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Research using GPR into the cause of cracks and depressions in the floor of the gallery of Hagia Sophia Museum

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HIGHLIGHTS

- Hagia Sophia is a important historical buildings in Istanbul.
- The main dome of Hagia Sophia collapsed several times.
- Mimar Sinan made the main reinforcement in the 16th century.
- Currently the presence of deformations is on the floor of the gallery.
- Hagia Sophia Museum was scanned with ground penetrating radar.

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ABSTRACT

Hagia Sophia Museum is one of Istanbul's most important historical structures. Considering its location in Istanbul and the use of the building through history, visible damage is noted in the structure. To determine whether this damage noted on the exterior of the building is present in the interior, the gallery of Hagia Sophia Museum was scanned with ground penetrating radar. The GPR scanning of the floor of the gallery revealed the presence of weak zones in the floor and varying scales of deformation within the structure. Detailed study of the vaults showed that the geometrical symmetry of the curve of the vault dome was disrupted. The results obtained in this study show that necessary precautions should be urgently completed to prevent damage to Hagia Sophia, especially when the earthquake expected near Istanbul is considered.

1. Introduction

Some "historical buildings" carrying past significance are currently assessed as a part of universal cultural heritage and preserved. To ensure these structures are preserved for future generations, the marks of natural (e.g., earthquakes, floods, storms, etc.) and manmade (e.g., war, fire, etc.) events occurring since their building should be removed by appropriate restoration. For appropriate restoration work, it is necessary to know all the characteristics of the structure and changes that have occurred over time. In the planning stage before restoration work, non-destructive testing methods can be used to identify problems within walls and floor without causing any physical damage to the building.

Among the most important monuments of global architectural history currently standing, Hagia Sophia has an important place in the world of art due to its architecture, magnificence, grandeur and functionality (Fig. 1a). Hagia Sophia was the largest church in the Eastern Roman Empire built in Istanbul and was constructed three times at the same location [5,6]. This magnificent structure was first built in 360 CE and was called the Megale Ekklesia (Great Church), before becoming known as Hagia Sophia (Holy Wisdom) in the 5th century [5,6]. Hagia Sophia was the crown of the Eastern Roman Empire, the largest church in the capital acting as a cathedral [5,6,13].

One of the most important historical buildings in Istanbul, construction of the current Hagia Sophia building was completed in 537 CE [1]. After the conquest of Istanbul in 1453, it began use as a mosque with the main dome collapsing several times before retaining walls and buttresses were constructed by Mimar Sinan (Sinan the Architect). The majority of collapses of the dome were linked to earthquakes in the region [13]. In the 16th century retaining walls and buttresses were constructed outside the building for support by Mimar Sinan (Fig. 1b). Additionally Mimar Sinan

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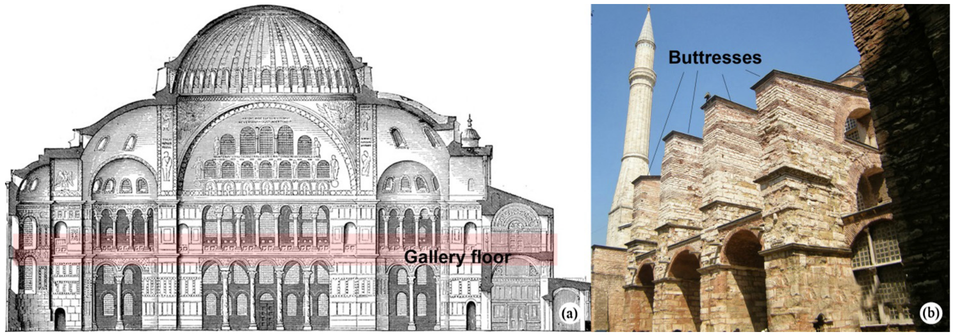

Fig. 1. Hagia Sophia. (a) Section view of Hagia Sophia (b) Buttresses of Mimar Sinan.

Fig. 2. A sample settled area and the cracks a on the Gallery Floor.

Fig. 4. 1 GHz GPR system with Pro-Ex control Unit and shielded 1 GHz antenna.

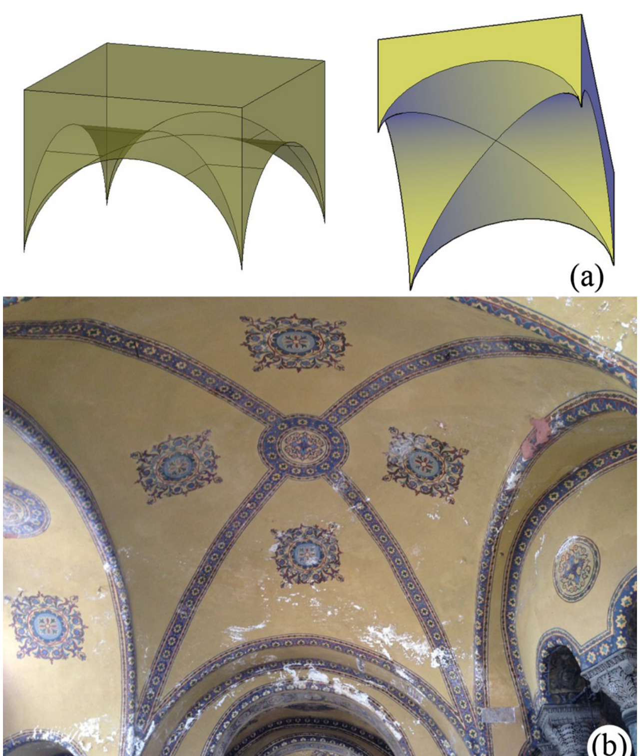

Fig. 3. Basic model of Hagia Sofhia vaults. (a) 3D model of original vaults. (b) Disturbed current vaults.

Table 1
Acquisition parameters of the GPR survey.

Antenna Frequency	1 GHz (1000 MHz)
Trace interval	0.02 m
Samples	480
Sampling frequency	7174.6
Time window	46.34
Profile interval	0.2 m

supported the load-bearing elements of the gallery floor with metal and wooden beams, especially, to prevent structural deformation within the building [13]. In the 1930s the Fossatti brothers, completed restoration and strengthening work on the main dome especially. After reinforcement by Mimar Sinan there is no evidence of any destruction of Hagia Sophia though there are many earthquakes recorded in historical records of the region. Currently the presence of deformation in the intensely-visited structure, especially the floor of the gallery, is noted.

Continuing as a popular site today, to determine whether deformation observed on the floor of the gallery (Fig. 2) affected the internal sections of the structure and the cause of deformation, high frequency GPR measurements were completed as part of restoration work on Hagia Sophia. Additionally, the situation of the vault structures supporting the gallery floor (Fig. 3) and the layers forming the floor were researched.

2. GPR (ground penetrating radar) method

Shallow geophysical methods are used to determine buried structures. The high resolution and rapid applicability of ground

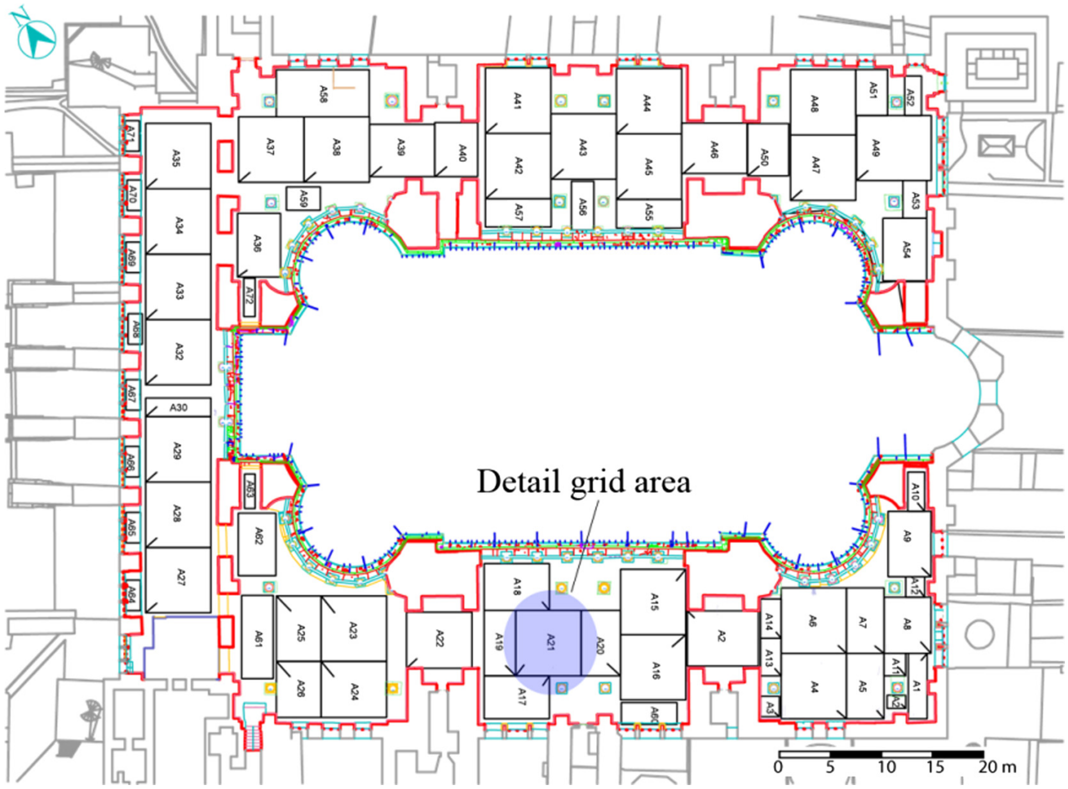

Fig. 5. Map of Hagia Sophia Gallery Floor with grid areas.

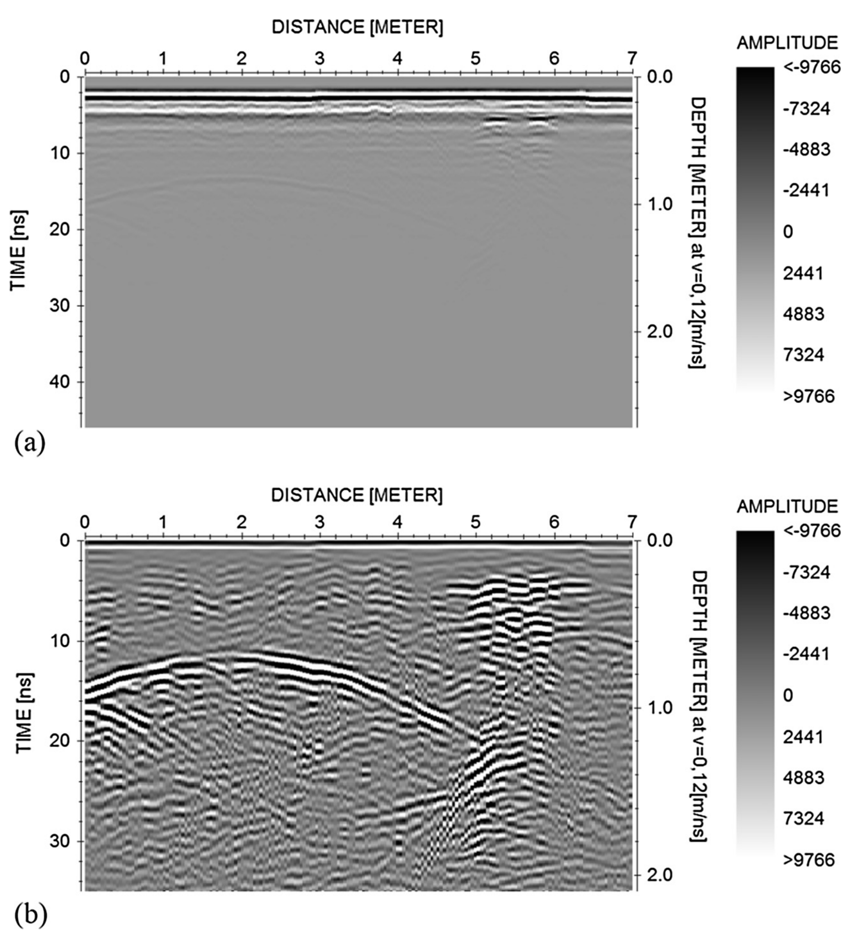

Fig. 6. Sample 1 GHz GPR Profile. (a) Raw data. (b) Processed data.

Table 2
Filter processing steps and parameters of the GPR survey.

Filter Name	Parameters
Time-zero correction	−1.9 ns
Subtract-mean (dewow)	1 ns
Band-pass filter	400/800/1200/1600 MHz
Energy decay	0.512
Subtracting average	31 trace/1 to 44.44 ns
Velocity analysis	0.12 m ns^{-1}
Diffraction stack migration	11 trace/0.12 m ns^{-1}/0 to 44.44 ns/ε_r = 8.7

penetrating radar (GPR) makes this method among the most effective used. Countless research into archeological and historical structures has been completed using GPR (e.g., graves, walls, roads, structural deterioration) [18,7,8,14,9,4,15,10,2,16,12,11,19,21]. With the GPR method it is possible to identify buried structures and/or deterioration that are not possible to discover using traditional research methods [3]. The GPR method investigates the time between the transmission and reception of high frequency radar signals (10 MHz-2.3 GHz) sent into the ground. Radar signals travel at

Fig. 7. 7 m × 7 m Detailed grid area (see Fig. 5 for location).

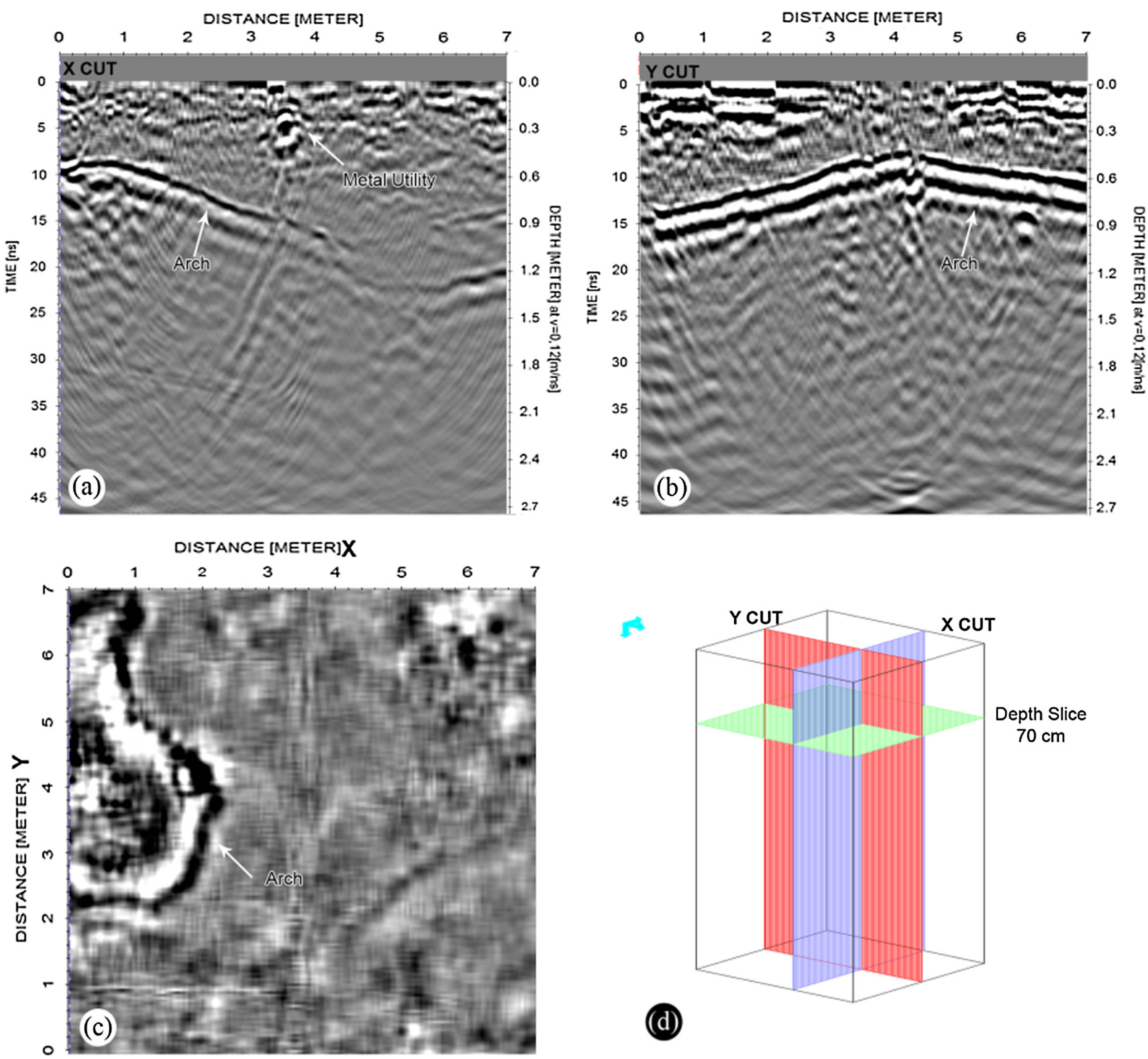

Fig. 8. The 3D results of detail grid area (a) X cut of the 3D cube (blue slices on (d)). (b) Y cut of the 3D cube (red slices on (d)). (c) Depth slice of the 3D cube (green slices on (d)). (d) Schematic view of 3D cube and slices. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

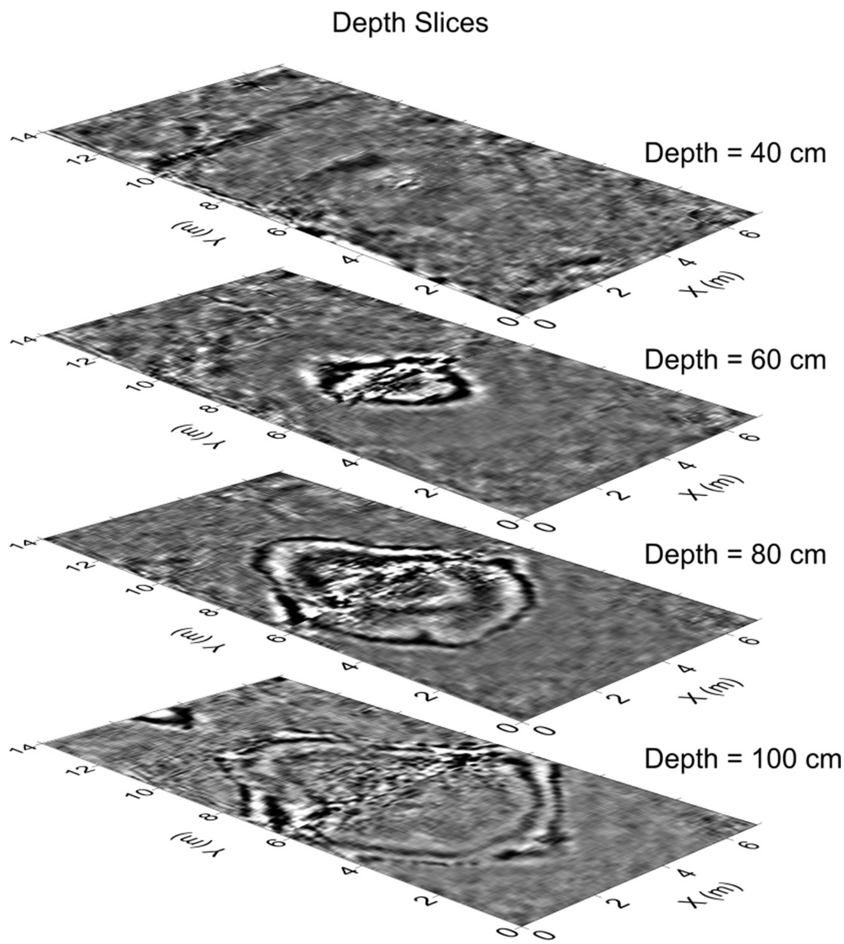

Fig. 9. Depth Slices of GPR results on a total vault (slices from 40, 60, 80 and 100 cm).

light speed (0.3 m/ns) in air but slow after entering the ground. Transitions into different materials and/or changes in reflection speed cause different reflection amplitudes observed in radar signals. The time for the GPR signal to leave the transmitter and be received by the receiver is related to the speed and may form depth axes. The system records all these waves (air wave, reflection wave and refraction wave) to obtain a trace. With hundreds or thousands of traces on a line, the GPR profile records at different trace intervals (1–50 cm) and as a result creates 2 dimensional profiles. By gridding the parallel 2 dimensional profiles, it is possible to obtain a 3 dimensional image best representing the underground features [3,21]).

3. GPR studies of the gallery in Hagia Sophia Museum

There are two main factors affecting ground penetrating radar (GPR) studies. One of these is completing measurements with the right choice of frequency and system, while the other is processing the data with aid of the correct program and parameters. By choosing the antenna and system configuration appropriate to the study topic and location, it is possible to collect data containing the targeted results, otherwise collecting unnecessary data leads to a loss of time and not reaching the results required. Another element is the importance of processing data which is very important in terms of making data collected in multi-disciplinary studies comprehensible.

3.1. Data collection

This study used a trade unit called the Mala RAMAC ProEx GPR and an antenna with central frequency of 1 GHz (Fig. 4). The

Fig. 10. Laser measurements from bottom of a vault.

antenna was placed in normal position on the ground and considering the resolution of the antenna and the structural elements being searched for, a 2 cm trace interval and 20 cm profile interval was chosen (Table 1). Images obtained with the most commonly used time interval for 3 dimensional radar studies used to produce maps and newly-developed 3 dimensional volume cubes have provided more understandable results in studies in different disciplines [20]. The study area covered the whole gallery comprising

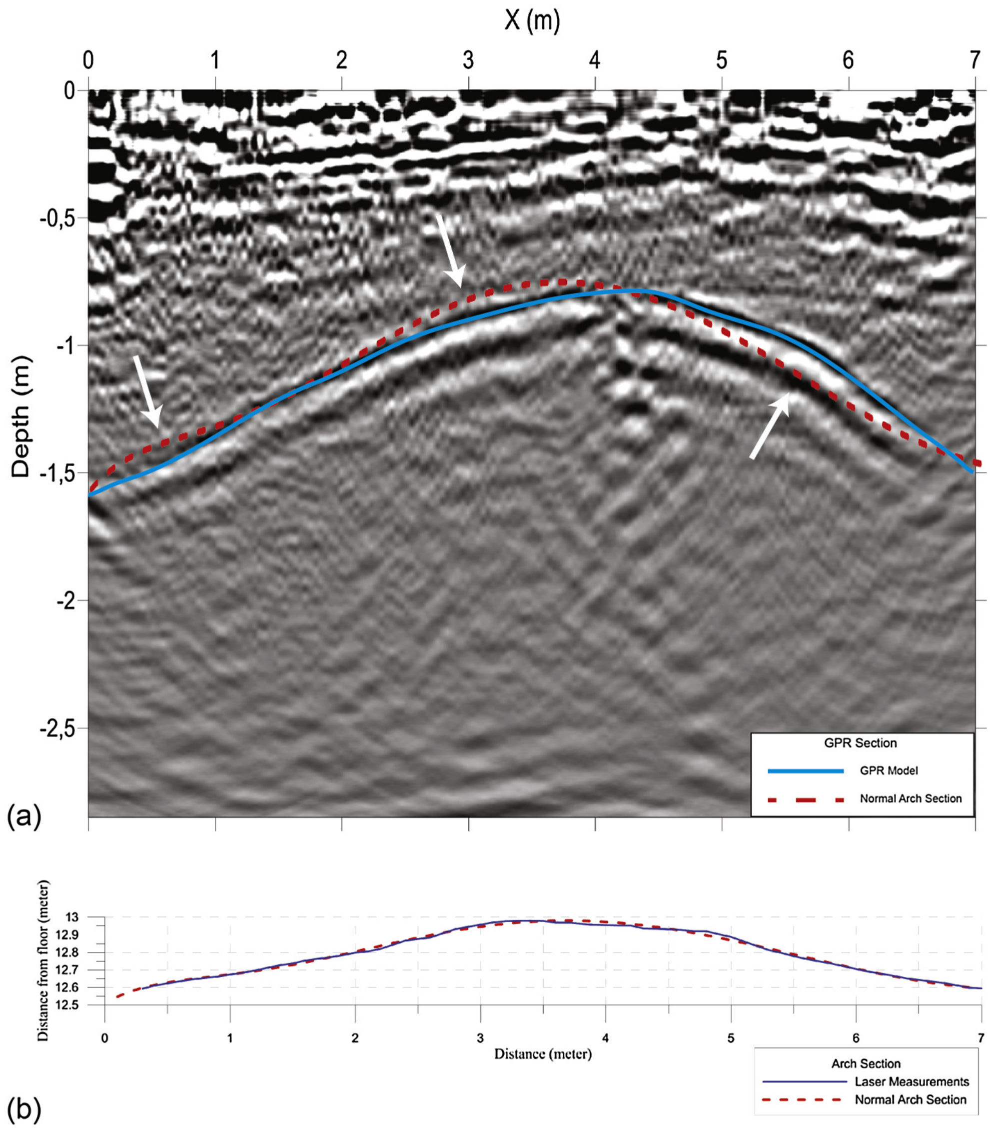

Fig. 11. Comparison of a normal vault section with GPR results and Laser measurement results (white arrows indicate disturbed areas).

an area of ~3200 m^2 (Fig. 5). Due to the high resolution of GPR data from the chosen antenna and measurement parameters, the whole area was divided into smaller areas with maximum area 7 m × 7 m and no gaps and measured appropriately for 3 dimensional data processing (Fig. 5). Details of measurement parameters are given in Table 1.

3.2. Data processing

To obtain better results in interpretation of the collected GPR data, the trade software Reflex W [17] was used (Fig. 6). The data processing stages of initial speed correction, eliminating DC effect, band pass filtering, energy delay filtering, mean value clean up and reflection stack migration were applied to each profile separately. The details of all filtering stages are given in Table 2.

3.3. Results

The GPR study of the floor of the gallery in Hagia Sophia was completed with a total of 52 different grid regions over an area of ~3200 m^2. The results obtained by the study, shown in Fig. 7, are given in detail for the grid region A21 and general conclusions

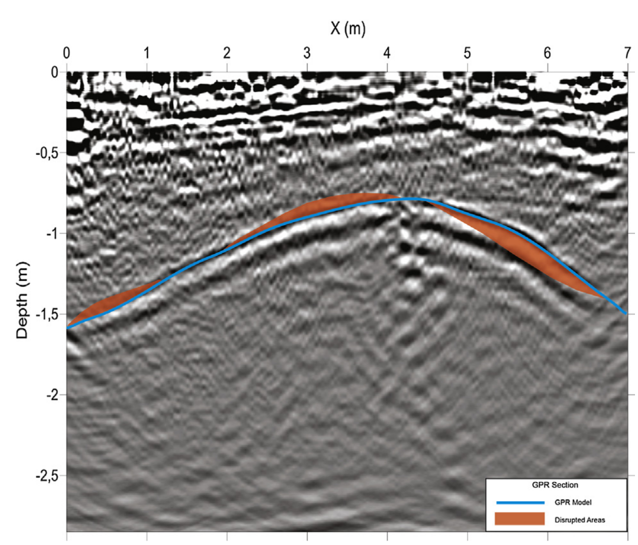

Fig. 12. GPR model of disturbed vault (blue line represents vault section, orange fills represent disturbed areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

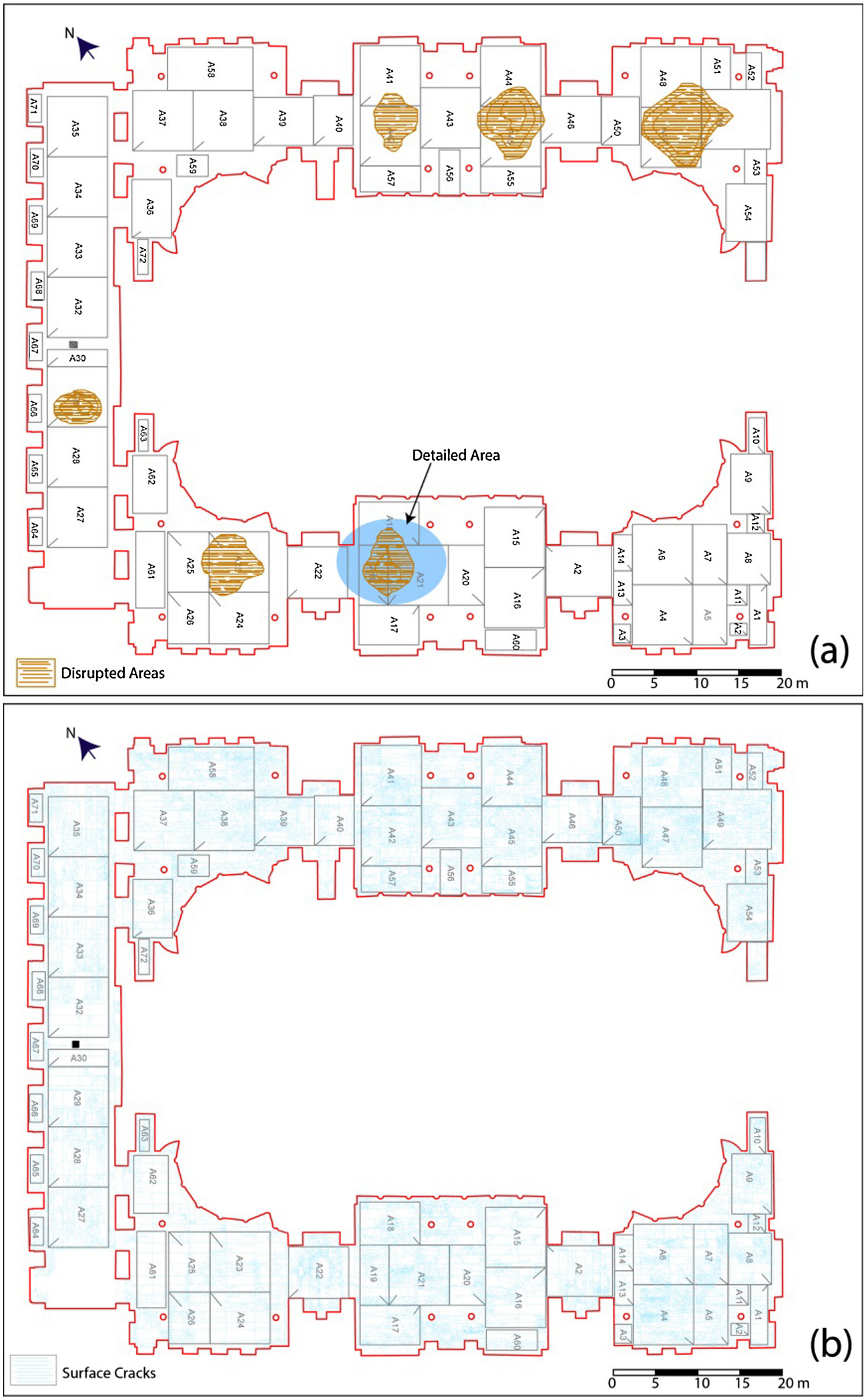

Fig. 13. Comparison disrupted areas with surface cracks. (a) Disturbed vaults (yellowish areas). (b) Surface cracks (blue lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

were reached. Accordingly when the 2 dimensional profile in the grid region is investigated, the amplitude changes in the vault structures supporting the floor and hyperbolic changes formed are clearly observed (Fig. 8a, b). When the 3 dimensional depth section obtained from the same data is investigated, the vault structure within the measurement area is partly determined in

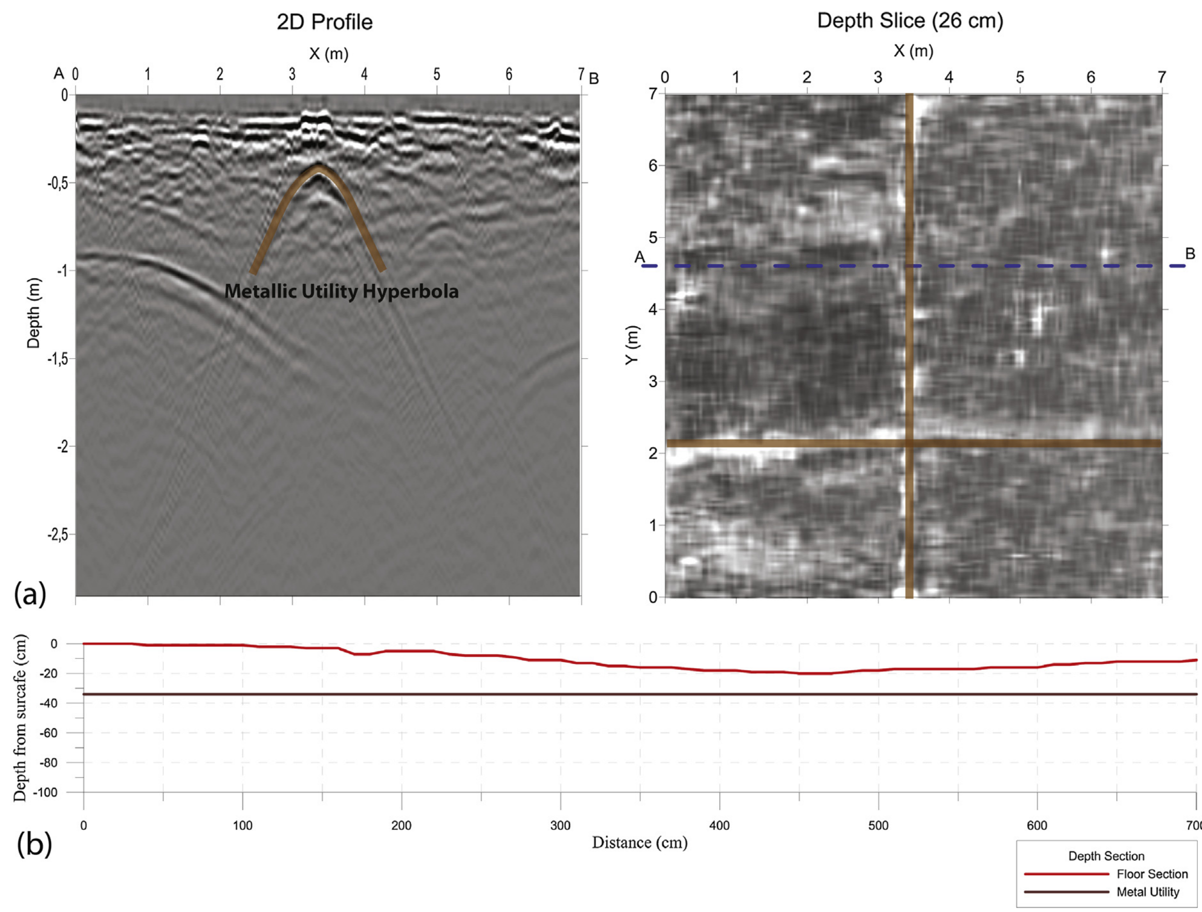

Fig. 14. Metal utility findings at Hagia Sophia Gallery Floor. (a) GPR section and depth slice of metal utility. (b) Schematic section of the floor with metal utility to demonstrate the collapsed area on the Gallery floor.

the depth section (Fig. 8c). The images showing 2 dimensional and 3 dimensional sections obtained from GPR data are schematically shown in Fig. 8d.

With the aim of better representing the vault structure in the data obtained from GPR measurements, data for two areas representing the full vault structure were combined. The vault structure determined with this combination is more easily understood and sections were created at different depths (40 cm, 60 cm, 80 cm and 100 cm) and presented as a layer map (Fig. 9). Clearly on the layer map the amplitude transition observed in the vault structure covers a smaller area at 60 cm depth and covers the largest area at 100 cm depth (Fig. 9). According to the structural properties of the vaults directly proportional growth is expected at this depth (Fig. 3).

4. Interpretation and discussion

Hagia Sophia Museum has preserved its importance as both an architectural structure and as an important historical element right up to the present day. The necessity for non-destructive shallow geophysical methods is understood from its success at revealing the causes of both known and unknown problems present in this type of structure. This study researched the causes of cracks and depressions in the gallery floor using the high sensitivity and resolution provided by ground penetrating radar (GPR) studies and identified sagging and deterioration of the main supporting elements of vault structures. Scanning the floor of the gallery with GPR revealed degradation of the load-bearing vault structures. Additionally the arches underneath the vaults were imaged using a laser meter set up on the ground (Fig. 10) and the arch image and GPR section for each vault were compared (Fig. 11). The Laser measurements were conducted from the entrance floor of the Museum for controlling the Gallery floor vaults.

The section image of any vault not exposed to any deformation is symmetrical (Fig. 3). However, when the section images of vaults scanned with GPR in this study are investigated, it is noted that they are not symmetrical (Fig. 9). When the GPR sections are compared with the arch images obtained with the laser meter, it appears that the degradation observed in the lower surface of the vault with laser meter is in accordance with the deterioration observed in the vault interior with GPR (Fig. 12). When the ground cracks present are compared with the identified vault deterioration, compliance is observed (Fig. 13).

When the deeper section of the gallery floor structure is investigated, the presence of supporting metal beams installed during improving and strengthening work in the Mimar Sinan period is revealed (Fig. 14a). Thought to have been used to connect a few points, it is understood that this metal reinforcement covers the entire floor at certain intervals. To understand the relationship between the cracks and depressions observed in the floor and this metal reinforcement, 2 dimensional sections were taken from different areas and it appeared that the floor depressions were not affected by the metal beams (Fig. 14b). This situation indicates that the reinforcement by Mimar Sinan supported the floor; however it did not prevent surface deterioration of the floor.

5. Conclusions

Within the zone of effect of earthquakes occurring on the North Anatolian Fault Zone, Hagia Sophia Museum has experienced many moderate earthquakes through history. In addition to earthquakes and other disasters, shown to be the cause of much damage in the past, many factors in the modern age have caused deformation of the historical structure. The most obvious of these is the intense interest of tourists with tens of thousands visiting every day causing interaction between the building and people walking and forming the main reason for cracking and depressions in the ground. When the current deformation effects are considered, if no precaution is taken for Hagia Sophia, it is unavoidable that irreparable damage may occur. Considering the expected earthquake on the section of the North Anatolian Fault Zone in the Sea of Marmara, this risk increases further. As a result, it should be determined whether the deformation or deterioration observed in the floor of the gallery in this study is present in other sections of the structure and necessary precautions should be urgently taken. Also it should be determined whether loads from the tramway line and main road and vibration motions affect Hagia Sophia Museum.

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References

[1] Akṣit Ilhan. Hagia Sophia. Akṣit Kültür ve Turizm Yayincilik, 2004.
[2] D. Chianese, M. D'Emilio, S. Di Salvia, V. Lapenna, M. Ragosta, E. Rizzo, Magnetic mapping, ground penetrating radar surveys and magnetic susceptibility measurements for the study of the archaeological site of Serra di Vaglio (southern Italy), J. Archaeol. Sci. 31 (2004) 633–643.
[3] L.B. Conyers, Ground-penetrating radar techniques to discover and map historic graves, Historical Archaeol. 40 (2006) 64–73.
[4] M. Dabas, C. Camerlynck, I. Freixas, P. Camps, Simultaneous use of electrostatic quadrupole and GPR in urban context: investigation of the basement of the Cathedral of Girona (Catalunya, Spain), Geophysics 65 (2) (2000) 526–532.
[5] F. Dirimtekin, Resimli Ayasofya Kılavuzu, İstanbul, 1956.
[6] S. Eyice, Book of Ayasofya, İstanbul, 1984.
[7] D. Goodman, Ground penetrating radar simulation in engineering and archaeology, Geophysics 59 (2) (1994) 224–232.
[8] D. Goodman, Y. Nishimura, J.D. Rogers, GPR time slices in archaeological prospection, Archaeol. Prospection 2 (1995) 85–89.
[9] J. Hruska, G. Fuchs, GPR prospection in ancient Ephesos, J. Appl. Geophys. 41 (1999) 93–312.
[10] J. Leckebusch, Ground-penetrating radar: a modern three-dimensional prospection method, Archaeol. Prospection 10 (2003) 213–240.
[11] J. Leckebusch, A. Weibel, F. Bühler, Semi-automatic feature extraction from GPR data, Near Surf. Geophys. 6 (2) (2008) 75–84.
[12] G. Leucci, S. Negri, Use of ground penetrating radar to map subsurface archaeological features in an urban area, J. Archaeol. Sci. 33 (2006) 502–512.
[13] Rowland J. Mainstone, Hagia Sophia: Architecture, Structure, and Liturgy of Justinian's Great Church (reprint edition). Thames and Hudson. ISBN 0-500-27945-4, 1997.
[14] W.A. McCann, GPR and archaeology in central London, Archaeol. Prospection 2 (1995) 155–166.
[15] S. Piro, D. Goodman, Y. Nishimura, High resolution ground penetrating radar survey at Forum Novum, in, in NovNovum e Vescovio: studying urbanism in the Tiber Valley, J. Roman Archaeol. 14 (2001) 59–79.
[16] K. Persson, B. Olofsson, Inside a mound: applied geophysics in archaeological prospecting at the Kingsngmounds, Gamla Uppsala, Sweden, J. Archaeol. Sci. 31 (2004) 551–562.
[17] K.J. Sandmeier, Reflexw 4.2 Manuel Book: Sandmeier Software (Karlsruhe, Germany), 2003.
[18] C.J. Vaughan, Ground penetrating radar surveys used in archaeological investigations, Geophysics 51 (1986) 595–604.
[19] C.C. Yalçıner, M. Bano, M. Kadıoglu, V. Karabacak, M. Meghraoui, E. Altunel, New temple discovery at the archaeological site of Nysa (Western Turkey) using GPR method, J. Archaeol. Sci. 36 (2009) 1680–1689.
[20] C.C. Yalçıner, 2-D and 3-diffraction stack migration method using gpr: a case study in Çanakkale (Turkey), Mediterr. Archaeol. Archaeom. 12 (2) (2012) 95–104.
[21] C.Ç. Yalçıner, Investigation of the subsurface geometry of fissure-ridge travertine with GPR, Pamukkale, western Turkey, J. Geophys. Eng. 10 (2013) 10 035001.