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FIELD STUDIES INVESTIGATING THE EFFECTS OF KARSTIC FORMATIONS ON ENGINEERİNG STRUCTURES IN SIIRT PROVINCE

SİİRT İLİNDE KARSTİK OLUŞUMLARIN MÜHENDİSLİK YAPILARI ÜZERİNDEKİ ETKİLERİNİN SAHA ÇALIŞMALARI İLE İNCELENMESİ

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ABSTRACT

Limestone and dolomite are carbonate rocks that gradually dissolve when exposed to groundwater and surface water, leading to the development of karstic features. Rainwater containing weak carbonic acid enlarges existing fractures and joints, forming voids, caves, and underground channels. These structures are highly sensitive to external influences such as structural loads, rainfall, groundwater fluctuations, climatic variations, and seismic activity. Even small hydrogeological or dynamic changes can disrupt the stability and cause sudden settlement or collapse. Understanding these processes is essential for ensuring the safety of engineering structures founded on carbonate terrains. In Siirt Province, karstic carbonate rocks are widespread in areas where various engineering structures are located. While these units seem stable under natural conditions, external factors can cause abrupt losses in bearing capacity and surface deformation, adversely affecting structural performance. This study evaluates more than 700 boreholes, supported by geophysical measurements and field observations across 147 plots. Additionally, several case studies were examined to identify mechanisms of stability loss in different parts of the province. The findings highlight that thorough geotechnical and geophysical investigations are necessary prior to construction in karst-prone zones. Integrating geological and hydrogeological data into urban planning is also crucial for ensuring safe and sustainable development.

Keywords: Karst formations, dynamic effects, loss of bearing capacity, sudden settlement, stability

ÖZET

Kireçtaşı ve dolomit, yer altı ve yüzey sularına maruz kaldıklarında yavaşça çözünen karbonat kayaçlarıdır ve bu süreç karstik yapıların gelişimine neden olur. Zayıf karbonik asit içeren yağmur suyu, kayaçlardaki mevcut çatlak ve eklemleri genişleterek boşluklar, mağaralar ve yer altı kanalları oluşturur. Bu yapılar, yapı yükleri, yağış, yer altı su seviyesi değişimleri, iklimsel farklılıklar ve sismik etkiler gibi dış faktörlere oldukça duyarlıdır. Küçük hidrojeolojik veya dinamik değişiklikler bile zeminin stabilitesini bozarak ani oturma ya da çökme gibi sorunlara yol açar. Bu süreçlerin anlaşılması, karbonat zeminler üzerinde inşa edilen mühendislik yapılarının güvenliği için büyük önem taşır. Siirt ilinde karstik karbonat kayaçları, birçok mühendislik yapısının bulunduğu alanlarda yaygın olarak görülür. Bu birimler doğal koşullarda kararlı görünse de dış etkiler taşıma gücü kayıplarına ve yüzey deformasyonlarına neden olur. Bu çalışma kapsamında, 700'den fazla sondaj kaydı incelenmiş; 147 parselde jeofizik ölçümler ve arazi gözlemleri değerlendirilmiştir. Ayrıca ilin farklı bölgelerindeki vakalar analiz edilerek stabilite kaybı mekanizmaları belirlenmiştir. Elde edilen bulgular, karst riski taşıyan alanlarda inşaata başlamadan önce kapsamlı geoteknik ve jeofizik araştırmalar yapılması gerektiğini ortaya koymaktadır. Güvenli ve sürdürülebilir kentleşme için jeolojik ve hidrojeolojik verilerin planlamaya entegre edilmesi de büyük önem taşımaktadır.

Anahtar Kelimeler: Karstik oluşumlar, dinamik etkiler, taşıma kapasitesinin azalması, ani çökme, stabilite

INTRODUCTION

Rocks are grouped into igneous, metamorphic, and sedimentary rocks based on their formation processes. These sedimentary rocks are formed through the breakdown, transportation and deposition of igneous and metamorphic rocks. Even carbonate rocks, which are one of the rock types, have a high composition of calcium carbonate ($CaCO_3$) or magnesium carbonate ($MgCO_3$) (Colas et al., 200; Boggs, 2014). The most common types of carbonate rocks are limestone, which is composed of calcite, and dolomite, which contains the mineral dolomite along with calcite. The rocks are typically formed in marine environments thru biogenic processes or in terrestrial environments thru chemical precipitation (Lolcama et al., 2002; Yazıcı, 2016).

The dissolution or melting of carbonate rocks occurs primarily thru a chemical process called carbonic acid dissolution (Pueyo Anchuela et al., 2016; Yan et al., 2019). Carbon dioxide (CO_2) in the atmosphere dissolves in rainwater, forming a slightly acidic solution. In addition, since the amount of CO_2 produced in the soil by plant roots and microorganisms is higher, the water in these soil structures is often more acidic than atmospheric water. This acidic water reacts with the calcium carbonate ($CaCO_3$) in the limestone, converting it into calcium bicarbonate ($Ca(HCO_3)_2$), which is soluble in water. Over time, dissolution concentrates along natural cracks, joints and faults in the rock, causing millimetre-sized voids to expand to metres and form caves and galleries (Klimchouk, 2007; Goldscheider & Chen, 2022; Stevanović, et al., 2024). Underground dissolution is most intense in water-saturated zones. When the water level drops, these voids become filled with air, and stalactites and stalagmites begin to form as calcite is deposited by dripping water. Over long geological timescales, this process leads to the development of karst features on the surface, such as sinkholes, uvalas, poljes, and lapiaz, and extensive cave systems and underground rivers (White, 1985; Hill & Forti, 1997; Fairchild & Baker, 2012; Zerga, 2024). The karst systems in the Taurus Mountains, formed by the combination of high rainfall, calcareous lithology, and a highly fractured structure, create Türkiye's most prominent karst areas. Natural formations like the Cennet-Cehennem sinkholes are typical products of this process (Yazıcı, 2016; Nazik, 2019).

Sulfate rocks, which can dissolve rapidly even in pure water and form large dissolution cavities in a short time, are called gypsum ($CaSO_4 \cdot 2H_2O$). This rapid dissolution property makes gypsum karst much riskier from an engineering perspective compared to limestone karst. Therefore, in gypsum areas, problems such as sudden collapses and settlements can develop quickly, requiring critical measures for structural safety (Yılmaz, 2007).

Considering the distribution of rocks on Earth, karst areas, with approximately 22 million km^2, make up about 12% of the total land area (Ford & Williams, 2013). Figure 1 shows that significant engineering structures, including dense human settlements, transportation networks, industrial facilities, and dams, are located on karst formations in many parts of the world. This distribution also includes extensive areas within Türkiye (Parise, 2010; Nazik, 2019).

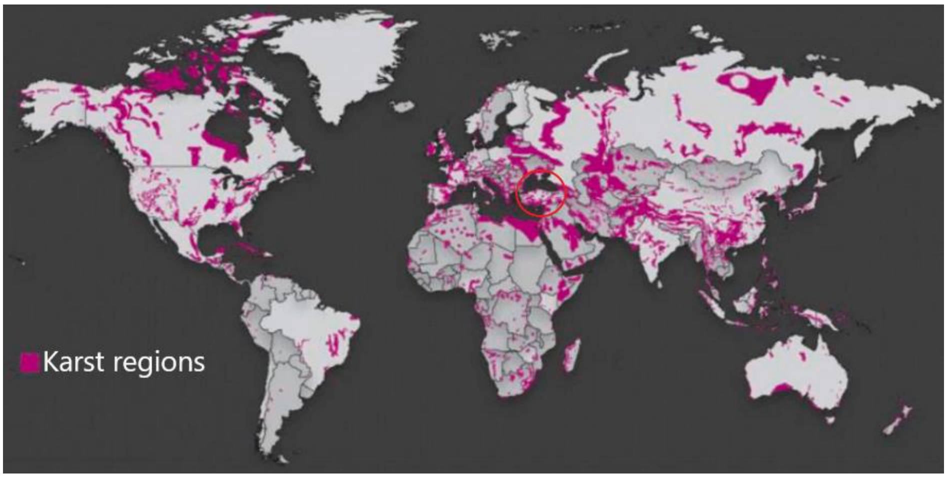

Figure 1. Distribution of Karst Regions on a Global Scale (Ershad, 2019)

The stability of these formations, which generally exhibit a stable structure in nature, can be disrupted by various external factors. Changes in the groundwater level and heavy rainfall are among the primary causes of instability. In addition, the transport of sediments from underground cavities, construction excavations, and blasting activities can further weaken the ground. Excessive groundwater extraction, dense urbanization, and dynamic loads from traffic, industrial machinery, trains, and metro lines also contribute to the loss of stability in karstic areas (Waltham et al., 2005; Gutiérrez et al., 2014). This leads to serious engineering problems such as loss of stability, sudden collapse, soil settlement, changes in groundwater regime, and reduced soil bearing capacity. This situation both increases the risk of loss of life and property and necessitates costly maintenance and repair work (Dotson & Tarquinio, 2003; Pavlič & Praznik, 2011; Bačić et al., 2020; Goldscheider & Chen, 2022; Zerga, 2024).

The sinkholes that have formed in the Konya Plain in recent years are among the most notable examples of this process in Turkey. The number of sinkholes has increased rapidly, drawing significant attention to the region's growing instability. The decline in the groundwater level, excessive agricultural irrigation, and the dissolution-prone structure of the limestone-dolomite lithology have caused numerous large-scale sinkholes in the region. Similarly, in the coastal karst areas of Antalya, karst collapse events have been reported in areas close to the sea due to coastal erosion and settlement density (Nazik, 2019; Doğan et al., 2019). These local examples demonstrate that geological, hydrogeological, and human impact factors must be considered together when engineering planning is carried out in karst areas across different regions of Türkiye.

Carbonate units and karstic formations pose significant challenges to engineering structures and potential risks to human life. These adverse effects can be mitigated through advanced technologies, effective soil improvement methods, and close collaboration between geotechnical, geological, and geophysical disciplines. Tao and Rao et al. (2022) investigated the Guiyang Metro project, where a tunnel passing beneath the Guiyang Railway Station faced serious risks of settlement and collapse. Detailed geological and geotechnical studies were conducted to detect cavities and weak zones, followed by grouting, pipe-shed support, and stepwise excavation. Monitoring showed that surface settlement remained below 3 mm. Cooper et al. (2011) demonstrated the importance of integrating karst geomorphology into planning and hazard management in Great Britain. Using national datasets, the British Geological Survey developed the GeoSure GIS system to map karst-related risks, highlighting the value of incorporating karst data into sustainable land-use planning. Tacim et al. (2023) analysed tunnel excavation beneath the Osmangazi Bridge in Türkiye, where near-surface karstic cavities within dolomitic limestone posed deformation risks. Pre-excavation grouting and numerical analyses ensured that deformations remained within safe limits. Similarly, Gracia et al. (2024) studied severe subsidence and sinkholes in gypsum-rich karstic terrains in Spain. Geological and geotechnical investigations identified the causes of instability, and mitigation involved mortar injection and geogrid reinforcement, which effectively restored ground stability. These examples show that proper site investigations and targeted engineering measures can significantly reduce karst-related risks. However, ground deformation and collapse events continue to occur worldwide under varying environmental and human-induced conditions (Abdeltawab, 2013; Stan-Kłeczek et al., 2022; Pisano et al., 2022; Li et al., 2025).

This study systematically investigated the effects of carbonate rocks on the stability of engineering structures and the potential risks associated with these formations. More than 700 boreholes, geophysical tests and field surveys conducted across 147 parcels in the Siirt Province were evaluated for this purpose. The obtained findings were assessed alongside case studies of karstic formations, and the relationships between lithological properties, void geometry, bearing capacity and their interaction with groundwater were examined in detail. The mechanisms through karstic dissolution and weak zones cause differential settlements, reductions in bearing capacity and local collapses that threaten structural integrity were analysed in depth. Furthermore, the relationship between carbonate rocks and the damage observed in existing engineering structures was revealed, providing direct evidence of the effect of geological and hydrogeological processes on stability within a cause-and-effect framework.

STUDY AREA and GENERAL CHARACTERISTICS

Carbonate rocks cover approximately 12% of the Earth's surface, and this proportion is around 30-40% in Türkiye as a whole. Specifically, Türkiye's karst formations are primarily concentrated in four regions: the Taurus Karst Region, the South-eastern Anatolia Karst Region, the Central Anatolia Karst Region, and the North-western Anatolia and Thrace Karst Region (Günay et al., 2015). Siirt Province is one of the regions with the highest concentration of karst formations in the South-eastern Anatolia Karst Region. Carbonate rock areas correspond not only geologically but also to sites with high population density, agricultural activities, settlements, and various engineering structures. Therefore, determining the distribution of carbonate rocks is of critical importance for engineering planning, geotechnical studies, and natural disaster risk management. Figure 2a displays the spatial distribution of carbonate rocks across Türkiye and specifically in Siirt, along with the study areas in this work (Şahin et al., 2002; TKGM, 2025). The study area shown in Figure 2b is dominated by carbonate rocks and includes regions such as the neighbourhoods of Kooperatif, Bahçelievler, Veysel Karani, and Meydandere Village, as well as the Tillo District, where building density is high. The dominant geological units in this area were identified by evaluating drilling data obtained from foundation excavations, alongside geophysical studies and field observations.

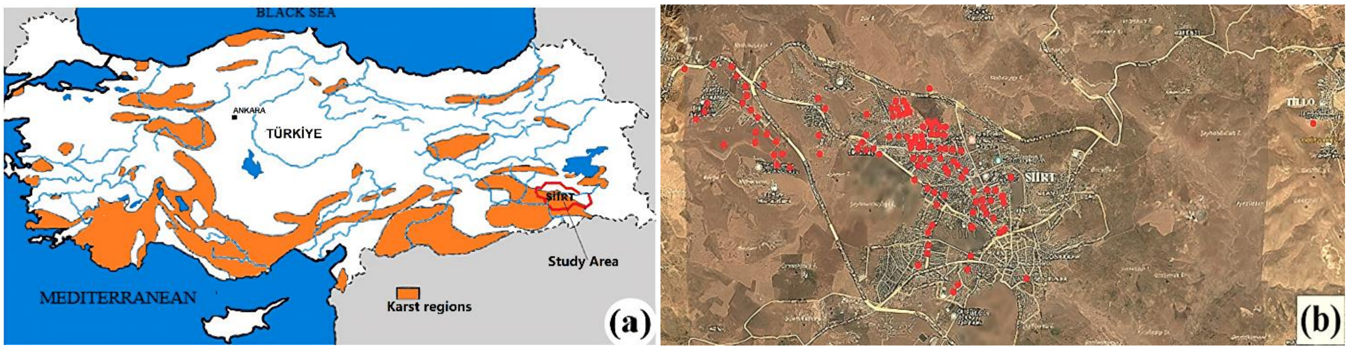

Figure 2. Distribution of Carbonate and Karstic Formations **a.** A General Map Showing Karst Regions Across Türkiye **b.** The Location of Parcels and Observation Sites within the Siirt Study Area

Red soils, particularly those formed by the dissolution of limestone with carbonic acid in rainwater and groundwater, were frequently encountered in the study area. During the formation of these soils, carbonate minerals dissolve and are removed from the environment, leaving behind insoluble clay minerals, quartz, and iron compounds. These iron compounds oxidize when they come into contact with oxygen and water, giving the soil its characteristic red colour. Thus, a fine-grained red surface layer rich in aluminium and iron oxides and poor in organic matter is formed.

Figure 3 shows different formation sections for the foundation excavation of structures to be built in the study areas. In the study area, despite the deep groundwater level, weak, dissolved zones formed by rainwater seeping from the surface within the limestone units are clearly observed. The weak zones expand over time, losing strength and leading to the development of large-scale melting cavities in the ground. Carbonate rocks were identified in the higher-altitude drilling zones within the investigation area (Figure 3a). The upper layers consist of red-brown soils that transition into weathered carbonate rock units (Figure 3b). The reddish soils are rich in aluminium and iron hydroxides. This colour is the result of iron minerals oxidising upon exposure to air and moisture. It has been observed that the degree of weathering and dissolution in these carbonate rocks decreases with depth. However, surface water infiltration has created weak zones in certain parts of the area (Figure 3c). In contrast, relatively low-lying and flat regions such as Kooperatif Neighbourhood are characterized by red-brown soils overlying carbonate rock, with some locations consisting entirely of red soil (Figure 3d).

Figure 3. Field Photographs from the Study Area **a.** Weathered Limestone **b.** Contact Between Red-Brown Soil and Weathered Limestone **c.** Dissolved and Decomposed Zones **d.** Alternation of Red-Brown Soil and Limestone

THE IMPACT OF KARSTIC FORMATIONS ON ENGINEERING STRUCTURES

Karst topography covers 12% of the Earth's surface, with up to 25% of the global population relying on karst regions for their water supply, highlighting the importance of understanding karst formations (Chen et al., 2023). Karstic formations pose significant risks to engineering structures due to voids, cracks, and weak zones formed by dissolution. Voids created by melting cavities developing underground and roof collapses, as well as sudden soil settlements and loss of bearing capacity, lead to differential settlement of foundations and structural damage. Roads, dams, tunnels, and buildings constructed on these grounds are exposed to engineering problems such as deformation, crack formation, and settlement differences in the long run. Negative impacts on engineering structures in terrains formed by the melting or dissolution of sacrificial rocks arise from the combination of different natural and artificial factors. Sudden changes in the groundwater level, excessive groundwater extraction, or rises after heavy rainfall can lead to stress changes in void ceilings, increasing the risk of collapse (Chen et al., 2023). Surface runoff from precipitation accelerates dissolution processes in the cracks and voids of carbonate rocks, leading to the expansion of existing voids and the emergence of potential stability issues. This process is directly related to the climate characteristics of regions where carbonate rocks are found and changes in these climate characteristics. In the South-eastern Anatolia Region, where climate change is clearly observed, and consequently in Siirt, the impact of the climate would be felt more strongly (Kartal et al., 2024). Therefore, it is clear that the South-eastern Anatolia Karstic Region, one of the four karstic regions in Türkiye, will also be affected by this process, and an increase in stability problems will be experienced in the coming periods. Türkiye is located in a geography with an intense concentration of fault lines, which necessitates the continuous updating of seismic codes and the incorporation of new findings in earthquake engineering studies (Akyildiz & Ayhan, 2022). More than 80% of Türkiye's land area is at seismic risk (Damcı et al., 2015).The Anatolian region is among the most seismically active areas globally (Baba et al., 2019).The East Anatolian Fault Zone, situated between the Anatolian Plate and the Arabian Plate, is bounded by the Dead Sea Fault Zone and the South-eastern Anatolian Thrust (İmamoğlu & Çetin, 2007). The Bitlis–Zagros Suture Zone, an extension of the Zagros Thrust Belt in Iran, extends westward through Hakkari, Şırnak-Beytüşşebap, Narlı, south of Siirt-Pervari, Batman-Kozluk, Diyarbakır-Kulp, north of Lice-Ergani, Çüngüş, and Adıyaman-Çelikhan, creating conditions for significant earthquakes (Akbaş, 1999; İmamoğlu & Çetin, 2007). Indeed, the 2011 Van-Erciş earthquake (Mw 5.9) and the 2020 Elazığ-Sivrice earthquake (Mw 6.8) have once again highlighted the active seismic hazard of faults surrounding Siirt, underlining the necessity of paying particular attention to the region's seismic risk (Doğruyol, 2021).

High traffic density, industrial vibrations and earthquakes can cause instability in weak zones, leading to sudden ground collapse (Waltham & Culshaw, 2005). The map presented particularly in Figure 4, which details the location of Siirt Province's borders in relation to active faults, highlights the potential risks of dynamic effects on the stability of these carbonate rocks. Considering the earthquakes centred in Kahramanmaraş and Hatay on 6 February 2023, the distances between their respective epicentres and the centre of Siirt are 450 km and 530 km. Despite this, the earthquakes were generally felt in Siirt with a magnitude of 4–5 (Earthquake Hazards Programme, 2025). Therefore, since every point in Türkiye carries the potential risks of earthquakes, these risks are always present for Siirt Province in terms of carbonate rocks. Although Siirt Province is located on the Bitlis-Zagros suture zone, below the fork-shaped area formed at the intersection of the North Anatolian Fault line and the East Anatolian Fault line, and although faults (blue colour) with a diameter of 400 km are found in the area, centred on Siirt, it is also observed that there are active faults (red colour) (Emre et al., 2013).

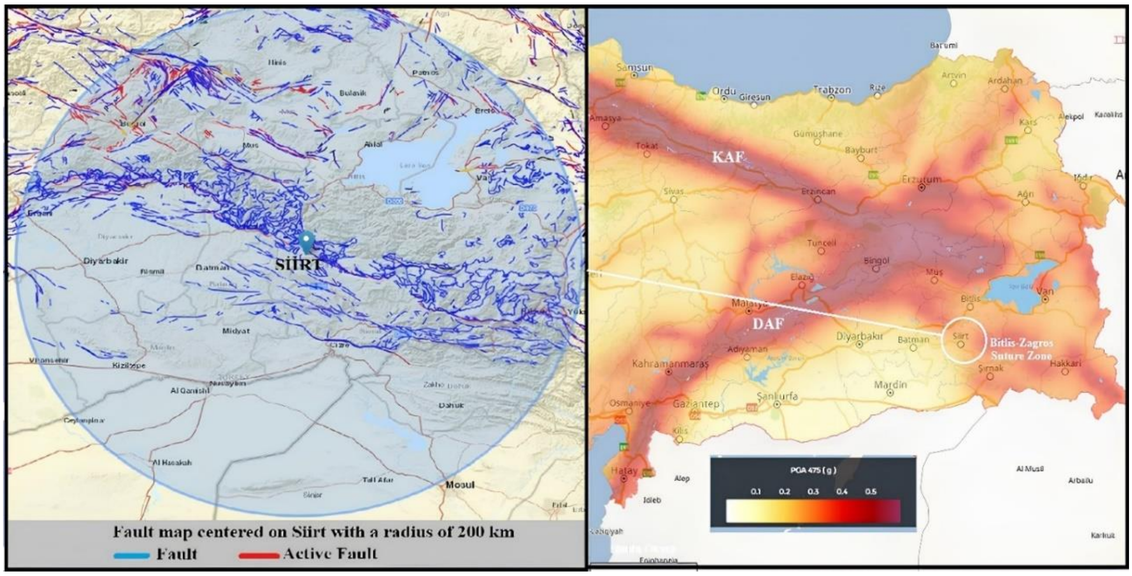

Figure 4. Faults in a 400 Km Diameter Area Centred on Siirt

Static loads, especially those applied by engineering structures like building foundations, bridge piers, or dam bodies, cause deformation and settlements in areas with low bearing capacity. Construction excavations and blasting operations disrupt the natural balance of underground voids, increasing the risk of collapse (Yılmaz, 2007). In addition, excessive agricultural irrigation leads to a decrease in water levels and an increase in the ceiling load, while sudden and intense rainfall, which is increasing due to climate change, accelerates melting and erosion processes, posing serious risks for engineering structures (Gutiérrez et al., 2014). When all these factors are considered together, the reflections of these effects on structures within the borders of Siirt Province were examined thru field observations.

The Case of Meydandere Village

Following statements from the residents of Meydandere Village in the central district of Siirt Province, who reported hearing underground sounds and observing damage to their homes, a detailed investigation was initiated. Comprehensive geological and instrumental geophysical studies were then conducted under the supervision of the Siirt Provincial Directorate of AFAD. As part of the studies, geophysical surveys and field observations were carried out within the study area to determine the lithological structure, layering status, potential fault zones and their magnitudes, underground cavity structures, and groundwater levels along different depths. When the initial field observations are evaluated together with the general geological structure of Siirt Province, it suggests a potential for ground instability. It appears that different surface settlements and structural damage may occur in the region due to the dissolution of carbonate rocks. Subsequent geological findings were seen to confirm this thesis, as the sound heard and the damage to the structures supported it. Figure 5 presents a visual of a masonry residential building identified as damaged due to different surface settlements, along with images obtained from field observations.

Figure 5. Structural Damage **a.** Final State of the Structure **b.** Different Surface Settlement

As part of geophysical studies performed in different regions within the study area, Seismic Refraction (MASW) was used for the depth range of 0–30 meters, Electrical Resistivity Tomography (ERT) for the depth range of 40–200 meters, and Ground Penetrating Radar (GPR) measurements were taken up to a depth of approximately 20 meters, with a total line length of 4,000 meters. ERT surveys were conducted using the Wenner–Schlumberger array configuration with electrode spacing varying between 2 and 5 meters and profile lengths ranging from 48 to 72 meters. Resistivity data were processed through inversion modelling using the RES2DINV software to obtain two-dimensional resistivity sections. MASW data were acquired with a 24-channel seismograph equipped with 4.5 Hz geophones, a 5 kg sledgehammer as the seismic source, and geophone spacing of 2 meters. Dispersion curves were extracted and inverted to generate shear-wave velocity (Vs) profiles for soil classification and stiffness evaluation. GPR surveys were carried out with antennas operating at frequencies between 100 and 250 MHz, providing a vertical resolution of 0.1–0.3 m depending on the subsurface conditions. The radar profiles were processed using standard gain and filtering techniques to enhance reflection continuity. Similar geophysical survey techniques and parameter settings were also applied in other investigation sites within the study area. However, minor adjustments were made according to local geological and topographical conditions. These comprehensive geophysical data provided detailed information about the lithological structure and the distribution of underground voids. In the final state, it was determined that the village, built on sloping topography, is located on a karst structure containing significant dissolution cavities and fracture zones. Figure 6 presents the results of an ERT experiment showing the geological structure of the soil.

According to the ERT measurement in Figure 6, the resistivity value is approximately 708.20 Ω·m in the range of 0.00–1.00 meters, 242.00–2,075.00 Ω·m in the range of 1.00–15.00 meters, and about 17,811 Ω·m below this level. The evaluation of the data indicates that a landslide zone exists at a depth of 2.00–16.00 meters along a profile length of 0.00–170.00 meters. In addition, wide cave-like voids were identified near the 40th meter of the section at depths of approximately 8.00–12.00 meters. Observational assessments of the study area were carried out by considering the regional climate conditions, the presence of dams near the settlement, and the current groundwater level. Field investigations show that the underground sounds reported by the villagers are associated with the dissolution and weakening of the carbonate soils beneath the village. These processes are thought to result from both natural and human-induced effects. The main source of these sounds appears to be the instability of the carbonate soil ceiling within large karstic voids. The detachment and collapse of ceiling blocks generate mechanical vibrations that create acoustic echoes along the walls of the voids. Such dissolution and roof collapse events are influenced by rainfall patterns, dam operations that alter groundwater levels, lithological characteristics of the carbonate rocks, and the presence of fracture and void systems. Geological and geophysical findings, including the detection of underground cavities, the loss of ceiling stability, and the presence of sinkhole-like structures, reveal significant ground safety problems in the settlement area. Based on the final evaluations by the Siirt Provincial Disaster and Emergency Management Directorate, detailed soil surveys and geophysical investigations were conducted in the village to ensure the safety of residents. It was also confirmed that all technical procedures were carried out carefully and systematically.

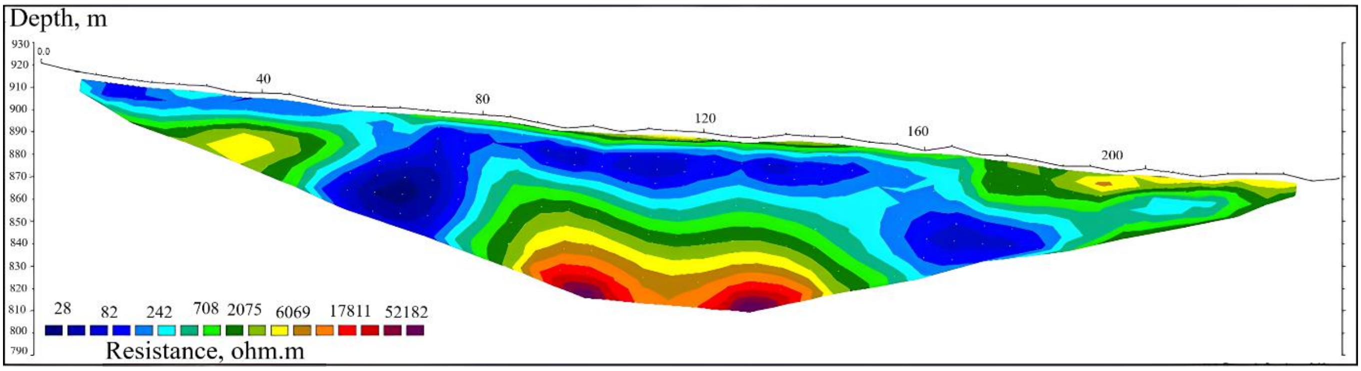

Figure 6. Geological Cross-Section of the Study Site Based on ERT 24 Test Results

Bahçelievler Neighbourhood Case Study

The Bahçelievler Neighbourhood is located in the city centre of Siirt, one of the most densely populated and developed areas. Situated on sloping terrain, the surface covering suddenly collapsed within a public event area (Figure 7a). Preliminary assessments revealed a large pool of water adjacent to the collapse site, with heavy rainfall having occurred shortly beforehand. Additionally, the inner walls and ceilings of the karstic voids were found to be wet. Following the event, detailed field observations and geophysical studies revealed that the area and its surroundings are underlain by extensive karstic cavities formed in carbonate rocks. For safety reasons, the deeper voids could not be examined in detail. However, limited observations showed the presence of relatively strong carbonate units where dissolution was incomplete (Figure 7b).

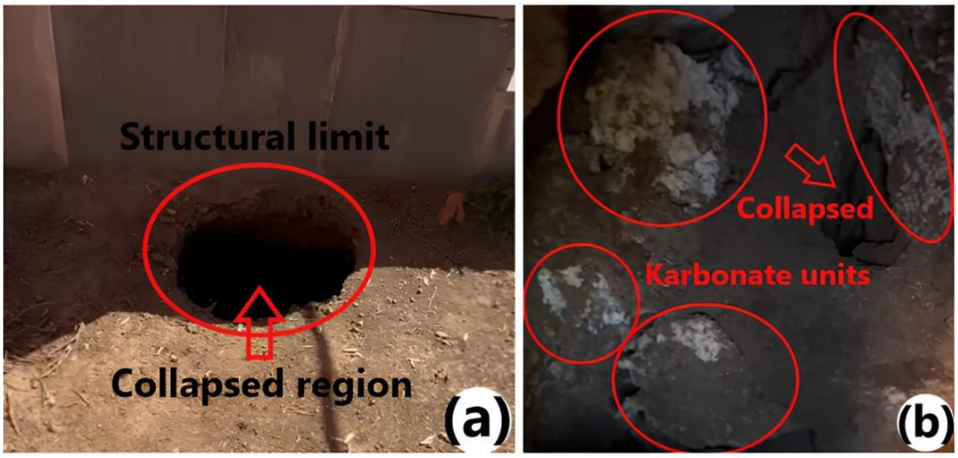

Figure 7. Field Observations **a.** Showing the Collapsed Zone **b.** Underlying Carbonate Rock Units

It was determined that these previously stable cavities had lost rooftop stability due to heavy rainfall and increased pore-water pressure. Although no major surface collapse occurred, the single-storey building located above the voids largely maintained its stability. Considering the long-term formation processes of these karst formations, it can be concluded that adequate preliminary geotechnical and geophysical studies had not been carried out in this area. As a result, the intense rainfall weakened the voids' roofs, ultimately triggering the collapse.

Figure 8 presents the findings obtained from geophysical data. Geophysical assessments have revealed the presence of multiple voids starting just below the surface and extending deep down. It has been determined that the collapse occurred due to the loss of ceiling stability in one of these voids, while the others pose similar risks in the future. This situation indicates that the area poses a high risk for engineering structures and intensive human use.

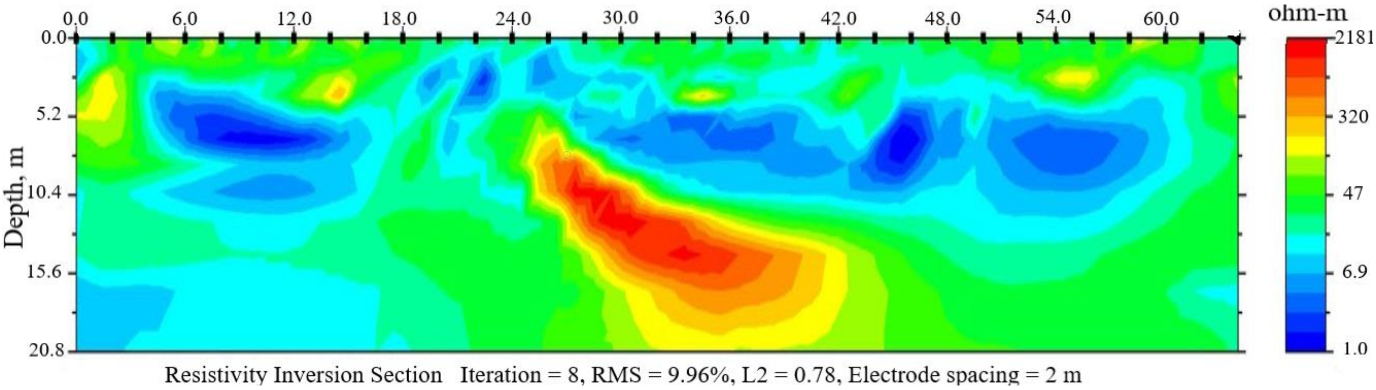

Figure 8. ERT 24 Test Results Showing Variations in Underground Resistance in the Research Area

Similar karst formations and stability issues caused by external factors are common not only in Siirt, but also across the world. A similar incident occurred in 2021 at the Ospedale del Mare hospital in Naples, Italy. A sudden ground collapse measuring approximately 2,000 m² in area and about 20 meters in depth developed in the hospital's parking lot (Figure 9a). Preliminary assessments indicated that the collapse was caused by the loss of stability of subsurface karstic cavities resulting from groundwater infiltration following heavy rainfall (The Guardian, 2021). This situation demonstrates that intense rainfall and the resulting increase in pore-water pressure play a significant role in causing sudden surface deformations in karstic areas. In the case studied in China, fluctuations in the groundwater level following heavy rainfall caused the roofs of karstic cavities that did not exhibit any surface signs to weaken, resulting in sudden collapse (Figure 9b). Geophysical measurements and field observations revealed that these hidden karstic cavities lost stability primarily due to heavy rainfall and changes in water pressure (Zhao et al., 2021). In the Alcalá de Ebro region of Spain, subsidence and surface deformations caused by these processes have occurred in gypsum-containing karstic soils (Figure 9c). The study area revealed that heavy rainfall and changes in the groundwater level are the main external factors triggering this subsidence. It also determined that low-flow grout injection and geogrid-reinforced fill effectively increase ground stability (Gracia et al., 2023). The these case studies exhibits similar geotechnical characteristics to the karstic roof collapse observed in the Bahçelievler Neighbourhood of Siirt, once again emphasizing the importance of conducting adequate geotechnical and geophysical investigations in such regions.

Figure 9. Sudden Collapses and Surface Settlements Caused by Changes in the Groundwater Level and Heavy Rainfall **a.** Italy **b.** China **c.** Spain

The Kooperatif Neighbourhood Case Study

One of the five boreholes conducted prior to the foundation excavation of a residential construction project located within the boundaries of Kooperatif Neighbourhood encountered a completely void structure in the depth range of 8–16 m. Following this finding, comprehensive geophysical studies were conducted in the region, and the data obtained were evaluated together with the drilling results. Additionally, observations made on the research pits that were opened revealed the presence of weak zones with a brownish-reddish colour developed from the decomposition of carbonate rocks in the near-surface sections of the study area (Figure 10). These weak zones pose different engineering risks due to their low bearing capacity and susceptibility to decomposition upon interaction with water.

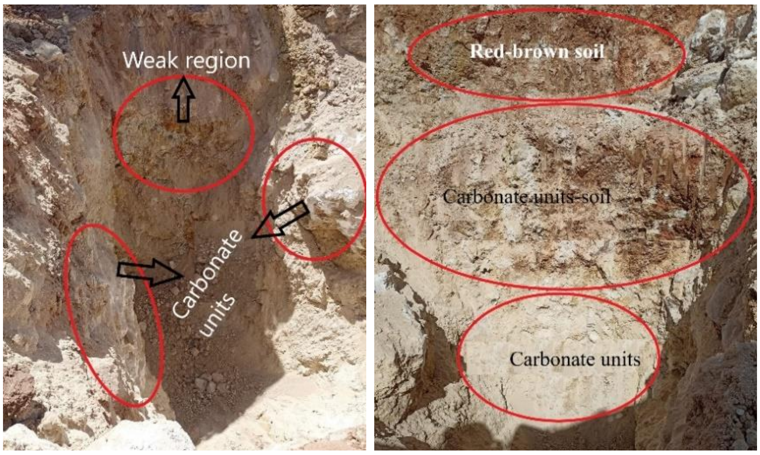

Figure 10 Field Photographs Showing the Lithological Structure of the Research Holes

Geophysical data, on the other hand, indicate the presence of advanced dissolution cavities at deeper levels, particularly within carbonate rocks (Figure 11). This situation reveals that the area has a soil structure that requires detailed engineering measures and soil improvements, both in terms of soil stability and structural safety.

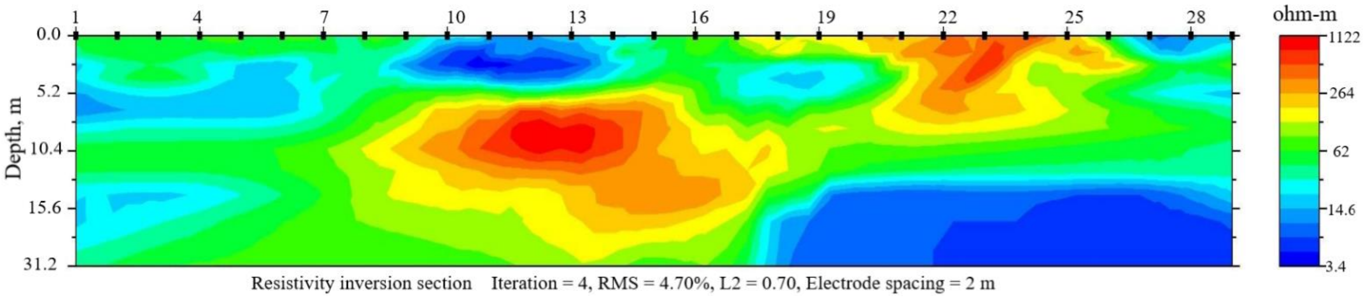

Figure 11. ERT 24 Test Results Showing Variations in Underground Resistance for a Section

Veysel Karani Neighbourhood Case Study

Karstic terrain containing underground cavities poses major challenges for road stability. Rainwater infiltrates through fractures and accelerates the dissolution of carbonate rocks. This process enlarges the cavities, weakens the roof layers, and reduces the bearing capacity of the surrounding soil. As the soil becomes saturated, it loses stiffness and shear strength. Under these weakened conditions, traffic loads generate additional dynamic stresses, which intensify deformation and can trigger local collapse. The combined effects of rainfall and loading eventually lead to settlement, cracking, and loss of structural integrity in the pavement system. In September 2025, a large sinkhole in Bangkok's Dusit District swallowed several vehicles (Figure 12a). The failure occurred because metro tunnel excavation, burst water pipes, and heavy rainfall jointly increased pore water pressure and reduced soil strength, leading to collapse (Reuters, 2025). A similar event along the Kuşadası–Söke highway was caused by intense rainfall that raised the groundwater level and heavy traffic loads that overstressed the weakened carbonate units (Figure12b). Poor drainage further accelerated soil softening, resulting in surface failure (Cumhuriyet, 2024). Figure 12c shows that case studies from Vietnam's North–South Expressway confirm that embankment pressure and vehicle loads increase shear stresses on karst cavity roofs, promoting instability and collapse (Phi et al., 2022).

Figure 12. Stability Issues in Road Structures in Karst Formations **a.** Bangkok **b.** Türkiye **c.**Vietnam

Recent studies recommend geotechnical improvement measures—such as grouting, subgrade reinforcement, and enhanced drainage—to minimise the impact of karst formations and carbonate units on road structures (Jones et al., 2005; Coni et al., 2023; Gutiérrez et al., 2014; de Castro et al., 2024).

The case study is located in the Kezer region of Veysel Karani Neighbourhood, on a section of road open to vehicle traffic. On this route, which showed no problems in daily use, an unexpected and sudden surface collapse occurred. Initial observations suggest that the voids or loose structure present in the soil may be related to the event, weakening under continuous vibration and repeated loads and exceeding the critical strength limit. Specifically, the repeated stresses caused by vehicle crossings have led to the propagation of micro cracks in sensitive areas deep within the soil and accelerated the rate of gradual deformation. It was assessed that the ceiling section suddenly broke and collapsed at the end of this process. The size of the collapse and its environmental impact indicate that the area's underground structure needs a more detailed engineering examination. A visual of the area where the landslide occurred is presented in Figure 13. In contrast to the cases shown in Figure 12, complete loss of roof stability did not occur in this event. As a result, no large-scale collapse zone developed. The failure remained relatively confined, indicating that parts of the roof retained some load-bearing capacity. Another important factor was the absence of intense or prolonged rainfall during the event. This prevented additional soil saturation and limited pore-pressure development. Therefore, the strength loss was primarily due to mechanical stress from repeated traffic loads rather than hydrogeological processes. These findings emphasise the need to assess both dynamic loading and hydrological conditions when analysing collapse mechanisms in karst-prone road sections.

Figure 13. Surface Collapse Observed on a Road Section Caused by Subsurface Void Development

CONCLUSIONS

This study analyses field observations, borehole data, and geophysical measurements from different parts of Siirt to assess the effects of karstic formations and their impact on engineering structures. The investigations identified weak zones, weathered carbonate units, and deep dissolution cavities, indicating that soil stability is influenced by both natural and human factors. These findings underline the need for detailed engineering analyses to ensure settlement safety and sustainable infrastructure. The following conclusions and recommendations aim to guide risk management in karst-prone areas.

1) The alternation of limestone and red-brown soils in Siirt poses serious risks for engineering structures. These soils, though stable under natural conditions, are prone to bearing capacity loss, settlement, and collapse when exposed to structural loads, dynamic stresses, groundwater fluctuations, or heavy rainfall. This heterogeneity highlights the need to evaluate the mechanical and hydraulic behaviour of carbonate soils under different conditions to prevent sudden failure.

2) Field investigations and on-site observations revealed dissolution voids and weathered zones within the carbonate formations. These findings confirm that karstic processes are still active in the region. Continuous dissolution enlarges existing voids and gradually weakens the overlying layers. As these cavities expand, the ground loses stiffness and bearing capacity, which increases the risk of long-term subsurface instability. Therefore, regional-scale assessments and continuous monitoring are essential to track karst development and to identify areas where further deformation or collapse may occur.

3) The instability of dissolution voids varies with local conditions. In Meydandere Village, groundwater fluctuations change pore-water pressure and weaken the roofs of cavities. In Veysel Karani Neighbourhood, repeated traffic loads and vibrations cause deformation and cracking in the weakened layers. In Bahçelievler, heavy rainfall and human-induced dynamic loads reduce subsurface strength and lead to local collapses. These case studies demonstrate that environmental and human factors both play a direct role in the loss of karst roof stability. Therefore, stability analyses of specific sites should consider hydrogeological conditions, dynamic loading and human activities.

4) The complex geological structure of Siirt shows that borehole data alone is not enough for engineering design and risk evaluation. Therefore, geophysical, geotechnical and hydrogeological investigations need to be integrated. The results should also be evaluated by experts to ensure structural safety and long-term soil stability. This multidisciplinary approach provides a more reliable understanding of subsurface conditions, enabling engineers to identify deformation mechanisms and develop specific mitigation strategies.

5) In regions dominated by karstic formations, detailed geophysical, geotechnical, and hydrogeological investigations must be carried out prior to construction to accurately determine subsurface conditions and identify potential voids. During the design and construction stages, these voids should be treated through appropriate stabilisation techniques such as grouting, compaction, or other soil improvement methods. Implementing these preventive measures is crucial to reducing the probability of sudden ground collapse, ensuring the long-term stability of engineering structures, and promoting safe and sustainable urban development in karst-prone areas.

Artificial Intelligence Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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