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HIGH-RESOLUTION GROUND PENETRATING RADAR INVESTIGATION OF YEREBATAN (BASILICA) CISTERN IN ISTANBUL (CONSTANTINOPLE) FOR RESTORATION PURPOSES

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ABSTRACT

New data are presented from non-destructive structural investigations in the Istanbul Yerebatan (Basilica) Cistern (placed in the top 10 sites in Turkey on the UNESCO World Heritage List) for restoration purposes. Degradation identified is discussed in relation to past earthquakes. Istanbul has housed many civilizations and searching for the traces of earthquakes in historical sites in a city which has experienced many large earthquakes during this process will assist in illuminating the past. It is possible to see traces of these earthquakes in the Yerebatan (Basilica) Cistern, serving as the largest enclosed water storage in Istanbul for nearly 1000 years. In line with this aim, research was completed with the high-resolution ground penetrating radar (GPR) method on both the floor and internal side walls of the cistern which is undergoing restoration. In this study, deformation was determined in the layers of water insulation on the floor of the cistern and it was understood these deformations were associated with degradation in the 336 columns acting as supports for the cistern. Drilling in anomalous sites determined by GPR screening identified traces of repairs and it was concluded that the degradation causing anomalies may be related to past earthquakes.

KEYWORDS: Cistern, Large earthquakes, Ground Penetrating Radar, Geoarcheology, Geophysics

1. INTRODUCTION

It is Constantinople (later named Istanbul by the Ottoman Empire conquest) which from the time of construction has been subjected to many attacks. As a result, a variety of problems occurred in the city. The most critical of these was providing water for the city. Water and food supplies to the city were cut off due to sieges lasting months and the Byzantines constructed giant cisterns as a solution as there was insufficient freshwater springs within the city. The cisterns were constructed in enclosed areas and are important structures in history in terms of both security and cleaning. It is estimated there were nearly 200 cisterns in Istanbul in the past. The most important and largest of these is the Yerebatan (Basilica) Cistern which is undergoing restoration work to remove the effects of time and traces of natural disasters (Fig. 1).

The basic aim of many restorations is to carry traces and the spirit of the past into the future. A random restoration plan means large economic and time investments which disrupt the habitual use of the building in order to complete the intervention. Multi-disciplinary studies are performed to avoid this. Within this scope, historical documentation is researched, the features of historical material and their sources are investigated, previous repairs are identified, and monitoring of effective environmental factors is completed. Then, macroscopic observations are made on site to determine the status of the materials which require preservation and the degradation effects within the structure. However, though degradation is large scale due to the features of the material, it may be possible to determine small degradations that will occur as a result of detailed investigation for long-term preservation. At this stage, the most effective method used is on site non-destructive testing. These methods with the abbreviation Non Destructive Testing (NDT) have many different applications, with the most effective route in terms of onsite investigations of historical structures being the GPR method.

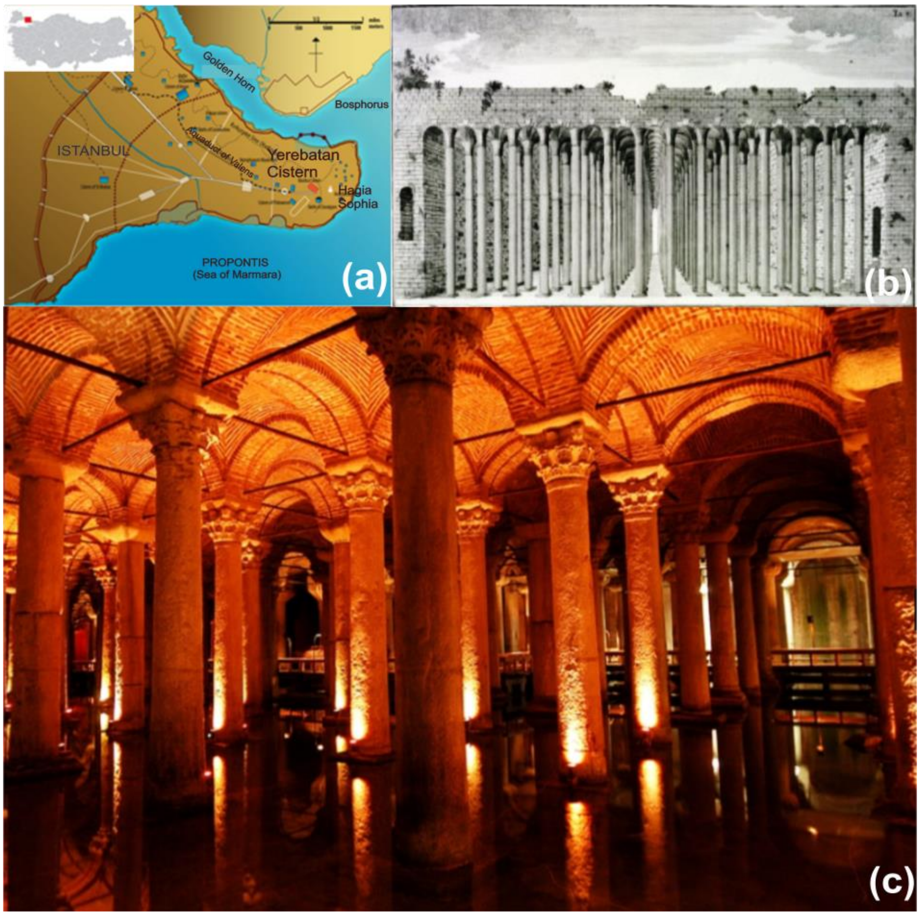

Figure 1. Study site in Istanbul, Turkey (a) Map of the water supply system, cisterns and baths in Byzantine Constantiople. The Yerebatan (Basilica) Cistern (redbox) is located southeast of Hagia Sophia, near to the Milion. White boxes and lines shows water system (b) Ancient model drawing (Comidas, 1794), (c) Modern view of Yerebatan (Basilica) Cistern (https://www.yerebatan.com/).

After the first rapid imaging stage, degradation mapping is performed and then limited material sampling is performed for laboratory investigations of the degradation products in order to determine the restoration method. A kind of diagnosis-treatment process is performed.

The stages of restoration work in Istanbul Yerebatan (Basilica) Cistern were the scene of a multi-disciplinary implementation. Research groups coming together proposed multi-disciplinary data collection methods and detailed investigation was performed in multi-departmental, multilateral and multi-disciplinary fashion. In line with this, in order to restore the cistern most appropriately to the original, archeologists, art historians, architects, static engineers and restorers participated in the study, in addition to geophysical engineers using the GPR method which has provided significant technological support for restoration work in recent years.

The GPR method is used in many areas from engineering geology to environmental research, from archeological studies to structural engineering work due to being non-destructive, easy to apply and providing high sensitivity high-resolution results (Daniels, 2004). Most recently, Yalçıner et al. (2019) used the GPR method and ultrasonic pulse velocity (UPV) tests as non-destructive techniques in studies before restoration of the Chora (Kariye) Museum in Istanbul and analyzed the stone quality, internal structure geometry and physical features of structural elements. Similarly, many studies have used the GPR method for non-destructive investigation of historical structures (Leucci et al., 2011; Leucci et al., 2012; Moropoulou et al., 2013; Kanlı et al., 2015; Gil et al., 2019). Due to technological developments, it has found a place among indispensable non-destructive test (NDT) methods with the use of high-frequency antennae (1-2.3 GHz) for restoration work of historically important buildings and structures (Savvaidis et al., 1999; Goodman and Piro, 2009; Drahor et al., 2011; Tsokas et al., 2014; Tsokas et al., 2015; Angelis et al., 2017, 2018; Yalçıner et al., 2019) and for sustainability purposes (Liritzis et al 2020).

In this study, observations were made on the floor and columns of the Yerebatan (Basilica) Cistern to research whether there was identifiable degradation present or not. Measurements of anomalies obtained on the floor and deformation (rotating, bending, breaking, etc.) in load-bearing columns in the cistern were compared and the presence of any correlation was researched. Drilling to identify variations in the impermeable layers in the floor of the structure and underlying natural bedrock revealed structural degradation and traces of repairs. In this way, the degree to which seismic activity in the region affected the structure was understood.

2. HISTORY AND STRUCTURAL ELEMENTS OF ISTANBUL YEREBATAN (BASILICA) CISTERN

Located across the Hagia Sophia Museum, Yerebatan Sarayı is also known as the Basilica Cistern because of a basilica that was once located nearby as a cultural centre. It is the largest surviving underground cistern of Istanbul. This subterranean cistern, the Stoa Basilica, in Greek kinsterne (κινστὲρνη), was called Basilica because it was located under a large public square on the First Hill of Constantinople where Hagia Sophia Church was built. Ancient texts indicated that the basilica contained gardens, surrounded by a colonnade and facing the Hagia Sophia. At this location, and prior to constructing the cistern, a great Basilica stood in its place, built between the 3rd and 4th centuries during the Early Roman Age as a commercial, legal and artistic centre. The Stoa was probably built by Constantine the Great but was destroyed around 475 AD. The cistern was formed as it is today, when it was rebuilt around 542 AD by the emperor Justinian I, after the period of Nika's Revolt, for the water supply of Constantinople throughout the Byzantine period and to supply water to the adjacent Grand Palace, where the Byzantine emperor had his seat.

From the 18th to the middle of the 20th century, restoration works were carried out to preserve the cistern, which after renovation, which began in 1985, has been open to the public since 1987 and is one of the most important and oldest public places (Onlu, 2010, Han, 2019; Yücel, 1967).

Cisterns are defined as water cellars surrounded by plastered walls, constructed under a building or under earth to collect rainwater or store river water. The water carried by aqueducts and channels from outside the city was stored in the cisterns.. Water from the cisterns was transported to the city fountains and houses by channels. Cisterns were important for city life and maintained their importance from the time of ancient cities to the foundation of modern cities. İstanbul Yerebatan (Basilica) Cistern is the most important example of water architecture from antiquity. Yerebatan cistern was also known as "Big Basilica Cistern" (Bogdanovic, 2008). The water collected in the cistern was delivered via 20 km long aqueducts from the reservoir in Belgrade forest near the Black Sea (Çeçen, 1991). There was a large basilica at the location of Yerebatan cistern before its construction. This structure was totally destroyed in a fire in 476.

The basilica was reconstructed later and had a porticoed courtyard with marble columns. This new structure did not remain standing for a long time; it was damaged by the Nika riot. It was repaired by Emperor Justinian in VI. century (Ktismaton, 1964). Yerebatan cistern dimensions are 138 × 64.6 m. on the ground plan and it is covered by brick cross vaults supported by 336 columns (Müller-Wiener, 1977) (Fig. 2a,b). Some columns are 8 m high, and it has a capacity of 78,000 m. A total of 12 rows of columns with 28 in each series carry brick arches and the vaults supporting them. Some columns in the southwest remain within the in filled wall (Anonim, 1893). The heads of the columns are in the Corinthian style and there are impost headers on them. The water capacity of the cistern, which covers an area of 9800 square meters, is about 100,000 tons. The outer walls 4.80 m in thickness were made waterproof by covering them with brick dust mortar 3.5 cm in thickness (Yılmaz, 2014) (Fig. 2c).

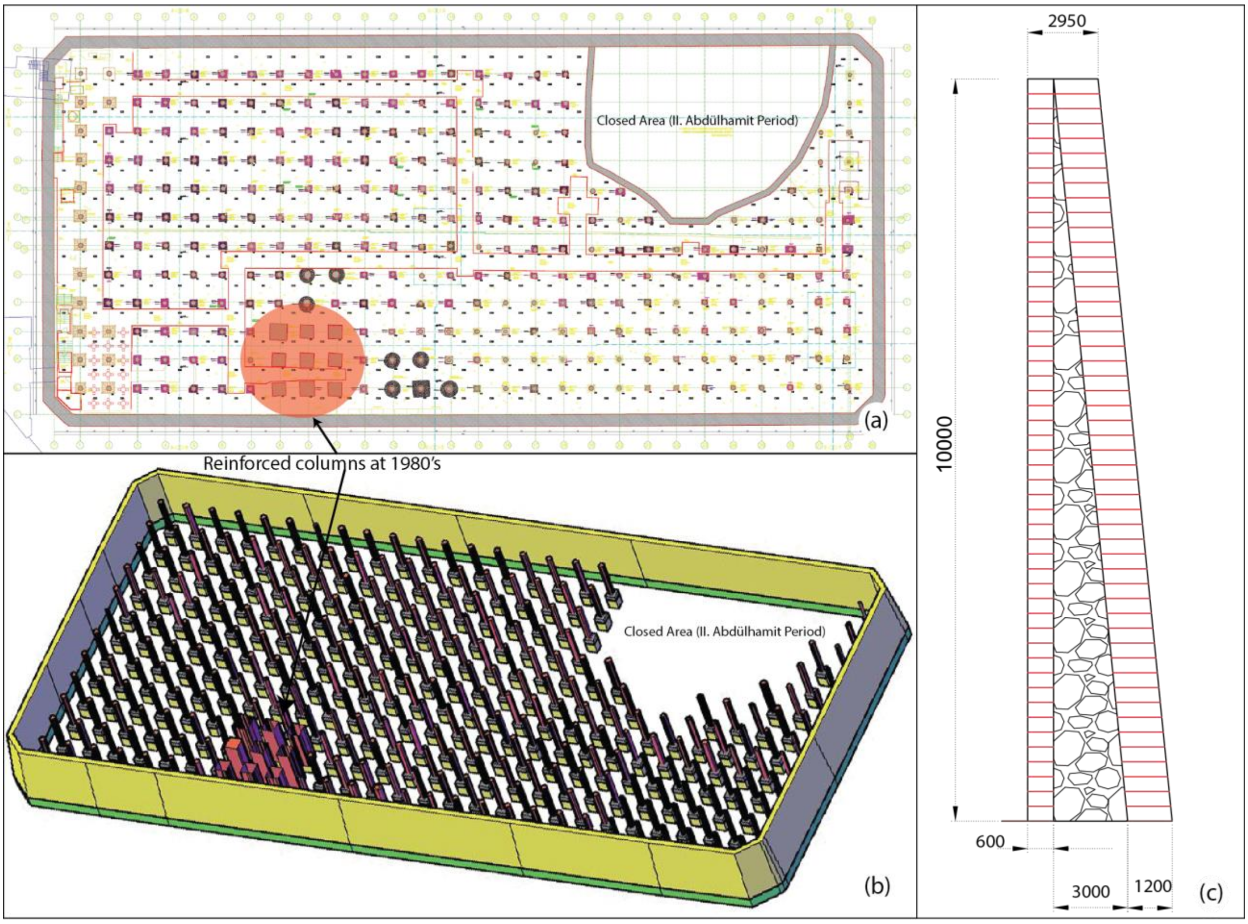

Figure 2. Technical drawing of Yerebatan (Basilica) Cistern (a) Plan view. (b) 3D Isometric view. (c) Sketch drawing of the side walls cross-sectional view

In addition to the insulation of the walls, water leakage from the bottom of the cisterns is the biggest problem. Mortar constitutes a significant building material, used in construction even from prehistoric times. Their structure and properties usually differ according to their functional role in construction (structural mortars, renders plasters, flooring), the technology of each era and the availability of raw materials (Stefanidou et al., 2013). Brick–lime mortars and plasters were widely used as water-proof materials in aqueducts, bridges and cisterns since early Hellenistic time. In Rome, very successful methods were found for this problem. Then the same methods were used for centuries. The material used for base insulation in water structures is generally the following materials. Hydrated lime (powder), White Cement, Natural pozzolan, Local clay (<0.25 mm), Sand of natural origin (0-4 mm), Gravel of natural origin (4-8 mm), Crushed brick, and Super-plasticizer 1% w/w of binders. The proportions of this material may vary depending on the structure. In recent decades, basic physical properties, raw material compositions, mineralogical, microstructural and hydraulic properties of brick–lime plasters from some historic water buildings were determined by XRD, SEM-EDX, AFM and chemical analyses (Uğurlu and Böke, 2009). The results showed that the baths and cisterns survived in hot and humid conditions without losing their strength and adhesion, and they explained the hydraulic character as due to the use of porous and pozzolanic bricks as aggregate in gypsum production.

Results of recent studies in this regard basically it proves that the same method was adopted at Yerebatan. The technique used for the 15 cm thick floor plaster determined with geophysical studies carried out in the Yerebatan cistern coincides with the studies described below. Structural mortars and plasters from cisterns and baths (thermes) from Roman, Byzantine and Ottoman periods in Greece were analysed in terms of their physico-mechanical, chemical, and microstructural characteristics, in order to find the key factors for their functionality. From the analysis, it was found that their coherent and dense structure is due to the action of different mechanisms caused by the selection and combination of raw materials and the interaction with the special environment in which they served. The binding system is mixed, with the combination of hydrated lime and materials with pozzolanic properties. The aggregates are both siliceous and brick fragments with different granulometry, according to the type of mortar (structural or plaster). The raw materials used as binders and aggregates and the technology practices during mortar application contribute to low porosity mortars with dense structure. Additionally, the environment of the cisterns and baths functioned to benefit the materials, as it favored the dilution of calcite and secondary phases formed in the porous mortars assisted in increasing the cohesiveness of their structure. The technology used to produce mortars applied in baths and cisterns for a long period of time proves the high knowledge of material behaviour in order to produce durable constructions, highly resistant to deteriorating factors (Stefanidou et al., 2014). The ratio of pozzolan usually increased in the intermediate mortar layer (nucleus). The systematic addition of pozzolan in these mortars probably emerged from the need to resist intense humidity, as well as be durable to loading (Stefanidou et al., 2013). In some cases and only in the external layers (supra nucleus, nucleus), brick dust was added probably in an effort to enhance the hydraulic properties of the mortars and increase their resistance to humidity.

3. EARTHQUAKE HISTORY OF ISTANBUL

Since Istanbul's (Constantinople) foundation to date, it has been rocked by more than 550 earthquakes. Some of these are due to faults around Istanbul and cause excessive damage, while the majority is caused by faults in the Balkan geography or between the Izmit-Duzce regions and cause less destruction in Constantinople (Afyoncu, 2018). The first earthquake in the records of the newly founded city in 342 occurred in the east and did not cause significant damage. Then an earthquake occured which caused major damage to Izmit and significant damage in Constantinople. After this earthquake, earthquakes occurring from 402-533 caused a variety of damage in Istanbul. The earthquake in 447 caused significant damage which destroyed a large portion of Constantinople's walls. Many houses, walls and statues were destroyed, and thousands of people died during a very severe earthquake occurring on 16 August 542. Again, after earthquakes in 546 and 557, encountered in historical records but not causing significant levels of damage, the earthquake on 7 May 558 collapsed the dome of Hagia Sophia and destroyed hundreds of houses. After this large earthquake, there were earthquakes in 583 and 611 but there is no record of significant earthquakes affecting Istanbul. One of the largest earthquakes experienced in Istanbul was on 26 October 740. After this, earthquakes occurred in 780, 790, 796 860, 866, 869, 948, 989 and 1010. Two earthquakes on 13 August 1032 and 6 March 1033 caused very significant damage. The earthquake on 1 March 1202 damaged the Byzantine palace. The severe earthquake on 11 March 1231 damaged the city and city walls. A large earthquake occurred on 1 June 1296 in Constantinople. Historians write that this earthquake did not leave any stone on top of other stones in Constantinople. Houses, palaces, churches and city walls were destroyed, and floods occurred. Aftershocks continued for up to two months. Constantinople experienced two sequential earthquakes in January 1303. The earthquake in 1332 was very intense and destroyed many houses and churches along with statues. The earthquake on 18 October 1343 damaged the city walls and Hagia Sophia. Among earthquakes in 1402, 1419 and 1437, a tsunami is reported to have occurred in 1419. The earthquake on 18 December 1488 destroyed the dome in Fatih Mosque and damaged different regions in the city. The earthquake on 10 September 1509 devastated the whole city. This earthquake is the largest earthquake to have occurred in the Eastern Mediterranean after 1000 and is called the 'Little Doomsday'. An earthquake on 10 May 1556 damaged Fatih Mosque, Hagia Sophia and the city walls. Another low-intensity earthquake occurred on 11 July 1690 and destroyed city walls and some wooden houses along with Fatih Mosque. A severe earthquake with regional effect occurred on 25 May 1719 and the area of effect encompassed Düzce, Izmit, Sapanca, Orhangazi, Karamursel and Yalova. An earthquake in Izmit on 25 May 1719 caused damage in Istanbul, severely damaging the city walls and destroying 27 towers. Collapses occurred in 40 mosques and the palace. The earthquake on 30 July 1752 in Edirne affected the region as far as Bulgaria; however, the earthquake did not cause much damage in Istanbul. An earthquake occurring most probably centered on Izmit on 2 September 1754 was not very severe, so it did not cause much damage in the city but did destroy the domes of Fatih and Bayezid mosques and one of the towers in Yedikule. A frightening noise was heard before the earthquake on 22 May 1766 and this noise was followed by shaking lasting nearly two minutes. After this, there was a lower intensity earthquake lasting four minutes. The aftershocks of this earthquake continued for eight months with a second earthquake occurring on 5 August. An earthquake which destroyed Bursa in 1855 affected Istanbul but did not cause much damage. Istanbul was shaken by an intense earthquake on 10 July 1894. The earthquake lasting 18 second and felt as three sequential waves affected Adapazarı, Izmit, Gebze, Kartal, Adalar, Uskudar, Istanbul, Buyukcekmece, Kucukçekmece, Catalca, some of the Sea of Marmara, Bozburun, Yalova, Karamursel, and Sapanca. The last large earthquake affecting Istanbul in the Ottoman Period was the earthquake (M=7.3) occurring on 9 August 1912 in Sarköy-Murefte. Causing great damage in the south of the Edirne province, the earthquake destroyed the chimneys of many houses in Istanbul, cracked walls and knocked telegraph poles. After that significant earthquake affecting Istanbul, from 1919 to 2019 earthquakes occurring close to Istanbul, especially in the south, did not cause very significant damage in Istanbul. However, damage in buildings caused some structures to become unusable. These earthquakes were earthquakes larger than 7.0 magnitude occurring in 1919, 1944, 1953, 1957, 1967, 1975 and 1999. The destructive earthquakes affecting Istanbul in the historical period (Byzantine and Ottoman periods) and the instrumental period (Republic of Turkey) are shown on Fig. 3.

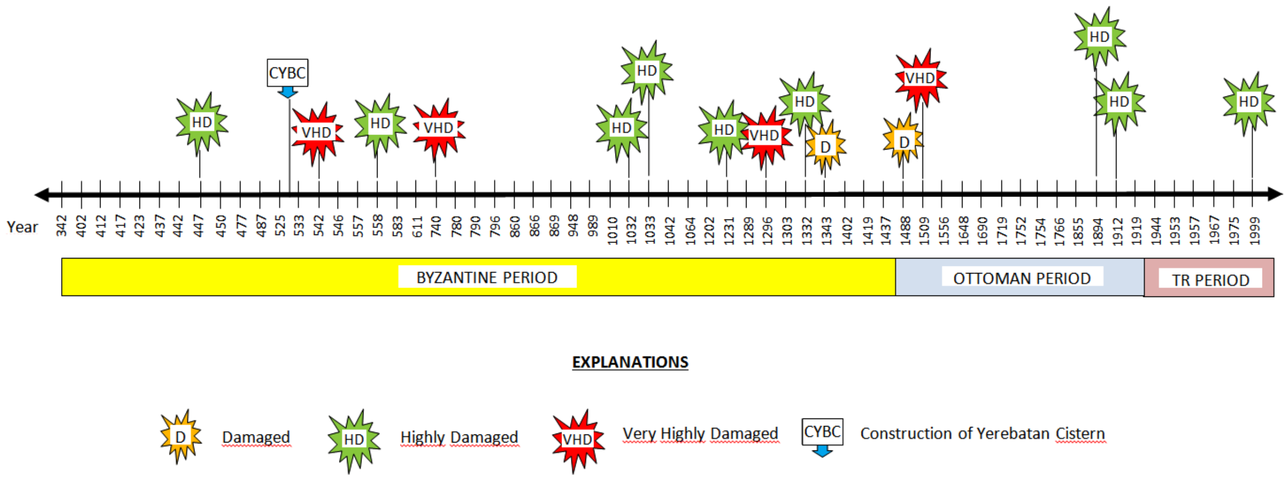

Figure 3. Chronologic order and intensity information for earthquakes affecting Istanbul

4. MATERIAL AND METHODS

Many geophysical methods applied horizontally to the ground have been used effectively in structures in recent years. They provide significant advantages for historical buildings requiring non-destructive investigation. Though many different geophysical methods have been applied successfully for many historical building investigation projects, the most effective method accepted by most implementers is ground-penetrating radar (GPR). Ground-penetrating radar is a geophysical method used very effectively and commonly in archeological sites and cultural heritage research (Martínez-Garrido et al., 2018; Johnston et al., 2018; Yalçıner et al., 2017; Yalçıner et al., 2019). GPR reveals structures invisible from the surface within walls and underground by transmitting electromagnetic signals and later receiving reflections produced by discontinuities that are present (Gracia and de la Vega, 2001; Ming-Chih et al., 2009; Persico et al., 2014). Antennae necessary for high-frequency GPR measurement setup send short electromagnetic signals at 1-60 ns intervals at very high and ultra-high (30-3000 MHz) bands. In this study, the Istanbul Yerebatan (Basilica) Cistern was investigated with the ground-penetrating radar method. Screening to obtain high-resolution images at up to 2 m depth was completed with measurements made in a total of 10 different regions with a Mala brand 450 MHz HDR PRO device in both horizontal and vertical orientations encompassing an area of 6975 m² (27900 meters total length of GPR profiling) (Fig. 4). Higher frequency antennae (500-800 MHz or more) may be used to obtain higher resolution; however, studies at these frequencies have reduced observable depth.

In order to cover the cistern floor most accurately and encompass the greatest area, 10 different grid regions were created by considering the present walking route and structural elements (Fig. 5). In line with this, the best representation possible of the cistern floor was completed. Parameters used for measurements are given in Table 1.

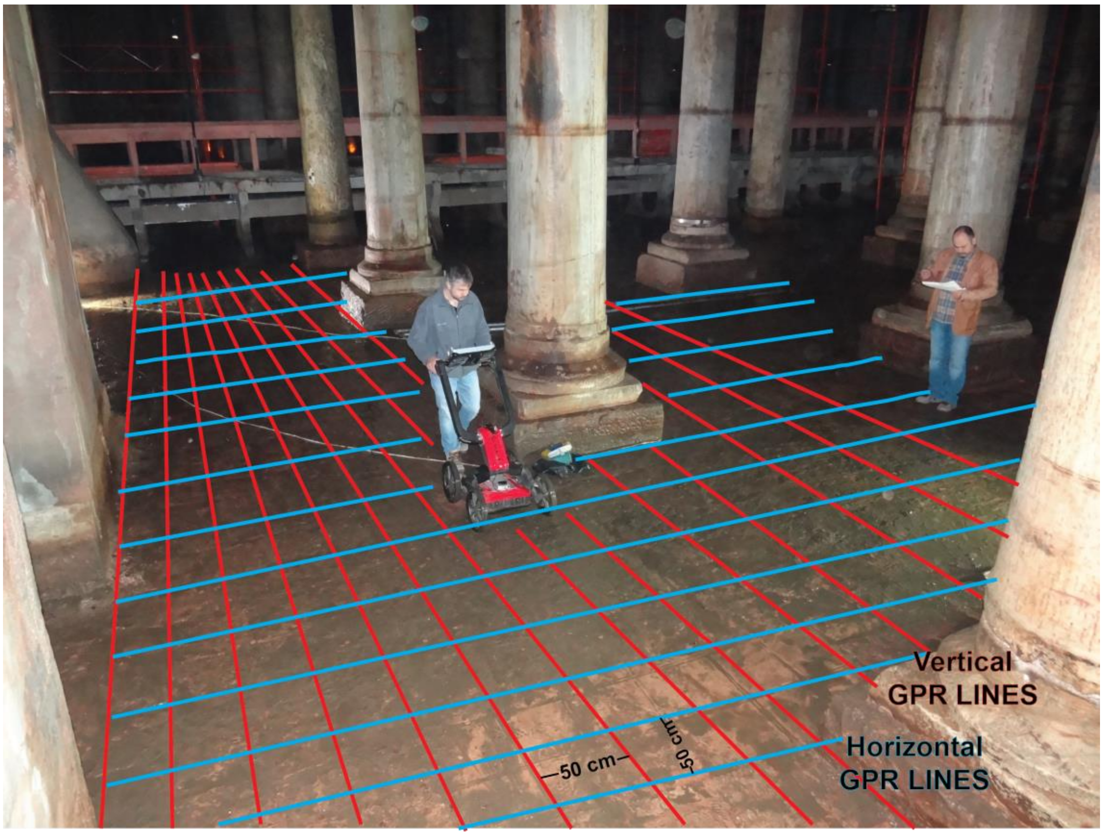

Figure 4. GPR profiles (red lines represent vertical profiles and blue lines represent horizontal profiles. All distance between profiles are 50 cm)

Numerical analysis of GPR profiles actually investigate the parabola produced by the GPR signal and it is the process of searching for areas with higher density of inhomogeneity. This process deals with the NDT approach to confirm the site and dimensions of structures under historical buildings. The data processing groups signal amplitudes for each profile and compares them. Later the depth of the first important variability in the signal amplitude is researched. The reason for the weakening of the GPR signal is defined. Finally, software filters are used to measure the variability in the propagation conditions of the signal.

Table 1. Acquisition parameters of the GPR survey

Antenna Frequency	**450 MHz (HDR)**
Trace interval	0.035 m
Samples	512
Sampling frequency	5120 MHz
Time window	114.45 ns
Profile interval	0.5 m

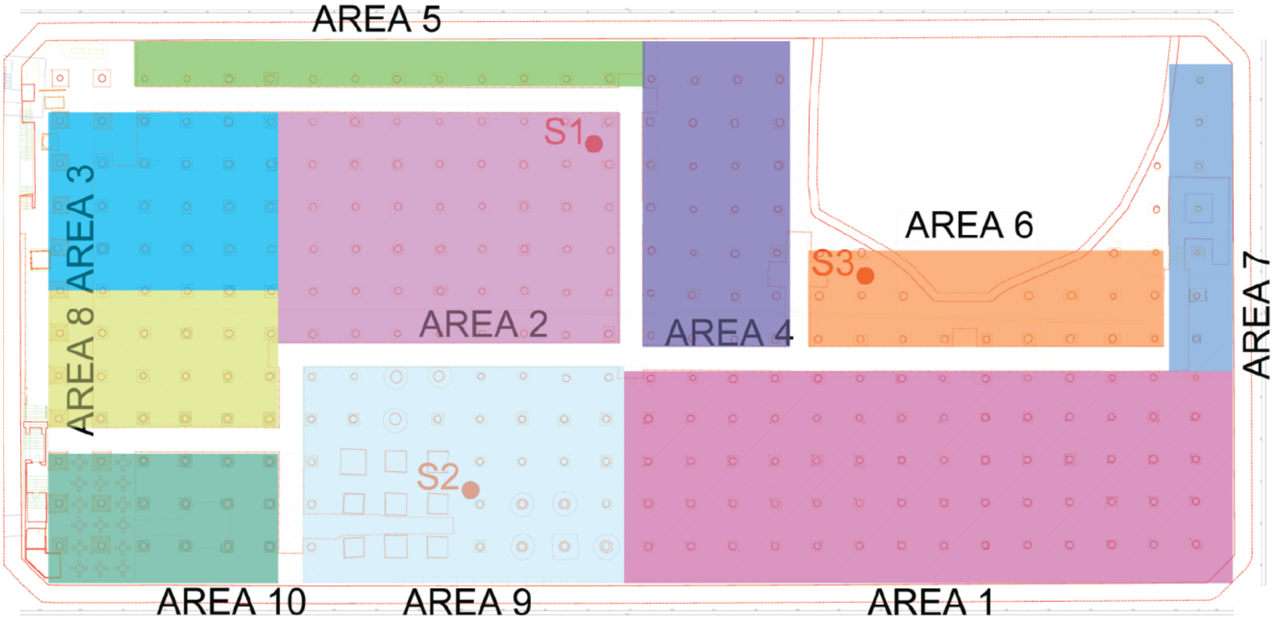

Figure 5. Areas with GPR measurements and drill locations S1, S2 and S3 in Basilica Cistern

5. RESULTS

Within the scope of studies about Istanbul Yerebatan (Basilica) Cistern, previous documents were reviewed, GPR measurements were planned and measured, GPR profiles were analyzed and drilling was performed at 3 determined points. Inclination measurements were completed on the 336 columns, the most important elements for the cistern to remain structurally intact.

GPR measurements of the floor of the Yerebatan (Basilica) Cistern obtained information about the floor and created enough information infrastructures to allow restoration planning. The main purpose of the restoration is to renovate the building and prevent future damage. Accordingly, a clear understanding of the state of the ground and underground structures plays an important role in performing the restoration process. With the aim of defining the general structure of the ground and the depth relationship between cistern foundations and bedrock, sections were created with 2-dimensional radargram modelling (Fig. 6). Generally, 3 different layers were observed in the cistern floor. The first layer was fill, the second layer was more compacted fill and the third layer was assessed as bedrock (Fig. 6). The groundwater depth was mean 2.5 m. Sudden plus - minus transitions in GPR traces cause dark black and white images on the profile. Since the main reason of these transitions are the changes in the dielectric constant, these regions are defined as the degradation zones (Fig. 6b). Sudden plus - minus transitions in GPR traces cause dark black and white images on the profile. Degradation observed in the fill material between the bedrock and the cistern floor was evaluated to be effects of remaining under water for long durations. It is considered the thickness of fill is at most 2 m as these effects were not observed after 2 m (Fig. 6). In Fig. 7 we applied time-cut filter (60 ns) for removing vault reflections from celling (Fig. 7b), and after we applied complex trace-analysis with Hilbert Transformation to calculate Envelope (instantaneous amplitude) for the complete energy of the signal at an instant of time (Fig. 7c). Additionally, the load-bearing columns in the cistern structure were successfully seated on bedrock. A marker of this situation is that degradation effects were not observed after the 2 m fill. Apart from foundation structures, there was no planar structures encountered ensuring integrity with the floor. Only in Area 1 was a possible planar structure observed at nearly 2 m depth, which may be a bedrock structure. All column foundations were linked to each other by both horizontal and vertical stone beams at nearly 1.5 m depth (Fig. 8). Drilling was completed at 3 different locations in order to visually and physically reveals other structural elements and where high amplitudes (possible wet and/or degraded zones) were identified on GPR measurements (Fig. 5). When determining these drilling locations, the first point (S1) was in the area with highest anomaly observed, the second point (S2) was in the section with lowest anomaly observed and the final (S3) was located in front of the region which was closed to use during the period of Abdülhamit II.

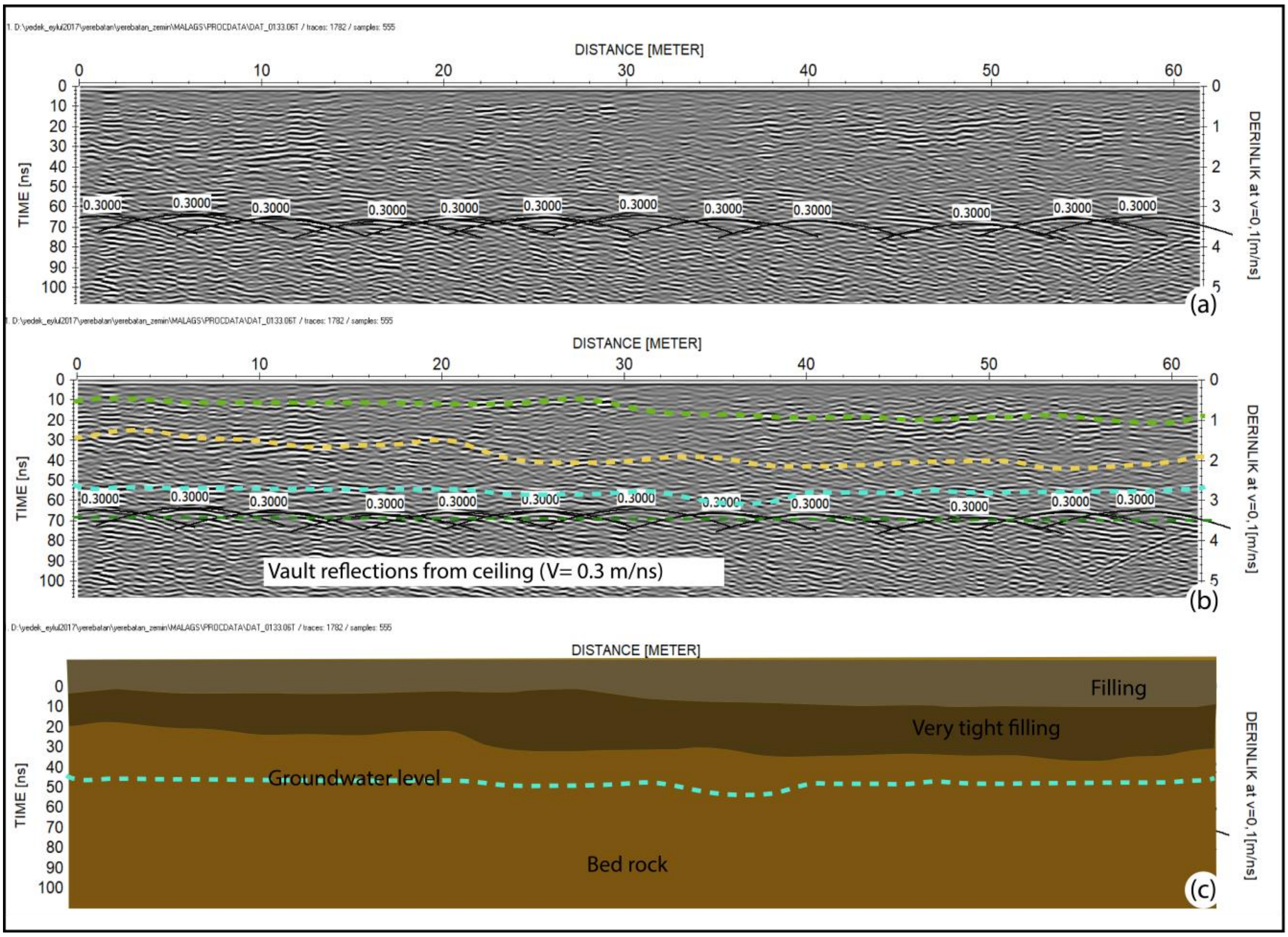

Figure 6. 2-D radargram section and interpreted section of cistern foundation (dashed green line is groundwater level)

The drill depths were kept to nearly 5 m with the aim of preventing damage to the structure. The drilling passed through several levels. S1 drilling passed through fill of Khorasan mortar mixed with brick in the first 80 cm, fill material of rubble and mortar mixture was encountered from 80-150 cm, while the greywacke level forming the bedrock in Istanbul continued after 150 cm (Fig. 9a). S2 drilling had less repairs as observed from GPR data and was a less damaged location with no traces of repair in this area. However, the first 50 cm was filled with modern concrete, there was filling of Khorasan mortar with brick from 50-140 cm and there was fill material of rubble and mortar mixture from 140-200 cm. Bedrock was entered after 200 cm (Fig. 9b). The location of S3 drilling was immediately in front of the area which was closed for use during the period of Abdülhamit II, with traces of repair with Khorasan mortar an indicator of high rates of destruction. The first 80 cm of the drilling found fill of mortar with bricks and fill material of rubble and mortar mixture was found from 80-120 cm. Drilling did not continue to bedrock as groundwater was encountered after this point (Fig. 9c).

With the aim of researching the relationship between the identified anomalies with structural deformation in columns like visible cracks, bending and twisting, digital inclination measurements were completed on all columns (suitable for measurements) and the inclinations were shown graphically (Fig. 10). In this way, the correlation between these deformations and the general situation was investigated. Inclination values measured digitally are classified according to the sales axis. Accordingly, values are assigned to the rotations in the clock axis (+) in the opposite direction (-) values are also determined. In addition, the highest rotation values (highlighted area in Fig. 10 with red) are determined.

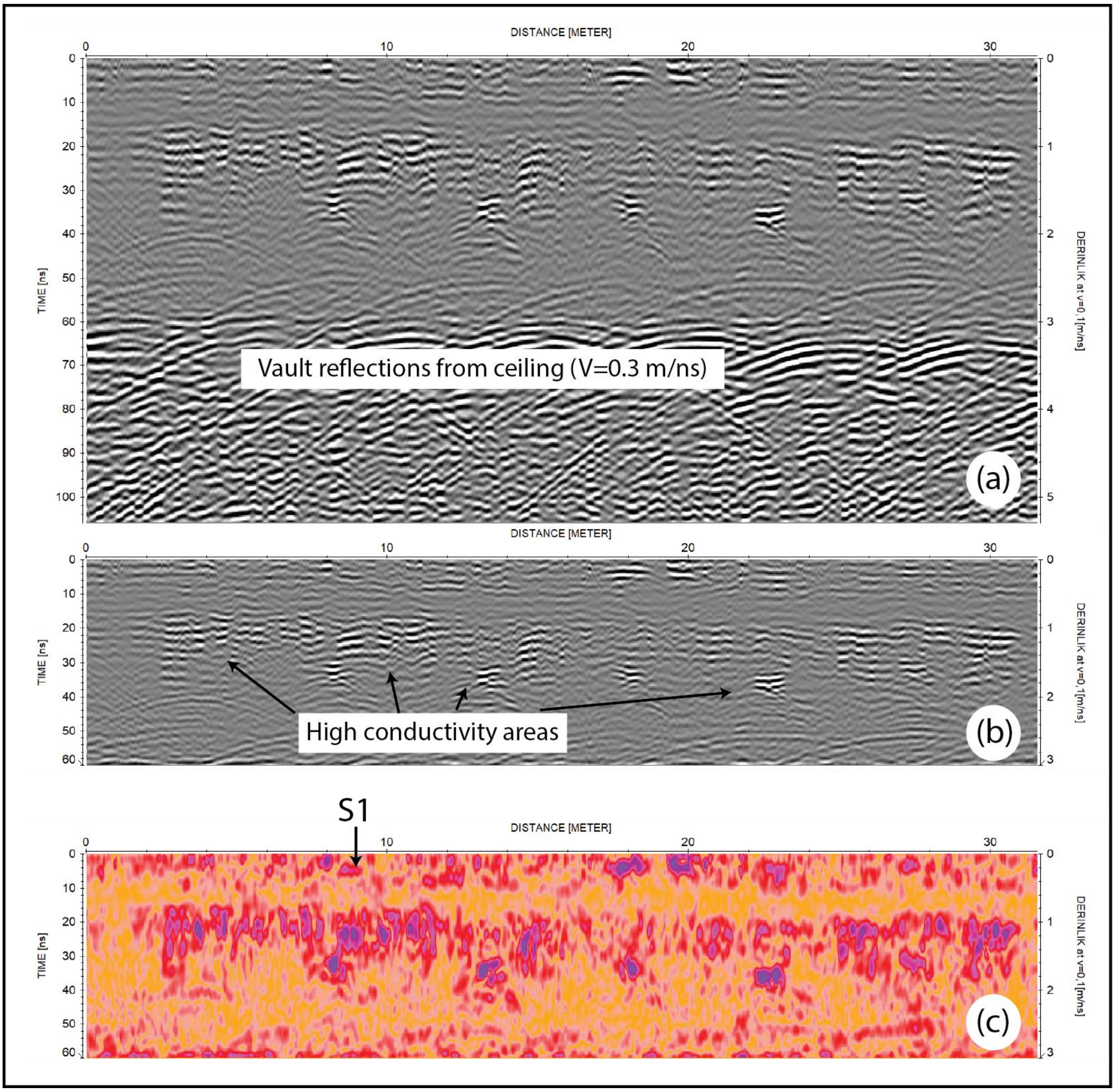

Figure 7. View of drill location (S1) on GPR profile in Area 1 (a) processed GPR profile, (b) GPR profile with ceiling reflections removed, (c) GPR profile with complex analysis applied (dark areas are equivalent to high conductivity).

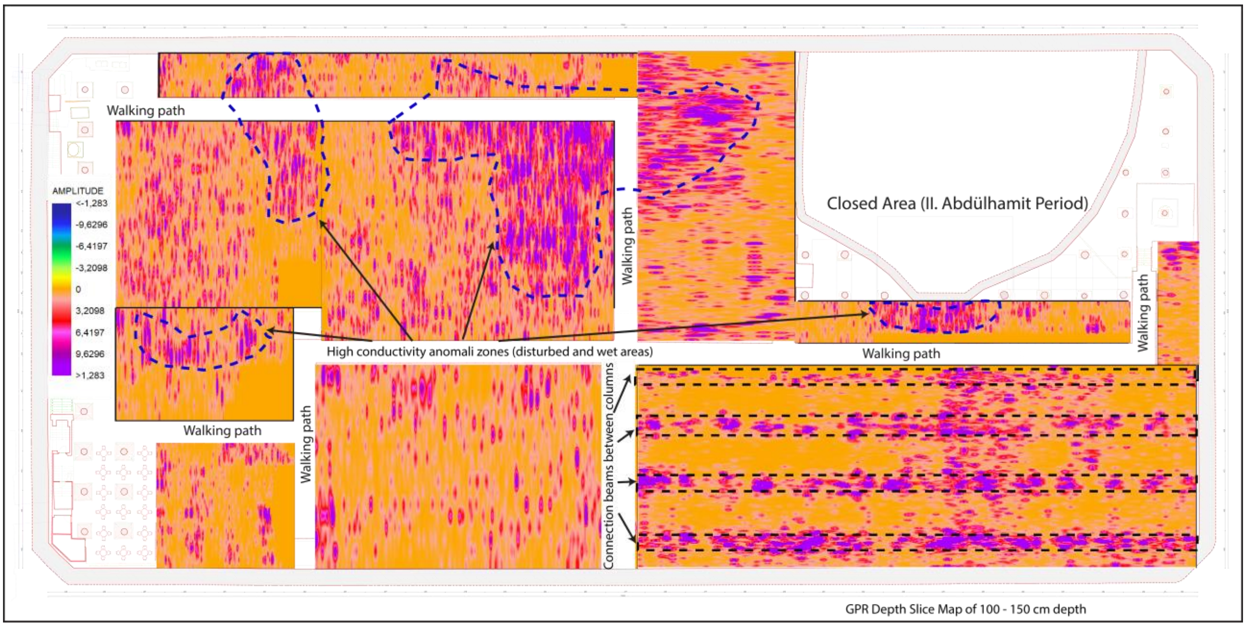

Figure 8. View of cistern floor and possible deformed regions obtained from GPR results

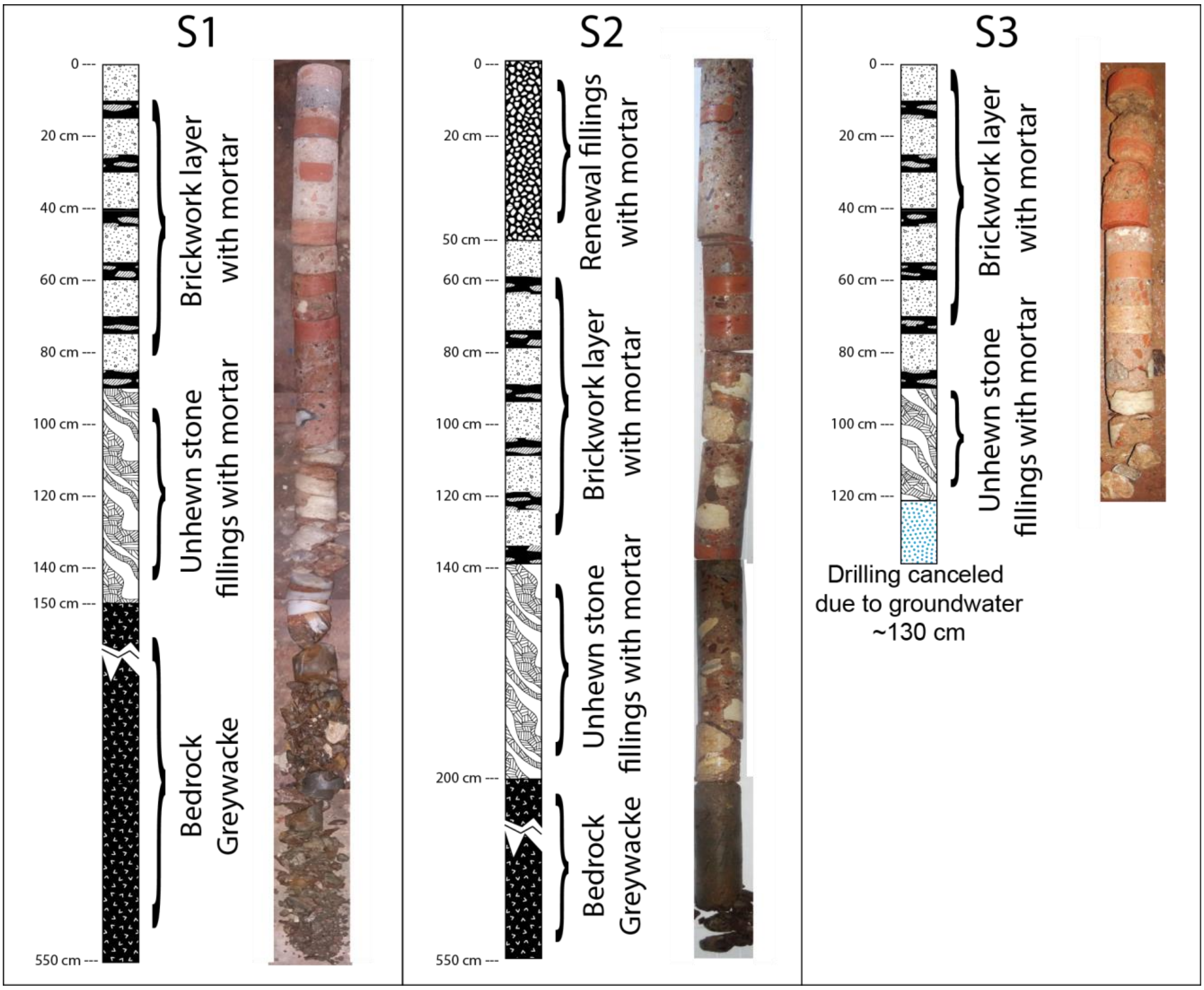

Figure 9. Logs from drilling in Istanbul Basilica Cistern

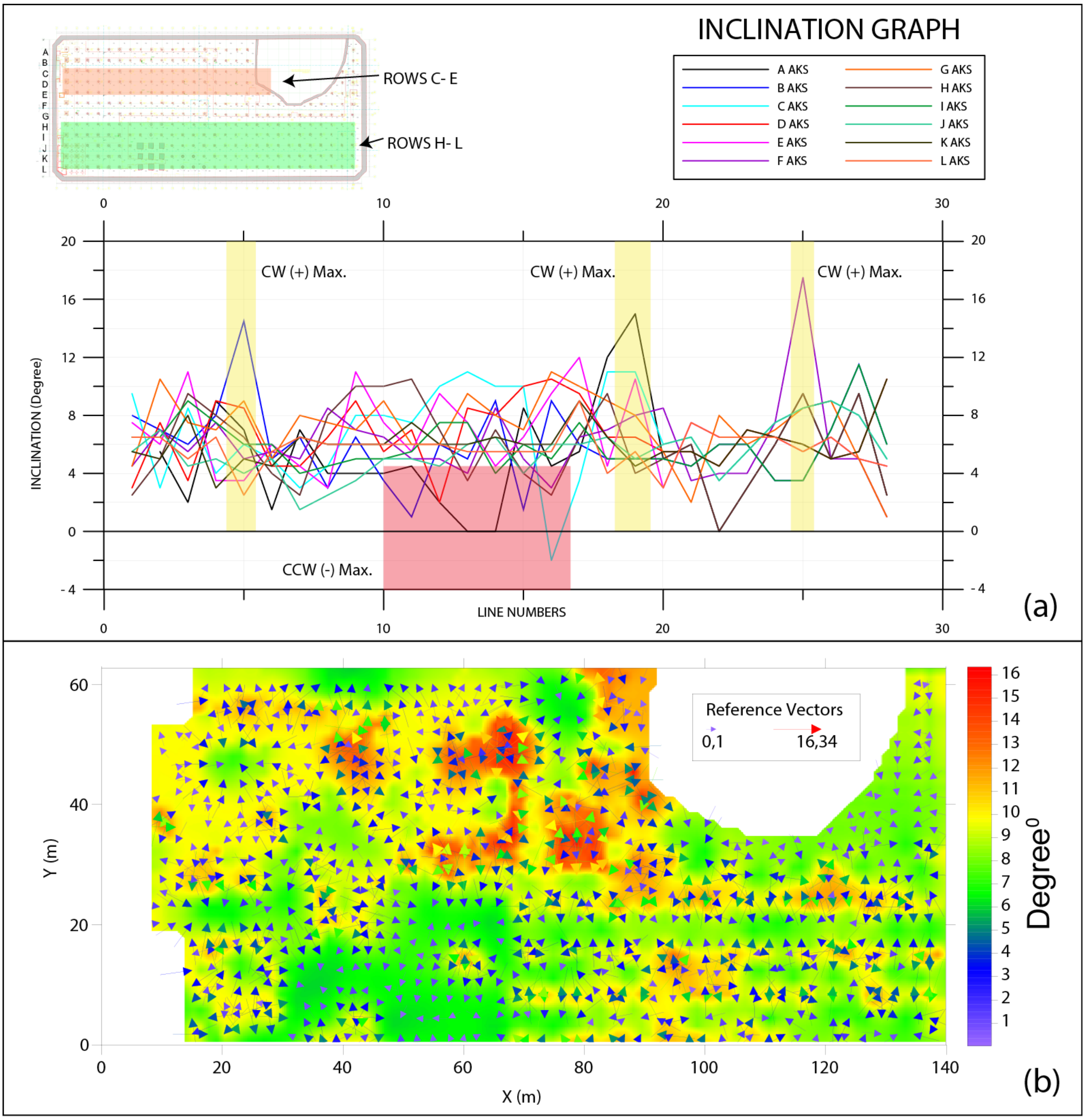

Figure 10. Graphical view of inclination measurements on columns

6. CONCLUSIONS

The results obtained in this study used these methods to research the floor and foundation structures of the Istanbul Yerebatan (Basilica) Cistern and were confirmed to be effective in accurately identifying degraded areas. At the same time, the materials forming these buried structures were identified allowing interpretation of construction processes. GPR measurements were completed by dividing the cistern floor into 10 associated areas. These measurements were combined to form a base map for depths from 100-150 cm. Accordingly, the north sections of the cistern were determined to be oversaturated degraded areas. Similarly, previously not well-known connecting beams between columns were identified. Information was reached about fill, compressed fill, basement rock depth and groundwater depth which are important in order to identify the structure of the cistern foundation. Three drillings were completed which confirmed the GPR results. Accordingly, brick and mortar and then rubble and mortar mixtures at varying depths to about 150 cm were lain directly on bedrock as a fill foundation or impermeable levels. The inclinations observed on the columns did not display very pronounced orientation distribution; however, the columns had greater inclination compared to other sections especially in the northern section where ground weakness was observed, and the column inclinations were about 10-16° for columns in rows C-E. The column inclinations appeared to be less than 10° in other areas with less ground deformation observed, with mean values from 7-8°. Especially in southwest section of the cistern, the column inclinations in rows H-L have homogeneous distribution with equivalent values (Fig. 10). When the orientation in this area is examined, the dominant orientation is observed to be west-southwest. Earthquakes affecting Istanbul are generally due to the branches of the right-lateral strike-slip North Anatolian Fault Zone within the Sea of Marmara. This overlaps with information obtained from old references about the source of the very destructive and high momentum earthquakes. This situation may explain the south-southwest oriented slops of columns observed in the Istanbul Yerebatan (Basilica) Cistern. However, the inclination variations in other areas are due to ground problems so a similar approach is not possible.

In this study the importance of discovering these elements in order to increase information about cultural heritage and to know and develop the preservation status of material forming these structures is emphasized. Results clearly show the versatility and potential of the recommended methods and provide favorable results for further implementation in other similar or more complicated case studies.

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