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Research article

Electrical Survey Applications in Karstic Terrain (Resistivity & IP Survey); Cave Detection, Macro & Micro Rock Zonation for Rock Stability: A Case Study of Naisar Waterfall, Kashan, Iran

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Abstract

Naisar is a small village located 23 km from the city of Kashan in Isfahan Province, Iran, and is famous due to the presence of a historical building known as Kooshk and a waterfall that attracts many national and international tourists. The rock present alongside the Naisar waterfall and below the historical building is highly karstified and unstable. The rock is a carbonate rock, mainly travertine, having intermixed impurities such as clay, sand, and gypsum, etc. It has undergone extensive weathering and erosion. It is assumed that the weathering and erosion of this host rock occur due to a dissolution process that takes place because of several factors, like changes in climate conditions and the continued exposure of the rock to underground water and waterfall water, making it more unstable day by day. The presence of highly karstic features, such as vugs, cracks, and caves, makes this area highly dangerous for both tourists and the residents of Naisar Village. In this study, a geophysical electrical resistivity survey was conducted to detect and characterize subsurface karst features in a highly karstified travertine formation located in an urban environment. The investigation aimed to identify the depth, geometry, and spatial distribution of karstic voids and weakened zones that pose potential risks to ground stability and urban infrastructure. Based on the interpretation of the resistivity data, the main karst features were delineated, and their geometrical characteristics were evaluated. Subsequently, macro- and micro-zoning maps were developed to classify the study area according to the degree of karstification and relative stability. The results provide a practical framework for ground stability assessment and support decision-making for urban planning, risk mitigation, and the design of appropriate stabilization and engineering measures in karst-prone areas.

1. INTRODUCTION

The carbonate rocks are karstified due to the exposure of rock to weathering, hydrological dynamics, and fracturing, and also, they are not fully identified using seismic methods (Bagni et al., 2022). The Naisar is a small town located approximately 23 km from the city of Kashan and it is well known due to the presence of the Naisar spring and every year many people visit this place not only the Iranian nationals but also the people from outside Iran like to visit these kinds of natural and historical places. Basically, karst refers to the process that involves dissolution of bedrock and development of underground drainage, and it is not only associated with limestone but also with other carbonate rocks (Waltham, Bell, & Culshaw, 2005). Schlumberger (2011) provided case studies in which the diagenetic effects, like karstification, created very large-scale vugs, which had increased the permeability of certain zones of carbonate reservoirs. The rock on which the Niyasr pavilion (Kooshk) is built is highly permeable and pours travertine limestone mass, having sandy marl and shale layers between it. Karstic cavities are the spaces that are created by dissolution, overlaid onto the fracture network (Emami Meybodi & Hussain, 2022).

The rock is very porous and permeable and highly karstified due to the known underground water source, also known as the Naisar spring. Due to the presence of underground water, the rock has many natural caves that were formed due to the dissolution process, one of the famous caves, which is approximately 1 km long, known as Raees cave is present under the Naisar Pavilion (Kooshk). In addition, the weathering process due to rain, snow, forest, and human activities has made the exposed rock more dangerous, as some rock fragments were broken down in the past and fell near the village. Also, there is a great chance in the future that these kinds of rocks will break down and can also cause a complete destruction of the historical Naisar pavilion (Kooshk).

The areas look very dangerous, and precautions should be made to ensure the safety of local and visiting people, but this should be the key concern while applying the engineering methods that the beauty and the unaltered appearance of the rock should be kept and preserved as much as possible. Karstification can make of rock slopes unstable (both natural and manmade) by creating dissolution cavities and expanding joints within the rocks (Meybodi et al., 2022). Zhang, Chen, and Liu (2024) demonstrated that integrated geophysical approaches significantly improve the reliability of karst hazard assessment in urban areas. Recent studies demonstrate that high-resolution ERT surveys can successfully delineate the depth, geometry, and spatial distribution of karstic cavities and fractured zones, even in complex geological environments ("High-resolution electrical resistivity tomography," 2025).

This study aimed to use geophysical electrical methods to identify karstified and mechanically weak zones within the rock mass (Amiri et al., 2025). This approach follows recent methodological advances that emphasize the role of geophysical techniques in the preliminary assessment and stabilization design of highly karstified rock formations (de Castro, Bezerra, & Oliveira Jr., 2024). Based on the data obtained from the geophysical surveys, the subsurface was classified into distinct zones according to the degree of karstification and weakness. By classifying zones according to the degree of karstification and structural weakness, geophysical zoning supports informed decision-making for ground stabilization and risk mitigation measures ("Application of geophysical methods," 2024). This zoning was then used as a framework for evaluating ground stability and for proposing appropriate stabilization measures.

2. GEOLOGY OF STUDY AREA

The geology of the area is studied using 1:100000 geology map of Kashan, Iran. The map is a picture of the geological map Kashan is attached below which is taken from the 1:100000 map of Kashan. The geology of the area is a bit complex as we have travertine limestone of Pliocene age that is surrounded by the igneous body at the NW side which is Eocene in age and dark grey to reddish grey pyroclastic and lavas (with different composition and textures interbeded with some nummulite bearing volcano sedimentary rocks, limestone represented with symbol EV6 on the geological map at the top and the bottom this rock body we have dark grey shale, green marl, limestone sandy marl, reefal limestone of QOM Formation Which is from Oligocene age and represented by OMq on the geological map. On the NW side above Qom formation, we have another outcrop of Oligocene age, which is an alteration of limestone with marl, shale and marl and represented on the map as OM ml q. On the NE side of our study area, we have the same extension of the Qom Formation, and the SW and SE sides are surrounded by green-grey siliceous tuff, tuff breccia, shale, marl, limestone, and pyroclastic rocks, locally meta-siliceous tuff, and the age of this rock body is Eocene. The geological map of study area is shown in Figure 1.

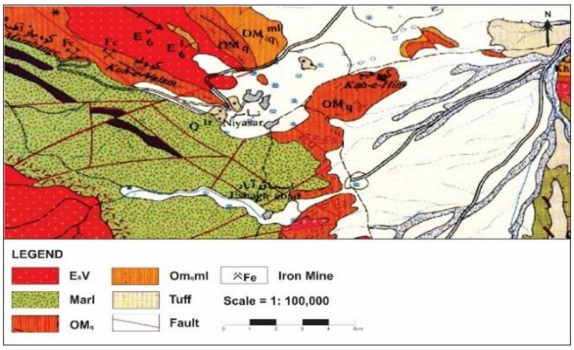

Fig. 1. Geological map of the study area 1;100000 (Aghanabati, 2004).

3. GEOPHYSİCAL STUDİES

To investigate and characterize the subsurface condition of the various geological layers around the pavilion, a geophysical (electrical resistivity) survey crew from Zharfāb Kāvosh Consulting Engineers was mobilized at the site on 7 Aban 1403 (29 October 2024) and collected data for two consecutive days. The electrical resistivity tomography (ERT) method is widely recognized as an effective tool for karst detection and stability assessment in urban environments (Loke et al., 2020; Martínez-Moreno et al., 2022). Variations in electrical resistivity are closely related to changes in porosity, moisture content, degree of weathering, and the presence of cavities or voids, making these methods highly effective for identifying subsurface karst features (Rembert et al., 2023). The field procedures and the results obtained are presented below.

One important aspect to consider in geoelectrical studies is the method of neutralizing self-potential (SP), as failure to eliminate its effects can negatively influence the final data. There are two main methods for SP elimination: Repeated measurements and algebraic averaging of data, Generation of a square pulse, and its injection into the ground. Among these, the second method is technically far superior to the first. Based on this, an instrument capable of fully neutralizing SP by generating square pulses was used.

In this study, a geoelectric device manufactured by Lippmann (Germany) was utilized. Following the removal of noisy data and bad points, inversion processing was performed to obtain the true resistivity (ρ). The data were collected along two approximately north-south oriented profiles using the pole–dipole array. The alignment and location of these profiles are schematically illustrated in Figures 2 & 3.

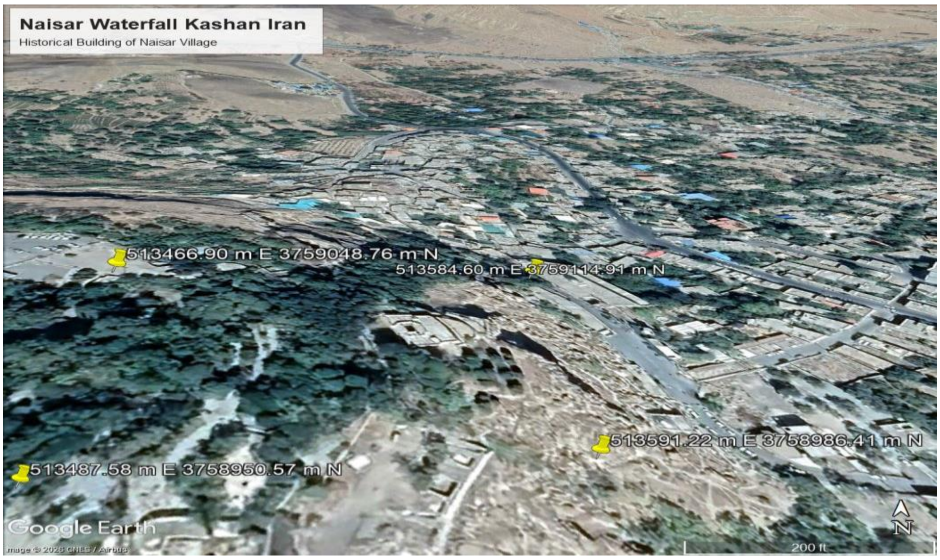

Fig. 2. Map Showing Naisar historical building and its geographic location.

Fig .3. Two profiles for geophysical data collection.

Table 1. Profile coordinates from the study area

S: No	Start	End
Profile 1	X=513541 Y=3758929	X= 513499 Y=3759065
Profile 2	X= 513516 Y=3758985	X= 513516 Y=3759055

The length of profile 1 is 144 meters, and the length of profile 2 is 88 meters. As mentioned, the profiles were surveyed using an electrode spacing of 8 meters. The relatively large spacing of 8 meters between measurement points represents the best achievable (optimal) field condition under the given site constraints. Due to the presence of paved park flooring, concrete surfaces, existing trees, and significant ambient noise associated with an urban environment, reducing the spacing was not technically feasible or practically executable. It should also be noted that the objective of this study was not to detect small-scale cavities on the order of 1–2 meters. Instead, the selected spacing was considered appropriate for identifying larger-scale subsurface features relevant to the engineering purpose of the study. Therefore, the adopted measurement configuration is consistent with the research objectives and the limitations imposed by the site conditions. A view of the profile acquisition is shown in Figure 3 below:

Fig. 4. Gathering geophysical data for profile 1.

The following sections in Figures 5 & 6 show the resistivity and induced polarization (IP) results corresponding to Profile 1.

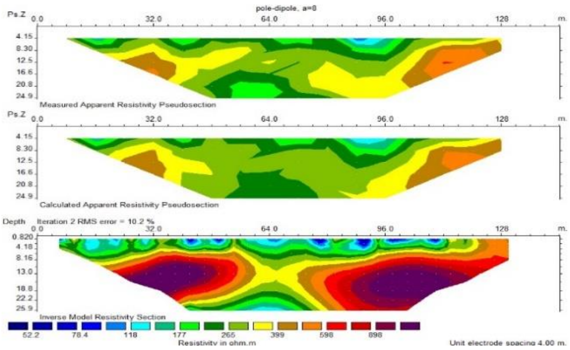

Fig. 5. Resistivity Sections of Profile 1.

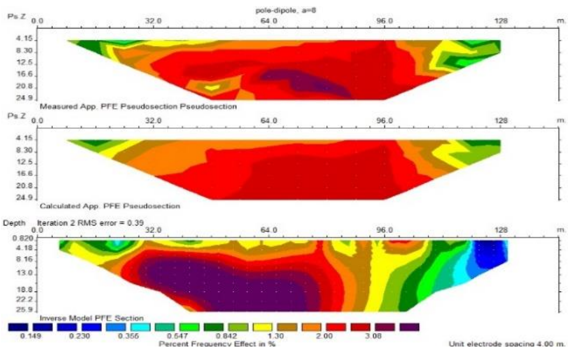

Fig. 6. Induced Polarization (IP) Sections of Profile 1.

The data for profile 1 were processed and inverted using the Res2DInv software. After the second iteration, the inversion converged to a final RMS error of 10.2%, which is considered acceptable for the given field conditions and data quality.

A view of the data acquisition for Profile 2 is shown in Figure 7.

Fig. 7. Gathering data for profile 2.

The following sections in Figures 8, 9 & 10 shows the resistivity and induced polarization (IP) results corresponding to Profile 2.

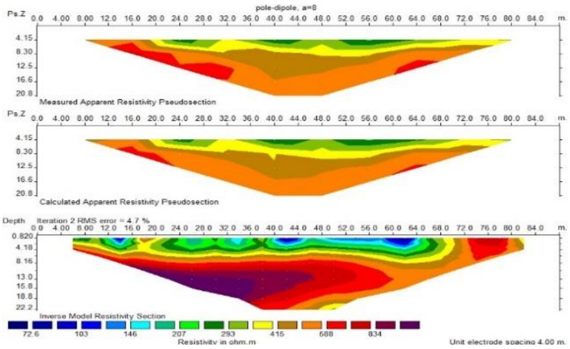

Fig. 8. Resistivity Sections of Profile 2.

The data for the profile were processed and inverted using the Res2DInv software. After the second iteration, the inversion converged to a final RMS error of 4,7%, which is considered acceptable for the given field conditions and data quality.

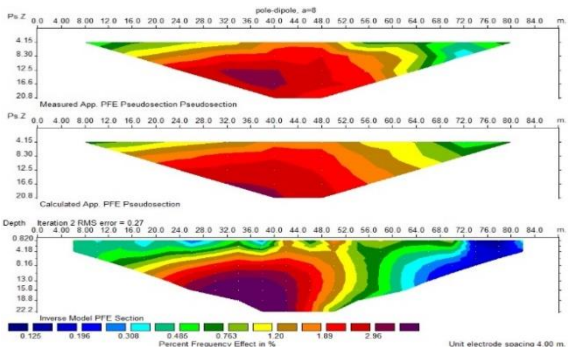

Fig. 9. Induced Polarization (IP) Sections of Profile 2.

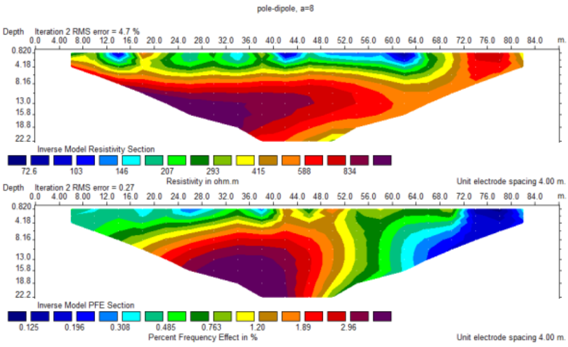

Fig. 10. Simultaneous Display of Final Resistivity and Induced Polarization (IP) Sections for Profile 2.

By combining the resistivity sections of the two mentioned profiles, a 2D Inversion Fence Diagram visualization of these sections was generated. The two-dimensional profiles were placed side by side in order to obtain **a** general and integrated view of the subsurface conditions across the study area**.** However, it should be emphasized that the mathematical inversion and modeling were performed strictly in two dimensions using the Res2DInv software. No three-dimensional inversion was assumed or applied in this study, and the interpretation was carried out within the limitations of a 2D modeling framework. Presented in Figure 11 below.

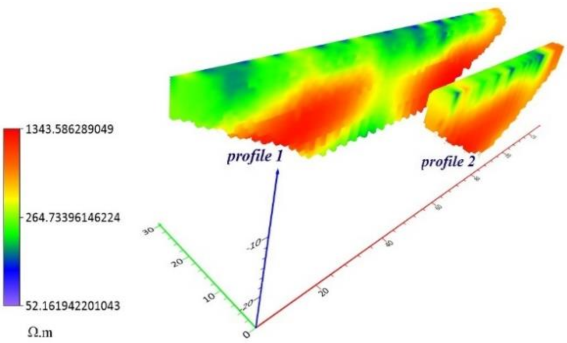

Fig. 11. 2D Inversion Fence Diagram Visualization of Electrical Resistivity Sections.

After analyzing the inverted sections and combining the profiles, the following conclusions can be drawn. The presence of argillaceous (clay–marl) formations within the travertines appears to play a significant role in the degradation and instability of the travertine material. In fact, clay impurities within the travertine may act as a slip plane, potentially causing the overlying travertine layers to slide. When water is present, it can lead to swelling of the clays and lubrication of the slip surface, thereby reducing stability and contributing to slope failure. Another mechanism that may lead to the instability of the travertines in this area is the presence of faults and fractured zones in certain regions. The filling of these fractured zones with clay and water can accelerate alteration and weathering processes, which in turn activate sliding mechanisms and cause instability in the overlying travertine masses.

Fig. 12. Representation of the Geology Downstream of the Koshk Structure and Its Geoelectrical Interpretation.

Many research studies confirm that the low-resistivity anomaly zones are often associated with highly fractured or clay-filled karst zones, whereas high-resistivity anomaly zones may indicate air-filled voids or massive carbonate rock (Zhou et al., 2022). If the aforementioned factors are considered key contributors to instability, then the zones with low resistivity values should be identified as anomalous and critical areas, which are highlighted on both profiles in Figures 13 & 14 below. The depth of investigation (DOI) was estimated directly from the inverted resistivity sections. Based on the penetration of the current electrodes and the reliability of the inverted models, the effective DOI in this study was approximately 26 meters. Interpretation was restricted to depths within this range, where the inversion results are considered reliable.

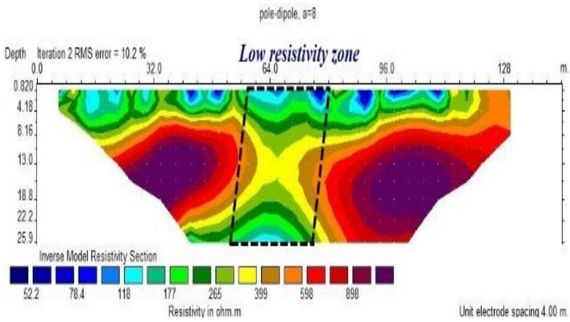

Fig. 13. Low Resistivity Zone of Profile 1.

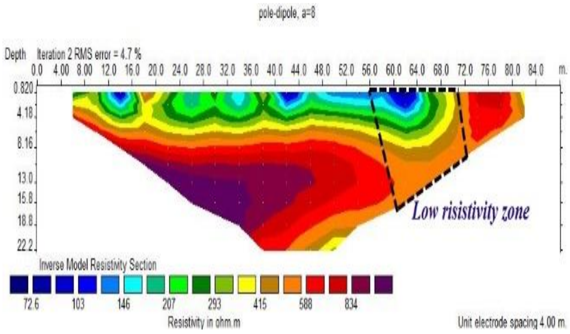

Fig. 14. Low Resistivity Zone of Profile 2.

Due to the urban setting of the study area, the measurements were affected by significant environmental and cultural noise, which reduced the reliability of the IP data. Urban noise and surface constraints significantly affect data quality and survey design (Perri et al., 2023). For this reason, although IP data are presented, they were not given substantial weight in the final interpretation. The interpretation was therefore mainly based on the resistivity results, which are considered more robust under the existing site conditions. Regarding the use of Ground Penetrating Radar (GPR), to the best of our knowledge, no GPR surveys have previously been conducted in the study area, and due to site limitations and logistical constraints, it was not possible to carry out GPR measurements within the scope of this study.

4. MACRO & MICRO ZONING

By translating geophysical anomalies into engineering-relevant zones, resistivity surveys provide a reliable basis for risk classification and stabilization planning, particularly in infrastructure projects constructed on karstified carbonate and travertine formations (Loke et al., 2023). Macro & Micro zoning of the study area was carried out based on the quantitative interpretation of Electrical Resistivity Tomography (ERT) data. The zoning criteria were defined using resistivity magnitude, anomaly geometry, lateral continuity, and depth extent of subsurface features. Based on these parameters, the subsurface macro and micro zoning was done, representing different degrees of karstification and mechanical stability, which allows us to propose a suitable stability model for Niasar Slope. According to the engineering geological map of the Niasar area, the upper part of the slope, located directly beneath the building, consists of marl and intermixed marl with travertine. This section is highly unstable, as marl represents the weakest component of the slope due to its low shear strength and susceptibility to weathering and water infiltration. The presence of intermixed marl further reduces the overall stability, making this part of the slope particularly vulnerable to deformation and failure. Beneath this weak upper layer, a zone of highly karstified travertine is present. This section exhibits partial instability due to the presence of extensive karstification, which creates voids, fractures, and irregularities within the rock mass. These karstic features can significantly weaken the structural integrity of the slope, making stabilization necessary. Appropriate engineering techniques such as grouting, rock bolting, or retaining structures may be required to enhance stability and prevent potential failure. Further below, the dark-colored travertine layer is characterized by lower degrees of karstification and reduced marl content. Compared to the upper sections, this part of the slope is more stable due to its stronger lithological properties and reduced susceptibility to erosion or collapse. As a result, fewer stabilization measures and engineering interventions are required to maintain its integrity. However, localized reinforcement may still be necessary to address minor instabilities or prevent long-term degradation. A thorough geotechnical assessment and monitoring plan should be implemented to ensure the effectiveness of stabilization measures, particularly in the upper and middle sections where instability poses a higher risk.

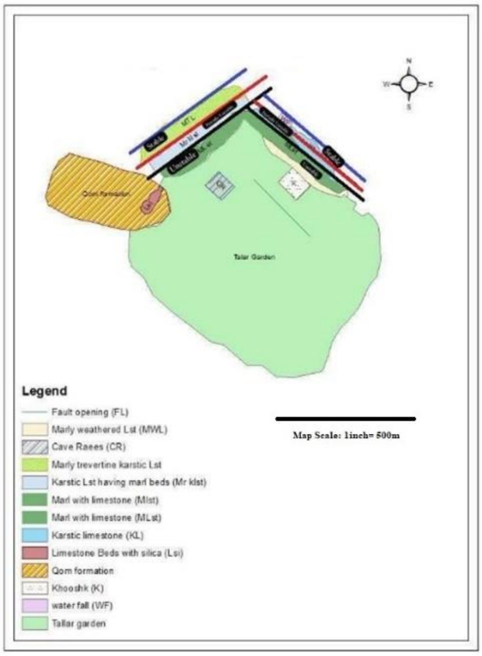

Fig. 15. Engineering geology map of Naisar waterfall.

Macro Zoning

Fig. 16. Macro zoning of Naisar Slope based on the results obtained from geophysical studies (Side view).

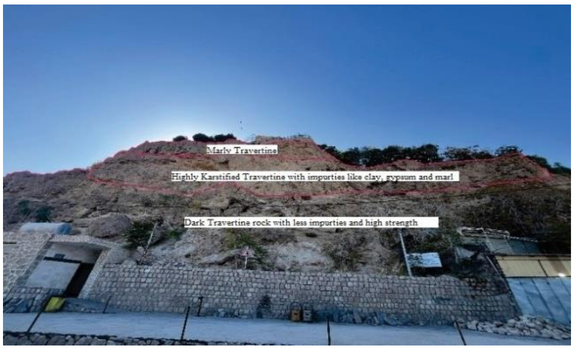

Fig. 17. Macro zoning of Naisar Slope based on the results obtained from geophysical studies (Straight view).

Micro Zoning

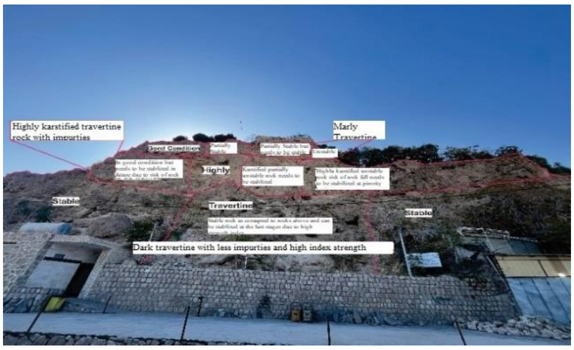

Fig. 18. Micro zoning of Naisar Slope based on the results obtained from geophysical studies (Straight view).

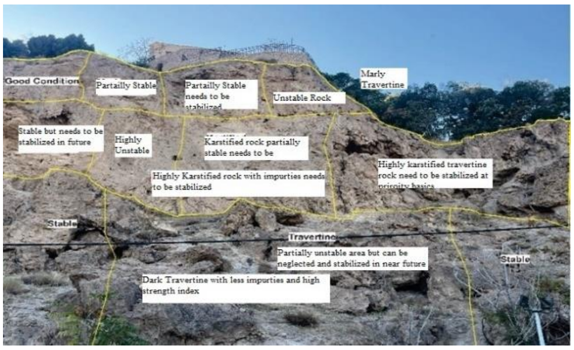

Fig. 19. Micro zoning of Naisar Slope based on the results obtained from geophysical studies (Side View).

Figures 16, 17, 18 and 19 present the zoning of the Niasar slope into three distinct stability classes and then into subclasses of stable, unstable, and partially stable. The uppermost zone consists of marly travertine and is characterized by poor mechanical competence, rendering it highly unstable. The middle zone, which is intensely karstified, exhibits partial to complete instability due to the presence of dissolution features and structural discontinuities. In contrast, the lowermost zone, identified as dark travertine, demonstrates comparatively greater stability than the overlying units, reflecting its more competent lithological and structural characteristics.

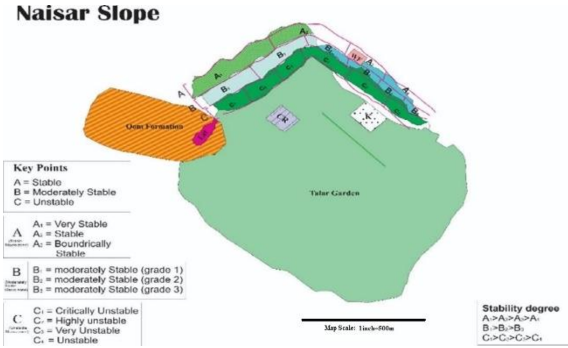

Fig. 20. Engineering geology zoning map classifying the rock into different grades of stabilization.

Figure 20 illustrates the engineering geological micro-zoning of the Niasar slope, where different stability conditions have been delineated. Geological mapping plays a vital role in identifying economically valuable geological formations and critical structural zones for both mining and engineering geology applications (Asadi Harouni & Asghari 2024). The map classifies the slope into stable, partially stable, and unstable zones, as indicated in the legend. The unstable and partially stable areas represent critical sections of the slope that should be prioritized for stabilization measures, as they require immediate attention and remedial action to mitigate potential geotechnical hazards.

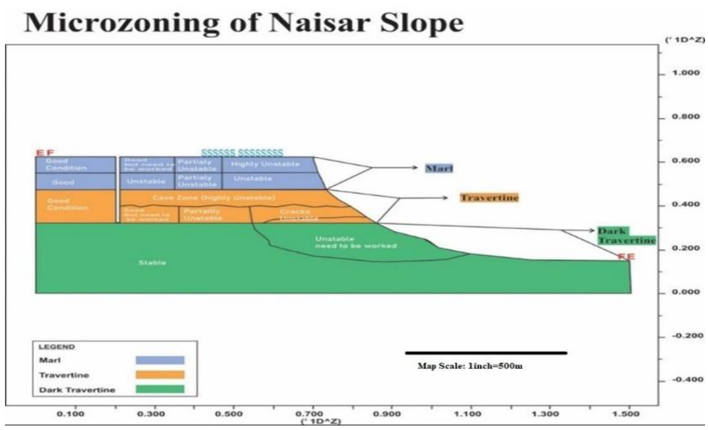

Fig. 21. Section showing the grade of stabilization under the historical building.

The geometrical shape of the detected anomalies (e.g., columnar versus lens-shaped) played an important role in the zoning and interpretation process. Based on field observations and profile analysis, anomalies with columnar or vertically continuous geometry were interpreted as potentially unstable zones, as such shapes may indicate weakened or disturbed subsurface materials extending with depth. In contrast, lens-shaped anomalies with limited lateral and vertical continuity were considered to have a lower impact on overall stability and were treated more conservatively in the zoning process.

5. CONCLUSION AND SUGGESTION

The geological interpretation of the high-resistivity zones identified in the study area provides important insights into the subsurface conditions of the host rock and its potential instability. The observed high-resistivity anomalies are most likely associated with carbonate rocks, including travertine, or with the presence of karstic cavities (Jabrane et al., 2023). El Hameedy, Mabrouk, Dahroug, and Metwally (2023) stated that the theoretically infinite resistivity of air-filled voids makes karst features a primary candidate for the observed electrical responses, suggesting that regions exhibiting elevated resistivity values are more prone to karstification. The mineralogical composition and internal structure of the rock are key factors governing its mechanical properties, directly affecting its strength, durability, and resistance to weathering and deformation (Haider et al., 2025). Such features can significantly influence the mechanical behavior of the rock mass, as the formation of cavities and dissolution conduits creates local heterogeneities and stress concentrations that may contribute to deformation or failure under external loads. In addition to karstic voids, the presence of argillaceous layers within the travertine is considered a key factor affecting stability. These clay-rich layers reduce cohesion and tensile strength along bedding planes, facilitating displacement and localized instabilities. Consequently, while karstic dissolution plays a role in rock instability, the presence of weaker lithological units is often the primary determinant of structural integrity.

Geophysical methods, particularly resistivity surveys, were central to the interpretation process. Although induced polarization (IP) techniques were considered to complement the resistivity data, their reliability in this context is limited (Mehdi, Akhssas, & Fadili, 2024). Karst zoning based on geophysical data provides a practical framework for engineering decision-making (Zhou et al., 2021). The absence of sulfide minerals in the study area reduces the likelihood of strong IP signals, while non-sulfide-related responses are generally weak and easily masked by environmental noise. As a result, IP data were treated cautiously and were not heavily relied upon for the final geological interpretation. Instead, resistivity data, coupled with geological observations and previous studies, formed the basis for mapping and characterizing the subsurface conditions.

Following the geophysical assessment, the host rock was systematically subdivided into macro- and micro-zones to delineate areas of differing mechanical behavior and stress concentration. Macro-zoning provides a broader view of the geological variations and highlights significant changes in rock material properties, lithology, and structural orientation. This level of zoning is particularly useful for identifying regions with a higher probability of instability due to variations in material composition or large-scale structural weaknesses. Micro-zoning, on the other hand, focuses on localized stress patterns, identifying specific areas that are under higher mechanical load or where fractures, cavities, or weak layers may compromise stability. The combination of macro- and micro-zoning allows for a more precise understanding of the spatial distribution of potential hazards and facilitates the prioritization of stabilization measures.

The practical implications of this zoning approach are significant for engineering applications. By identifying zones that require stabilization, engineers can focus interventions on areas where reinforcement is critical, optimizing the use of resources and minimizing unnecessary construction or treatment in less vulnerable areas. In addition, this methodology provides a framework for monitoring and maintenance, as high-risk zones can be targeted for regular inspections and preventative measures. Furthermore, the integration of geophysical data with geological and structural information enhances the reliability of hazard assessments, reducing uncertainty in the prediction of potential rock failures. Overall, the interpretation of high-resistivity zones, combined with detailed zoning analysis, offers a robust approach to understanding the subsurface characteristics of carbonate rock masses. It highlights the complex interplay between karstic features, lithological variations, and stress distributions, providing a scientific basis for engineering decisions. By systematically identifying areas prone to instability and differentiating them from more stable zones, this approach supports effective planning, risk mitigation, and sustainable management of the site. Such comprehensive analysis is essential in regions where karstic processes and weak lithological layers coexist, ensuring that both natural hazards and anthropogenic activities are carefully considered in engineering design and construction practices. The findings emphasize the importance of integrating geophysical techniques with geological observations to achieve a detailed and practical understanding of rock behavior in complex karstified terrains.

This study demonstrates the effectiveness of electrical resistivity surveying as a non-destructive, reliable, and practical tool for identifying karst features, especially in urban travertine formations, and for developing engineering-oriented macro- and micro-zoning maps. The proposed zoning approach provides valuable support for ground stability assessment and mitigation planning. However, there are some limitations, such as the fact that the results are influenced by field constraints such as limited electrode spacing, urban noise, and the use of 2D inversion, which may reduce resolution and limit the detection of small-scale cavities. Future studies incorporating 3D surveys and complementary investigation methods could further improve the accuracy and reliability of karst characterization.

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