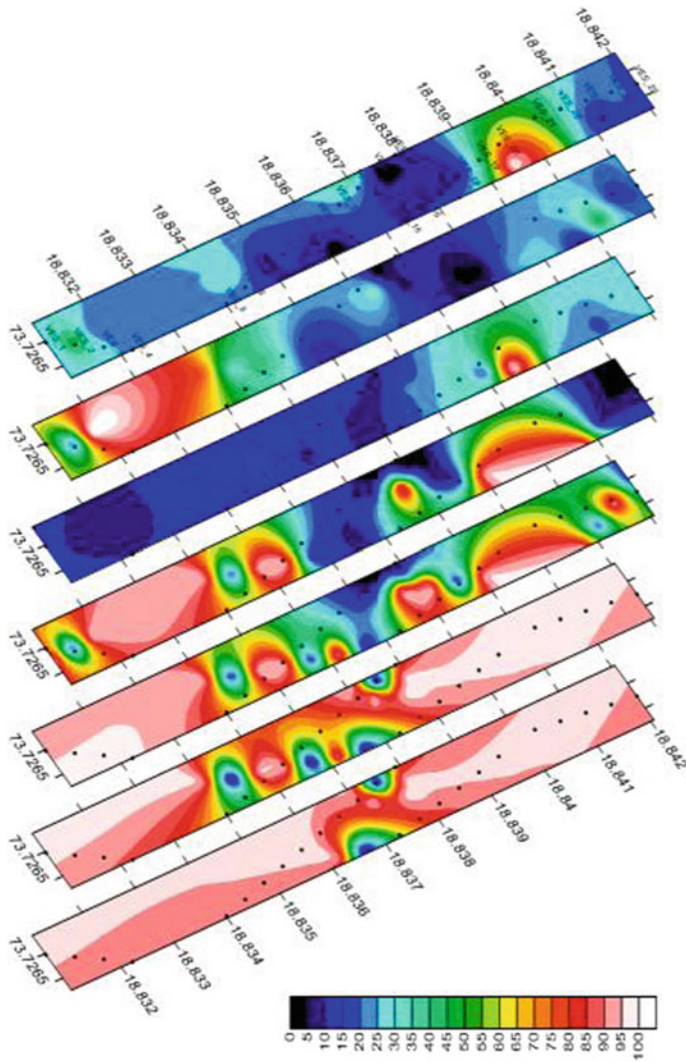
Fig. 8 Stacked layer thickness contour map (ISM)

depth to bedrock because of occurrence of thin high-resistivity layer at comparatively shallow depth (8.78 m, 2.17 m, 5.37 m, 2.03 m, 2.08 m, respectively). Thus, it has failed to consider the average resistivity of layers underneath this thin layer. The ISM decompresses the layers at greater depth identifying the better layer resistivity variation at a greater extent as compare to IR. Thus, giving a greater number of layers at greater depth. In IR method, the lower layers are compressed on logarithmic scale. Each geoelectric layer obtained by the investigations is not exactly the response from the individual litho units but the response of equivalent resistivity or the average of
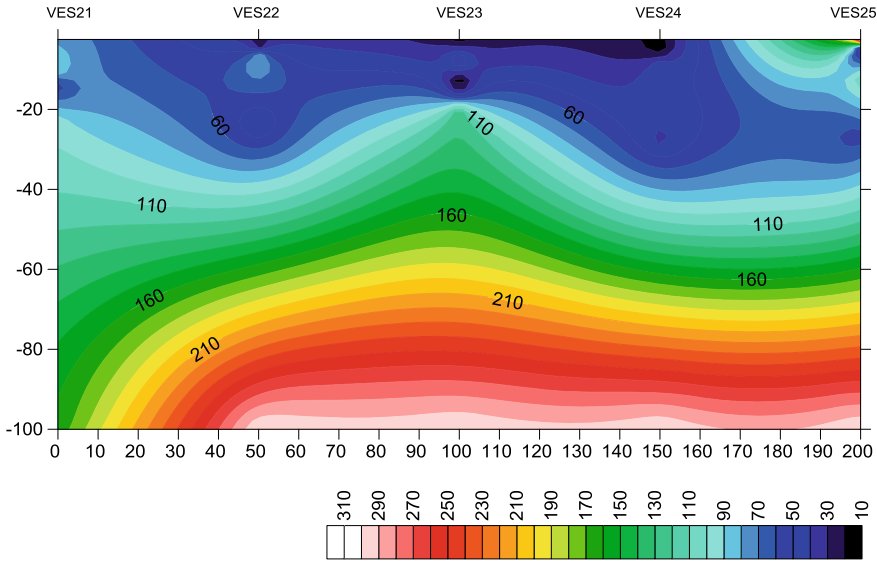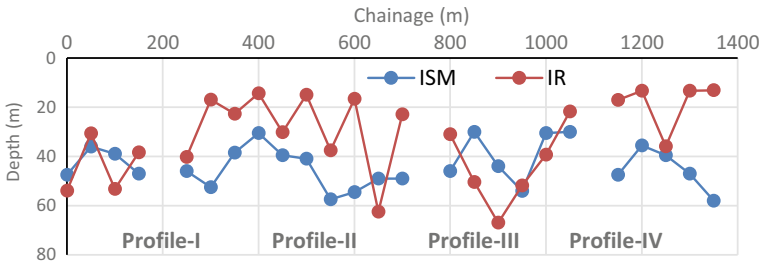
Fig. 9 Profile-IV VES 21_25 (ISM)

Fig. 10 Bedrock level comparison parallel to dam alignment

number of subsurface litho units. The resistivity variation observed in both methods is justified based on the different approaches of these methods.

It is also deduced that the study area can support low to high engineering structures as availability of competent bedrock normally around 30–40 m in most of the area underlain by fresh basement rocks at comparatively shallow depth. The study area can support engineering structures because of their shallow depths to the underlying rock after removal of the overburden soil and weathered formations.

The subsurface model derived by inverse slope method (ISM) is more comparable with borehole data compared to conventional curve matching-based resistivity inversion method (IR). Overall, the vertical electrical sounding (VES) interpretation by ISM have shown substantial correlation with the geological exploration data. (Fig. 6). The ISM is found to be more promising for interpretation of intermixed,

Table 3 Average depth to competent bedrock at VES points

Method	Depth to competent bedrock/foundation depth (m)		
	Left abutment (VES_1 to VES_7)	Middle portion (VES_8 to VES_20)	Right abutment (VES_21 to VES_25)
IR method	37	35	19
ISM method	43.8	42.7	45.5
Avg. foundation depth adopted	7.49		26.71

Table 4 Weaker zones in foundation strata at VES points

VES station	Approx. chainage (m)	Inverse slope method (ISM)		
		Location	Depth to bed rock (m)	Remark
VES_3	700	Left abutment	39.00	Bedrock followed by weaker section
VES_18	−42	Middle portion	54.00	Bedrock followed by weaker section
VES_23	−340	Right abutment	39.50	Fractured Bedrock followed by weaker section

composite, non-stratified igneous formations. Table 3 shows the calculated average depth to competent bedrock at the left abutment, middle portion and right abutment of dam.

The competent bedrock is available normally around 30– 40 m for most of the project area, which is underlain by fresh basement rocks. Resistivity survey has ascertained the occurrence of existing weaker zones identified by core logs, and it has also mapped the weaker zones in foundation strata at greater depth, which were unnoticed due to insufficient depth of conventional exploration. Also, Table 4 shows the weaker zones in foundation strata mapped using resistivity method. Towards the left dam abutment (Irrigation Cum Power Outlet—ICPO section), the resistivity increases with depth, implying less heterogeneity, thus indicating the consistent geological formation there. However, more resistivity anomalies were observed towards dam right abutment (spillway) section. These finding are in consistent with the known site geology [13]. The result interpretation suggests that the failure at the spillway section is likely due to seepage through these weaker zones (Figs. 3, 5 and 9). Therefore, it is recommended that these low-density sections need to be grouted to the appropriate depths.

VES results are also consistence with geological studies and Central Water and Power Research Station, Pune findings. Towards spillway location there is low-resistivity formation (35 Ω m) at depth of 40–45 m (Fig. 6) (Profile-IV) and Table 2. The results correlated with the geological data established that at the tail channel, there is an occurrence of red Tachylytic basalt with lava matrix, near to the stilling

basin area (energy dissipating assembly—EDA portion). The low-density Tachylytic basalt with lava matrix formation that is sandwich between fractured and jointed compacted basalt has seepage potential.

4.4   Limitations of Resistivity Methods

Resistivity interpretations may be ambiguous, thus, requiring independent conventional geological controls for verification. At dam valleys, the results of resistivity surveys are affected by the irregular terrain topography and by differences in electrical properties of dry material at the abutments and the wet material beneath the valley floor. The basic limitation with all 1-D resistivity inversion methods is that they only consider vertical variations in the subsurface resistivity. The electrical profiling (EP) is better than VES method for subsurface geological layers having lateral spatially variable resistivities [14].

5   Conclusion and Recommendations

The primary objective of the study was to enhance the geological understanding of site through resistivity study. A definitive conclusion cannot be drawn based on the resistivity study alone. The findings of resistivity survey complement available exploration data. After comparing the results, the following inferences can be made,

1. The basic purpose of investigation was to find depth of rock and major features like fracture at different depths and profile of hard rock. Location of anomalous foundation features and delineation of boundaries between overburden soil, weathered zones and fresh rock.
2. Electrical resistivity method when combined and correlated with results of the site exploration, improve overall geological understanding, subsequently reducing risk in the overall analysis. The resistivity interpretations are consistent with known site geology. The interpretation has ascertained the weak zones identified in geological investigation. Hence, the resistivity method can be used to identify problematic areas that needs careful consideration.
3. The electrical resistivity investigation has revealed the inadequacy of depth of geological exploration at study site. Electric resistivity survey prior to core drilling may have helped to plan the further detailed investigation and proper site selection for spillway location. Dissimilarities between profiles and boring log data can exist due to the heterogeneity of the site, as well as the resolution capabilities and data smoothing associated with each method.

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