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Determination of Ground-Based Structural Problems in the Historical Four-Legged Minaret with Ground Penetration Radar

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Masonry structure,
Minaret,
Nondestructive testing method

Abstract: The Four-Legged Minaret, which has an important place thanks to its building period and unique architecture, is located in the southeastern part of the historical Suriçi region of Diyarbakır. This structure located outside the courtyard of Sheikh Mutahhar Mosque and inside the Dört Ayaklı Minare Street was built on a monolithic stone column from basalt stone in a tetragon plan and is carried by four columns that are in cylindrical form. After 2015, partial damages occurred to the minaret. During the restoration works carried out between 2016-2019, these partial damages were tried to be repaired. But the condition of the ground was not instrumentally detected and investigated in these restoration works. In the present study, observational geological and instrumental geophysical studies were carried out on the Four-Legged Minaret and its surrounding area. The ground condition of the Four-Legged Minaret and the situation of its construction materials were determined by scannings achieved from the ground penetration radar and whether the damages in the structure were related to the ground condition was analyzed. As a consequence of the study, fractures and cracks were detected in the wall, and fractures, cracks, and water leakage-dependent collapses were detected on the floor. Besides, finally, repair recommendations for these damages are also presented in this study.

Tarihi Dört Ayaklı Minare'de Zemine Dayalı Strüktürel Sorunların Yer Radarı ile Belirlenmesi

Anahtar Kelimeler
Tarihi yapı,
Yer radarı,
Yığma yapı,
Minare,
Tahribatsız deney yöntemi

Öz: Hem inşa edildiği dönem hem de sahip olduğu eşsiz mimariyle önemli bir yere sahip olan Dört Ayaklı Minare, Diyarbakır'ın tarihi Suriçi Bölgesinin güneydoğu diliminde yer almaktadır. Şeyh Mutahhar Cami avlusu dışında ve Dört Ayaklı Minare Sokak içinde bulunan bu yapı, yekpare taş sütun üzerinde bazalt malzemeden dört köşeli olarak inşa edilmiş olup, dört adet silindirik formlu sütunla taşıtılmaktadır. 2015 yılından sonra minarede kısmi hasarlar meydana gelmiştir. 2016-2019 yılları arasında yapılan restorasyon çalışmalarında bu kısmi hasarlar giderilmeye çalışılmıştır. Ancak yapılan bu restorasyon çalışmalarında zemine yönelik herhangi bir aletsel tespit ve inceleme yapılmamıştır. Bu çalışmada, Dört Ayaklı Minare ve çevresinde gözlemsel olarak jeolojik ve aletsel olarak jeofizik etütler yapılmıştır. Dört Ayaklı Minare'nin zemin durumu ve yapı malzemelerinin durumu, yer radarından yapılan taramalarla tespit edilmiş ve yapıda meydana gelen hasarların zemin durumu ile ilgili olup olmadığı analiz edilmiştir. Yapılan çalışma neticesinde, duvarda kırık ve çatlaklar, zeminde kırık, çatlak ve su sızıntılarına bağlı çökmeler olduğu tespit edilmiştir. Son olarak, bu hasarlara yönelik onarım önerileri de bu çalışmada sunulmuştur.

1. INTRODUCTION

The United Nations Educational, Scientific and Cultural Organization (UNESCO) describes the term 'cultural heritage' as the legacy, inherited from past generations, reaching today, and endowing for the benefit of future generations, that is associated with intangible attributes and physical science artifacts of a society or group [1,2]. But this term has been applied to tangible cultural heritages such as monuments, historical places, buildings, works of art, artifacts, and books, as well as intangible cultural heritages such as beliefs, traditions, language, folklore, knowledge, and customs, and natural heritages such as culturally significant marine ecosystems, landscapes, and biodiversity [1]. However, not all legacies passed down through the centuries qualify as legacy; rather, the item is designated as heritage by society [3]. In this manner, the preservation of historical buildings in all their physical forms makes this an important issue as it is a special component of the collective identity [4]. Human involvement and natural disasters like earthquakes, landslides, floods, etc. are typical causes of the deterioration of such buildings as time passes. Therefore, finding a route that combines and safeguards such historical structures should be created and followed to boost the efficiency of the fortification, conservation, and restoration method [4,5].

In this context, historical mosques, which are centers of worship and belief that have an important place in the social and cultural life of cities from past to present, can be regarded as tangible cultural heritage, implicitly also intangible cultural heritage. After the acceptance and spread of Islam, mosques were built in different forms and plans, reflecting the characteristics of the period in which they were built and used as places of worship. In many periods from the past to the present, minarets have been built in mosques for the purpose of reciting the azan and making reciting the azan heard. In this context, the first minaret example in the mosque was built in the Mosque of 'Amr ibn al-'As in Egypt in 673 AD, and it was built with a balcony to announce the azan [6].
Minarets, which were built from stones, bricks, and wood, did not have a certain shape in the beginning and there are two styles of minarets that might be described in general: the first style is inspired by ancient lighthouses and/or bell towers having a square/rectangular cross-section in-plane and the second style that originated in Asia constructed in a cylindrical slender body [7]. Minarets can be considered one of the distinctive and essential structural components of the Islamic cityscape [8]. Throughout history, countless majestic minarets have been built in various parts of the world adapting structural approaches and utilizing various materials [6]. Similar to many other ancient structures, the historical minarets are made of brick/stone and mortar and they are regarded as tower-like structures [9].

Diyarbakır which has hosted many civilizations and still has born traces of these civilizations is located in southeast Turkey. In the course of these periods, the social, cultural, religious, and interaction of communities from different cultures and traditions with the local resident increased over time. With the spread of Islam, the majority of the city community perpetuated living according to Islamic traditions and rules. In this manner, mosques have become the buildings where the people of the city performed their religious worship and have been actively used in many parts of the city [10].

In the yearbooks of Diyarbakır, it is stated that there were 24 mosques and 21 masjids in the city center in the 1900s. In the Suriçi region, a limited number of the mosques that were constructed during the early Islamic period have survived to the present day, and a majority of the structures have been destroyed. Besides, there are no mosques or masjids that have survived to the present day from the Umayyad period, while information about the mosques belonging to the Abbasid period is learned from the inscriptions and reliefs on the city walls. The oldest mosque in the city is the Diyarbakır Ulu Mosque, which was built in the 7th century with the characteristics of Arabic architecture. Many of the other mosques were built during and after the Akkoyunlu period.

Khoja Ahmet (Ayn Minaret) Mosque (in 1489) was built in the southwest of the Suriçi region, Sheikh Mutahhar and the Four-Legged Minaret (in 1500) and Lala Kasım Bey Mosque in the southeast of the Suriçi region, Nebi Mosque (in 1503) and some masjids (such as İbrahim Bey, Hacı Büzrük, Tacettin masjids) were built in the northwest of the Suriçi region. Fatih Pasha (Kurşunlu) Mosque (in 1516-1520) and Nasuh Pasha Mosque (in 1601) in the northeast of the Suriçi region, Hüsrev Pasha Mosque and its madrasa (in 1521-1528) in the southeast of the Suriçi region, Ali Pasha Mosque (in 1534-1537) and Defterdar Mosque (in 1594) in the south of the Suriçi region, İskender Pasha Mosque (in 1551) and Melik Ahmet Pasha Mosque (in 1587-1591) in the northwest of the Suriçi region, Behram Pasha Mosque (in 1564-1567) in the southwest of the Suriçi region are among the Ottoman period mosques [11]. In Diyarbakır mosques, the minarets are built in either square (or nearly square) form or cylindrical form, while the minaret of the Khoja Ahmet (Ayn Minaret) Mosque has an octagonal form. The minarets of the Ulu Mosque, Nebi Mosque, Hz. Süleyman Mosque, Hüsrev Pasha Mosque, and Sheikh Mutahhar Mosque are in a square plan order. However, there are cylindrical annexes in most of these minarets. Figures 1a-n exhibit the mosques and their minarets in the Suriçi region in Diyarbakır.

Among the aforementioned minarets, the Four-Legged Minaret has an important status from the point of cultural heritage, due to its building period and peerless architecture, and the historical events it has witnessed. During the repair and restoration works carried out on the minaret, drilling works and compression tests were carried out in 2011 by the Regional Directorate of Foundations to determine the soil condition of this area. However, after this date, there is no convenient and useful examination of the soil condition of this building and its surrounding area. For this reason, the present study has importance since it is aimed to examine the structural status of the building in regard to its soil condition. Because of that, the investigation of cracks, fractures, and partial axis slippage problems in the minaret depending on the soil structure was carried out with a non-destructive measurement method called ground-penetrating radar, and thereby, the structure was evaluated in this context. Here, it can be stated that nondestructive testing (NDT) is the examination of a system and its components and materials, in terms of situations and features using a number of analytical procedures [12]. Though fast progress in NDT technology has been witnessed due to increasing performance expectations from current buildings and engineering materials, the process of adapting NDT technologies to historical buildings is still in its infancy [5]. However, Moropoulou et al. [13] have recently defined NDT methods as essential instruments for cultural heritage buildings. The capacity to use NDT methods in situ and the elimination of the necessity for disruptive sample taking are the two most important benefits of using them on ancient buildings. They can be used not only to determine material situations and characteristics like density, moisture content, strength, dimension, stiffness, etc., but also to detect discontinuities, anomalies, internal cracks, and voids in structure and/or its components. Additionally, they can be employed in displaying the architectural detailing and layouts, evaluating frame and structural performances of the building, and monitoring anomalies underground. Examining the qualities of historical materials, studying the origins of these materials, analyzing the environmental consequences, considering prior interferences, and, most importantly, searching the historical records may all be done as part of extensive studies on historical structures [4,13,14]. NDT methods which can be grouped into four major groups: electromagnetic, penetrating radiation, sound, and optical, can be particularly considered a valuable diagnostic tool for determining material qualities, environmental influences, and prior interferences [5]. In this way, using NDT methods on historical buildings prior to attempting any conservation or restoration may reveal specific scientific knowledge of the structure.


(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l) (m) (n)

Figure 1. The photographic view of mosques and their minarets in the Suriçi region in Diyarbakır (taken in 2021): (a) Ulu Mosque, (b) Hz. Süleyman Mosque, (c) Safa (Parlı) Mosque, (d) Khoja Ahmet Mosque, (e) Sheikh Mutahhar Mosque (Four-Legged Minaret), (f) Nebi Mosque, (g) Fatih Pasha Mosque, (h) Hüsrev Pasha Mosque, (i) Ali Pasha Mosque, (j) İskender Pasha Mosque, (k) Behram Pasha Mosque, (l) Lala Kasım Bey Mosque, (m) Melik Ahmet Mosque, and (n) Nasuh Pasha Mosque

The GPR technique, which is one of the significant NTD methods, has been used frequently in the literature to assess and monitor the condition of historic buildings. By incorporating another nondestructive testing method, Alani et al. [15], for example, employed GPR to monitor the state of the stone arch bridges. Imposa [16], on the other hand, used the GPR technique to examine the inside walls of the "Sala delle Nicchie" of Florence's Pitti Palace. Similar to this, before the Collemaggio Basilica, a medieval church in L'Aquila (central Italy), was restored, Ranalli et al. [17] assessed the Collemaggio Basilica's façade's condition of conservation and determined the thickness of its walls using the GPR approach. In order to create a structural model based on finite elements, Lubowiecka et al. [18] also used the GPR technique to determine the homogeneity or heterogeneity of the interior construction of an old bridge. Masini et al. [19] also provided three instances of GPR prospecting to see historical monuments. Three distinct constructional components, including a wall, a masonry pillar, and a marble column, were chosen for this study to describe the masonry, detect and locate fractures, and document the metallic reinforcing bars. In another investigation, Pieraccini et al. [20] used the GPR method to find cracks in the stone walls of the famous "Salone dei 500" chamber in the Palazzo Vecchio (Firenze, Italy). In addition to the investigations stated above, Yalçiner et al. [21] employed the GPR technique to find a new temple at the Nysa archaeological site in western Turkey.

In this context, the target of the study is to investigate the subject of geological formations, the sequence changes, geometric behavior patterns, underground cavity structures and dimensions of ground/sub-structure fractures. For that purpose, a GPR device having 100-MHz and 1.8-GHz antennas were used for measurements, and 3D analyzes were carried out using the data obtained. The working area was separated into distinct places, and GPR sections in the shape of lines/profiles were obtained at each of these places. Penetration depths differ in regard to the measurement location: for example, 2.00 m was designated for the scanning of the load-bearing elements whereas 10 m as the shallowest and 20 m as the deepest were chosen for the ground scanning.

2. ARCHITECTURAL PROPERTIES AND LOCATION OF THE FOUR-LEGGED MINARET

Diyarbakır which is also included in the UNESCO Cultural Heritage List owing to its historical city walls [22] is located in the southeast of Turkey, as shown in Figure 2. Sheikh Mutahhar Mosque and Four-Legged Minaret, located in the southeast part of the Suriçi region that is surrounded by city walls and 82 towers as shown in Figure 2, were constructed in 1500 during the Akkoyunlu's period [23]. The Suriçi region is largely populated with historical buildings [24].

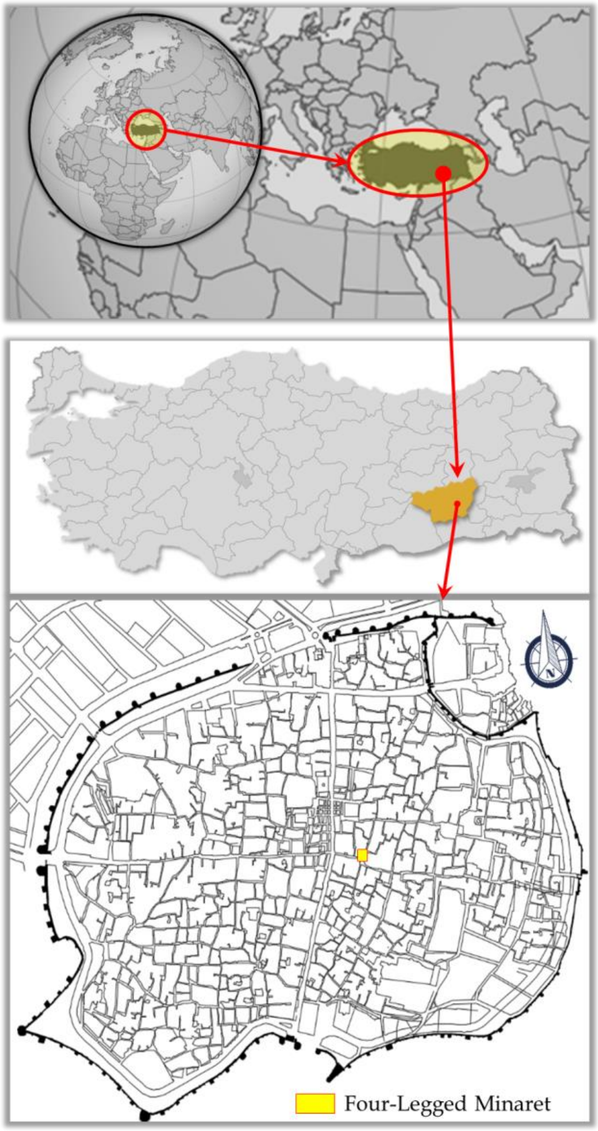


Figure 2. The location of Diyarbakır province on the map [25,26] and the Four-Legged Minaret in the Suriçi region

The Four-Legged Minaret is one of these historical buildings and it is located to the northeast of the Sheikh Mutahhar Mosque. The minaret has been repaired and restored many times from the time it was built to the present day in order to eliminate the existing problems in the minaret. However, nowadays, the minaret remained outside the borders of the mosque due to the widening of the street and the introduction of a wall boundary for the mosque, and hence, the minaret remained as an independent minaret in Yenikapı Street (known also as Four-Legged Minaret Street). The square-formed minaret is carried by four cylindrical columns as can be seen in Figure 3a. The minaret, which was built with the masonry technique, has a height of 18.54 m up to the spire and 22.44 m up to the top including the finial as marked in Figure 3b. The main building material used in the minaret is basalt; however, at certain intervals, brick was also used as a girder as indicated in Figure 3b. Besides, there are four wooden girders above the cylindrical columns and under the square minaret base as shown in Figure 3c.

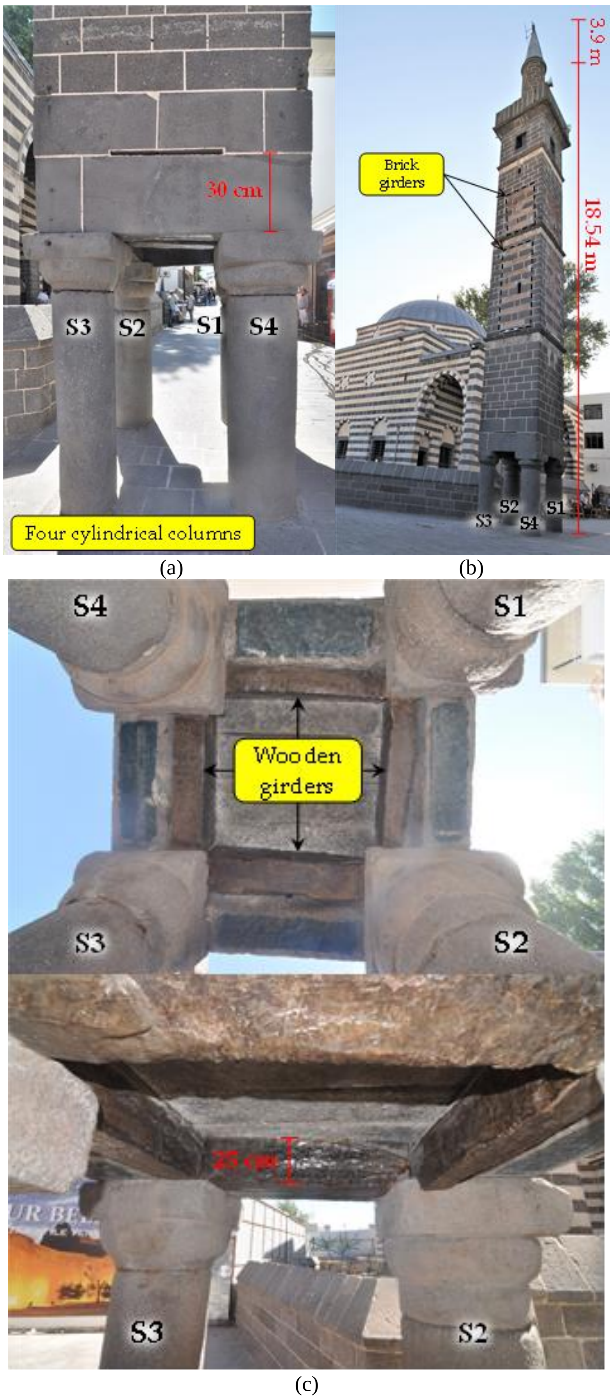


Figure 3. Photographic view of: (a) four cylindrical columns (west view), (b) brick girders (west and north views), and (c) wooden girders (bottom view)

The diameter of each load-bearing column in the Four-Legged Minaret is different from the other: the diameters of the S1 (in the northwest direction) and S4 (in the northeast direction) labeled columns are about 51 and 55 cm, respectively, whereas that of the S2 (in the southwest direction) and S3 (in the southeast direction) named columns are 59 and 49 cm, respectively. For the array and labeling of the columns, see Figure 4a. There are wooden beams having a 25-cm height on these columns as shown in Figure 3c and a basalt lintel with a height of approximately 30 cm above these beams as can be seen in Figure 3a. A spiral staircase that can be also seen in Figure 4b starts after the level of +1.00 m in the minaret.

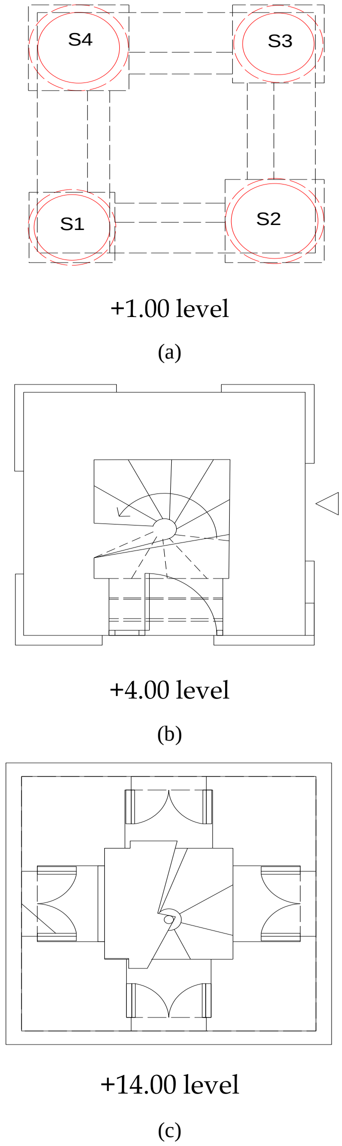
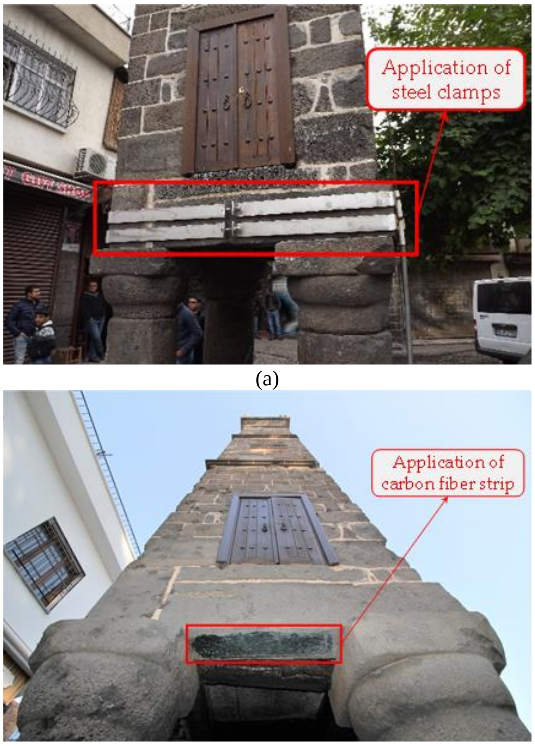


Figure 4. Plans of Four-Legged Minaret at: (a) +1.00, (b) +4.00, and (c) +14 levels

There are basalt cornices as three horizontal bands on the body. Between these cornices on the surfaces of the body, there is brickwork as partial stripes. The upper body section of the square planned minaret is located after a height of 15.37 m. This body in the basalt cylindrical form was completed with a lead spire as shown in Figure 3b. Besides, in the last section of the body, there is a window on each surface of the minaret, as can be seen in Figure 3b and shown in the plan view presented in Figure 4c.

During the restoration work of the Four-Legged Minaret carried out between 2011-2012, the cracks in the north and east directions were reinforced by injection. In addition, steel clamps were added to the lintels as part of this restoration as shown in Figure 5a. However, in 2015, the clamp added around the minaret was removed. Besides, the lintels on the columns of the minaret were strengthened using carbon fiber strips as can be seen in Figure 5b.



(a)

(b)

Figure 5. Photographic view of strengthening work on the Four-Legged Minaret: (a) application of steel clamps (taken in 2015) and (b) application of carbon fiber strip (taken in 2021)

3. MEASUREMENT METHOD

The GPR measuring technique consists of a simple system involving a recording device (computer) and two antennas named receiving and transmitting, as schematically exhibited in Figure 6.

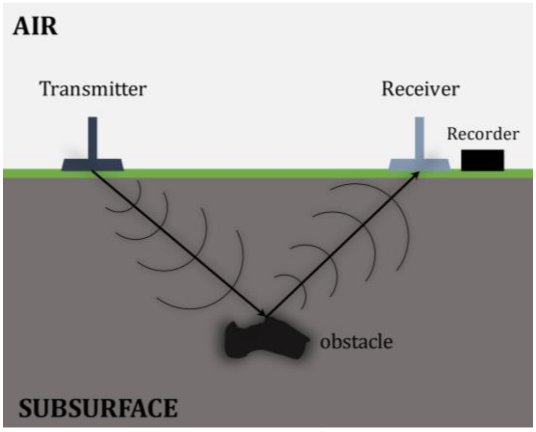


Figure 6. Schematical demonstration of the working principle of a typical GPR system

The transmitting antenna generates multi-nanosecond electromagnetic waves in the horizontal direction, parallel to the electric field vector. During the measurement progress, any anomaly, obstacle, disturbances, and/or negativity leads to the reflection and scattering of the waves under the ground and on the surface. In such conditions, waves are reflected and start to move through the upstream direction, and thereby, they are captured by the receiving antenna, and then the receiving antenna transfers these waves to the computer. In broad, this method is based on the difference between electromagnetic signals produced by the transmitting antenna and captured by the receiving antenna, during its underground travel [27]. The most important components of these signals are the electrical and magnetic constants of the energy transfer process. The resulting data and fluctuations are therefore called “radar traces”. These nanosecond measurements and radar traces are concatenated into a time unit, and the resulting portions are called “radargrams” [28].

GPR signals arrive at the objective by determining their speed according to the physical and chemical characteristics of the environment it is traveling to, thus collecting information about the target during this travel. In situations where the travel time is known and the speed of the medium is also known, the target depth can be determined with precision. Herein, the most important factors are the signal distribution and the environments in which the travel of electromagnetic signals can be affected. As previously stated, the receiving (R_x) and transmitting (T_x) antennas constitute the GPR system where the short high-frequency radio signals are emitted by transmitting antennas and the signals are picked up by the receiving antennas while being reflected by the obstacle or target, or by layers with different dielectric constant. Unlike seismic reflections, GPR produces reflections from both strata and buried objects. Objects with different electromagnetic properties such as water tables, sediment layers, foundation structures, buried tanks, and archaeological remains lead to reflections in the GPR. In other words, GPR reflections generally occur because objects have different dielectric constants. The dielectric constant reveals how much charge an object can store when an electromagnetic charge is applied to it. In this context, Conyers [27] graphically demonstrated an inverse relationship between radar travel speed and partial dielectric constant, as shown in Figure 7.

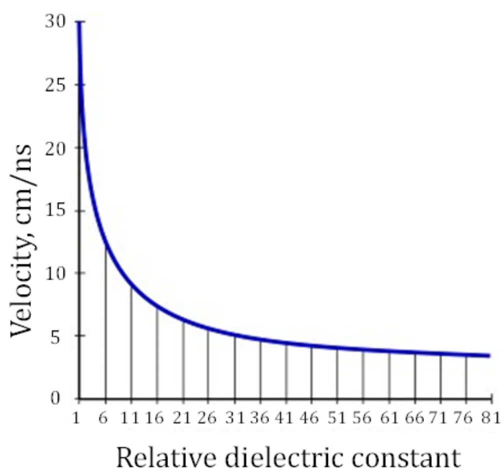


Figure 7. The inverse relationship between radar travel speed and partial dielectric constant [27]

There are just a few studies in the literature that look at the dielectric constants of various materials [29-31]. In radar frequencies, the dielectric constant of dry rocks usually ranges from 3 to 5, while water has dielectric values of 80-81. In general, dielectric constants of rocks, which contain water, vary between 6 and 30, depending on the amount of water they retain. In the present study, a device setup having a constant width between the transmitting and receiving antennas was used to examine the ground and structure-dependent damages of the Four-Legged Minaret. Sheltered antennas were used in the measurements and both the transmitting and receiving antennas were placed into a box then, it was moved on the ground, and thereby traces under the ground were collected in the course of this movement process. Subsequently, thousands of traces were collected, which form the profile when they are put together. After some measurements, anomaly situations on the surface were clarified with the help of three-dimensional images. In order to carry out the GPR scanning on both Four-Legged Minaret and its surrounding area, a Python-3 named GPR device having frequency values of 250/100/50/38/25 MHz and the antenna length changing between 1 to 4 m depending on the frequency value was employed [32] and besides, Prism 2 named software was used to manage the data processing steps in the GPR measurement works. The internal Wi-Fi system in the device provided the data transmission to the computer. The device may be used with both default and custom digital filters, and it can display 16-bit digital data. The device also features a user-selectable time range of 1 to 2500 ns with a 1 ns step, as well as a 28 and 1024x16-bit scan rate and samples per scan, respectively. 100 MHz and 1.6 GHz antennas were used for measurements in this study. In addition to these measurements, 3D analyzes were carried out using the data obtained.

The subject of geological formations, the sequence changes, geometric behavior patterns, underground cavity structures, and dimensions of ground/sub-structure fractures are included in this study. Besides, the conditions and changes of the formations and the classifications according to the characteristics of the host rocks and their electromagnetic permeability were also taken into consideration. In this case, the working area was separated into distinct places, and GPR sections in the shape of lines/profiles were obtained at each of these places. The exact depth capability of the GPR is highly dependent on the antenna frequency, the soil conditions and material properties, the quality and capability of the equipment, and the size of the target. The depth of radar penetration and the ability to identify the target object at any depth depends on the soil properties in that area. If the soil is highly conductive, the GPR method may be ineffective. In this regard, the maximum penetration depth of the GPR into the ground can be determined by the total propagation loss, which is determined by the electrical properties of the materials. Different penetration depths have been determined depending on the GPR equipment and antenna used in this study, the soil characteristics of the area being surveyed, and the size of the target. For example, 4.00 m was designated for scanning the structural elements, while 10 m was chosen as the shallowest and 20 m as the deepest for scanning the ground. Figure 8 shows some representative photographs taken during the GPR measurements.

Figure 8. A typical application of the GPR on: (a) the ground of the surrounding area of the minaret, (b) the basalt lintel of the minaret, and (c) the column of the minaret

For good data to be generated, it is necessary to perform proper filtering after careful measuring, which is suitable for interpreting [21]. Converting the obtained numerical data into understandable images is the basis of data processing in GPR measurements. The following filtering processes which are explained in detail by Işık et al. [14] are applied to obtain understandable images once the pure data is obtained from the site [33]:

i. First-time filter
ii. Current correction (Dewow)
iii. Energy delay
iv. Average value cleaning:
v. Velocity analysis

4. RESULTS AND DISCUSSION

As previously noted, the research location, which has a 5-degree slope and a 660 elevation, is located in Diyarbakır province's Sur district (called Suriçi region). The lithological sequence from the earth's surface to the subterranean in this study region, its near surrounds, and certain section cuts are detected as vegetable soil unit, clayey sandy unit, and clayey silty sand unit in accordance with the prior geological and geotechnical research. Despite these sequence alterations revealing local variances in areas, they generally follow the same pattern as the one described above.

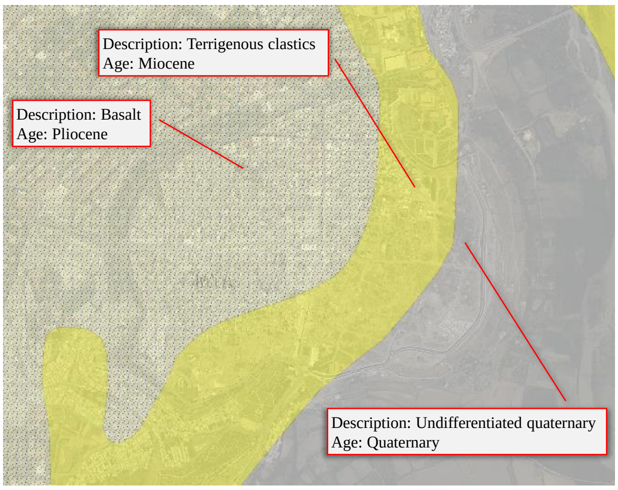


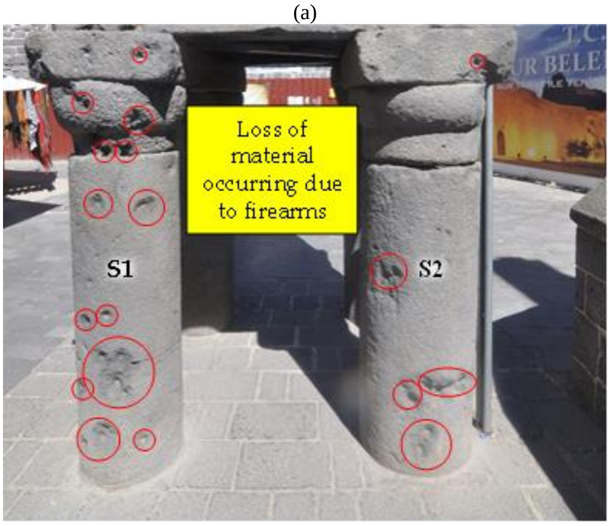
Figure 9. Possible geology map related to the immediate environment of the study area [34]

In regard to the General Directorate of Mineral Research and Exploration, as shown in Figure 9, the geology of the research region and its close surrounds comprises basalt, terrigenous clastics, and undifferentiated quaternary belonging to the Pliocene epoch, Miocene epoch, and quaternary period, respectively. Terrigenous clastics from the Miocene epoch, on the other hand, are widespread in this research region and its close surroundings.

4.1. Observationally Detected Structural Problems in the Four-Legged Minaret

Due to the fact that the minaret was outside the courtyard of the mosque due to its location, partial material losses occurred due to vehicle hits. In addition, in 2015, damage such as fragmentation and abrasion due to firearms occurred on columns S1 and S2 in the northwest direction of the minaret, and bullet holes occurred in some places (see Figure 10).

(a)



(b)

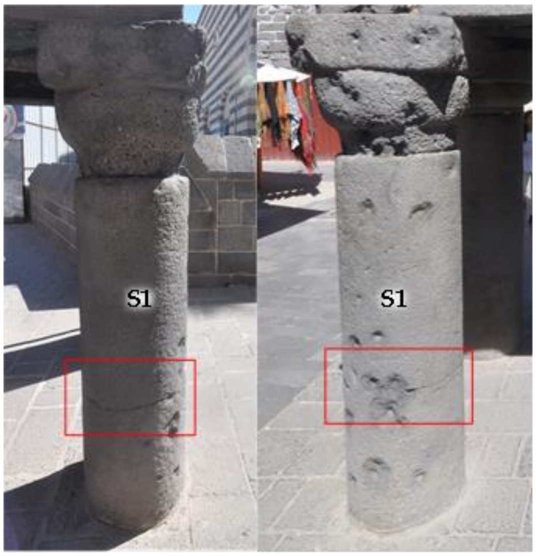
Figure 10. Photographic views of damages caused by firearms on: (a) the body and (b) columns of the Four-Legged Minaret (taken in 2021)

During the restoration work carried out between 2016-2017, no comprehensive repairs were made to the minaret, except for cleaning and removing mortar losses. Especially, there has not been any attempt to complete the material losses in the minaret during the period of vehicle traffic. The existing crack in the lintel of the minaret in the northwest direction was filled with injection during the repair works. In addition, macro-sized (visible) cracks were detected on the lintels on the columns in the northeast and southeast directions (see Figure 11).

(a) (b)

Figure 11. Photographic view of crack damage on lintels on: (a) S1-S4 columns in the northeast direction and (b) S3-S4 columns in the southeast direction (taken in 2021)

There are level irregularities on the street floor where the minaret is located. Although the street floor where the minaret is located was renewed with cut stone during the repair works, no detailed examination was done on the cause and correction of the level irregularities on the street floor. Besides, partial axis slippage due to vehicle hit, vibration, and level irregularity on the street floor has been observationally detected at the column heads. However, these irregularities and damages were not eliminated during the repairs. In addition, there is a horizontal crack in the middle part of the S1 column due to the loss of material because of the hit of a large number of bullets in that area and the impact of these bullets (see Figure 12). The wooden girders on the minaret columns are original but partially damaged. During the repair work, they were maintained by applying impregnation and protective paint for wood protection, and thereby, the current condition of the wooden girders was preserved.



(a)

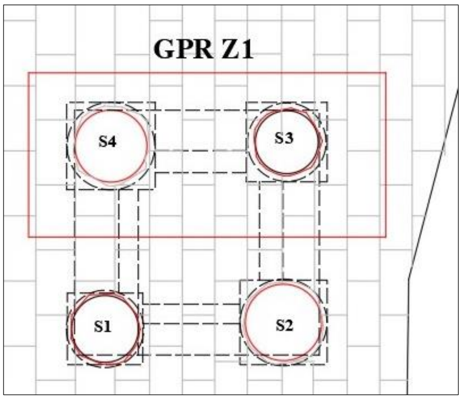
(b)

Figure 12. Photographic view of: (a) the horizontal crack on column S1 and its location and (b) the current condition of wooden girders

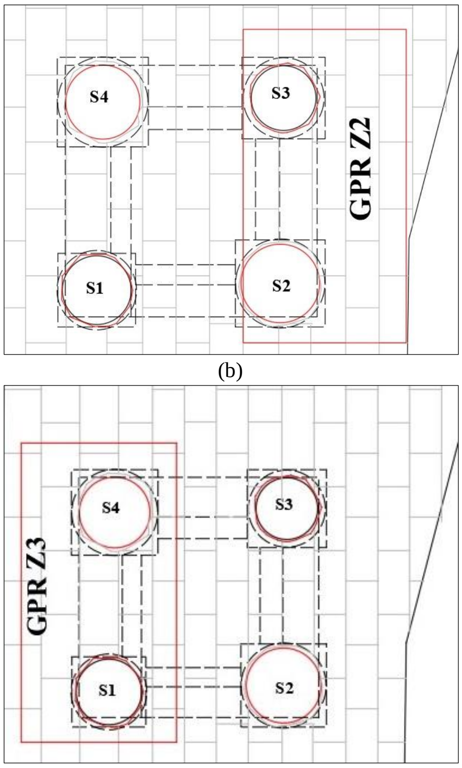
4.2. GPR Measurements and Evaluations on the Four-Legged Minaret

4.2.1. Ground scanning

GPR scannings on the ground of the Four-Legged Minaret were carried out by dividing the area into zones. Figure 13 indicates the location and border of each zone in which the GPR scannings were carried out. The GPR Z1 labeled zone had a profile length of 80.0 m while the GPR Z2 and GPR Z3 labeled zones had profile lengths of 50.0 m and 74.0 m, respectively. In all zones, the penetration depth was designated as 20.0 m.



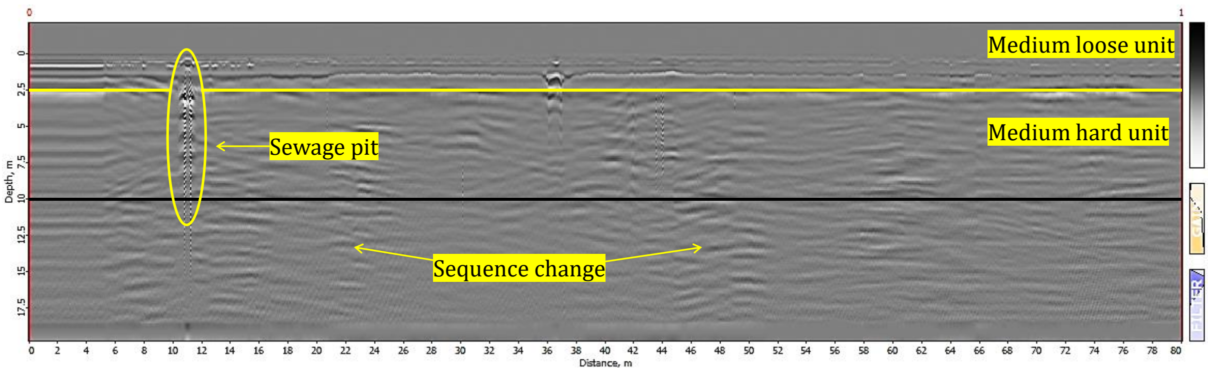
(a)



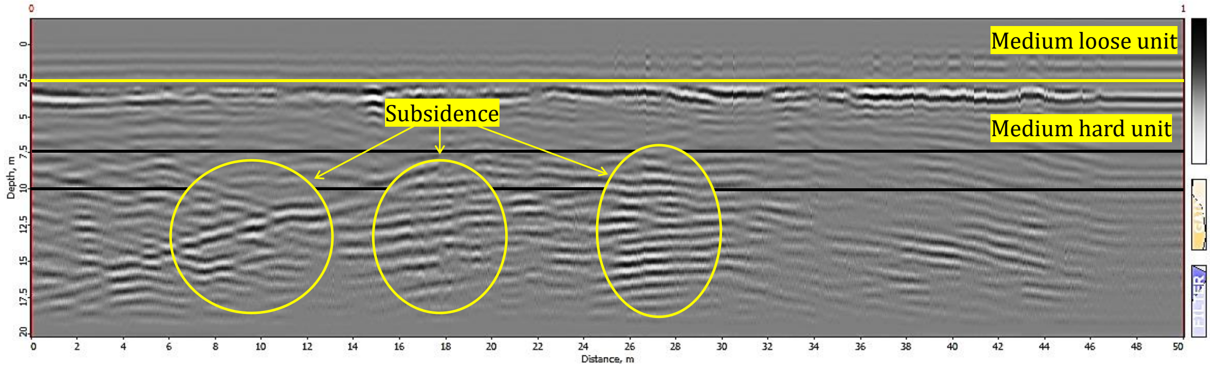
(c)

Figure 13. The locations and borders of the GPR scanning zones on the ground (each zone is shown by the box in red color)

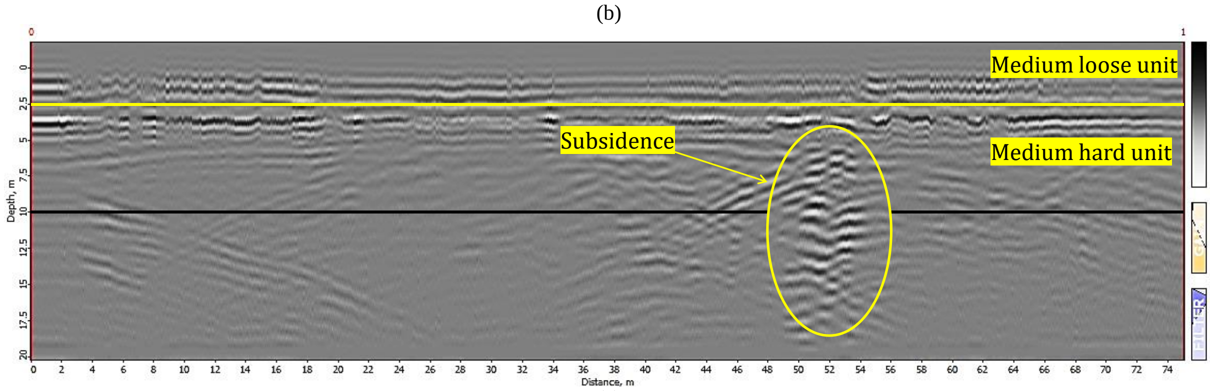
Figures 14a-c demonstrate the 2-dimensional GPR sections taken at zones 1, 2, and 3, respectively. As marked in these figures, 2 different levels were observed from the radargram section of each zone. It is considered to be a medium loose unit of about 2.50 m in the upper part, and a medium hard unit between 2.50 and 10.00 m. As indicated in Figure 14a, there is a sewer pit starting at a depth of 2.50 m and lasting about 10.00-12.00 m throughout the profiling of zone 1. Additionally, in this zone, there is no anomaly formation on the ground, except for the sequence changes. On the other hand, subsidence anomaly formations were identified in the profiling of zone 2. As can be seen in Figure 14b, the regions starting at a depth of 7.50 m lasting through 10.00 and 26.00 m took in water, thus collapsed. In the profiling of zone 3, only subsidence deformations caused by taking in water were detected, as pointed out in Figure 14c. These anomalies are starting at the depth of 5.00 m and lasting through the 50.00 and 52.00 m.



(a)



(b)

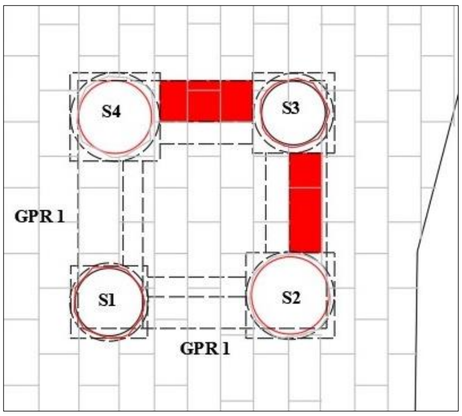


(c)

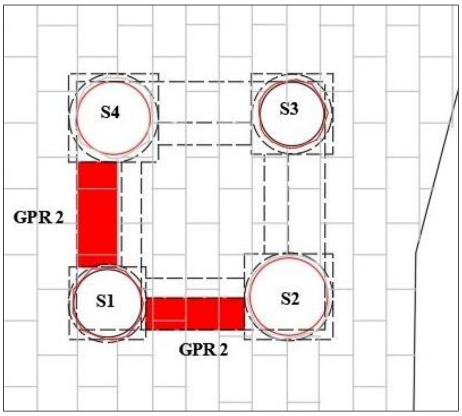
Figure 14. GPR sections: (a) taken at zone 1, (b) taken at zone 2, and (c) taken at zone 3

4.2.2. Lintel scanning

In addition to the GRP scannings on the ground, the lintels on the columns of the Four-Legged Minaret were also scanned by dividing the area into two regions named GPR 1 and GPR 2. Figure 15 indicates the border of each region in which the GPR scannings of lintels were carried out. In the scanning of the region named GPR 1, the profile length was designed as 10.0 m while in the GPR 2 labeled region, it was chosen as 15.0 m. In both regions, the 4.00-m penetration depth was designated. Region 1 involves the lintels on the S2-S3 columns and S3-S4 columns while region 2 includes the lintels on the S1-S2 columns and S1-S4 columns.



(a)



(b)

Figure 15. The indication of the GPR scanning regions on the lintels (each region is shown by the red color)

In regard to the radargram section obtained from region 1 (see Figure 16a), it can be stated that it has been observed that the cracks and fractures in the lintels are at a level that will affect the load-bearing system of the minarets. It is considered that cracks and fractures, the smallest 12.00 cm and the largest 20.00 cm, have been detected on the lintels in this area. On the other hand, broken V-type crack systems are at the maximum level in the lintels of region 2, as pointed out in Figure 16b. It is thought that the detected damages on the lintels may adversely influence the load-bearing system of the minaret.

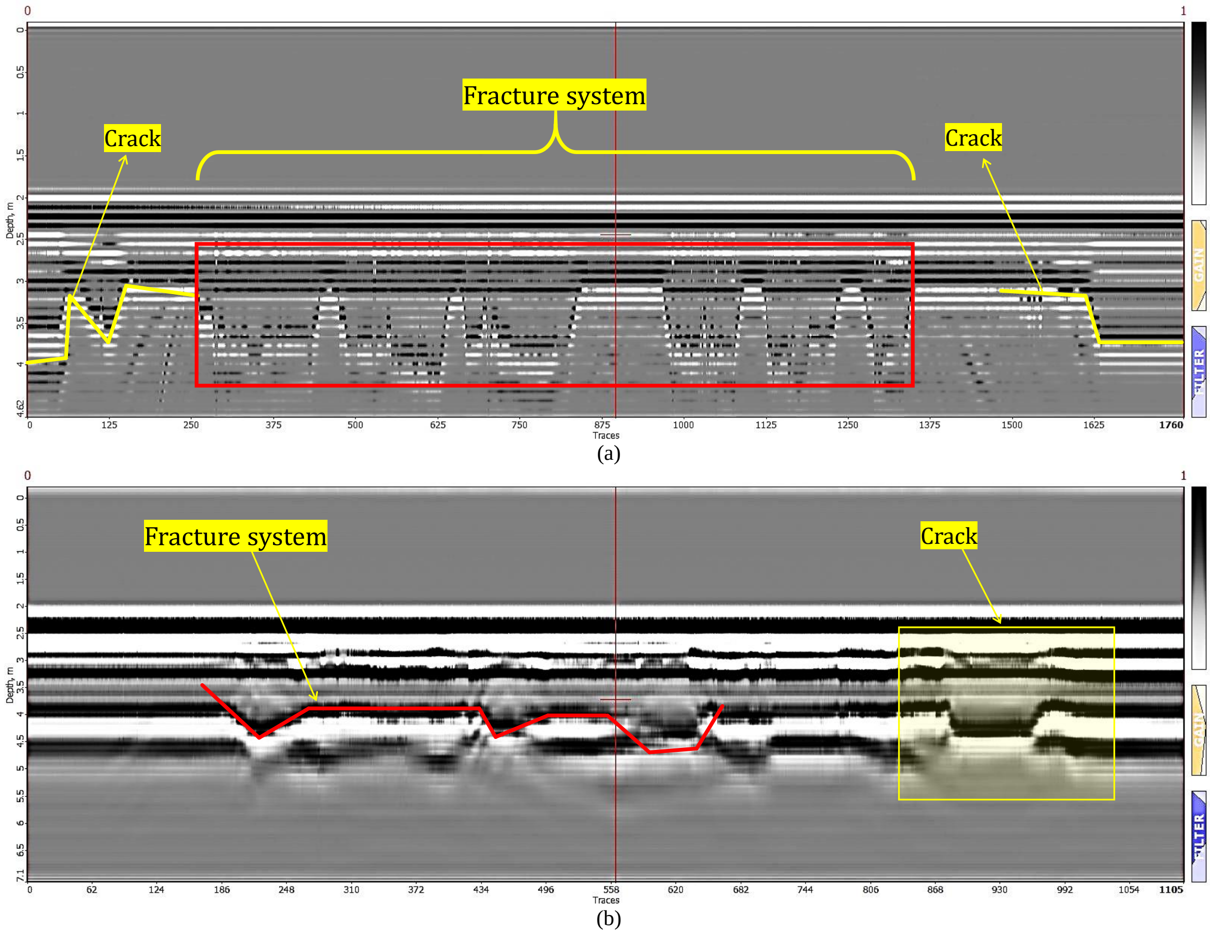
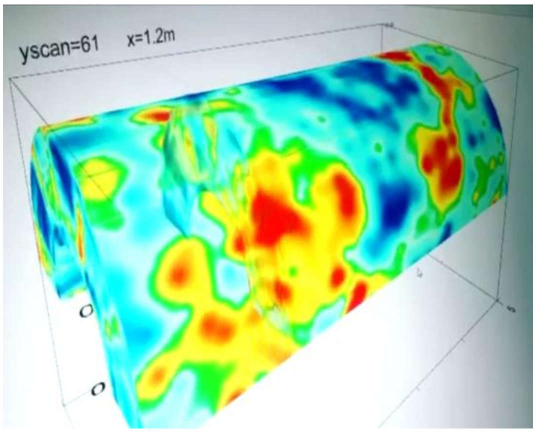


Figure 16. GPR sections: (a) taken at Region 1 and (b) taken at Region 2

4.2.3. Column scanning

Unlike the GPR scannings carried out on the ground and lintels of the Four-Legged Minaret, 3-dimensional GPR scanning was performed on the S2 named column. Crack-, fracture-, and corrosion-dependent deformations were detected in this scanning. In order to simulate the crack and fracture formations, spectral color was appointed in the radargram section of column 2, as shown in Figure 17. In the scanning, the areas and locations involving cracks and fractures are demonstrated by red color. In regard to the radargram sections, it can be stated that the cracks and fractures accumulated in the lower regions of the scanned column.



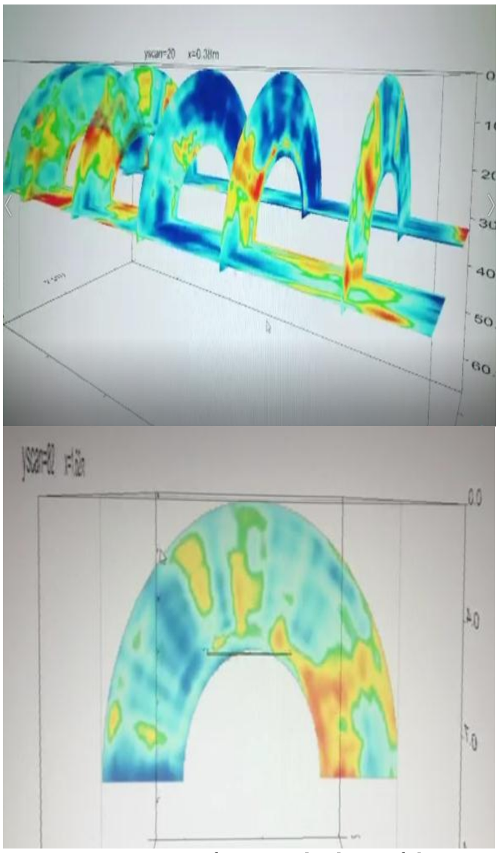


Figure 17. 3D GPR sections of S2 named column of the Four-Legged Minaret

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the findings presented above, the following conclusions and recommendations can be drawn:

GPR scans and studies were carried out for the existing damages under the ground and on the load-bearing members of the Four-Legged Minaret in the Suriçi region of Diyarbakır province. In the studies carried out, the current condition of the ground and possible damages and deformations in the load-bearing members were determined and revealed by the radargram sections obtained from the GPR scannings. In the scannings carried out on the Four-Legged Minaret, the conditions of the deformations, their variations, the properties of the surrounding rocks, and their classification according to their electromagnetic permeability were taken into account. As a result of the ground scanning, it was observed that the sequence changes were differentiated at 2 different levels. A medium loose unit was detected from the ground to a depth of 2.50 m, and a medium-hard unit formation was detected between 2.50-10.00 m. It was detected that there was a sewage pit in the scanning zone named GPR Z1 to the east of the minaret. On the south of the minaret, in the scanning zone named GPR Z2, deformations caused by water leakage and related collapse were detected after the levels of 7.50-10.00 m. In the ground scans of the zone called GPR Z3 to the north of the minaret, voids due to collapse were detected in the soil. Some cracks and fractures can be visually seen on lintels in the north and east directions of the Four-Legged Minaret. During the restoration works carried out in 2012 and 2017, the existing cracks were filled with injections. However, in the GPR scans, it was detected that the existing cracks and fractures continued into the inside of the lintels. On the other hand, fragment losses caused by vehicle hits during the periods when the street was open to vehicle traffic were detected on the columns by observational investigation. In addition, by the time, axis slippages have occurred due to the absence of any tension ring or any protective application between the top caps of the columns and the column bodies. The column diameters of the minaret are close to each other. There are fragmentations and abrasions caused by firearms in 2015 in the columns (S1 and S2) in the northwest and southwest directions of the minaret. In the S2 named column, 3D GPR scannings were made and material losses, corrosion, and cracks were detected, and besides, it was observed that they accumulated in the lower regions of the column.

To repair the existing damages on the Four-Legged Minaret, comprehensive survey and restoration projects should be prepared under the leadership of the relevant experts, and reinforcement applications should be carried out immediately. In addition to the determination of the damages on the minaret with non-destructive methods, observation pits should be opened in the regions determined by the experts and the physical condition of the ground should be determined. Soil improvements should be carried out around the building, and also columns and walls having axis slippages should be suspended, and reinforcement work should be conducted. In the past years, GPR scanning was not carried out during the restoration works carried out on the ground and load-bearing members of the Four-Legged Minaret. For this reason, it is very important because it is the first study to determine the problems in this cultural heritage using the GPR technique. In recent years, damage assessment studies using non-destructive methods employed for historical buildings continue increasingly. The GPR technique is an important non-destructive geophysical method used for historical buildings. For this reason, it is thought that this method, which will be used for historical buildings, will be an up-to-date guide for all historical buildings, specific to the Four-Legged Minaret.

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