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2D Resistivity Tomography of Doly Rostey Proposed Small Dam Site, Soran Subdistrict, NE of Erbil City-Iraqi Kurdistan Region

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ABSTRACT

The present study investigates the subsurface conditions for a proposed small dam in Doly Rostey, situated in the extreme northeastern part of Erbil City within the Iraqi Kurdistan Region. To achieve this, four profiles were surveyed: one along the dam axis (NW-SE direction), two along the abutments, and one along the stream parallel to the abutments (NE-SW direction). Each profile spanned 355 meters, employing a Wenner-Schlumberger electrode configuration with 5-meter electrode spacing. Field data were processed and interpreted using the software “RES2DINV” (version 3.59.117), generating four detailed 2D resistivity inversion sections. The results revealed the Qamchuqa Formation as the dominant subsurface feature, with resistivity values of 500 to 60,000 Ω·m, indicative of dolomitic and limestone layers. The study also identified karstic features, fractured zones, and potential faults, highlighting structural complexity and pathways for water movement. Additionally, low-resistivity zones (45–500 Ω·m), corresponding to surface sediments and marly limestone within the uppermost 16–60 meters. These findings emphasize the site’s structural and lithological variability and highlight the critical need for detailed geotechnical and hydrological evaluations to ensure the dam's stability and safety.

1.Introduction

Rapid urban development, population growth, and low rainfall over the past two decades have created water supply challenges in the Kurdistan Region of Iraq, affecting drinking water, agriculture, and irrigation. To address this, authorities have constructed 23 dams, with 11 more under construction, totaling 34. These include major dams like Dukan, Darbandikhan, and Duhok which were constructed during earlier times in the twentieth century, vital for water storage, electricity generation, agriculture, and tourism. The region’s annual rainfall of over 500 mm provides a significant water source, requiring proper storage solutions. Engineering and geological studies, such as 2D Resistivity Tomography surveys, are essential for ensuring dam safety and efficiency.

The Electrical Resistivity survey is among the most cost-effective techniques for addressing civil engineering challenges. There is extensive literature on this issue, including works by, Abbas et al. (2022), Van Schoor (2002), Zhou et al. (2002), and Abu-Shariah and Shariah (2009). Natural voids and cavities within subsurface limestone present significant challenges to civil engineering and environmental management (Alemdağ et al., 2024). The term "subsurface cavity" refers to all underground features such as cavities, caves, caverns, voids, karsts, and sinkholes. These cavities primarily develop through dissolution processes affecting carbonates (such as limestone and dolomite) and evaporites (including salt, gypsum, and anhydrite).

The Doly Rostey area and its surroundings have experienced substantial geological transformations and intensive development activities over the years. This is primarily due to its proximity to the suture zone associated with the Zagros Range; a region characterized by active tectonics. The area lies near the boundary where the Arabian and Iranian plates converge, resulting in frequent tectonic movements, folding, faulting, and uplift. These dynamic geological processes have significantly shaped the landscape and influenced the region’s structural complexity, making it a zone of both scientific interest and developmental challenges. The area of study is predominantly covered by the Qamchuqa Formation. A preliminary geological reconnaissance revealed several surface and subsurface cavities at varying locations as observed in the field. Consequently, surface geophysical exploration was strongly recommended, especially in open and undisturbed areas. The primary objective of this survey was to investigate shallow subsurface weak zones, voids, cavities, and various fault types. Mapping these hazards is crucial for designing the dam foundation and identifying safe construction zones.

The study area is situated about 100 km northeast of Erbil City and 13 km east of Soran town. The dam site is bound by latitudes 36° 37' 29"N to 36° 37' 44"N and longitudes 44° 41' 34"E to 44° 41'5 4"E (Fig. 1).

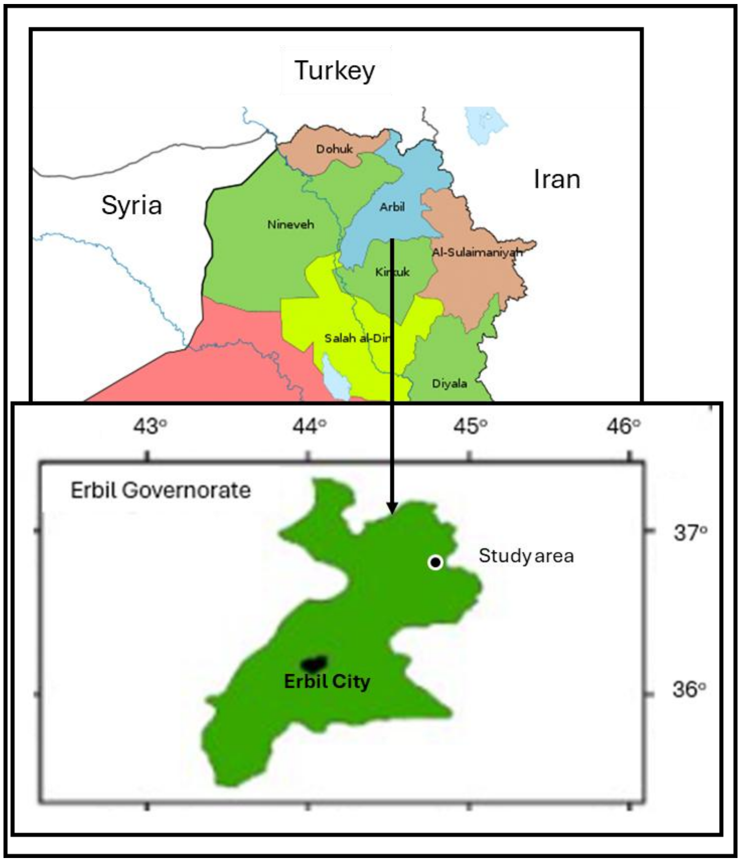

Figure: 1: Location map of the area

2.Tectonic and Geologic Settings

According to (Buday and Jassim, 1987), Iraq is divided into three main tectonic zones: the Stable Shelf, the Unstable Shelf (including the foothill and high-folded zones), and the Geosynclinal

Zone. The study area lies on the boundary between the Central Thrust Geosynclinal Zone and the Balambo-Tanjero Zone (Fig. 2). This thrust zone is characterized by compressional deformation, producing thrust faults and folds in Paleozoic to Tertiary sedimentary rocks, where older strata are pushed over younger ones.

In the absence of a detailed local geological map, the authors relied on field observations and previous studies such as Bellen et al. (1959) and Jassim and Goff (2006). The site is covered by a thin soil layer, underlain by two Lower Cretaceous formations: the Sarmord Formation and the overlying Qamchuqa Formation.

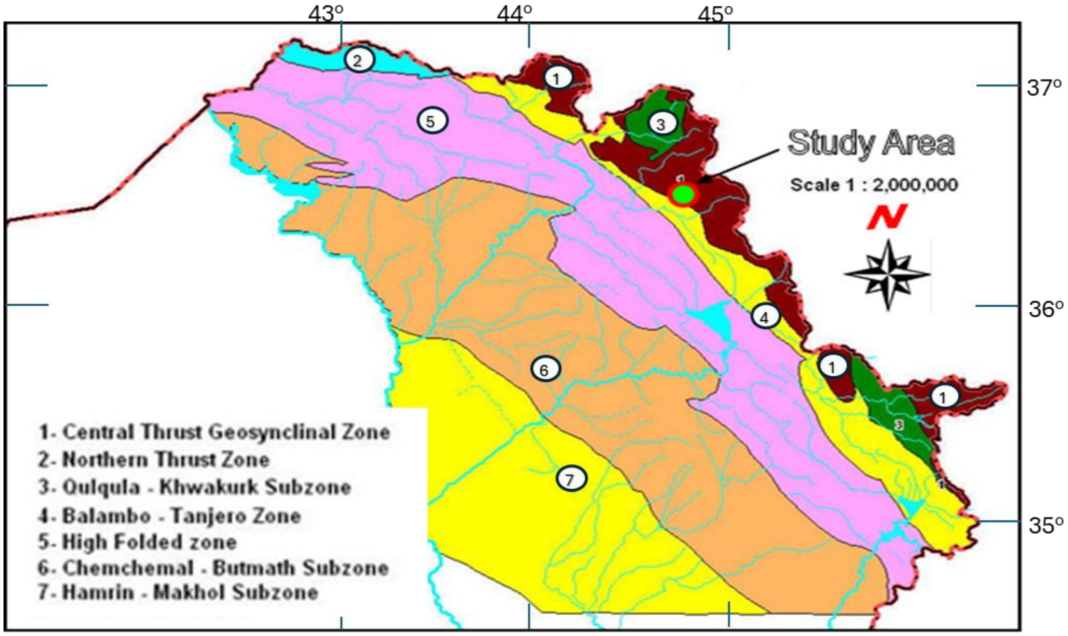

Figure 2: Tectonic subdivision of northern Iraq (Buday and Jassim, 1987)

2.1 Sarmord Formation (Valanginian–Hauterivian)

The Sarmord Formation is around 455 meters thick and comprises marl, limestone, and shale, with some sandstone beds. Fossiliferous limestone indicates a marine depositional environment from deep to outer shelf settings. It conformably underlies the Qamchuqa Formation and occasionally interfingers with the Balambo Formation (Balaky et al., 2023).

2.2 Qamchuqa Formation (Hauterivian–Albian)

First identified in Qamchuqa Gorge, this formation consists mainly of dolostone, dolomitic limestone, and dolomitic mudstone. Its thickness ranges from 250 to 500 meters in the High Folded Zone (Jassim and Goff, 2006). The lower sections are rich in reefal limestone and fossils like rudists, corals, and algae, indicating a reefal to shoal depositional environment (Ameen and Karim, 2008). It grades laterally into the Balambo Formation and is unconformably overlain by the Kometan Formation.

3.Resistivity surveying

The 1D resistivity sounding method has been used since the early 20th century to investigate subsurface structures. It involves measuring apparent resistivity at increasing electrode spacings while keeping the array center fixed, allowing estimation of layer thicknesses and resistivities. The two main electrode configurations used are Schlumberger and Wenner. In both, four aligned electrodes are used, with the outer current electrodes moving outward to increase depth, and the inner potential electrodes adjusted only when needed (Fig. 3).

Resistivity imaging, or resistivity tomography, is an advanced form of traditional resistivity surveying that produces detailed 2D or 3D models of subsurface resistivity. Unlike 1D sounding, it provides cross-sectional views that reveal both vertical and lateral variations in subsurface geology.

The method uses 50 or more electrodes placed at equal intervals along a survey line. These are connected to a computer-controlled resistivity meter via multi-core cables and a switching unit. Electrode spacing is chosen based on required depth and resolutions; smaller spacing offers higher resolution but shallower depth, while larger spacing reaches deeper with less detail (Fig. 3).

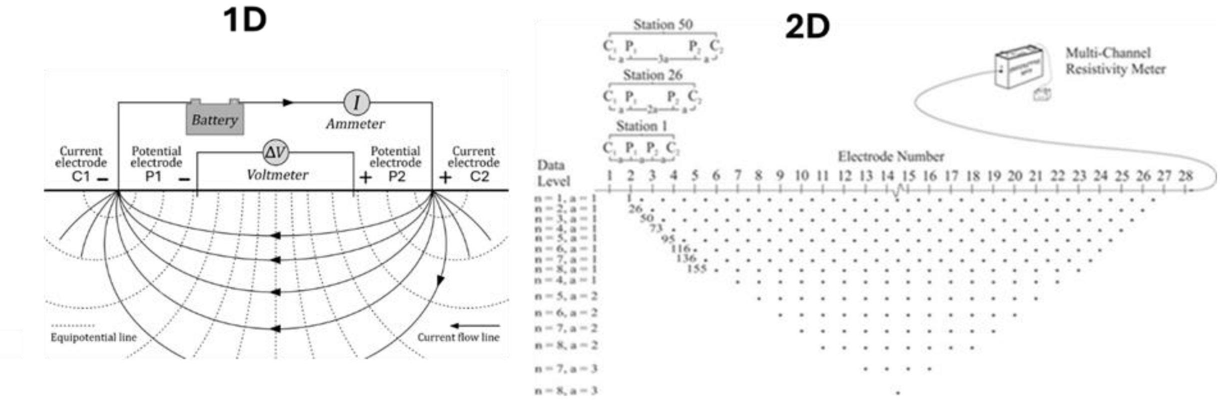

Figure 3: Electrode configuration (1D and 2D)

The switching unit automatically records resistances between various electrode pairs. Measurements begin with closely spaced electrodes for shallow data, then spacing increases to probe deeper layers. The collected data is processed with inversion software that converts resistance values into accurate 2D or 3D resistivity models, correcting for electrode geometry and other effects.

These models are displayed as color-contoured cross-sections representing resistivity variations. Geophysicists interpret them alongside geological data to identify features like soil layers, aquifers, faults, and bedrock. This technique is widely used in geotechnical studies, groundwater surveys, environmental assessments, and mineral exploration. Figure 3 illustrates both 1D and 2D electrode setups. For further readings, review Griffiths and Barker (1993), Loke and Barker (1995), Dahlin (1996), LaBrecque et al. (1996) and Oldenburg and Li (1999). Over the last 20 years, the availability of commercial resistivity imaging systems has steadily increased, making the method a widely used tool. This growth has been supported by a variety of field equipment and inversion programs. Modern instruments enable detailed mapping by continuously collecting profile-oriented data.

Measured apparent resistivity values are processed using inversion software to generate a 2D resistivity cross-section, or tomogram, representing the true resistivity distribution. Data acquisition for this study utilized a modified ABEM Lund Imaging system, specifically an IRIS SYSCAL Switch Resistivity-meter. The inversion software output displays this inverted resistivity model. Interpreting the resistivity image geologically requires knowledge of typical resistivity values for various subsurface materials (given in any geophysical textbooks) and the local geology. It's important to note that the resistivity of rocks and soils within a survey area can vary significantly.

3.1 Selecting suitable array type

The Wenner and Wenner-Schlumberger arrays are theoretically the most suitable electrical resistivity configurations for addressing the specific conditions of the studied area. Based on the surface geology and structural features, the targets to be mapped primarily consist of both horizontal and vertical rock units. Therefore, achieving both horizontal and vertical resolution is essential for effective mapping. To meet these requirements, the Wenner-Schlumberger array was selected for conducting the 2D imaging survey across the study area.

3.2 Data points density for 2D imaging

Field survey measurements to achieve optimal results should be conducted systematically to ensure all possible data points are collected. This approach significantly affects the accuracy of the interpretation model obtained from the inversion of apparent resistivity measurements. Based on personal experience (Aziz, 2005, Aziz, 2013) and other previous studies in the Kurdistan Region (GARDI et al., 2018), a data density ranging from 110 to 265 data points is considered most suitable for electrode spacings of 5 and 10 meters.

The pseudo section contouring method is typically used for visualizing data from a 2D imaging survey. The lateral position of a data point corresponds to the midpoint of the electrodes used for the measurement, while the vertical position is proportional to the separation distance between the electrodes.

3.3 Fieldwork

The resistivity survey fieldwork was carried out over a three-day period, from June 25 to June 27, 2014, as shown in Plate 1. During this time, a total of four resistivity profiles—designated as P1, P2, P3, and P4—were systematically surveyed to assess the subsurface characteristics of the proposed small dam site. Each of these profiles extended for a total length of 355 meters, with electrodes placed at regular intervals of 5 meters, ensuring consistent and detailed spatial resolution across the surveyed lines.

For data acquisition, the Wenner-Schlumberger electrode configuration was utilized, combining the advantages of both Wenner and Schlumberger arrays to enhance depth penetration and resolution. This configuration was particularly suitable for imaging complex subsurface features expected at dam foundation sites.

The layout of the profiles was strategically planned to ensure comprehensive coverage of the study area. Two of the profiles were positioned to cover the right and left abutments of the proposed dam site, both trending in a northeast-southwest (NE-SW) direction. An additional profile was placed in between, aligned along the mainstream channel and following the same NE-SW orientation to investigate potential variations in subsurface conditions beneath the watercourse. A fourth profile was oriented perpendicular to the others, trending in a northwest-southeast (NW-SE) direction, along the dam axis. This cross-sectional orientation allowed for an integrated understanding of lateral and longitudinal subsurface variability. The spatial arrangement of these profiles is depicted in figure 4, providing a clear overview of the survey layout in relation to the topographic and structural elements of the site.

Plate 1: Some slides showing the fieldwork activities

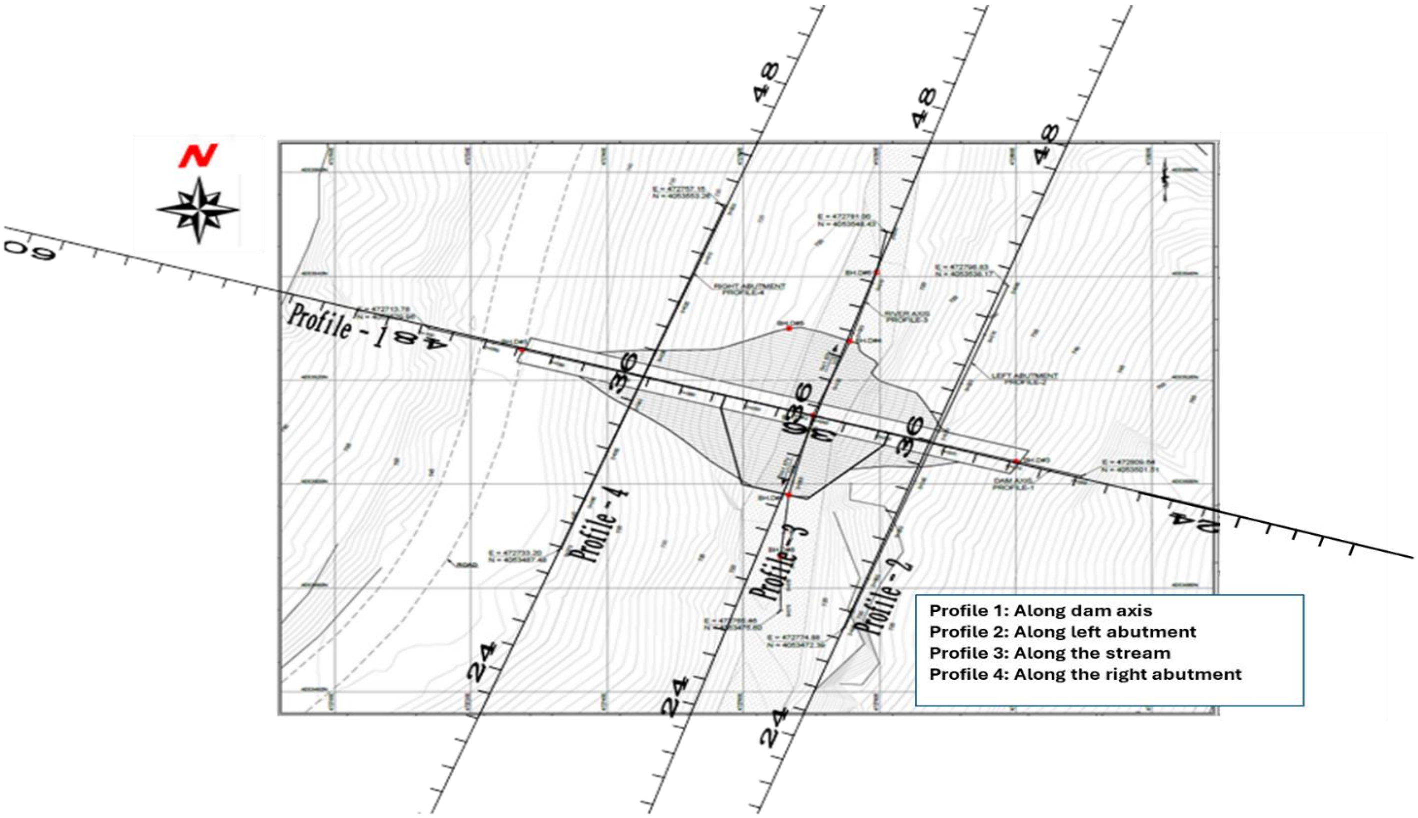

Fig.4: Display of profiles and electrode distribution

3.4 Presentation of 2D field data

The next step involves transforming the data into 2D imaging representations of the subsurface. For each sounding, the software generates three sections: the measured pseudo-section, the calculated section, and the inverse section, all under the guidance of the interpreter. This process requires selecting the most suitable software parameters, which depend on the interpreter's efforts to gather geological, structural, and hydrogeological information about the study area. As a result, the interpreter's understanding of the area and their expertise play a crucial role in fine-tuning the software parameters to achieve accurate and meaningful results.

4.Results and Interpretations

The 2D model interpretation was conducted using the latest version of the software package "RES2DINV" (version 3.59.117). This software employs smoothness-constrained inversion based on finite-difference forward modeling and Quasi-Newton techniques (Loke and Dahlin, 2002).

A crucial aspect of the inversion process for 2D imaging data is the quality of the field data. High-quality data typically exhibit smooth variations in apparent resistivity values on the pseudo-section. The sounding curves in this study ranged from well to fair quality. However, some localized anomalies with higher or lower resistivity compared to their surroundings were observed in the pseudo-sections. To ensure accurate inversion results, erroneous data points were removed from the dataset. This was achieved by plotting the data in profile form, which helped identify and highlight the problematic points for elimination.

4.1 Profile 1, dam axis (Fig. 5)

Profile 1 is running WNW-ESE along the dam axis and parallel to the strike of outcrops of the Qamchuqa Formation. This formation exhibits beds with dips ranging from 70° to 85°. The rough terrain in the area led to numerous bad data points, compromising the quality of the data collected. Most of these points were excluded to minimize their impact on the inversion process.

At the center of the inverted section, beneath electrodes 24 to 48, river terraces are identified (marked in blue) with resistivity values ranging from 110 Ω.m to 480 Ω.m. These relatively high resistivities are attributed to the intense accumulation of pebbles and boulders, with thicknesses varying between 1 m and 16 m, as shown in the figure.

The Qamchuqa Formation demonstrates a broad resistivity range, from 420 Ω.m to 24,500 Ω.m, reflecting the presence of diverse lithologies:

1- Marly Limestone: Identified by lower resistivity values of 200 Ω.m to 600 Ω.m (blue).

2- Limestone: Displays moderate resistivity values ranging from 850 Ω.m to 7,000 Ω.m.

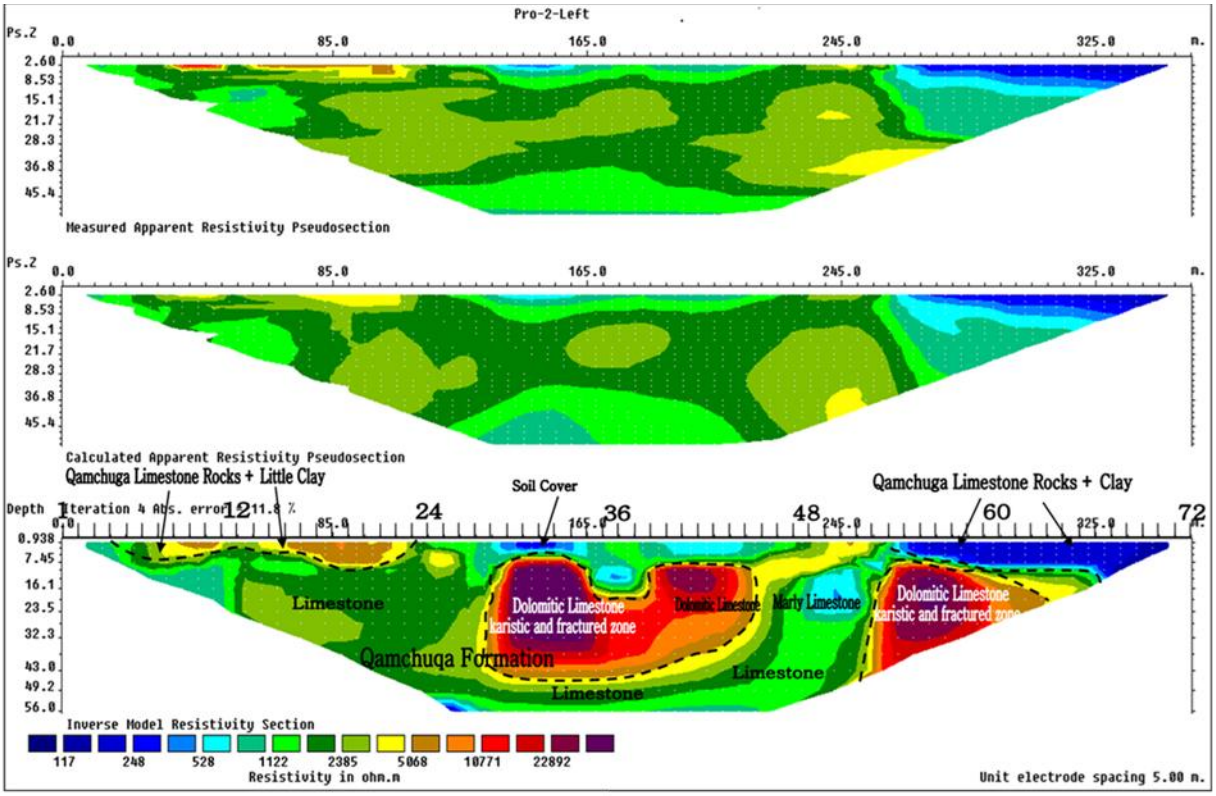

Fig. 5: Interpretation of the 2D Sounding profile 2 (left abutment)

4.2 Profile 2, left abutment (Fig. 6)

The profile extends along the left abutment of the dam in a NE-SW direction. The quality of the recorded data is fair, necessitating the removal of several erroneous data points. Near the surface, low resistivity

3- Dolomitic Limestone: Characterized by very high resistivity values ranging from 7,000 Ω.m to 24,000 Ω.m, attributed to the highly fractured nature of the zone and the presence of numerous voids and cavities in dry conditions.

This resistivity variation highlights the heterogeneity of the Qamchuqa Formation and its structural complexity.

Zones (marked in blue) have been identified between electrodes 28–46 and 53–72. These zones consist of recent sediments containing rock fragments of varying sizes from the Qamchuqa Formation, with resistivity values of 117 Ω.m to 528 Ω.m.

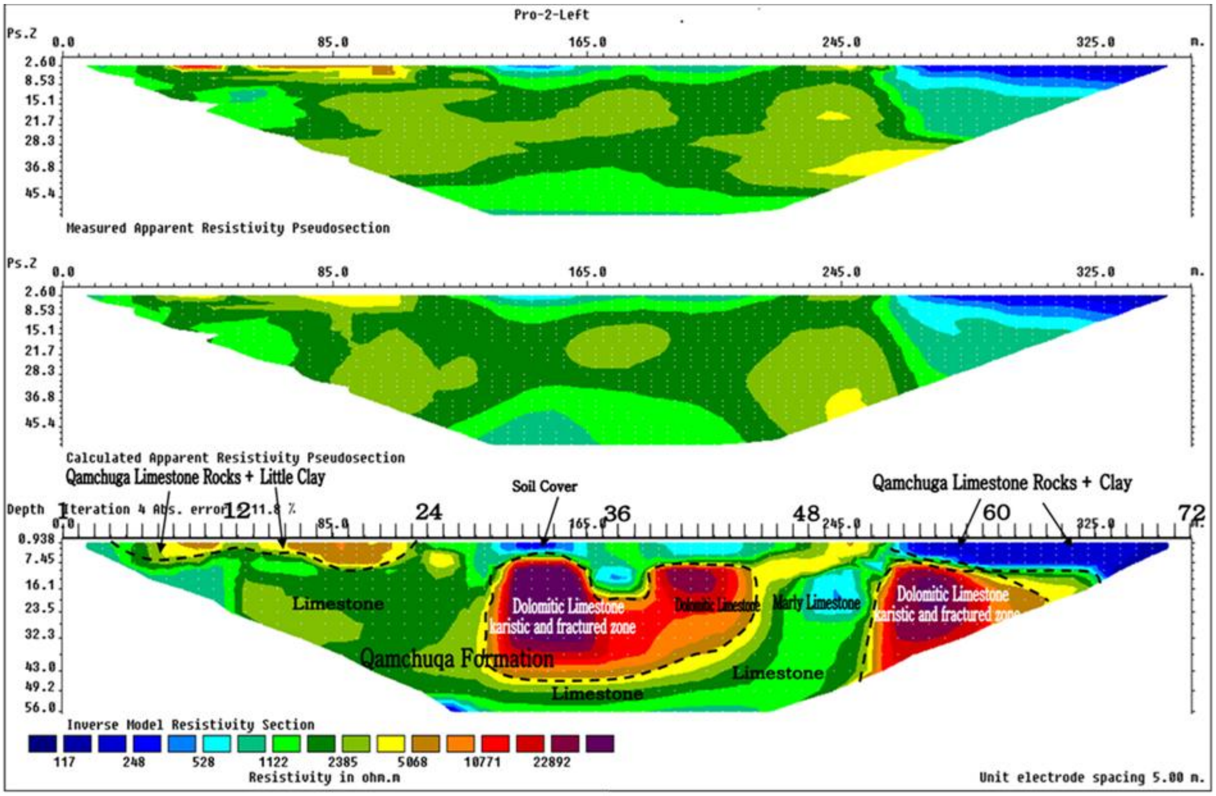

Fig. 6: Interpretation of the 2D Sounding profile 2 (left abutment)

The Qamchuqa Formation exhibits layers with very high resistivity values of 500 Ω.m to 40,000 Ω.m, distributed across the entire section. These layers include dolomitic limestone (marked in red) with very high resistivity and limestone with moderate resistivity, detected beneath electrodes 1–72 and extending to a maximum investigation depth of 60 meters.

Two high-resistivity zones, indicative of highly fractured and karstic dry regions within the dolomitic limestone of the Qamchuqa Formation, have been identified:

1- First Zone: Located beneath electrodes 28–44, this zone extends from depths of 7–16 meters to a maximum depth of approximately 43 meters.
2- Second Zone: Found beneath electrodes 52–63, this zone extends from depths of 10–18 meters and exhibits resistivity values ranging from 6,000 Ω.m to 40,000 Ω.m.

Both zones are characterized by fractures and karstic features within the dolomitic limestone, reflecting the structural and geological complexity of the Qamchuqa Formation.

4.3 Profile 3, along the stream (Fig.7)

The surveyed section follows the course of the stream and runs parallel to the profiles of the abutment. The uppermost portion of the section reveals low-resistivity layers (marked in blue) between electrodes 1 and 46. These layers consist of river terraces and recent sediments containing limestone rock fragments of varying sizes, which are weathering products of the Qamchuqa Formation, giving rise a resistivity value of 150 Ω.m to 500 Ω.m.

Beneath this area, high-resistivity rocks of the Qamchuqa Formation, with values ranging from 500 Ω.m to 14,000 Ω.m, are observed between electrodes 1 and 46. These layers, composed of limestone and dolomitic limestone (indicated in red), exhibit very high resistivity due to the presence of fractures and karstic features.

A nearly vertical dolomitic limestone body is identified beneath electrodes 40 to 47 at a depth of approximately 15 meters. Its high resistivity values (7,000 Ω.m to 14,000 Ω.m) suggest significant fracturing within the rock formation.

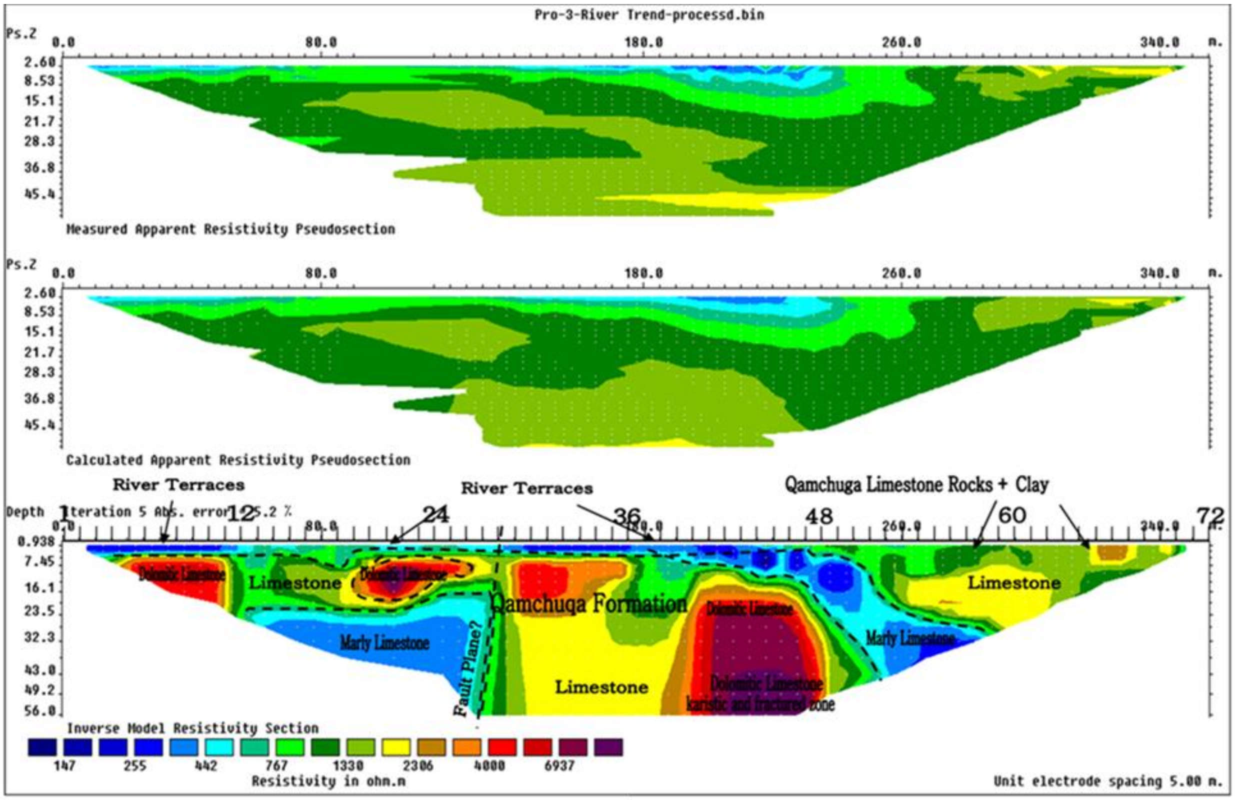

Fig. 7: Interpretation of the 2D Sounding profile 3 (along the stream)

Additionally, marly limestone layers are detected beneath electrodes 12 to 28 and 46 to 56, with resistivity values varying from 147 Ω.m to 500 Ω.m. Intermediate-resistivity layers (marked in green and yellow), ranging from 700 Ω.m to 2,300 Ω.m, are also present and likely represent pure limestone from the Qamchuqa Formation. A potential vertical fault is suspected beneath electrode 28, extending to a depth of 60m which is the maximum investigation.

4.4 Profile 4, right abutment (Fig. 8)

Profile-4 runs along the right abutment of the proposed dam, parallel to Profiles 2 and 3. The surface is covered by recent low-resistivity sediments (indicated in blue) with resistivity values of 45 Ω.m to 300 Ω.m. These sediments are interspersed with outcrops of the Qamchuqa Formation, which exhibit dips between 70° and 85°. The surface layer, composed of 4 to 16 meters clay mixed with rock fragments of varying sizes. Large blocks of Qamchuqa limestone are particularly evident beneath electrodes 12 and 25.

Beneath the surface layer, the Qamchuqa Formation is identified, with resistivity values ranging from 1,000 Ω.m (moderate) to 60,000 Ω.m (very high). This formation comprises dolomitic limestone (marked in red) with very high resistivity, as well as limestone layers with moderate resistivity.

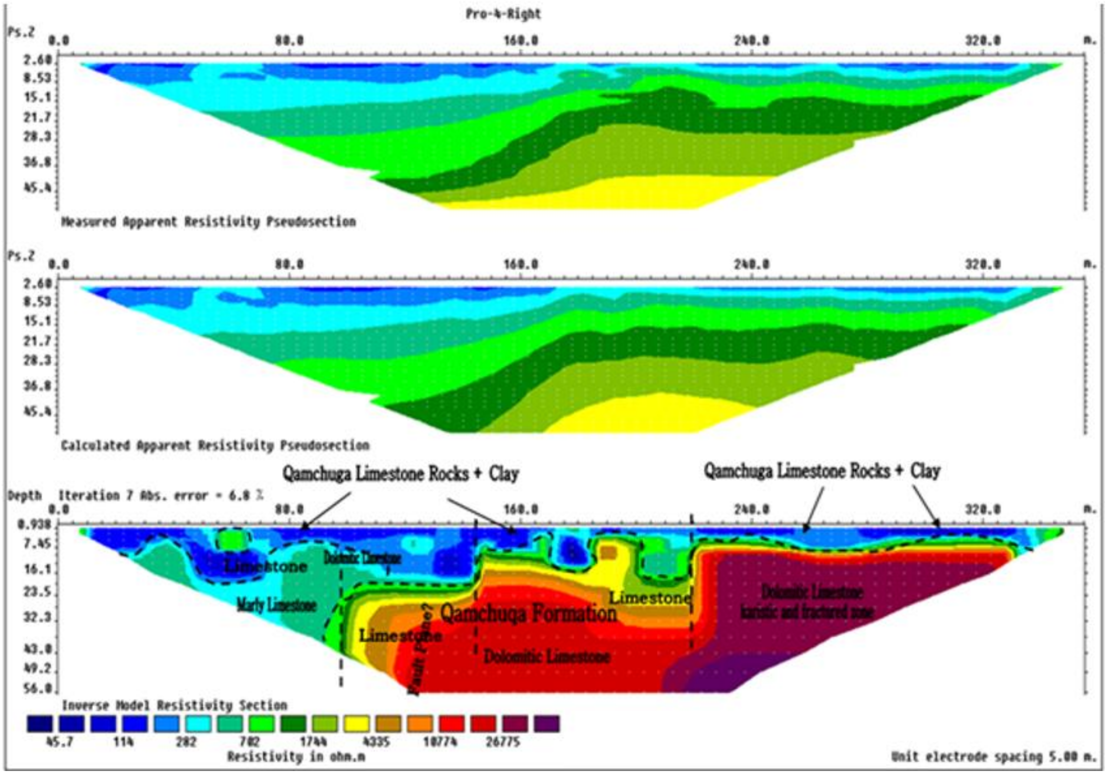

Fig. 8: Interpretation of the 2D Sounding profile 4 (right abutment)

Several faults are detected beneath electrodes 21, 30, and 45, with small vertical displacements estimated at 6 to 16 meters. Additionally, a low-resistivity zone is identified beneath the surface layer near electrodes 1 to 20. This zone is likely associated with the contact between the Qamchuqa and Kometan Formations.

5.Discussion

The 2D resistivity imaging survey conducted across the proposed dam site has revealed significant subsurface geological and structural variations within the Qamchuqa Formation. Key findings from the resistivity profiles include:

Heterogeneity of the Qamchuqa Formation:

The resistivity data illustrates the lithological diversity and structural complexity of the formation. Marly limestone shows low resistivity values (200–600 Ω·m), typical limestone displays moderate resistivity (850–7,000 Ω·m), while dolomitic limestone is associated with very high resistivity (7,000–60,000 Ω·m), indicating variation in composition and degree of compaction or cementation.

Presence of Karstic and Fractured Zones:

High-resistivity anomalies within the dolomitic limestone are interpreted as evidence of extensive fracturing and the development of karstic voids and cavities, likely dry. These features appear prominently beneath electrodes 28–44 and 52–63 in Profile 2, and electrodes 40–47 in Profile 3, highlighting potential zones of structural weakness.

Surface Sediments and River Terraces:

The near-surface layers, characterized by low resistivity values (45–528 Ω·m), comprise recent alluvial sediments, clay, and weathered rock fragments derived from the Qamchuqa Formation. In Profile 1, river terraces containing pebbles and boulders were identified beneath electrodes 24–48, indicating fluvial depositional activity.

Structural Features:

Several fault zones were detected, including electrodes 21, 30, and 45 in Profile 4, with vertical displacements ranging from 6 to 16 meters. Additionally, a vertical fault beneath electrode 28 in Profile 3 appears to extend down to the survey's maximum depth of 60 meters, suggesting deep-seated tectonic activity.

Geotechnical Implications:

The observed fracturing and karstic development, particularly within the dolomitic limestone, may pose engineering challenges for dam foundation integrity and reservoir sealing. The identified faults and resistivity contrasts suggest zones that warrant further detailed geotechnical and hydrogeological investigation to mitigate potential risks.

6.Conclusion

The 2D resistivity imaging technique proved to be an effective tool for delineating the subsurface conditions at the proposed dam site. The survey results offered critical insights into the lithological variation, structural discontinuities, and geotechnical challenges present in the area. These findings provide a fundamental basis for: Informing dam foundation design and construction planning. Assessing the suitability of the site for water retention and long-term structural stability. Guiding further investigations aimed at reducing geological and hydrogeological uncertainties.

The integration of resistivity imaging into the site assessment process significantly enhances the understanding of subsurface conditions, contributing to more informed decision-making for the safe and sustainable development of the proposed dam project.

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