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One-Dimensional Electrical Resistivity Prospecting for Small Dam Projects: A case Study Smaqui Dam, East Erbil City, Kurdistan Region of Iraq

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Abstract:

Abstract: This study employs the One-Dimensional Vertical Electrical Resistivity technique to elucidate the subsurface stratigraphy and structures beneath the axis and abutments of the suggested Smaquli dam, situated to the east of Erbil City in Kurdistan Region of Iraq (KRI). Three traverses were conducted using a Schlumberger array. Data interpretation was performed using the Russian commercial software, IPI2WIN. Each measurement point featured a maximum total electrode spread ranging from 400-600m, reaching an investigation depth of 130m to 150m. The inter-distance between successive measurement points varied from 16m to 17.5m. Geo-electrical sections were generated by interpreting the data, revealing three distinct lithological groups: alluvial deposits (upper first group) with a thickness ranging from 3 to 10 meters, marl and marly limestone of the Shiranish Formation (second group) with thickness ranging from 18 up to 110 meters, and dolomitic limestone of the Bekhme Formation (third group) which its thickness is not defined. These lithological groups exhibited significant resistivity contrasts, rendering the resistivity method effective for delineating their interfaces. The resistivity of the upper horizon ranged from 18 to 136 Ω·m, the second horizon exhibited values between 19 and 304 Ω·m, while the lower third horizon showed high resistivity values ranging from 97 to over 50000 Ω.m.. The relatively low resistivity values of the lower horizon (Bekhme Formation) are interpreted as fractured and water-saturated limestones, whereas the high values are indicative of bituminous material. A correlation was established between the geo-electrical sections and borehole geologic columns, demonstrating consistency in indicating the presence of two rock units within the uppermost 20m, which corresponds to the borehole depth.

1.Introduction

Resistivity methods can be effectively used for the investigation of dam sites, especially when the targets are relatively shallow. Among these methods, the one-dimensional Vertical Electrical Sounding (VES) can be used, although two-dimensional resistivity imaging is increasingly replacing the one-dimensional survey. In Iraq, (Al-Saigh, 2010) used the Vertical Electrical Sounding method to study the embankment of the proposed Badoosh reservoir near Mosul City to check for any faults that might cause water seepage through the embankment. In the Iraqi Kurdistan Region, (Aziz et al., 2013) used both one-dimensional and two-dimensional methods together to survey the Rezan dam site northwest of Sulaimaniyah City and comparing the results with borehole data.

According to United Nations reports, approximately 1.1 Billion people around the world do not have access to portable water (Sikah et al., 2016). During 1998, 1999, 2000, and 2008, the Kurdistan Region of Iraq (KRI) and its surrounding countries experienced severe drought conditions. In response, responsible authorities in the region aimed to address water management challenges effectively, and the construction of small dams has become a key initiative. The Smaquli Valley site was identified as suitable for a small dam. Drought conditions of Iraq between the years 1987 and 2019 was discussed by (Albarakat et al., 2022).

After extensive studies conducted in 2008 and 2009, the Smaquli dam was successfully constructed and has become a notable tourism area near Erbil City. Prior to the construction, a comprehensive range of studies, including geological, hydrological, environmental, seismicity, soil, geophysical resistivity, geotechnical, and borehole studies, were undertaken. Resistivity investigation specifically serves as a case study in this context. ZAE Company in Erbil conducted the overall study, presenting the findings to the Ministry of Water Resources of the Iraqi Kurdistan Regional Government (KRG).

Situated in the Smaquli valley, 67 km east of Erbil City in the Kurdistan Region of Iraq, the dam project encompasses a catchment area estimated to be 101 km^2. The dam has a height of 20m, a length of 325m, and an estimated capacity of 8,500,000 m^3. An open channel runs alongside the dam, measuring 40m in width and spanning a length of 21 km. The project is located around the coordinates of longitude 44°35'15.5 °E and 36°10'12.6″ N (Plate 1 and Figure 1), (Ghaib, 2008).

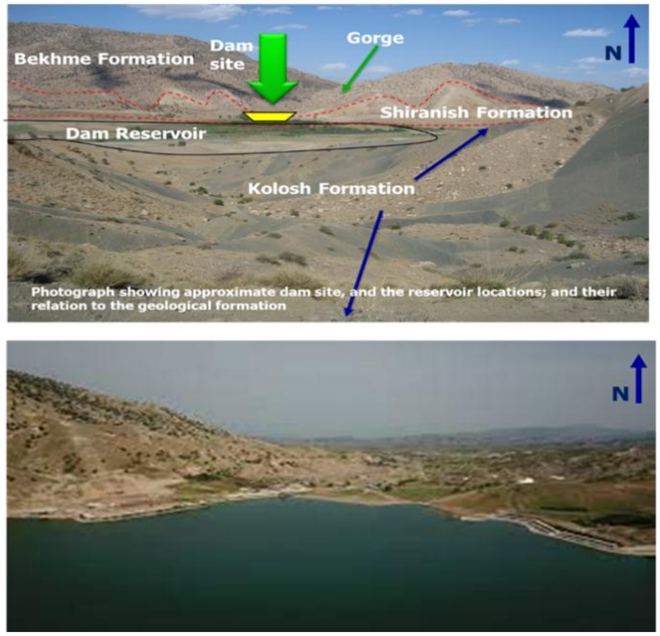


Plate 1: The dam area before and after construction. (ZAE-Company, 2008b)

2. Tectonic and geological settings of the study area

From a tectonic perspective, the dam site is situated within the foreland basin, as documented by (Numan, 1997). In alignment with other subdivisions within Iraq, the region falls under the classification of Unstable Shelf of Iraq (Jassim and Goff, 2006) and precisely within the Foothill Zone nearer to the High Folded Zone (Fouad, 2015). The area around the project site is characterized by numerous high amplitudes, closely spaced tightness, and overturned folds, displaying diverse geometries and sizes. The topography is marked by landforms dominated by erosion-resistant Cretaceous rock units, giving rise to highly structured features, such as rugged anticlinal mountains interspersed with narrow, deep synclinal valleys, as depicted in Figures1 and 2.

The Smaquli area exhibits a geologically straightforward configuration, featuring hilly terrain within a syncline between two NW-SE trending anticlines, Safeen and BnaBawi .A detailed geological survey was conducted by the geological team of the company by updating the details which are given by (Buday and Jassim, 1980), and (Jassim and Goff, 2006). The survey identified several formations that crop out in the area around the project, as shown in figure 2. Below are brief descriptions of these formations:

I. Qamchuqa Formation (Hautervinian - Albian)

It comprises the safen anticline core, consisting of thick bedded coarsely crystalline limestone alternating with dolomitic limestone.

II. Bekhme Formation (U) Campanian - L. Maastrichtian)

It forms prominent anticlinal ridges in this area. Together with Qamchuqa, they constitute the bulk of the core of the Safeen Anticline. It is composed of massive and recrystallized dolomite and dolomitic limestone, exhibits karstic and cave features, and is highly fractured.

III. Shiranish Formation (U. Campanian - Maastrichtian)

It is exposed around the Safeen Anticline as a continuous belt. It is composed of thin-to medium-bedded to marly limestone. The beds are highly jointed and fractured, and the weathered surfaces are fragmented into chipsets.

IV. Kolosh Formation (M. Paleocene - L. Eocene)

Kolosh Formation is characterized by alternating thin beds of sandstone with siltstone, mudstone, and argillaceous limestone. The formation is easily eroded because it is friable; therefore, it occupies the lowlands and undergoes differential weathering.

V. Sinjar Limestone Formation (U. Paleocene - L. Eocene)

This formation is found as a narrow ridge around the margin of the catchment area, mostly outside the studied area. It is composed of thick-to medium-bedded recrystallized and algal reefs, with marly interfingering with the Kolosh Formation.

VI. Gercus Formation (M. Eocene)

It is composed of thin-to medium-bedded shales, mudstone, sandy marls, pebbly sandstone, and conglomerates. When weathered, it fragments into small chips. It generally forms high and steep slopes at the feet of hard Pilaspi Formation.

VII. Pilaspi Formation (M.- U. Eocene)

This formation is the youngest one that appears in/or in the vicinity of the area. It is composed of well-jointed dolomitic and chalky limestone. Rocks are resistant to weathering. Hence, high cliffs and ridges with very steep slopes have occurred.

VIII. Lower Fars (Fat'ha) Formation (M. Miocene)

It is composed of medium-bedded alternating limestone and claystone.

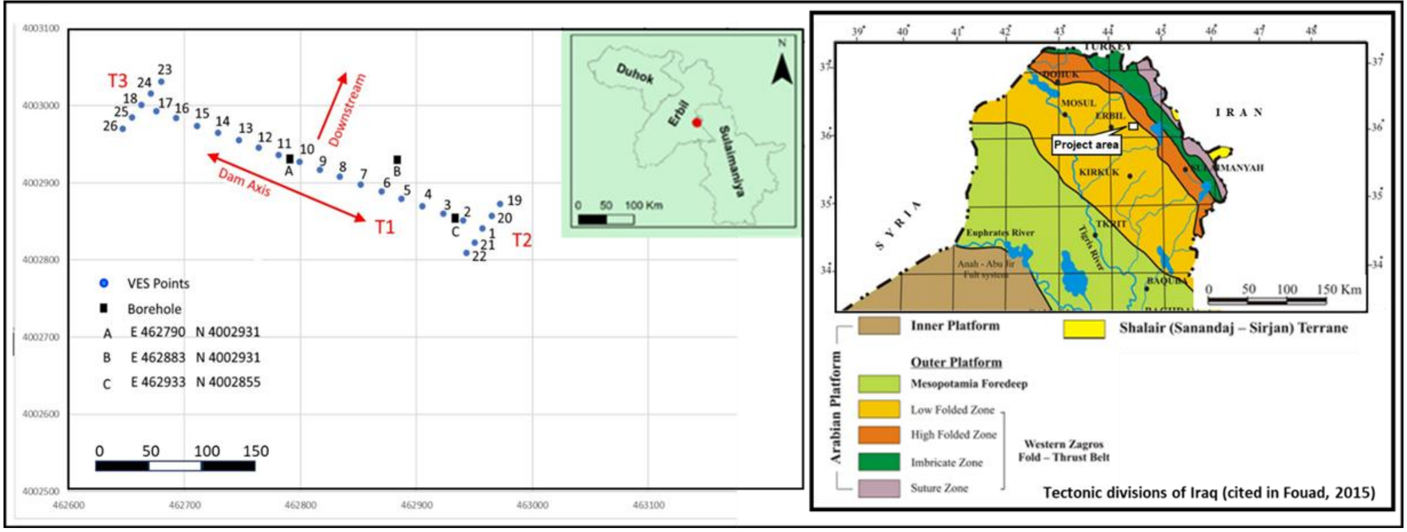


Figure 1: Tectonic map of Iraq showing the study area and resistivity traverse.

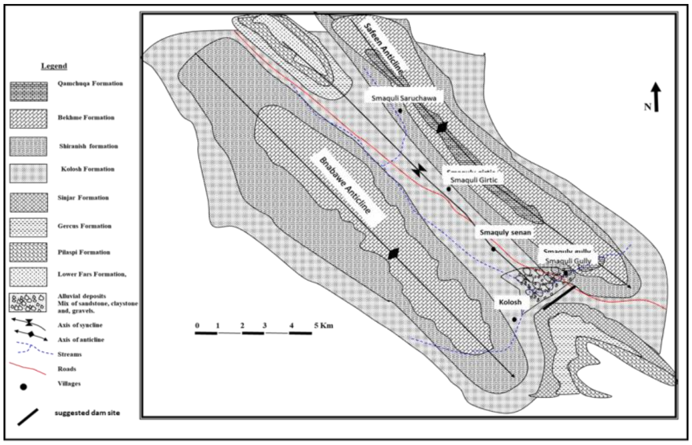


Figure 2: Geological map of the studied area

3.Resistivity Method (Vertical Electrical Sounding)

Resistivity surveys were conducted to determine subsurface resistivity distribution by measuring the ground surface. These measurements serve as a basis for estimating the true resistivity of the subsurface, with ground resistivity being intricately linked to geological parameters, such as mineral and fluid content, porosity, and water saturation in the rock.

Typically, measurements involve injecting current into the ground through two current electrodes (A and B) and measuring the resultant voltage difference at two potential electrodes (M and N), as shown in figure 3. The apparent resistivity (ρ_a) is then calculated from the current (I) and voltage (V) values using the formula $\rho_a = k\ V/I$, where k represents the geometric factor determined by the electrode arrangement (Zohdy and Bisdorf, 1989, Kearey et al., 2002, Reynolds, 2011).

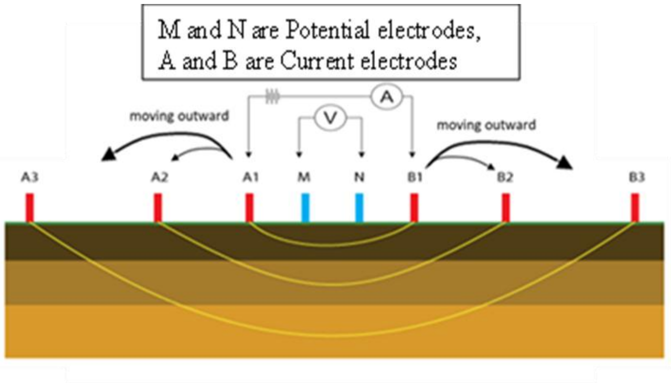


Figure 3: Schlumberger array

It is important to note that the calculated resistivity value is not the true resistivity of the subsurface but an "apparent" value, indicating the resistivity of a homogeneous ground that would yield the same resistance value for the given electrode arrangement. The relationship between the "apparent" and "true" resistivity is intricate. Special standard curves or dedicated software tools were employed to ascertain the true resistivity. In this study, the commercial program (IPI2Win, 2000) was used to determine the true resistivity values of the subsurface rock units. The penetration depth in the homogeneous ground is directly proportional to the separation between the electrodes. Varying electrode separation allows for the exploration of ground stratification, as noted by (Loke, 2004).

The interpretation of multiple points along the dam site, where the results showcasing the variation of resistivity with depth are interconnected, yields a section known as a "geo-electric section." This section is comprised of numerous geoelectric horizons, each corresponding to a distinct lithological unit. The geo-electric section provides valuable insights into the subsurface structure and facilitates identification of different geological layers based on their electrical resistivity characteristics.

4. Resistivity survey

A total of 26 Vertical Electrical Soundings (VES) were systematically conducted at the Smaquli dam site in October 2008, as illustrated in Figure 1 and Plate 2. Among these, 18 VES were strategically positioned along the proposed dam axis, aligned in the NW-SE direction, perpendicular to the stream Five VES points were also situated along each abutment, including VESs 1 and 18 from the previous traverse (Figure 1). The inter-distance between successive measurement points ranged from 16m to 17.5m throughout all traverses, ensuring comprehensive coverage. The coordinates of the VES points are detailed in Table 1.

Plate 2: Field activities

The initial traversal covered a distance of 300 meters, while each of the subsequent two traversals extended over 70 meters each. In adherence to the Schlumberger configuration, the electrodes' maximum total spread at each point varied between 400 and 600 meters. To minimize potential errors stemming from the dip, the electrode spread remained consistently aligned in the strike direction at all points. Resistivity measurements were carried out using the ABEM SAS3000 Terrameter, and a Garmin model GPS device facilitated accurate positioning and elevation measurements of the investigation points. Notably, the field data obtained exhibited high quality, examples are given in figure 4.

5. Interpretation of resistivity data

The quantitative interpretation of electrical surveys poses a significant challenge within the realm of geophysical methods, owing to the intricate theoretical foundation of the technique. Analyzing resistivity curves over complex, multilayered structures, as exemplified in the current case, involves a manual partial curve matching process. This entails aligning the master theoretical curves of a two-layer case with specialized sets of auxiliary curves. While this manual approach has traditionally been employed, modern advancements have included the utilization of computer programs. In this investigation, the Russian software, (IPI2WIN, 2000), was effectively used for interpretation (Fig. 4).

Table 1: Coordinates of the VES points

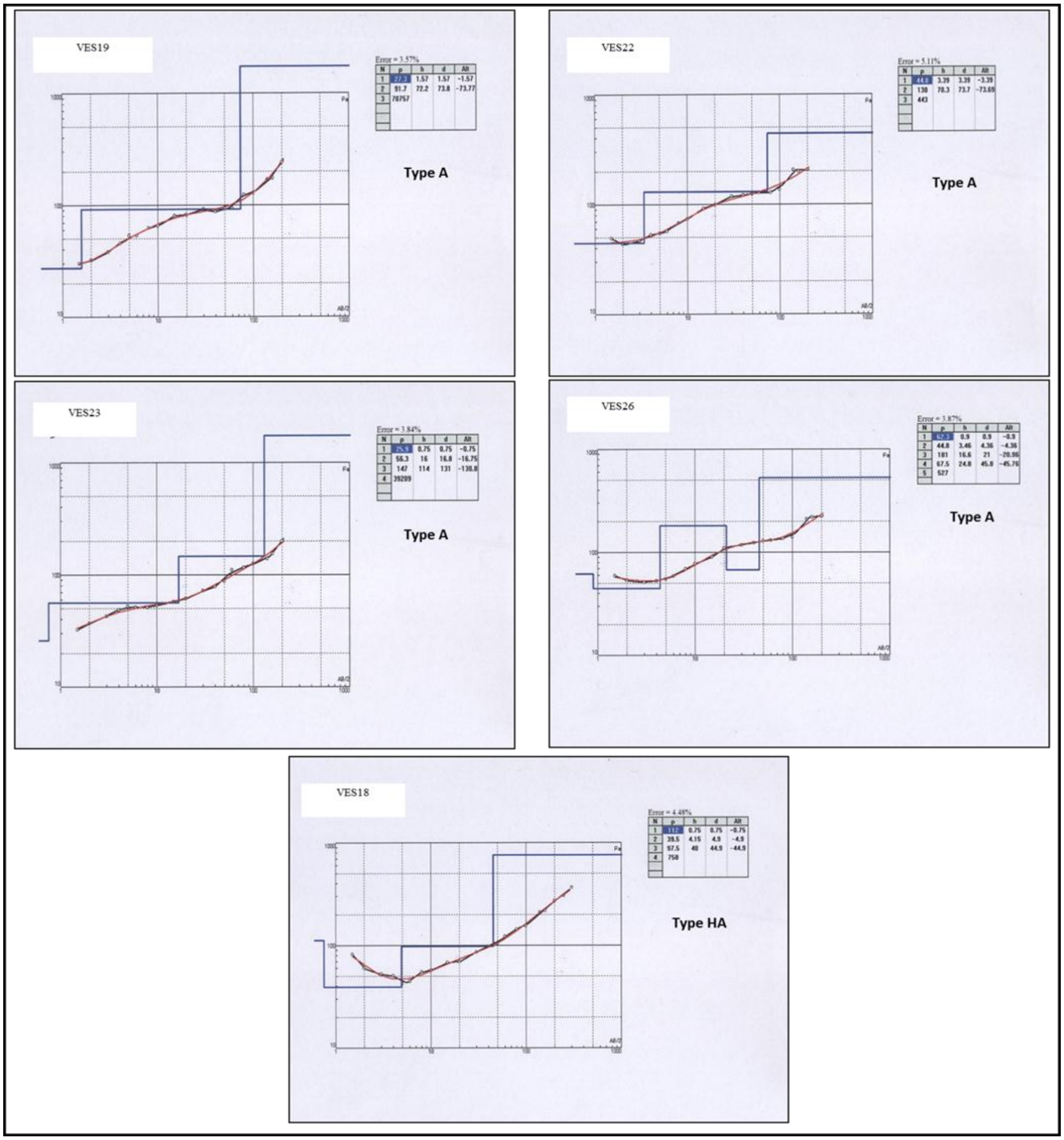
VES No.	X	Y	Z (m.a.s.l.)	VES No.	X	Y	Z (m.a.s.l.)
١	٤٦٢٩٥٧	٤٠٠٢٨٤١	٧٣٠	١٤	٤٦٢٧٢٩	٤٠٠٢٩٦٥	٧٢٤.٦
٢	٤٦٢٩٤٠	٤٠٠٢٨٥١	٧٢٣.٢	١٥	٤٦٢٧١١	٤٠٠٢٩٧٤	٧٢٥.٤
٣	٤٦٢٩٢٣	٤٠٠٢٨٦٠	٧١٤.١	١٦	٤٦٢٦٩٣	٤٠٠٢٩٨٤	٧٢٦.٧
٤	٤٦٢٩٠٥	٤٠٠٢٨٧٠	٧١٠.٩	١٧	٤٦٢٦٧٦	٤٠٠٢٩٩٣	٧٢٨.٤
٥	٤٦٢٨٨٧	٤٠٠٢٨٧٩	٧١٠	١٨	٤٦٢٦٦٣	٤٠٠٣٠٠١	٧٣٠
٦	٤٦٢٨٧٠	٤٠٠٢٨٨٩	٧١٠	١٩	٤٦٢٩٧٢	٤٠٠٢٨٧٣	٧٢٧.٥
٧	٤٦٢٨٥٢	٤٠٠٢٨٩٨	٧١٠.٨	٢٠	٤٦٢٩٦٥	٤٠٠٢٨٥٧	٧٢٥.٨
٨	٤٦٢٨٣٤	٤٠٠٢٩٠٨	٧١١.٣	٢١	٤٦٢٩٥١	٤٠٠٢٨٢٥	٧٢٤.٥
٩	٤٦٢٨١٧	٤٠٠٢٩١٧	٧١١.٨	٢٢	٤٦٢٩٤٣	٤٠٠٢٨٠٩	٧١٩
١٠	٤٦٢٧٩٩	٤٠٠٢٩٢٧	٧١٤.٥	٢٣	٤٦٢٦٨٠	٤٠٠٣٠٣١	٧٣٣
١١	٤٦٢٧٨١	٤٠٠٢٩٣٦	٧١٧.٩	٢٤	٤٦٢٦٧١	٤٠٠٣٠١٦	٧٣١.٥
١٢	٤٦٢٧٦٤	٤٠٠٢٩٤٦	٧١٩.٧٥	٢٥	٤٦٢٦٥٥	٤٠٠٢٩٨٥	٧٠٠.٥
١٣	٤٦٢٧٤٧	٤٠٠٢٩٥٥	٧٢٢.٣	٢٦	٤٦٢٦٤٧	٤٠٠٢٩٧٠	٧٠٠.٥

The presence of an apparent surface geology in the study area facilitates accurate interpretation. The primary rock types in the investigated area consist of alluvial deposits (upper first group) at the surface, followed by marl and marly limestone of the Shiranish Formation (second group),

which overlay the dolomitic limestone of the Bekhme Formation (third group). It is worth noting that three VES points (1, 19, and 23) exhibited abnormal high resistivity values for this formation. However, these points did not affect the results.

These three lithological groups exhibited significant resistivity contrasts, making the resistivity method favorable for delineating the interfaces. The varied physical properties of these rock types result in distinct responses to electrical fields.

Once the layer models have been produced and assessed, thin layers with approximate resistivity values and very small thicknesses have been averaged for each VES. To construct the geo-electrical sections, the models were displayed side by side, like borehole logs. These sections are pictures of both the vertical and lateral variations in resistivity (Gardi, 2017). The resulting sections were plotted in terms of geology by relating each resistivity horizon to its probable equivalent rock formation (Figs. 5, 6, and 7).



Error = 3.57%

N	ρ	h	d	Alt
1	27.3	1.57	1.57	-1.57
2	91.7	72.2	73.8	-73.77
3	70757			

Error = 5.11%

N	ρ	h	d	Alt
1	44.8	3.39	3.39	-3.39
2	130	70.3	73.7	-73.69
3	443			

Error = 3.84%

N	ρ	h	d	Alt
1	25.9	0.75	0.75	-0.75
2	56.3	16	16.8	-16.75
3	147	114	131	-130.8
4	39209			

Error = 3.87%

N	ρ	h	d	Alt
1	67.3	0.9	0.9	-0.9
2	44.8	3.46	4.36	-4.36
3	181	16.6	21	-20.96
4	67.5	24.8	45.8	-45.76
5	527			

Error = 4.48%

N	ρ	h	d	Alt
1	112	0.75	0.75	-0.75
2	39.5	4.15	4.9	-4.9
3	97.5	40	44.9	-44.9
4	758			

Figure 4: Examples of sounding cures interpreted using the (IPI 2Win, 2000) program

6.Description of geo-electrical sections

In all sections, three main geo-electrical horizons were identified. Fortunately, there is simple geologic stratification along all the surveyed lines. These horizons are well-defined by almost sharp, clear boundaries, each representing a separate lithological unit.

Traverse 1, (Figure 5)

It involved 18 VES points spread along the proposed dam axis. The uppermost horizon (1) represents alluvial deposits, including thin topsoil cover under alluvial deposits. Its thickness varied between 3 m and 10 m. The highest values were observed beneath VESs 3, 6, 7, and 12 through 16, while the lowest values were noted under VESs 10 and 11, diminishing along the right bank of the valley where Shiranish Formation outcrops are exposed between VESs 2 and 3. Between VESs 1 and 2, the horizon comprises weathered Shiranish outcrops and soils drained by erosion from the highly located Shiranish marls (resistivity ranging from 42 to 57 Ω.m.). Under VES 9, it consists of silty clay with a resistivity value of 18 Ω.m., whereas other sections of this horizon consist of silty and sandy deposits, all influenced by flood activities. The resistivity values for the entire horizon ranged from 18 to 154 Ω.m., indicating variations in lithology with different ratios of clay, silt, and sand. There were minimal indications for the presence of gravel.

Horizon (2) represents marl and/or marly limestone of the Shiranish Formation. The present thickness does not indicate the original thickness of the formation owing to erosion. It ranged from a maximum value of 78m under VES 1 on the top of a nearby hill to approximately 25m under VES 9 on the other side of the valley. The resistivity value along the horizon ranged from 27 to 171 Ωm. The minimum resistivity value is under VESs 12 and 13 (i.e., the lens pocket Z2'), at which it has a moderate thickness. Underneath this site, the low value of resistivity indicates that the formation is possibly fractured and water saturated. It is recommended that a borehole be drilled to ascertain the problem. Other than this area, no diagnostic geological features were observed along this section.

On the other hand, the lowermost horizon (3) mostly represents dolomitic rocks of the Bekhme Formation (Fig. 5). The lower boundary of this horizon is not defined throughout this study, and it is not necessary to do this within the present scope. The depth of the upper boundary of the horizon varies from 50m under VES 18 to approximately 83m under VES 1. The resistivity values in this horizon had a wide range. This range is 454 to 40250 Ω.m. Such high resistivity values generally characterize the dolomitic massive limestone of Bekhme Formation unless the investigated site is highly fractured, and water saturated. The higher values are due to the massive and bituminous contents, whereas low values indicate fracturing and moisture content.

Traverse 2 (Figure 6)

This line ran along the right suggested dam abutment. This involved five VES points. The mid-point is point 3 of traverse 1. The length of the line was 70m (35m on each side of the axis trace of the dam). Again, the same layering pattern was observed. Three geoelectric horizon scans are easily defined. The following is a detailed description of the interpretation results, followed by a table summarizing the details.

The first uppermost horizon (1) represents topsoil underlain by alluvial deposits. It has a resistivity value ranging from 27 to 57 Ω.m., reflecting a lithology that is expected to be clayey to silty and sandy mixtures. The ratio of silt and/or sand to clay increased towards the northeast. The horizon had a mean thickness of approximately 5m along the traverse.

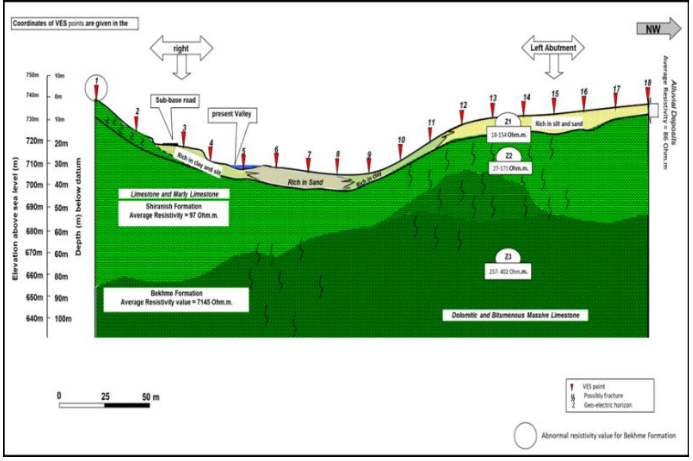


Fig. 5: Geoelectric section of traverse 1, along the dam axis.

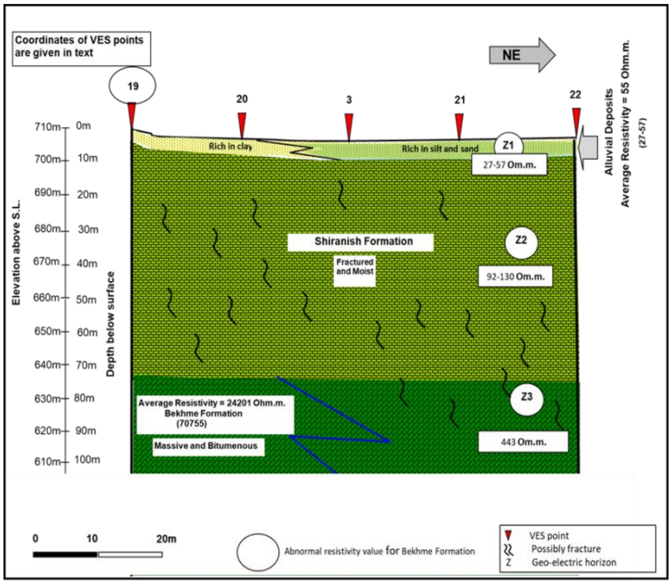


Fig. 6: Geoelectric section of traverse 2, along the right abutment

The middle horizon (2) represents rocks of the Shiranish Formation. The thickness along the line was almost constant and equal to approximately 65m. The resistivity values ranged from 92 to 130 Ωm. This range shows no abnormal geological risk features that may affect the dam.

It represents rocks belonging to the Bekhme Formation. It has very high values of resistivity under VESs 19 and 20, indicating a massive and bituminous manner (440-70755 Ω.m..). In contrast, the resistivity values were low for VESs 21 and 22. In this part of the traverse, this formation is characterized by fractures possibly filled with water.

Traverse 3 (Figure 7)

This traverse runs along the left suggested dam abutment. It involves five VES points. The mid-one is point 18 of traverse 1, with a maximum length of 70m (35m on each side of the axis trace of the dam). Again, the same pattern of layering is present. These three geoelectric horizons can be easily defined.

The uppermost horizon (1) represents again the topsoil underlain by alluvial deposits. It has a resistivity value ranging from 40 to 78 Ω.m., reflecting a lithology that is expected to be clayey to silty and sandy mixtures. The silt and/or sand to clay ratio increased in the central area underneath VES 18. The horizon has a mean thickness of approximately 10m along the traverse, increasing to more than 15m under VES 23 and decreasing to reach about 5m under VES 26.

In the middle, horizon (2) represents rocks of the Shiranish Formation. Its thickness along the line increases towards the southwest. It is approximately 22m under VES 26, whereas it increases to reach about 110m under VES 23. The resistivity values ranged from 68 to 181 Ωm. This range shows that fracturing increases towards the northeast.

Finally, the lowermost horizon (3) represents the rocks that belong to the Bekhme Formation. It had very high values of resistivity under VESs 23 and 24, indicating a massive and bituminous manner. In contrast, the resistivity values were low for VESs 25 and 26. In this part of the traverse, this formation is characterized by the presence of fractures that are possibly saturated by water. Its depth is approximately 130m under VES 23, whereas it is only approximately 28m under VES 26. Tables 2, 3 and 4 brief the results of the three traverses.

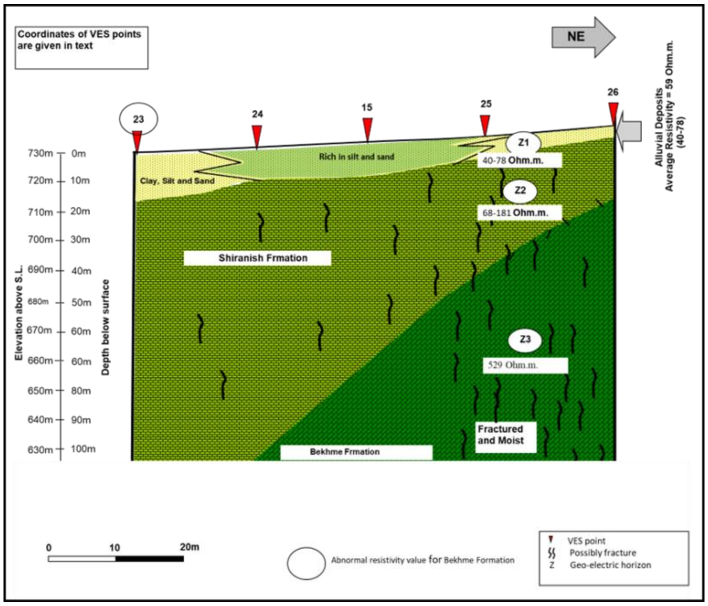


Fig. 7: Geoelectric section of traverse 3, along the left abutment.

Table 2: A brief of the results of Traverse 1

Horizon No.	Thickness Range (m)	Resistivity Range (Ω.m)	Lithology	Diagnostic Feature
1	3-10	18-154	Slope deposits of marly materials in the area between VES 1 and 2 while it is silty clay or silty and clayey sands in others	Thinner on the northwestern bank of the valley.
2	18-78	27-171	Mostly lithified and jointed layers of marl.	Possibly highly fractured under the site of VES 12. minimum thickness is under VES 9.
3	Not defined	257- 402	Massive dolomite or dolomitic limestone	Possibly highly fractured under the sites of VES 6, 11 and 12

Table 3: A brief of the results of Traverse 2

Horizon No.	Thickness Range (m)	Resistivity Range (Ω.m)	Lithology	Diagnostic Feature
1	5	27-57	silty clay or silty and clayey sands.	Almost constant thickness
2	65	92-130	Jointed layers of marl or marly limestone	None
3	Not defined	443-70755	Massive dolomite or dolomitic limestone	Possibly highly fractured under the sites of VES 21 and 22

Table 4: A brief of the results of Traverse 3

Horizon No.	Thickness Range (m)	Resistivity Range (Ω.m)	Lithology	Diagnostic Feature
1	5-10	40-78	silty clay or silty and clayey sands.	None
2	22-110	68-181	Jointed layers of marl or marly limestone	Thin in the northeast side and thick in the other.
3	Not defined	529-39206	Massive dolomite or dolomitic limestone	Possibly highly fractured under the sites of VES 25 and 26

7.Comparison with boreholes

In addition to geophysics, the technical team has performed many boreholes to investigate the subsurface. Five boreholes ranging in depth between 20m and 35m were specified for both suggested abutment axes: one borehole at the intake, one borehole at the spillway, and one borehole at the reservoir (ZAE-Company, 2008a). Unfortunately, the locations of these boreholes do not precisely coincide with the VES sites, even the intake one is located downstream about 40m from VES 6 (B in figure 1). Two of those boreholes are located on the main axis of the dam (A and C in figure 1). Nevertheless, the results of these three boreholes were juxtaposed with those of the geo-electrical section (Fig. 8). VESs 3, 6, and 10 were compared to the nearest borehole sections. There are mainly two units within the drilled 20 m in the geo-electrical sections. The upper layer is mainly composed of topsoil and alluvial deposits collected owing to the weathering activities of the Shiranish and Bekhma Formations. It ranges in thickness between 2 and 5 m. The details provided in the geological columns of the boreholes are not shown in the same details in the geo-electrical sections. Nevertheless, a minimal comparison can be made because both techniques show the presence of two main rock layers.

It is possible that a two-dimensional resistivity survey can provide more details than a one-dimensional survey.

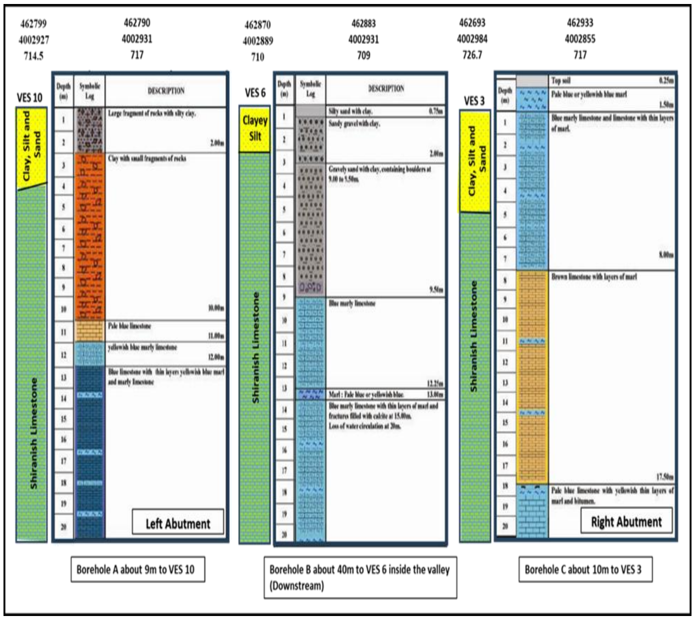


Fig. 8: Borehole geological columns as compared with geo-electrical sections (coordinates are given in the top)

8.Conclusions

This resistivity investigation aimed to define and show a general subsurface geological picture along the suggested dam axis and abutments. The results of the study in terms of the thickness of the subsurface layers, their resistivity values, expected lithology, and any diagnostic features that might be present are summarized. in three tables.

In the three geo-electric sections, the Shiranish Formation, mainly composed of thin-to medium-bedded limestone to marly limestone, is well shown. Generally, the formation is well fractured and jointed. This should be considered in future studies. Some electrical horizons clearly show this property, such as underneath VESs 25-26, VES 5, VES 21, VESs 10-14. The main foundation of the body of the dam will be the competent Bekhme Formation which is quite stable.

A moderate comparison can be made between the geo-electrical sections and geological columns, as illustrated by the borehole results. In general, both techniques showed the presence of two main layers within the drilled 20m.

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