



Investigation of structural problems on the ground and walls of Diyarbakir Historical Behram Pasha Mosque by the georadar (GPR) method

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ABSTRACT

Behram Pasha Mosque is one of the historical mosques, which is the work of Mimar Sinan [1], located in the southwest of Diyarbakir's Suriçi Region.

Georadar (GPR) method is one of the geophysical applications in which possible gaps, fractures, collapses, etc. damages are determined non-destructively on the walls and floors of historical buildings.

Therefore, in one of the historic mosques in Diyarbakir Behram Pasha Mosque, expert geophysical engineers carried out the GPR scanning of the grounds and walls without damaging the mosque's physical structure.

In GPR surveys, the depth of investigation (penetration) was chosen as 20 m on the ground and 4 m on the wall. It is aimed to show the anomaly structures in the study area and its immediate surroundings due to the determination of the underground void structures and the continuity of the surface fractures at the research depth.

In GPR studies, it has been determined that there are cracks and fractures on the walls of the mosque, of which the smallest was 12 cm and the largest was 40 cm, water leakage on the ground, deterioration due to corrosion, and partial collapses. The regions with the detected deformations are marked on the radar sections.

The study was completed with the thought that the determined structural problems will contribute to the restoration and strengthening works to be done in the future in the mosque as an up-to-date guide.

Introduction

Diyarbakir Suriçi Region is a settlement center bearing the traces of culture and civilization where are historical mosques, churches, bazaars, inns, Turkish baths, and traditional houses. Except for the Ulu Mosque, which was built in the 7th century in the Suriçi Region, most of the other mosques were built in the 15th-16th centuries and later [2].

Behram Pasha Mosque, located in the southwestern part of the Suriçi Region, is the only mosque that has a two-row portico courtyard. According to its inscription, Behram Pasha, who is one of the governors of Diyarbakir, between 1564-1572, built Behram Pasha Mosque. In "Tuhfetul Mi'marin", which describes Mimar Sinan's works, it is reported that the mosque is the work of Mimar Sinan [3].

The existing problems in the mosques that have survived in the Suriçi Region were corrected by carrying out restoration and strengthening works in due course. The

determination of general problems, especially structural problems in mosques, is done in two ways, instrumentally and observationally. In addition to evaluating the damage level by making observational determinations, it is very important for the restoration and strengthening of the structures to support the damage levels and the region by supporting them with instrumental determinations.

In recent years, non-destructive testing methods that do not damage the historic structure have been widely employed. Georadar (GPR) method is one of the measurement techniques made by sending electromagnetic waves to the damaged areas of the building or to the whole building scale. Georadar (GPR) is one of the high-frequency electromagnetic geophysics methods used to investigate damages on floors and walls. The ease of use of this method, its fast data collection feature, and the fact that it does not damage the structure while applying the method are among the main advantages of this method. In addition, precise detection of damage with high-resolution 2D and 3D imaging possibilities has been one of the features that

made this method widespread [4-7], as its working principle is shown in Figure 1.

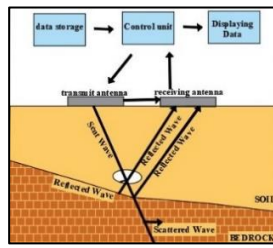


Figure 1. Working principle of the GPR device [7]

In this study, measurements in Behram Pasha Mosque were made with a Zond Python 3 GPR device having 250/100/50 /38 /25 MHz central antenna with 1.6 GHz and other outdoor antennas, as indicated in Figure 2.



Figure 2. Georadar scans with Zond Python 3 GPR device in Behram Pasha Mosque

The current locations and levels of damage were determined by GPR scans made on the floors and walls. In the surveys made by expert geophysicists, 20 m on the ground and 4 m on the walls were designated as the research depth. Because of the scans made inside the mosque and in the courtyard, it was determined that there were cracks and fractures on the walls of the mosque and corrosion and discharges due to water leakage on the floor. It has been observed that there are cracks and fractures especially on the ground of the mosque minbar and its surroundings after approximately 2.50 m and it is concentrated in these areas. Cracks and deformations, of which the smallest is 12 cm and the largest is 40 cm, were detected in the scans carried out on the walls. The radargrams achieved as a result of the scans were filtered and the areas involving structural problems were marked.

Location and architectural features of Behram Pasha Mosque in the Suriçi Region

Behram Pasha Mosque is located in the southwestern part of the Suriçi Region, on Bayram Pasha Street in the Süleyman Nazif District, as shown in Figure 3 a, b. It was built between 1564-1572 [3, 9] using the traditional masonry construction technique.

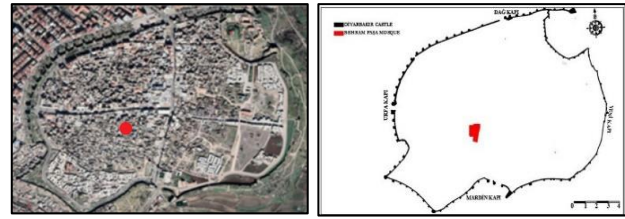


Figure 3. Location of Behram Pasha Mosque in the Suriçi Region

There are two entrances in the Behram Pasha Mosque. The entrance from Bayram Pasha Street is closed and the entrance to the mosque is provided from the southeast direction. There is a five-domed portico in the north of the square-planned harim and a second portico with a wooden ceiling in front of it. Braided columns made of limestone and basalt stone, as can be seen in Figure 4 carry the portico.



Figure 4. Behram Pasha Mosque (2021)

The structure with its alternating (two-colored) masonry and stalactite stone decorations collectively resembles İstanbul mosque architecture in plan layout [10]. It is entered to the harim of the mosque through a stalactite crown door with stone ornaments. There are two windows on the east and west sides of the crown door and a mihrabiye between the windows. The floor and dome of the entrance door are decorated with ornaments, as shown in Figure 5.



Figure 5. Detail of the muqarnas on the crown gate of Behram Pasha Mosque

There are two rows of the portico in the mosque, one with a wooden ceiling and the other with five domes, as demonstrated in Figure 6 a, b.

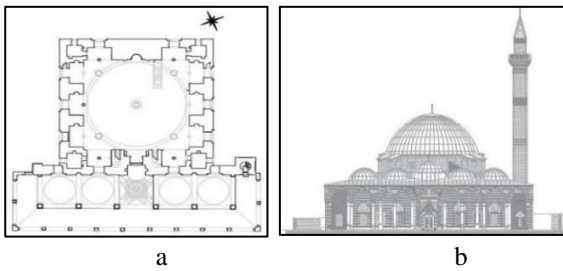


Figure 6. The plan layout and northern façade of Diyarbakır Behram Pasha Mosque [11]

It is stated in the sources¹ that the portico with wooden ceiling was built after the other one. The portico place in the first row consists of six white stone columns while the portico in the second row consists of eight columns, two of which are alternately braided, and two pillars. The height of the portico with a flat ceiling made of wood is at a lower level than the first constructed, domed one. The domed portico, first constructed, and the east and west parts of the crown door are approximately 40 cm above the floor, and the wooden ceiling portico is approximately 20 cm above the ground. There are tension rods between the arches in the portico. The photographic view of the porticos is presented in Figure 7 a and b.

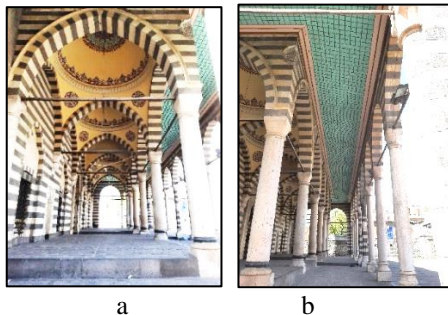


Figure 7. The photographic view of portico of Behram Pasha Mosque (2021)

The minaret in the northwest of the mosque has a cylindrical form. The honor section is decorated with stone and its cone is lead-coated. In the courtyard of the mosque, there is an octagonal fountain with a pointed cone roof and woven columns, as demonstrated in Figure 8.



Figure 8. Photographic view of minaret and fountain of Behram Pasha Mosque (2021)

The entrance to the square planned harim is through a crown door with a stalactite. On the right and left of the entrance of the harim, there are stairs with stone steps leading to the mahfil. The entrance to the qibla and rooms (cells) in the direction of the north is provided by niches. The square-planned harim was transformed into an octagonal form with the help of squinches. The dome made of limestone is seated on an octagonal drum at the top. The main dome and the domes of the portico are lead-coated, as shown in Figure 9.



Figure 9. The lead-coated domes of Behram Pasha Mosque (2021)

Besides, the photographic view of the eastern and southern interior walls of the harim section of Behram Pasha Mosque is presented in Figure 10 a and b.



Figure 10. The eastern and southern interior walls of the harim section of Behram Pasha Mosque (2021)

There are three iwan-shaped niches on the east and west sides of the harim. The vaulted iwans are arranged as two for each direction due to the crown door and the mihrab in the entrance region. The bottom of the mahfil region on the north wall is a flat slab paved with interlocking stones. In the original form of this floor, no binding material was used. However, in the restorations made over time, the spaces between the stones were partially filled with mortar, as can be seen in Figure 11.

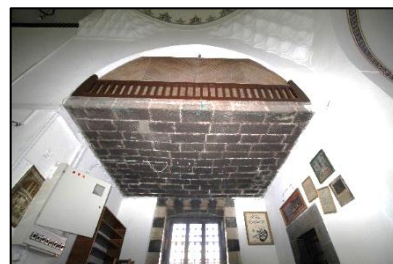


Figure 11. Flat floor made with interlocking stones under the mahfil (2021)

¹ Tuncer, O. C. (1996) "Diyarbakır camileri " Diyarbakır Büyükşehir Belediyesi yayımları. Diyarbakır.

Approximately 1 m of the bottom part of the walls of harim are covered with encaustic tiles. The mihrab is covered with colored stone material. There is a small mihrab on the upper part of the east and west walls of harim. There are mihrabiyes on the east and west sides of the crown gate in the portico of the mosque, as indicated in Figure 12 a, b and c.

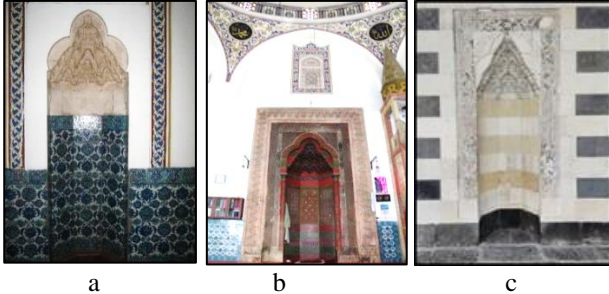


Figure 12. Encaustic tile decoration in the harim and the mihrabiye in the mihrab and portico (2021)

Structural problems detected in Behram Pasha Mosque

Behram Pasha Mosque occupies an important place in Diyarbakır thanks to its plan layout, construction technique, and original stonework and decorations. The mosque has undergone many repairs in the past. However, no extensive restoration has been carried out in the mosque recently. For this reason, some structural problems have occurred in the building over time. An observational field study was conducted to determine the existing structural problems in the mosque. During the fieldwork, partial cracks were detected on the northern façade of the mosque and the lintels of the minaret entrance door and window on the southern façade, as shown in Figure 13 a, b, c. Vertical cracks and partial level irregularities in the mosque cause to think possible settlements due to the ground.

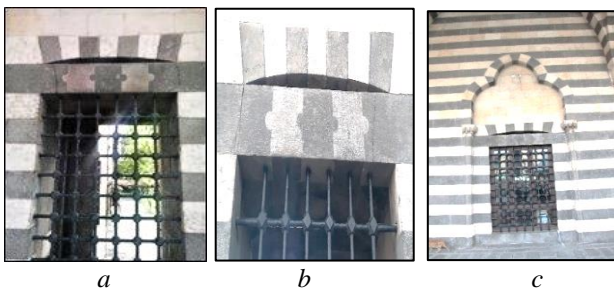


Figure 13. Cracks in the lintels of the Behram Pasha Mosque (2021)

In the harim, partial material losses occurred on the windowsills and outer surfaces of the niches defined as the iwan. There are also mortar losses on the southern and western façades of the mosque. There is a loss of material in the lower and upper column headings of the portico. Due to the absence of tension rings on the columns, partial slidings occurred between the column base and the sub-headings. Temporary solutions were made by filling the

column parts with mortar, as can be seen in Figure 14 a, b and c.

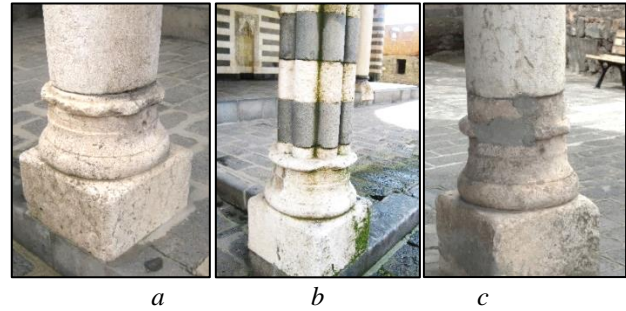


Figure 14. Material loss in columns and partial axle slip damage (2021)

Mortar losses and contaminations have occurred on the façade due to external conditions. Especially, on the southern and western façades that were exposed to the sun, discharges depending on mortar losses and separations on the wall have occurred. There are darkening and partial stone deterioration and moss on the façade surfaces where pollution is intense, as demonstrated in Figure 15.

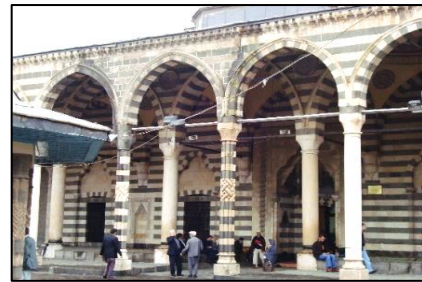


Figure 15. Weathering damages and contamination on façades (2021)

Some of the lead plates in the domes have been corroded over time due to the effects of external conditions, and openings have occurred between some of the lead plates, as can be seen in Figure 16. There are mortar losses between the stones on the flying buttresses made of limestone in the dome. In addition, there are material losses and deterioration due to pollution in the balcony section of the minaret, as shown in Figure 16 a and b.



Figure 16. Openings between lead plates and segregation damages in buttresses (2021)

Instrumental measurements made by GPR method in Behram Pasha Mosque

GPR method is the comparison of the changes in the signals that were produced by electromagnetic waves, generally manufactured by antennas, with the original signals during their underground travel and return [12]. GPR signals determine their velocities according to the physical and chemical conditions of the environment. After the signals reach the desired point, it starts to collect data. By knowing the time the signals reach and the speed of the measuring medium, the investigation depth can be determined precisely. The travel time of GPR signals is measured in nanoseconds. The antennas of the measuring device are fixed or displaced in the range of 2-20 cm [13].

Instrumental surveys were carried out with the GPR method in order to determine the causes of the structural problems detected in the Behram Paşa Mosque, located in the southwest of Diyarbakır Suriçi Region. In the scans made on the floor and walls of the mosque, the investigation depth was chosen as 20.00 m for the ground and 4.00 m for the walls. Possible deformations were investigated by scanning with Zone Python 3 device having high-resolution antennas. During this study, observational geological and instrumental geophysical studies were carried out to examine the source(s) of underground space/voids, the deformations in the ground/wall and the dimensions of sub-floor surface fractures, geometric behavior patterns and soil/wall stratigraphic changes.

After the investigation of the geological features of Behram Pasha Mosque and its surroundings, scanning was started. The geology of the study area is Miocene and consists of continental clastics belonging to this age. In the geological and geotechnical studies carried out in the study area and its immediate surroundings, lithological ordering from the ground to the underground; the vegetable soil unit continues as a clayey unit, clayey sandy unit, and clayey silty sand unit. Although the stacking changes in the ground differ locally, in general, the order has not changed [14].

This study was carried out to determine the causes of the structural problems in the Behram Pasha Mosque. The current situation of the structural problems on the floors and walls has been intended to determine instrumentally. Non-destructive methods can be used to detect structural problems in historical buildings without damaging the building and the GPR method is one of the non-destructive methods. For this reason, the structural problems in the mosque, the causes of damage were investigated by scanning the floors and walls.

GPR scanning locations and evaluations on the ground of Behram Paşa Mosque

In GPR scanings, a surveying depth of 20.00 m was chosen for the ground. The anomalies and deformations detected according to the data obtained because of the scans made on the ground are shown in the radargram sections². Ground scans were carried out in the harim, portico, and courtyard, as can be seen in Figure 17 a and b.

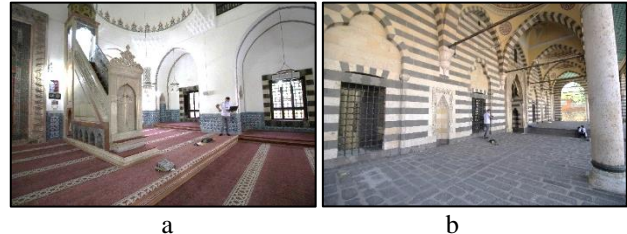


Figure 17. Photographic view of ground scans of Behram Pasha Mosque; harim and portico (2020)

The locations of the GPR scanning are marked on the plan layout of the mosque that presented in Figure 18.

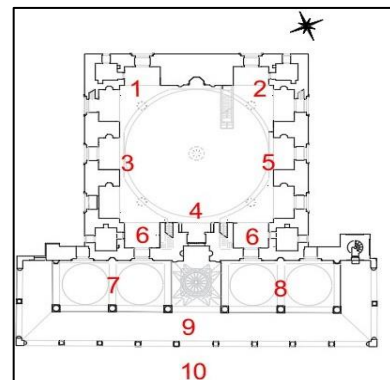


Figure 18. Locations of GPR scans on the ground of Behram Pasha Mosque

Behram Pasha Mosque GPR scans of grounds

Scanning at the ground of location 1

70 m profile length and 20 m depth of research were selected in the ground survey carried out in the southeast part of Behram Pasha Mosque, GPR 1 (1). According to the obtained radargram sections, two different levels of the medium, one is loose unit lying from the ground to 2.5 m depth and the other one is hard unit starting from 2.5 m and ending at the 10.00 m depth, were detected in the scanned area. No deformation was detected in this section (Figure 19).

² Radargram: Radar tracks at all measurement points along a profile are 2D radar cross-sections whose horizontal axis (x-direction) is the distance from the profile starting point (profile length), vertical axis is nanosecond

(ns) recording time (round-trip) when they are aligned with their positions on the profile [5,15].

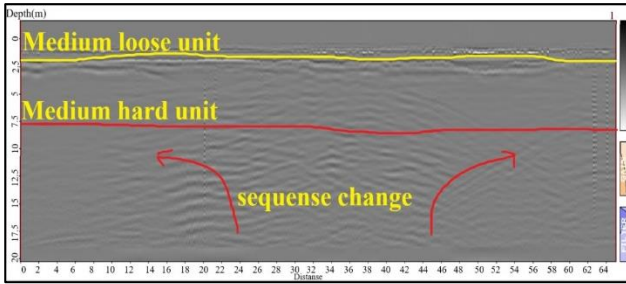


Figure 19. Radargram section of the ground of location 1

Scanning at the ground of location 2

A profile length of 30 m and a surveying depth of 20 m was designated at the southwest of the mosque, location number 2. According to the obtained radargram sections, two different levels of the medium, one is loose unit lying from the ground to 2.5 m depth and the other one is hard unit starting from 2.5 m and ending at the 10.00 m depth, were detected in the scanned area. In this region, subsidence deformations between 2.5 m and 6.00 m were detected. It was determined that there are stack changes between 6.00 m and 9.00 m (Figure 20).

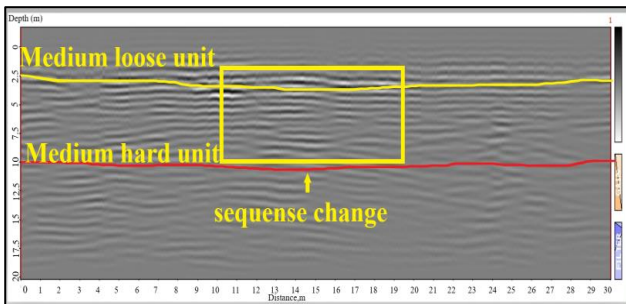


Figure 20. Radargram section of the ground of location 2

Scanning at the ground of location 3

In the harim of the mosque, namely location number 3, no deformation was detected except for the changes in the stack (Figure 21).

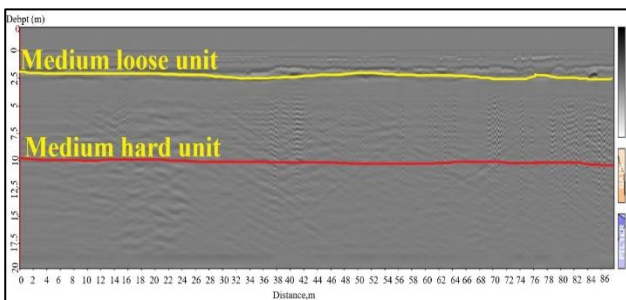


Figure 21. Radargram section of the ground of location 3

Scanning at the ground of location 4

In the scans made in the direction of the entrance door of the harim and mihrab, in other words at location number 4, two collapsed deformations were observed. It was

determined that the first collapse is between 1.00 m and 4.00 m, and the second collapse is between 1.00 m and 6.00 m (Figure 22).

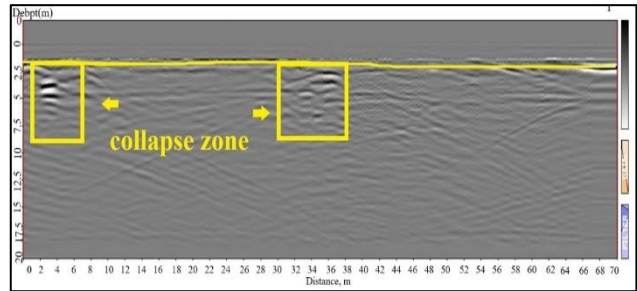


Figure 22. Radargram section of the ground of location 4

Scanning at the ground of location 5

According to the obtained radargram sections, two different levels of the medium, medium-loose unit between 0 and 2.5 m depth and medium-hard unit between 2.5 m and 10.00 m depth, were detected in the scanned area. In this part of the mosque, no deformation was observed except for the changes in the stack (Figure 23).

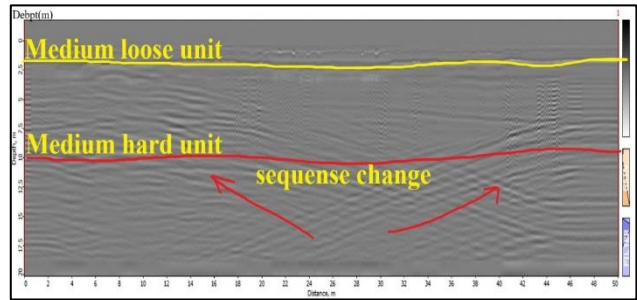


Figure 23. Radargram section of the ground of location 5

Scanning at the ground of location 6

In the scans made under the mahfil on the northern façade of the mosque’s harim, a medium-loose unit up to 2.50 m and a medium-hard unit between 2.50-10.00 m were identified.

According to the radargram sections and velocity analyzes obtained, it was determined that there was a dense water structure after 12.50 m. Partial collapse deformations are thought to occur in areas where water is concentrated (Figure 24).

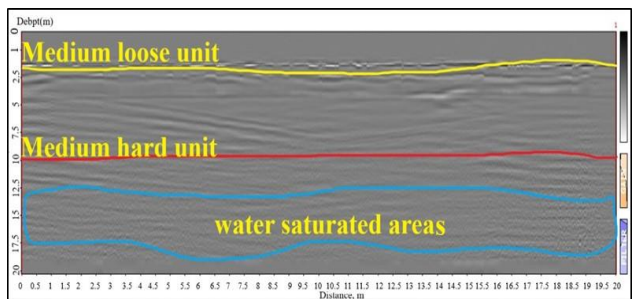


Figure 24. Radargram section of the ground of location 6

Scanning at the ground of location 7

In the GPR surveys made in the northeast direction of the first portico, it was determined that the ground was medium-loose unit up to 2.5 m and medium-hard unit differentiation between 2.50 m and 10.00 m. Intense water-saturated areas were detected in the 1.00-5.00 m range of the scanned area. There are partial collapses in these areas (Figure 25).

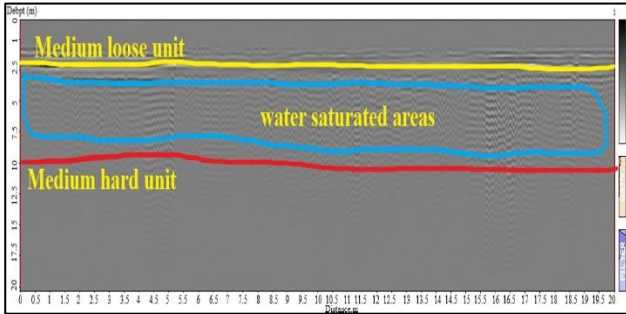


Figure 25. Radargram section of the ground of location 7

Scanning at the ground of location 8

In the scans made in the northwest of the first portico of the mosque, it was observed that there is a medium-loose unit up to 2.5 m and a medium-hard unit in the range of 2.50-10.00 m. In this part of the portico, it has been determined by radargram sections that there is no deformation except for the stack changes (Figure 26).

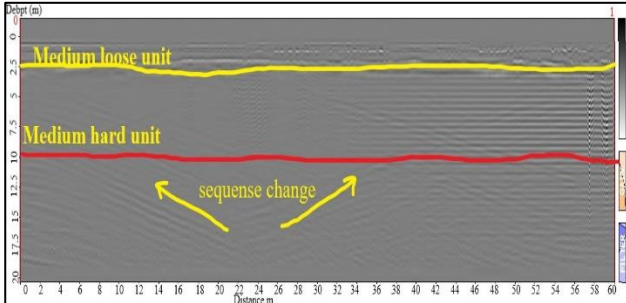


Figure 26. Radargram section of the ground of location 8

Scanning at the ground of location 9

GPR scans made in the second portico of the mosque revealed a gap of 2 m in diameter at a depth of 1 m between the depth of 1 m and 8.00-10.00 m (Figure 27).

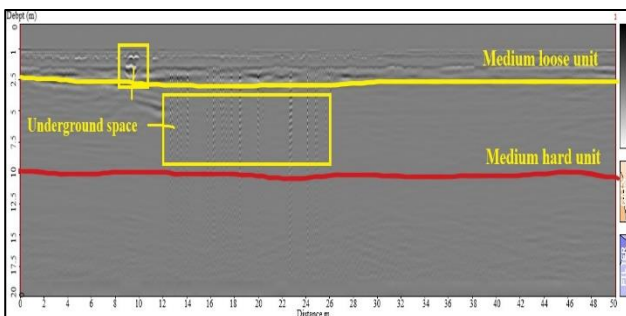


Figure 27. Radargram section of the ground of location 9

Scanning at the ground of location 9

GPR scans made in the second portico of the mosque revealed a gap of 2 m in diameter at a depth of 1 m between the depth of 1 m and 8.00-10.00 m (Figure 27).

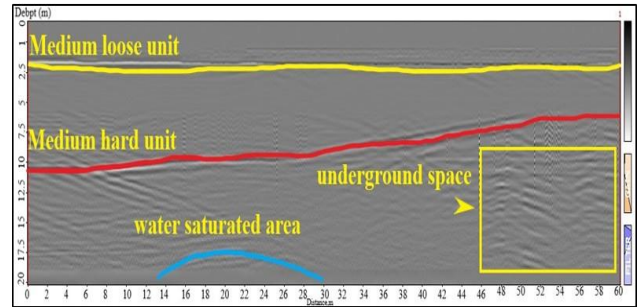


Figure 27. Radargram section of the ground of location 9

Scanning at the ground of location 10

In the georadar scans made in the courtyard of the Behram Pasha Mosque, a 90-m profile length and a research depth of 20.00 m were selected. It has been determined that there are a medium-loose unit up to 2.50 m, a medium-hard unit between 2.50-11.00 m, and three different levels where firmness increases. It has been determined in the radargram sections that there are two void structures and flooded areas on the courtyard floor after 18.00 m. It is thought that the parts that receive water originate from the fountain in the courtyard (Figure 28).

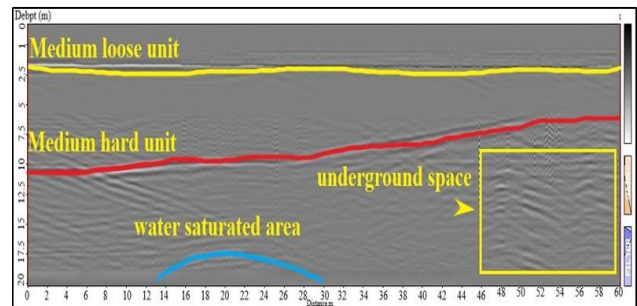


Figure 28. Radargram section of the ground of location 10

Behram Pasha Mosque GPR scans of walls

In the Behram Paşa Mosque, GPRscans were made on the walls in the harim (Figure 29 a and b). In the scans made on the walls, the profile dimensions were taken as variable and the depth of the survey was chosen as 4.00 m. In some of the walls in the harim region, gap deformations due to cracks and fractures were detected.

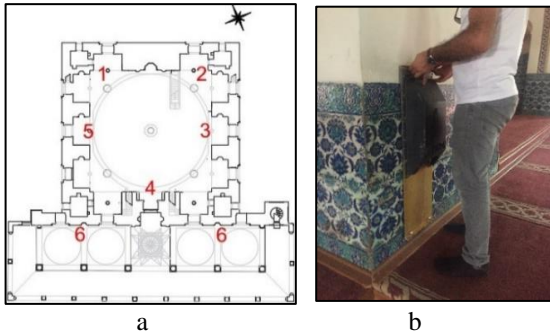


Figure 29. Locations and applications of GPR scans done on the mosque walls

Scanning at the wall of location 1

In the radargram sections obtained as a result of the scans made on the southeast walls of the harim and mihrab, no deformation was observed at the inner wall till a depth of 1.25 m. However, after a depth of 1.25 m, a corrosion structure caused by water leaks was determined (Figure 30).

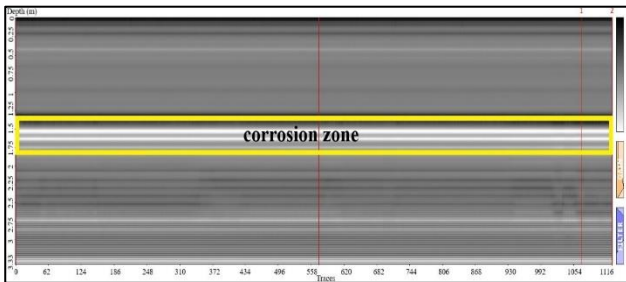


Figure 30. Radargram section of the wall of location 1

Scanning at the wall of location 2

According to the radargram sections obtained as a result of the scans made on the southwest wall of the harim, it was determined that there were deformations due to corrosion after 1.50 m from the inner wall to the outside (Figure 31).

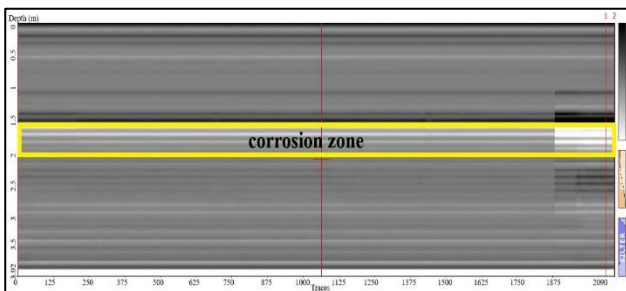


Figure 31. Radargram section of the wall of location 2

Scanning at the wall of location 3

In the radargram sections obtained after scanning on the wall in the northwest direction of the harim, it was determined that there were cracks and fracture deformations after 1.00 m of the wall. There are also cracks in the lintels on the outer parts of these walls (Figure 32).

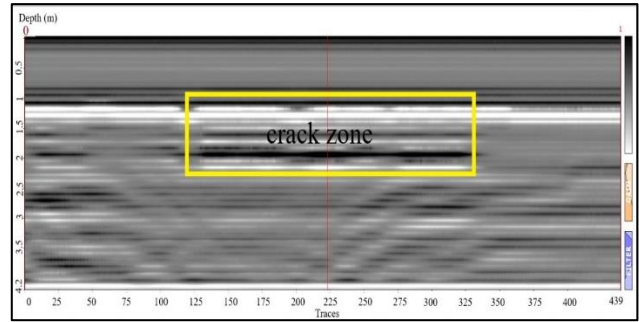


Figure 32. Radargram section of the wall of location 3

Scanning at the wall of location 4

Numerous cracks and fracture deformations were detected after 2.50 m in the radargram section obtained as a result of the scans made on the entrance door of the harim and the northeastern wall. It is thought that these deformations will increase the structural problems in the mosque over time (Figure 33).

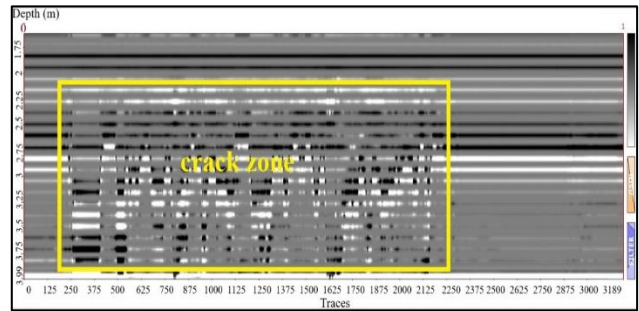


Figure 33. Radargram section of the wall of location 4

Scanning at the wall of location 5

It has been determined that there is 1 crack deformation at a depth of 2.00 m in the radargram sections obtained as a result of the scans made on the eastern wall of the harim (Figure 34).

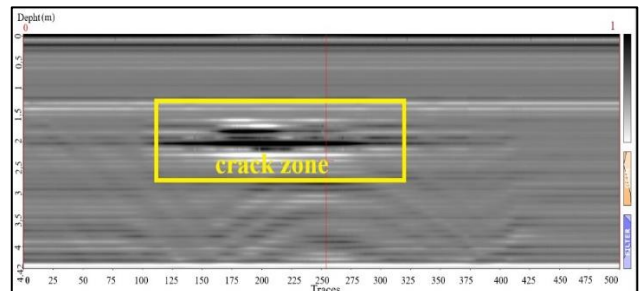


Figure 34. Radargram section of the wall of location 5

Scanning at the wall of location 6

GPR scans were made on the northern wall including the entrance to the harim. In the radargram sections, broken deformations were detected on the walls in both directions of the entrance door with a size of 7 cm at 2-m depth (Figure 35).

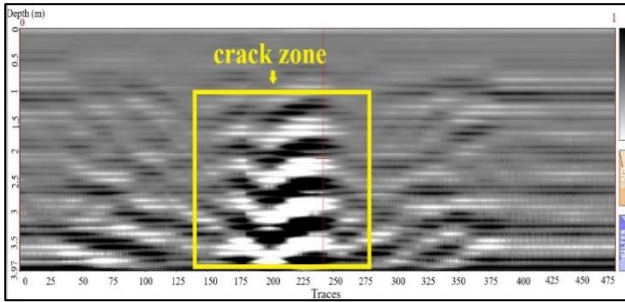


Figure 35. Radargram section of the wall of location 6

Conclusions and recommendations

Diyarbakır Behram Paşa Mosque is one of the historical mosques in the Suriçi Region, which has an important place in terms of its original architecture and construction technique. Behram Pasha Mosque, which is different from the classical Diyarbakır mosques with its technique and style, is actively used today. Original stonework, two rows of the portico with domed and wooden ceilings, and alternating knitted columns and façades have an important place in our architectural heritage.

In order to determine the structural problems of Behram Pasha Mosque, observational determinations were made in the field study. GPR scans were made with the thought that the vertical cracks in the lintels may occur due to the ground, and it was determined that there were discharges on the ground where the crack damage was located. In the structural problems of the mosque, cracks, fractures, weathering, material loss damages due to natural conditions were examined and GPR scans in these areas were increased.

Although restoration work was carried out in the mosque in the past, the GPR method was not used on the floors and walls in the previous studies. For this reason, it is the first time, this type of study was applied to this mosque. In this study, after the observational determination of the structural problems of the mosque, the GPR method was used to determine the damage levels of the existing problems on the ground and load-bearing walls. Scans that do not harm the structure were made with the GPR method. The deformations detected in the radargram sections obtained after the scans were marked, and the status and levels of the structural problems in the mosque were determined.

According to the results obtained from the scans;

- It has been determined that there are generally two different soil groups in the ground: medium-loose units up to 2.50 m and medium-hard units between 2.50-10.00 m. In the surveys made in the courtyard, the floor group was divided into three groups.
- During the scans made in the harim, deformations in the form of collapse and stack changes were detected on the floor between the entrance and the mihrab.

- It was detected that there are areas with water leakage in the northern façade of the harim and the northeastern part of the portico.
- In the scans made on the ground of the region, which is the second portico, it was observed that there were partial discharges and collapses.
- It was shown in GPR sections that there are areas exposed to water on the ground of the courtyard and its environment (the grounds at locations 6 and 7)
- It is thought that the discharges and collapses on the ground are responsible for the formation of structural problems in the mosque.
- It was determined that the smallest of the fractures at the walls was 12 cm and the largest was 40 cm.
- Corroded structure areas have been detected in the areas with water leaks on the walls. It was observed that there was contamination on the façade walls of the mosque, material loss in the columns, and partial axis shifts.

It was recommended in Behram Pasha Mosque, which is among the important mosques of the city:

- The preparation of comprehensive survey and restoration projects in their current form will facilitate the restoration works in the mosque.
- In light of the findings and data obtained from the ground surveys, examination pits should be opened in several places in the mosque and the physical condition of the ground should be determined. The physical determination of the deformations detected in the ground by GPR scans by opening the research pits will contribute to the improvement and strengthening applications.
- Reinforcement projects should be prepared in areas where are collapse deformations on the ground and appropriate solutions should be produced.
- The mosque should be restored and the damaged materials should be completed in accordance with the original to eliminate the deformations detected on the mosque walls and the existing damages on the façade.
- Mosque domes should be replaced with new ones due to corrosion of the existing tension rods in order to prevent the opening of the arches.

As a result of this study, structural problems were observed in the Behram Paşa Mosque and the study was enriched with GPR scans, which is one of the non-destructive methods [16] [17]. With the thought that the study will be a viable current example for all historical buildings in the city, the surveys and determinations were carried out sensitively and the study was completed.

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