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«M.Sc. Protection of Cultural Heritage and Monuments of
Nature from the Effects of Climate Change»

Postgraduate Dissertation

«Hagia Sophia in urgent need of protection from the effects of
seismic activity»

Maria Karkali

Patra, September, 2026

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«Hagia Sophia in urgent need of protection from the effects of
seismic activity»

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Abstract

This thesis focuses on protecting Hagia Sophia in Istanbul from the effects of seismic activity. Boasting a 1.500-year history and unique Byzantine architecture that remains impressive to this day, it is one of the world's most significant cultural heritage monuments. It has long been studied by engineers worldwide, and its preservation requires a meticulous approach given its vulnerability to earthquakes. The area in which the Hagia Sophia is located is well known for its high seismic activity, which has repeatedly damaged the monument throughout history. Istanbul lies near the North Anatolian Fault, one of the world's most active faults, and is therefore one of the most seismically active regions in the world. The monument's architecture is complex and unique, combining a massive central dome, semi-domes, arches and massive piers. This study aims to formulate an action plan exploring conservation approaches designed to enhance seismic resilience without compromising the monument's historical integrity. The methodology integrates detailed historical documentation and an evaluation of strengthening interventions, as well as the building's history of earthquake-related damage. The immediate objective is to mitigate and control seismic risk. This study will contribute to the sustainable preservation of Hagia Sophia, an integral part of world history. Finally, the thesis proposes a practical action plan covering the various stages of a seismic event and its management, providing a framework for long-term preservation in the face of seismic threats.

Keywords:

Cultural Heritage, Seismic activity, Earthquakes, Monument, action plan, preservation

Περίληψη

Η παρούσα Διπλωματική ασχολείται με την προστασία της Αγίας Σοφίας στην Κωνσταντινούπολη από τις επιπτώσεις της σεισμικής δραστηριότητας. Πρόκειται για ένα από τα σημαντικότερα παγκόσμια μνημεία της Πολιτιστικής κληρονομιάς. Αποτελείται από μια ιστορία 1.500 χρόνων και μία μοναδική Βυζαντινή αρχιτεκτονική που εντυπωσιάζει ακόμη και σήμερα. Έχει υπάρξει στο επίκεντρο των μελετών εδώ και πολλά χρόνια από πολλούς μηχανικούς ανά τον κόσμο ενώ η προστασία του χρειάζεται λεπτομερή χειρισμό καθώς πρόκειται για ένα ευάλωτο σεισμικά μνημείο. Η περιοχή όπου βρίσκεται η Αγία Σοφία είναι ευρέως γνωστή για την υψηλή σεισμική δραστηριότητα της και από τους ιστορικούς ακόμα χρόνους έχει επιβαρύνει το μνημείο με επανειλημμένες ζημιές. Η Κωνσταντινούπολη είναι μία από τις πιο σεισμογενείς περιοχές στο κόσμο, καθώς βρίσκεται κοντά στο Ρήγμα της Βόρειας Ανατολίας το οποίο είναι από τα πιο ενεργά. Η σύνθετη αρχιτεκτονική του είναι μοναδική καθώς συνδυάζει έναν κεντρικό τεράστιο τρούλο, ημιθόλους, καμάρες και ογκώδης πεσσούς. Η παρούσα μελέτη στοχεύει σε ένα σχέδιο δράσης που διερευνά προσεγγίσεις συντήρησης που στοχεύουν στην ενίσχυση της ανθεκτικότητας στους σεισμούς χωρίς να αλλοιωθεί η ιστορική ακεραιότητα του μνημείου. Η μεθοδολογία ενσωματώνει την αναλυτική ιστορική τεκμηρίωση, την παλαιότερη παθολογία του κτιρίου λόγω των σεισμών και την αξιολόγηση επεμβάσεων ενίσχυσης. Άμεσος στόχος είναι ο μετριασμός και έλεγχος του σεισμικού κινδύνου. Η μελέτη συμβάλλει στη βιώσιμη διατήρηση της Αγίας Σοφίας ως ένα μνημείο που αποτελεί αναπόσπαστο κομμάτι στην παγκόσμια ιστορία. Τέλος, η Διατριβή προτείνει ένα πρακτικό σχέδιο δράσης για τα στάδια του σεισμού και της διαχείρισης του, παρέχοντας ένα πλαίσιο για τη μακροπρόθεσμη διατήρηση ενόψει σεισμικών απειλών.

Λέξεις κλειδιά:

Πολιτιστική κληρονομιά, Σεισμική δραστηριότητα, Σεισμοί, Μνημείο, Σχέδιο δράσης, Διατήρηση

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1 Introduction

The Hagia Sophia is one of the world's most significant architectural monuments and has been extensively studied historical structures in terms of earthquake resistance and seismic vulnerability. Seismic activity is one of the most dangerous natural hazards, particularly with regard to the protection of cultural heritage. The Hagia Sophia is located in Istanbul, Turkey, very close to the North Anatolian fault zone. Throughout its 1.500-year history, it has experienced numerous earthquakes. Constructed in 537 AD by order of the Byzantine Emperor Justinian I, the monument has suffered repeated structural damages over the years, including the collapse of the main dome, cracked walls and numerous deformations. Despite these challenges, the monument has survived thanks to continuous repairs, reinforcements, and architectural modifications carried out during both the Byzantine and Ottoman periods.

The seismic behavior of Hagia Sophia is of particular importance because the structure combines massive masonry elements, a large central dome, semi-domes, arches, and supporting piers, all of which respond differently to earthquake forces. For many years, researchers from all over the world have been studying the monument, not only as an architectural masterpiece, but also as an example of how ancient builders attempted to solve complex structural problems in an earthquake-prone region. Modern seismic analysis has revealed that the survival of Hagia Sophia is due to a combination of innovative engineering, flexible construction materials, and centuries of restoration works. However, the monument remains vulnerable to future earthquakes, especially considering the continuing seismic threat in the Marmara region near Istanbul. For this reason, Hagia Sophia represents both an extraordinary achievement of historical engineering and an ongoing challenge for modern conservation and earthquake protection.

This thesis focuses on investigating the seismic vulnerability of the monument and exploring appropriate protection strategies. Particular emphasis is placed on examining the monument's weak and compromised areas, past interventions and new measures that do not compromise its authenticity.

The research focuses on the following questions:

1. In what ways is the monument's seismic response affected by its current condition?

2. Which methods are most suitable for protecting and reinforcing this specific structure?
3. What action plan would be suitable for establishing a sequence of priorities for the stages of inspection and intervention?
4. Which monitoring methods have been used in the monument in the past?

1.1 Methodology

1.1.1 Analysis of methodology

This thesis aims to investigate and analyze Hagia Sophia in the context of seismic activity. More specifically, it examines past earthquakes, their impact on the monument and the interventions that have been carried out. It also proposes a protection and intervention plan for future earthquakes. As a globally significant cultural monument with a long history of transformation, Hagia Sophia has been the subject of extensive research and discussion over the years. Its location in one of the world's most seismically active regions makes its history even more remarkable. The central question of this research is how to ensure the monument's future protection. This may rely on historical intervention methods, as well as modern techniques. Another important question is how the 1,500-year-old monument can survive for even longer. Remarkably, it is still standing despite numerous interventions and maintenance works over the years. Consequently, a continuous monitoring plan we required to ensure its optimal protection. Various sources were used, including research studies and articles published in recent years. The compilation of the theoretical material was carried out primarily between January and April 2026. Finally, publications and sources in Greek and English were used.

1.1.2 Limitations of the study

This thesis is certain to many limitations, resulting in the research and its conclusions being primarily theoretical in nature

- .
- 1. Firstly, access to the monument is limited, meaning on-site measurements and invasive testing are restricted. Hagia Sophia is both an active place of worship and a monument of significant cultural value.
- 2. Reliance on secondary sources. This research project primarily relies on published studies, historical archives and technical reports, as there is no opportunity to collect primary data.
- 3. Uncertainty of the historical record. Descriptions of earthquakes and damage are based on the accounts of chronicles or later analyses, and are not always complete or consistent. Especially considering that the monument has 1500-history, it is practically impossible for all authentic records to have survived to the present day.
- 4. A lack of direct seismological data means that there are no recorded measurements of ground motion intensity for past earthquakes. This limits the accuracy of the analysis.
- 5. The monument has undergone numerous interventions. Successive repairs and reinforcements make it difficult to distinguish between the monument's original and current structural behavior.
- 6. The interdisciplinary nature of the subject. Understanding seismic behavior requires knowledge from several disciplines, including seismology, structural engineering, history, and architecture and materials science. It is challenging for a single study to cover all these dimensions comprehensively.

7. The temporal scope of the research. The study reflects the knowledge available when it was conducted. New scientific data or future earthquakes may alter these conclusions.

2. Historical and structural evolution of Hagia Sophia

Its long history reflects the political, religious, and cultural changes that shaped both Istanbul and the wider world. Throughout different historical periods, Hagia Sophia has remained a symbol of architectural and historical achievement.

Byzantine Period

The Byzantine period was one of the earliest and one of the most significant phases in the Hagia Sophia's history. During this period, the monument served as the religious, political and cultural center of the Byzantine Empire and became the most important church in Eastern Christianity. Constructed during the reign of the Emperor Justinian I, the Hagia Sophia was a symbol of power, wealth and spiritual authority of Constantinople, the capital of the Eastern Roman Empire. Completed in 537 AD, it served as the principal cathedral of the Eastern Orthodox Christianity for almost 1.000 years. It was commissioned by the Justinian, after the Nika revolt. During the Byzantine period, Hagia Sophia faced significant structural challenges due to continuous earthquakes. Constantinople was located in a seismically active region, and several earthquakes caused serious damage to the building. In 558 AD, just a few decades after its completion, a major earthquake caused the central dome to collapse. The dome was rebuilt under the supervision of Isidore the Younger, nephew of the Isidores of Miletus, who modify it to improve its stability by increasing its height and altering its curvature. Additional earthquakes in later centuries caused further cracking and structural damage, leading Byzantine engineers to continuously reinforce the structure. The end of Byzantine period of Hagia Sophia ended in 1453 with the Ottoman conquest of the city. Following this, Hagia Sophia was converted into a mosque, marking the transition from Byzantine Christian to Ottoman Islamic rule. During this period, four minarets were added to the building.

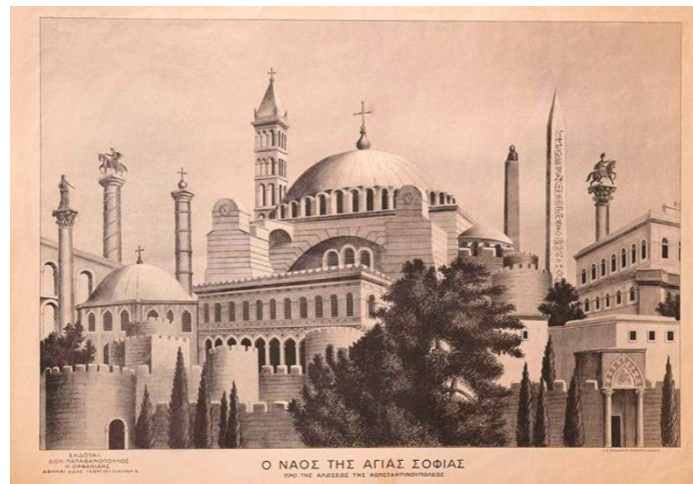


Figure 1. Hagia Sophia before Ottoman conquest. Source: ProtoThema

Ottoman conquest period

On Friday, 29 of May 1453, the city was captured by the Turkish. Constantine Palaiologos IX was defeated, and the Hagia Sophia was converted into a mosque by Sultan Mehmed II following the Ottoman conquest.

The Ottoman conquest was one of the most important turning points in the history of Hagia Sophia. It brought an end to the Byzantine Empire, which had existed for over one thousand years, and transformed Constantinople into the new capital of the Ottoman Empire. The conversion of one of the most important churches in Eastern Orthodox Christianity into a mosque symbolized the transfer of political and religious power from the Byzantines to the Ottomans.

By converting it into a mosque, the Ottomans demonstrated their victory and established Islamic authority over the newly conquered capital. At the same time, however, the structure itself was preserved, enabling one of the world's greatest architectural monuments to survive to this day.

Modern period- Present

In 1935, Mustafa Kemal Ataturk, the founder of the Turkish Republic, converted the Hagia Sophia into a museum and opened it to the public. During World War II, the structure began to deteriorate due to neglect. Damage occurred during this period, including moisture entering from below, which increased humidity levels and caused cracks to appear in the building's copper roof.

The modern era of the Hagia Sophia began in the 20th century, following the collapse of the Ottoman Empire and the establishment of the Republic of Turkey. This era brought significant political, cultural and religious changes that alerted the monuments function and global significance. During this period, the Hagia Sophia evolved from an Ottoman Imperial mosque into a museum, and was later, in 2020 returned to its status as a mosque.

Ataturk introduced a series of reforms aimed at modernizing and secularizing the new Turkish state. The decision to transform the Hagia Sophia from an exclusively religious space into a cultural monument representing the shares heritage of humanity was highly symbolic.

Converting the building into a museum enabled scholars and restorers to begin extensive conservation work. Many Byzantine mosaics, which had been concealed during the Ottoman period, were uncovered and restored, revealing some of the finest surviving examples of Byzantine art. Important Islamic features such as calligraphic panels, the mihrab, and the minbar, were also preserved, resulting in a unique fusion of Christian and Islamic artistic traditions within the same structure. As a result, Hagia Sophia has become an international symbol of cultural dialogue between the East and West, Christianity and Islam, and Byzantine and Ottoman civilizations.

The Hagia Sophia is also recognized as one of the world's most significant architectural and historical monuments. Millions of visitors from around the world travel to Istanbul to study and admire the building. In 1985, it was added to the UNESCO World Heritage Site list as part of the historic areas of Istanbul, and is recognized by UNESCO as a unique cross-cultural monument, blending Byzantine engineering with Islamic additions (United Nations Educational, Scientific and Cultural Organization (UNESCO), 1985). This recognition emphasized the monument's universal cultural value and the need to preserve it for future generations.

2.1 Historical Significance of Hagia Sophia

The Hagia Sophia is one of the most important monuments in the world history because it reflects the religious, political, cultural and architectural development of several civilizations over nearly fifteen centuries. Located in Istanbul, Turkey, the Hagia Sophia is a unique symbol of the interaction between Christianity and Islam, as well as between the Eastern and Western Worlds. Its long and complex history demonstrates how architecture can represent a powerful authority, religious identity, and cultural continuity.

It is recognized as both the world's largest domed building and one of its most significant historic structures (T. A. Ozkul, E. Kuribayashi, 2007). The architects Isidore of Miletus and Anthemius of Tralles solved the age-old problem of constructing a circular dome on a square base by using pendentives-curved triangular sections that transition from square corners to a circular dome base. This innovative technique, which had never been used or was possible before, created a much larger, more open interior space (Hagia Sophia, n.d.). This style of architecture was so influential that churches are still built this way today.

The Hagia Sophia site originally hosted two earlier churches. The first, a monumental basilica known as the great church, was built by Constantinus I and II in 360 AD. After it burned down during riots, a second church was completed in 415 AD under the reign of Theodosius II. Both constructions were destroyed during the Nika Revolt in 532 AD (B. Atchison, 2008). Following the revolt, Emperor Justinian I ordered the construction of a completely new church. It was completed in five years, in 537 AD. According to the legend, when Justinian entered the church, he proudly exclaimed: "Solomon I have surpassed you".

Externally, the building appears massive and austere. The enormous dome, supported by hemispherical niches, dominates the exterior. The buttresses (some of which were added later) enhance its stability.

Despite the changes through the years, Hagia Sophia remains a symbol of both Byzantine heritage and world architectural history. It has suffered several devastating earthquakes over the years, with magnitudes reaching up to 7.4 on the Richter scale.

The recorded earthquakes are listed in chronological order in Table 1. It has been reported that, since the church became inactive, it has experienced a dozen of earthquakes, including those in recent years. Unfortunately, there are no complete records of all the earthquakes or their exact dates.

The structure has suffered extensive earthquake-related damage. The most critical incidents occurred in 558 AD with the collapse of the eastern arch, 989 AD with the collapse of the western arch and 1346 AD were once again, collapse of the eastern arch, along with sections of the main dome and the semi-domes. Notably, the damage in 558 was so severe that the dome collapsed and had to be replaced (T. A. Ozkul, E. Kuribayashi, 2007). The form and structural behavior of the dome were changed.

In addition to the interventions that followed the aforementioned earthquakes, the architect Mimar Sinan's reinforcements are also highly significant. In the 16th century, he built retaining walls and buttresses outside the building for support (Cahit Çağlar Yalçiner et al., 2017). The Ottoman government also hired the Fossati brothers to oversee the structure's latest restoration in 1846. According to Richard Winston, the author, from 1847 onwards, the brothers helped to align the building's columns and reinforced the northern and southern arches with tie rods to limit lateral thrusts. They also fortified the dome by wrapping it with a pair of iron chains. They also removed the flying buttresses on the north and south sides of the dome, deeming them unnecessary for the buildings structural integrity. Winston also noted that they repaired some of the marble cladding inside the building. The restoration was completed in 1849 (T.R. Witcher, 2022).

The seismic damage and subsequent repairs played a decisive role in gradually altering the monument's structural behavior.

2.2 Period of construction

The current Hagia Sophia was constructed in the remarkably time of five years, from 532 to 537 AD. It was designed by the architects Anthemius of Tralles and Isidore of Miletus and it was built following the destruction of the previous church during the Nika Riots (Editors of Britannica, n.d.)

It is considered one of the greatest construction works of the Middle Ages.

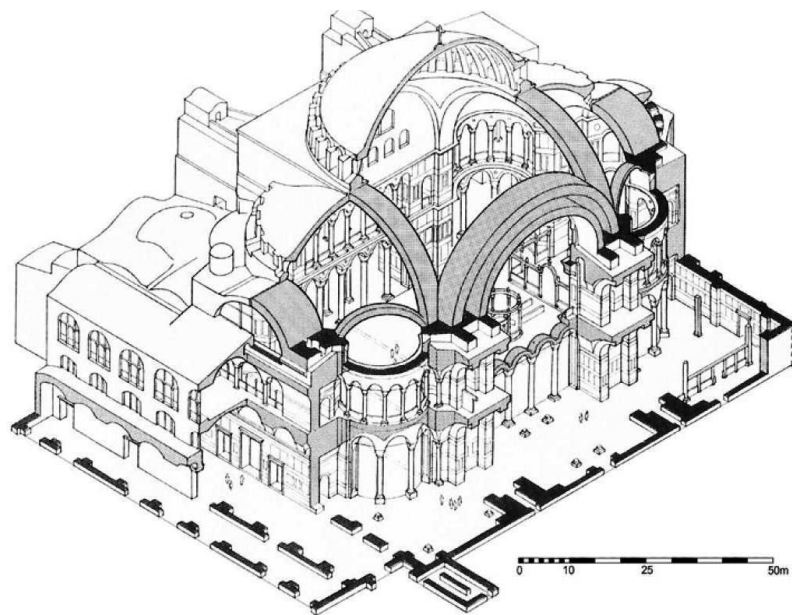


Figure 2. Hagia Sophia, isometric view (Mainstone 2006) Source: ResearchGate uploaded by Karl Schweizerhof

The original church to occupy the site, called the Megali Ekklesia, was commissioned by the Emperor Constantine I in 325. It was razed during a public disturbance in 404, later rebuilt, and destroyed once again in 532, before Justinian commissioned the current building. Throughout the Byzantine period, mosaics were added, and structural modifications were made in both the Byzantine and Ottoman periods. Features important to the Islamic architectural tradition were also constructed under the Ottoman emperors (Editors of Britannica, n.d.). The name "Hagia Sophia" did not come about until around 430 CE. This is not the only name by which the structure has been known. The main reason the church was built in the first place was for Justinian to make a political statement through the building's religious function. Its

enormous scale was intended to demonstrate imperial power and the prosperity of Hagia Sophia.

2.3 Architectural and structure system

It is undoubtedly, a masterpiece of Byzantine Architecture that ingeniously combines a traditional longitudinal basilica with a centralized, domed structure. The specific architectural and structure systems is one of the most innovate in history because of the combination of the basilica and a centralized domed structure.

According to a structural analysis by Princeton university Department of civil engineering, it is considered possible that the Pantheon was the main structural model for translating Roman concrete into large-scale brick construction in the Byzantine era (R. Mark et al. ,1993). This masterpiece of Byzantine architecture combines Byzantine engineering with eastern aesthetics. The results are a square space that symbolizes the Earth. (Hagia Sophia 1500 years of history, n.d.)

- **Domed Basilica Hybrid**

It merges a longitudinal basilica plan (a rectangular hall) with a central dome creating a vast, unified interior space. This hybrid system was revolutionary technique at the time. Measuring 31.87 meters in diameter, this particular dome was the largest spherical dome built until the 16th century. Forty windows open around the perimeter of the pseudo-dome, creating the feeling that the dome was floating above the temple due to refraction of light. Initially, the dome was lower and a hemisphere. Due to the greater thrusts that were developed, however, it could not withstand its own weight and collapsed after twenty years of its construction in 558 AD. A closer examination to the dome from below reveals irregularities that may some find surprising. There are expected since the innumerable repairs and deformations caused by earthquakes and the 1500 year old building. The greatest achievement was placing the dome not on the exterior walls, but on four immense arches resting on four massive piers. The transition from the square to the round dome was achieved by filling in the empty corner spaces with spherical triangles called pendentives (Confinity Heritage

Editorial, 2026). This structural innovation made it possible to extend the building with vaults and semi-domes beyond the dome’s own extend. Extending the dome using adjoining semi-domes creates a harmonious expansion that is impressive from every angle.

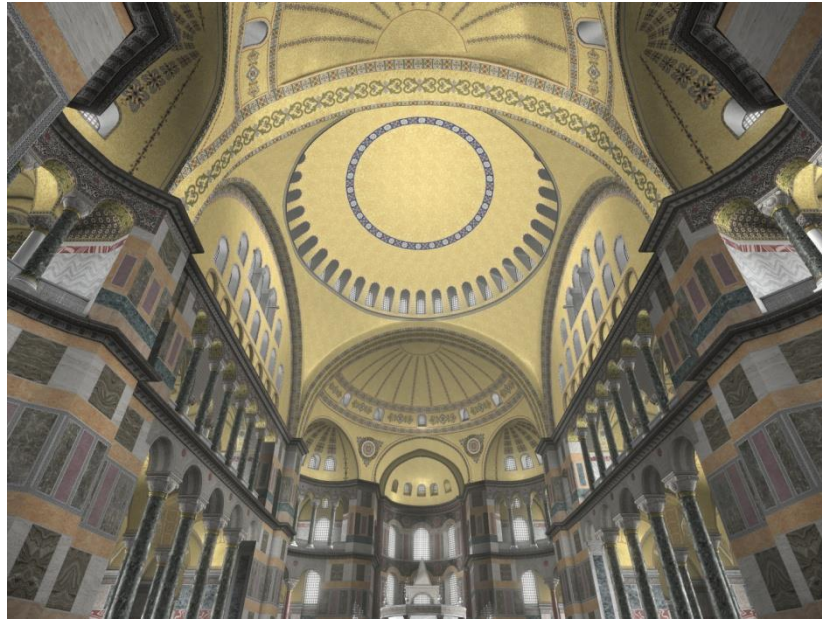


Figure 3. Digital 3D reconstruction of the interior of Hagia Sophia in Istanbul.. Source: ime.gr

- Spherical Triangles (pendetives)

Supporting a dome in a square space required an innovative design involving four spherical triangles- a method that had never before been used in architecture. Earlier systems, such as semi-cones and the projecting systems were imperfect and could only cover much smaller areas. The spherical triangles transfer the enormous load of the dome’s circular base to its four supporting points (Hagia Sophia, 1500 years of history).

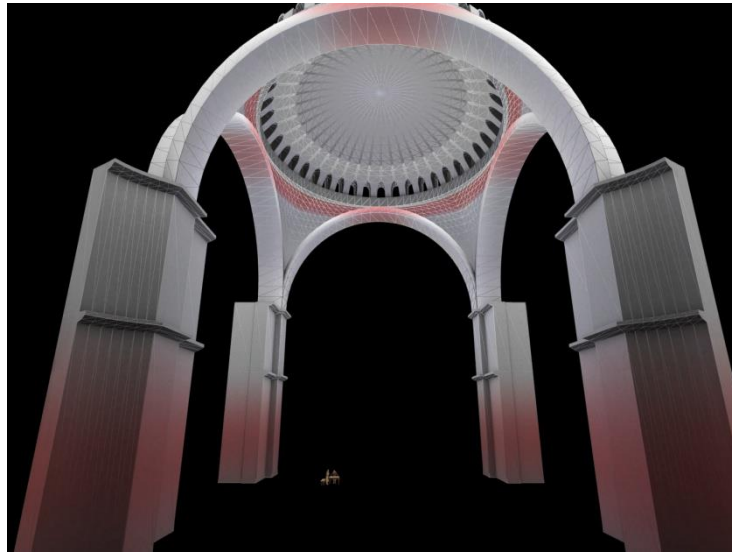


*Figure 4. The spherical triangles supporting the dome transfer the immense loads from the dome's circular base to four supports.
Source: fhw.gr*

- Central dome on pendentives

Dome is “a rounded roof with a circular base.” (Oxford Keys, 1980, p.112) The massive central dome, which is about 31 meters in diameter, rests on four arches. These arches are supported by four massive piers. The transition from the square base to the circular dome is achieved using pendentives, a key structural innovation.

- Semi-domes

Two enormous semi-domes are positioned to the east and west of the central dome of Hagia Sophia. This positioning counterbalances the significant lateral forces and distributes the weight of the roof throughout the rest of the structure. As there are no intermediate walls or columns on the east and west sides, the interior sides appear to flow seamlessly beneath the semi-domes. Each semi-dome is shaped like a tetrahedron of a sphere. Together with the central dome and smaller niches they create a sense of continuous curvature. Important elements of the temple are also revealed on the surfaces of the semi-domes, including depictions of Christ, the Virgin Mary and the Apostles.

Buttressing

The four massive internal stone and granite piers, some added in different periods in history to prevent walls from buckling under lateral weight.

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Figure 5. Buttresses Source: HagiaSophiaturkey.com

2.4 Materials and construction techniques

2.4.1 Material Introduction

The core structure of the Hagia Sophia is made of brick and mortar and is faced with marble. It is also decorated with colored stone and gold mosaics. These were primarily employed in the construction of arches, vaults, walls, and the dome. The bricks were relatively thin and flat, in the Roman style. The main advantage of this material is that it is much lighter than the stone. According to an ancient text, it was manufactured on the island of Rhodes. Unlike those from other churches, the bricks had 45% porosity (A. Moropoulou et al., 2004), which reduces the weight carried by the building's structural supports. This is particularly important in the dome, minimizing dead load is essential here. The bricks were bonded with lime mortar, and the mortar joints were often thicker and more elastic than the bricks themselves, improving the structure's flexibility and ability to absorb seismic forces. Hagia Sophia's material reflects a combination of Roman engineering and Byzantine luxury. The main materials that are used for the core structural are:

- **Masonry mortar:** The original Byzantine mortar was made from lime, crushed brick and a volcanic ash, known as pozzolana. This mixture is classified as an advanced cement-based composite material. This could explain why the structure has lasted so long. The mortar joints in the Hagia Sophia are notably thicker than the bricks themselves. This enables the walls and arches to absorb and redistribute stresses, providing strength and durability. This combination of materials is characterized by a very long curing period (Moropoulou A. et al., 2006). This is a significant factor in the building's seismic resistance, given that Istanbul is one of the most seismically active cities in the world.



Figure 6. Masonry detail with exposed thin bricks and integrated thick mortar joints

Source hagiasophiatrkey.com

- Marble, was used for the interior decoration of Hagia Sophia. Imported from across the Byzantine Empire, the costly colored marble and ornamental stone inlays were taken from ancient buildings and reused to support the interior arcades. Key marble materials included green columns from the Temple of Artemis in Ephesus, Celtic marble from France and white marble from Marmara (Tribe, 2025). Procopius says, “...Who could recount the beauty of the columns and the stones with which the church is adorned? One might imagine that he had come upon a meadow with its flowers in full bloom....”(Hagia Sophia, n.b.).



Figure 7. Colored and decorative stones in Hagia Sophia

Source: hiagiasophiatrkey.com

Types of marble:

Proconnesian marble: From Marmara Island, (formerly Proconnessos). It is white with grey veins, and is the most common material used for floors, lower wall sections, columns, and so on. This marble is highly valuable thanks to aesthetic appearance and ease of processing. It is a medium-grade rock (S. Ongen, N. Aysal, 2020).

Thessalian green marble (Verde Antico): is a vibrant green stone with white patterns and is mostly used for columns and large panels. It was considered a very prestigious material due to its rarity and bright color (B. Atchison,n.d.).

Phrygian purple marble (Pavonazzetto): Located in Phrygia, it has been used in many Mediterranean structures, and the violet color of the marble is due to the presence of iron oxide and phlogopite minerals (M.Y. Celik, M. Serte, 2020).

Egyptian granite (a porphyry very similar to marble): It is a deep red/purple color and is extremely hard and rare, and a symbolizing the imperial power. It was particularly used for the imperial thrones and mosaic frames.

Marble was primarily used for surface and architectural finishes rather than as a primary structural material. Not only does it add significant character to the already impressive structure thanks to the marble's inherent qualities, but each piece also tells a unique story and represents a specific location, lending an additional layer of symbolism.

The newspaper clipping below, (Γ. Λεκάκης, 2003), mentions the twelve different types of marble found in Hagia Sophia and the symbolism behind this choice.

Ελληνικό Λεξικό

60 | ΕΘΝΟΣ ΤΗΣ ΚΥΡΙΑΚΗΣ | 14 Δεκεμβρίου 2003

Γράφει ο συγγραφέας - λαογράφος ΓΙΩΡΓΟΣ ΛΕΚΚΗΣ

Ξέρετε ότι...

12 ΔΙΑΦΟΡΕΤΙΚΑ είδη μαρμάρων είχαν συλλεχθεί και επιστρατευθεί για να κοσμήσουν τον ναό των ναών, την Αγία Σοφία της Κωνσταντινουπόλεως. Κι αυτό γιατί και η Γη αποτελείται από 12 χρωματιστά είδη δέρματος, εάν τη δει κάποιος από ψηλά (Πλάτων «Φαίδων»), χρώματα που έχουν αντιστοιχίες στους 12 αρχαίους Έλληνες θεούς και τα 12 ζώδια. Αυτά ήταν:

Το πράσινο θεσσαλικό ή μολοσσικό, το λευκό βοσπόριο (εκ του Βοσπόρου), το πορφύρεο από τις Θήβες, το κιτρινόλευκο με τις αμύγδαλες φλέβες, το ιασικό (από την Καρία της Μ. Ασίας), το πρασινόλευκο καρύστιο (από την Κάρυστο), το μαύρο με τις γαλακτώδεις κηλίδες, το κελτικό (από τη Γαλατία της Μ. Ασίας), το πράσινο με τους πολύπλοκους ελιγμούς, το λακωνικό (απ' τα μάρμαρα που εξορύσσονται από τον Ταΰγετο), το υποκίτρινο χρυσαφί ή κροκώδες, το λιβνικό (από τη Λιβύη), το ωχρό με τις ερυθρές κηλίδες, το λυδικό (από τη Λυδία της Μ. Ασίας), το ζωηρό μελί με τις κυματοειδείς ζώνες, ο όνυχας ή αλάβα-

στρος από την Αίγυπτο, το λευκό με τις ελαφρώς φαιές ραβδώσεις, το προκοννήσιο (από την Προκόννησο του Μαρμαρά). Τέλος, το ροδόχρωμο με τις λευκές κηλίδες, το φρύγιο ή μυγδόνιο (από τη Φρυγία των Μακεδονοθρακών στη Μ. Ασία).

Εργάστηκαν 10.000 εργάτες για το κτίσιμο και δαπανήθηκαν περισσότερα από 300.000.000 χρυσές δραχμές! Παρ' όλα αυτά, το έργο τελείωσε σε απίστευτο χρόνο: Μόλις σε λιγότερο από 6 χρόνια! Ο θεμέλιος λίθος τέθηκε την 24η Φεβρουαρίου 532 και τα εγκαίνιά της έγιναν την 27η Δεκεμβρίου 537 μ.Χ... Το σουράνιο εγκαλλώπισμα φωτίζεται από 40 περιμετρικά παράθυρα και στηρίζεται σε 4 κίονες, ύψους 24,3 μ. ο καθένας, προς την κορυφή του τετραγώνου, τόσο ευφάνταστα αρχιτεκτονικά, ώστε δίνει την εντύπωση πως ο ολόχρυσος τρούλος αιωρείται. Σε αυτόν τον ναό χωρούσαν να εκκλησιασθούν 23.000 άτομα!

Για περισσότερα: Θεοφάνης, Προκόπιος, Ανώνυμος χρονογράφος κ.ά.



Figure 8. Article from a newspaper in 2003 about the marbles in Hagia Sophia. Source: Ethnos tis kiriakis-Giorgos Lekkas

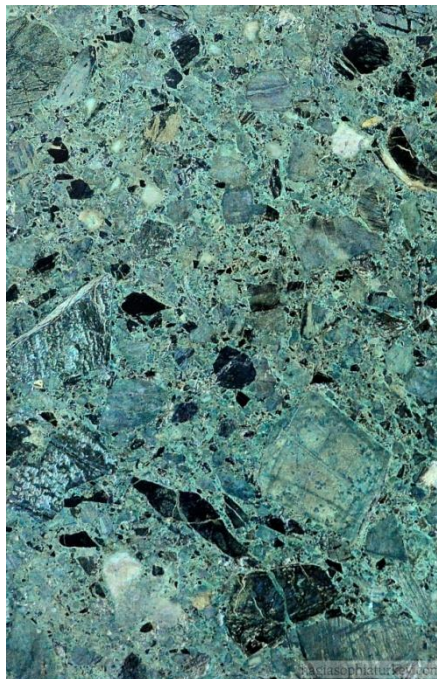


Figure 9. Verde Antico in Hagia Sophia. Source: hagiaphotography.com

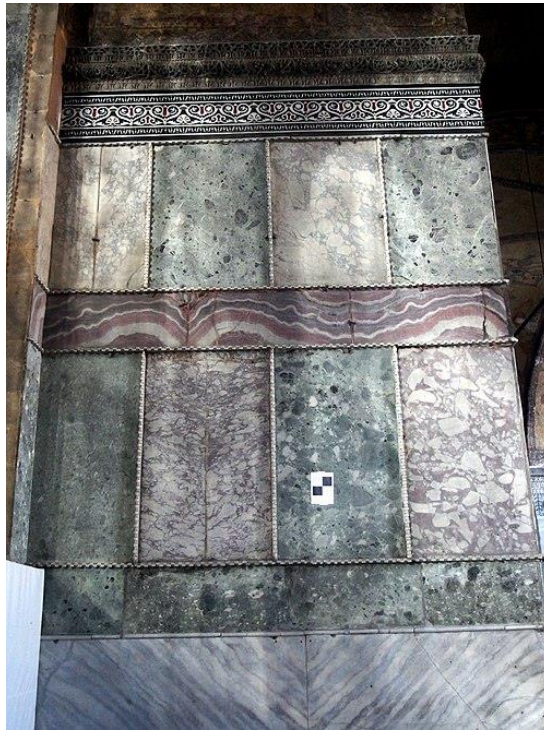


Figure 10. Source hagiasophiaturkey.com



Figure 11. Light-colored sections of Proconnesian marble). Source hagiasophiaturkey.com

- Stone, were mainly used for foundation and load-bearing elements
- Mosaics, consisting of small pieces of colored glass and stone arranged together, were used to decorate the interior. They depicted scenes from the lives of Jesus, the Virgin Mary, and various saints. Several mosaics were added to the Hagia Sophia changing its appearance (Freeman E., n.d.) .It was believed that the color of gold symbolized light, and that light was a metaphor for God.
- Although timber was not the primary material used, it was very important during the construction process. It was used for scaffolding and to provide temporary support. It was also used to support arches and vaults while they were being built. Despite its importance, timber was still mostly used temporarily. However, legend has it that the Imperial Door in Hagia Sophia was made from no ordinary timber, but from Noah's Ark itself. This majestic door, which stands at around seven meters tall, was built using oak timbers (The editors of the Madain Project, n.d.). The original wooden roof was later replaced with lead sheets.



Figure 12. Cross section of a wooden log embedded horizontally in a textured
Source: hagiasophiatrueky.com

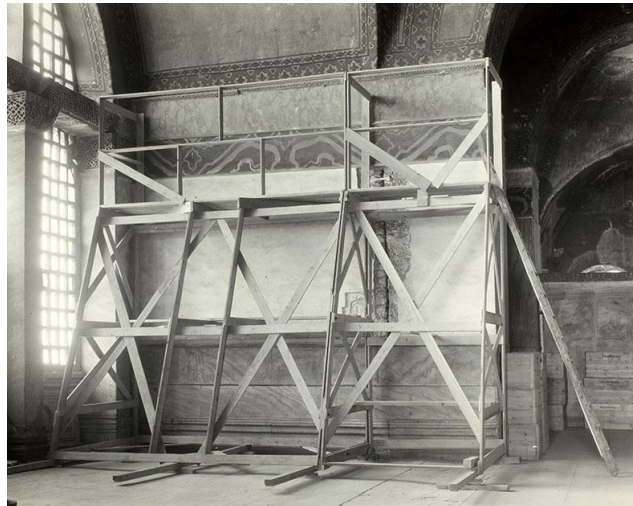


Figure 13. Wooden scaffolding in Hagia Sophia. Source: Pallasart Web Design

- Plaster was mainly used to cover the walls and ceilings. Following the Ottoman conquest of 1453 they were applied over the Christian gold mosaics inside the Hagia Sophia (T.F. Madden, 2016). While some mosaics were uncovered during restorations in the 19th and 20th centuries, others remain hidden to this day and some were completely destroyed.

Table 1. Material used in the Hagia Sophia

Material	Main use	Main purpose
Brick	Dome, arches, vaults, walls	Lightweight structural masonry
Mortar	Between bricks, thicker than the bricks	Flexibility and durability
Marble	Walls, columns, floors	Decoration
Stone	Structure and architectural	Strength and durability

	elements	
Mosaics	Decoration	Decoration
Plaster	Interior walls and vaults	Covering of mosaics
Timber	Scaffolding, construction support	Supporting

2.4.2 Construction techniques

Hagia Sophia is widely regarded as one of the greatest structures in history, not only because of its age and historical significance, but also because of its impressive construction process, which remains revolutionary even by modern engineering standards.

The core structural technique of the monument is its central load-bearing system, which supports the main dome. Specifically, the dome is supported by four great arches, and the spaces between them and the dome are filled in with spherical corner triangles called pendentives. This design feature enabled the transition to a square base from a hemispherical structure (Mudje Altin, 2001). This technique is still considered innovative to this day. Even more impressive is the fact that it was achieved within the technical limitations of the 6th century, when the monument was constructed. Many engineering developments have been implemented on the monument over the centuries. Yet this particular development is arguably the most impressive and significant of all.

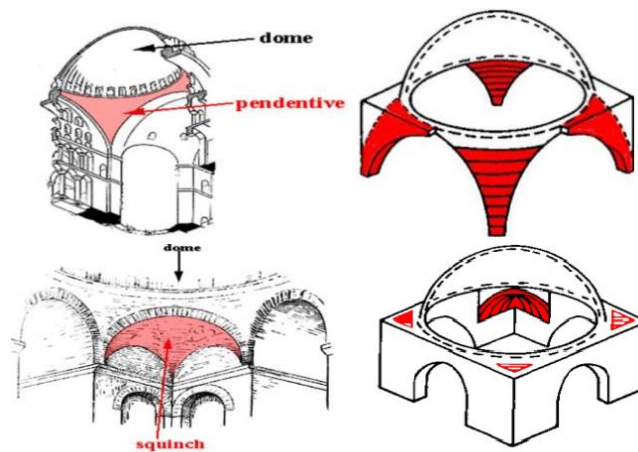


Figure 14. Shows transferring dome to a square plan by pendentives. Source: Saqer Saqur

In addition, the large arches and semi-domes help to distribute the weight and outward forces of the central dome towards the surrounding walls and supports. As previously mentioned, the builders opted for a combination of lightweight brick and thick mortar to reduce the overall weight of the upper structure, while also allowing for flexibility to this day during earthquakes. External buttressing provides additional support in the form of 40 spaced short ribs, which act as small windows, and deep foundations that transfer the buildings enormous weight into the ground. All of the above makes the complex structural system possible. Furthermore, the structure features a large number of windows to ensure optimal lighting. The dome alone contains an impressive 40 windows, creating an even more spectacular and majestic effect. The interior is paneled with colored marble and ornamental stone inlays (Mudje Altin, 2001).

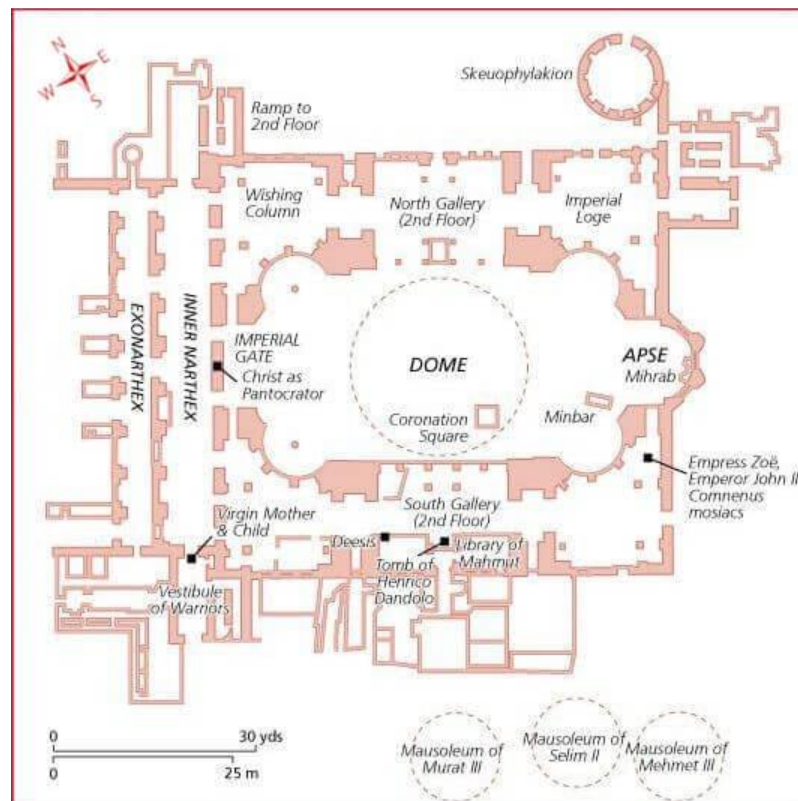


Figure 15. "Hagia Sophia Floor Plan" Source: muze.gen.tr

3. Seismic and Geology Context of Istanbul

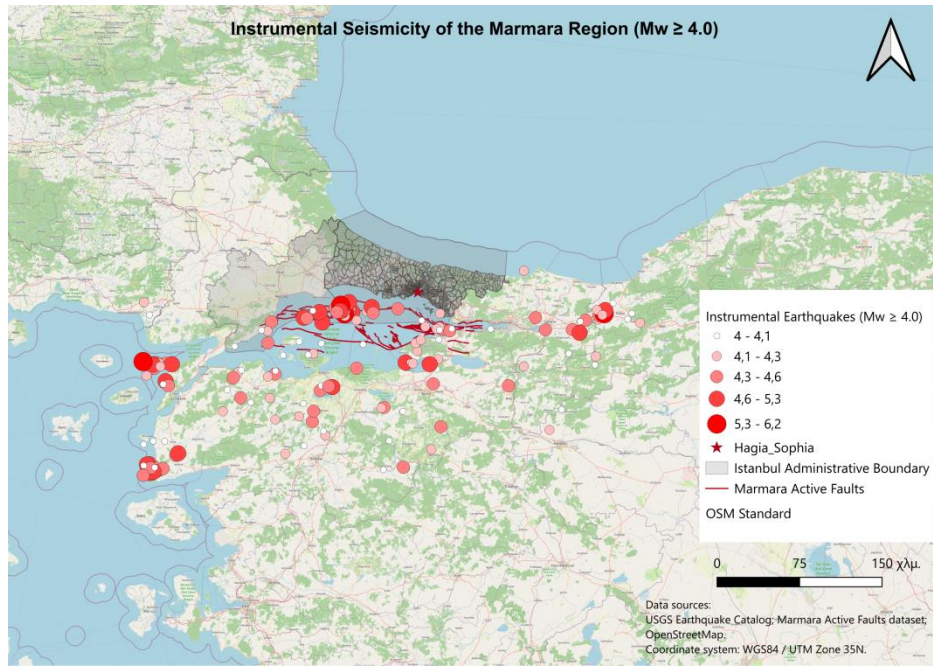


Figure 16 .Instrumental Seismicity of the Marmara region, Source: Maria Karkali using qgis

Tectonic Framework

Istanbul is considered to be in an extremely seismic area, as it is located near the North Anatolian Fault, one of the world’s most active seismic zones. This fault is situated approximately 20km south of the city and 17 km from the monument (GFZ, 2010). Around 98% of Turkey is prone to earthquakes, with approximately one third of the country located in high-risk areas. More specifically, most of the Turkey lies within a complex zone where the Arabian, African, and Eurasian tectonic plates interact. The westward movement is hosted by two major fault zones: the North Anatolian Fault in western Turkey and the East Anatolian Fault in the southeast of the country. As the largest African and Arabian plates move westward, Turkey is squeezed, while the Eurasian plate prevents any northward movement. Consequently, Turkey sits on many faults.

In the journal *Geophysical Research Letters* (Martinez-Garzón et al.,2025), a team led by Dirk Becker and Marco Bohnhoff from the German Research Centre for Geosciences (GFZ) in Potsdam presents the first systematic analysis of deformation involving locked and creeping sections along the ‘Marmara seismic gap’. This is based on a new, high high - resolution catalogue of seismic activity, which has compiled using the latest data processing techniques. While slowly creeping fault sections host small, recurring earthquakes in local areas of brittle material, known as “repeaters”, these do not occur along locked segments, where strain energy accumulates until the rock’s strength is exceeded and a larger earthquake begins. The researchers found that most of the tectonic energy is released through slow seismic creep in the western part of the Sea of Marmara. Further east, the proportion of creep decreases systematically until the fault becomes fully locked immediately south of Istanbul. Given the region’s seismic hazard, this study provides valuable insights into earthquake scenarios and into the assessment of seismic risk in the megacity.

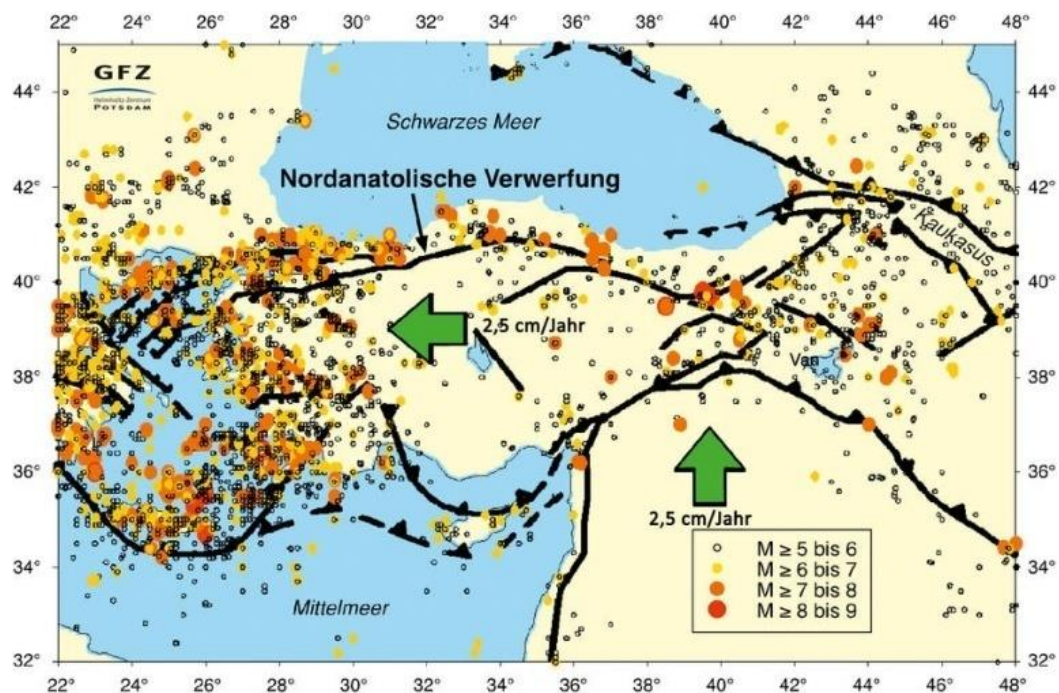


Figure 17. Earthquake hazard in Turkey, epicenters, and location of major fault zones. Source: GFZ

North Anatolian Fault – NAF

It is one of the world's largest active continental fault systems. Extending across northern Turkey, it runs from the Karliova region in the east towards the North Aegean. Published estimates of its total length range from 1.200 to 1.500 km depending on how the fault is defined. It is predominantly a right-lateral strike-slip fault. This means that the two sides of the fault move horizontally past each other, rather than one side simply moving vertically over the other. It is the dominant element of the seismic framework. It has a total length of 1.500 meters reaching the centre, and a slip rate of approximately 20-25 mm per year. Since the Erzincan earthquake in 1939, seven major earthquakes exceeding 7 on the Richter scale have been recorded, with the epicenter moving ever further west (M.C. Morton, 2014).

Main Marmara Fault – MMF

The Marmara Fault, an offshore section of the North Anatolian Fault Zone, poses the greatest seismic risk to Istanbul and is the most hazardous and risk-prone fault zone in Europe as a whole. It is the only part of the North Anatolian Fault Zone, which marks the boundary between the Eurasian and Anatolian plates, that has now experienced a major earthquake since 1766 (Magnitude greater than 7) . The concept of a single, continuous ‘Main Marmara Fault’ (MMF) beneath the Sea of Marmara has long been used to inform seismic hazard assessments. However, recent geological, geophysical, and geodetic evidence suggests a more complex picture, involving a network of interacting strike-slip segments, pull-apart basins and subsidiary fault-zone structures. Based on this rationale, the current seismic tectonic framework requires re-evaluation. This must take into account the possibility of a single, continuous rupture, as opposed to a segmented or distributed shear zone. Furthermore, hazard models must fully incorporate the behavior of the fault network, as well as cascading rupture scenarios and the potential activation of multiple segments within and beyond the current seismic gap (M. Bohnhoff, 2013). The MMF has traditionally been conceptualized as a relatively simple continuous strike-slip fault capable of producing a single large earthquake (Le Pichon et al., 2001). However, other studies based on marine

geophysical surveys, high-resolution bathymetry seismic reflection data, and geodetic measurements challenge this simplification, instead postulating the presence of several "en-echelon" normal faults beneath the Sea of Marmara (R. Armijo et al. 2002). Analysis of earthquake focal mechanisms indicates the occurrence of both strike-slip and normal faulting events within an overall transtensional stress regime, with local variations. This is evident along the Marmara fault zone (C. Wollin et al. 2018). The fault is also divided into several sections with distinct characteristics under the Marmara Sea Fault. Studies indicate that a large amount of seismic energy has accumulated in the central section, which has the potential to generate an earthquake measuring between 7 and 7.5 on the Richter scale. A 2016 study published by the USGS estimated a significant probability of an event affecting Istanbul over a 30-year period, depending on the probability model used. Another concern is the possibility of a tsunami. As the fault lies beneath the Sea of Marmara Sea, moderate Tsunamis are possible, especially if underwater landslides are triggered. Although not usually associated with major earthquake in subduction zones, they could still affect low-lying coastal regions. This possibility is also based on the fact that over 30 tsunami events have been recorded historically over the last two millennia. Examples include the earthquakes of 1509 and 1766, although precise measurements and data are unavailable due to the limited historical records. One notable instance was the 1999 Izmit earthquake, which measured 7.6 on the Richter scale. According to UNESCO, the average run-up was approximately 2.5 meters, reaching a maximum of around 4 meters at Gölcük. This event caused damage to the naval base's facilities. Gölcük and several other coastal areas are now permanently flooded due to tectonic subsidence and landslides.

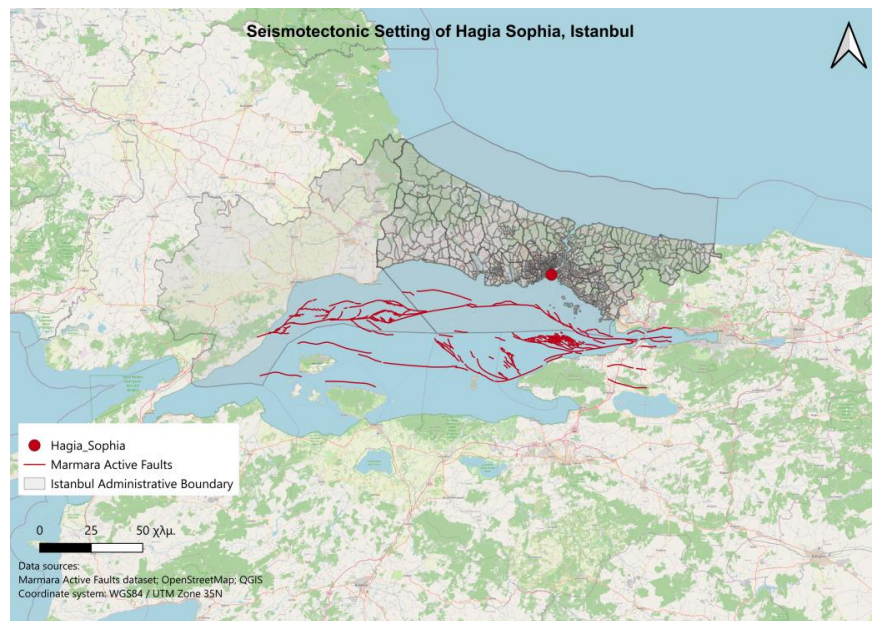


Figure 18. Seismic tectonic Setting of Hagia Sophia, Source: Maria Karkali using qgis

3.1 Historical Earthquakes of the region

Table 2. Earthquakes during Early Byzantine Period

Date	Estimated Magnitude/ Intensity	Reported Damage to Hagia Sophia	Interven tion/ Repa ir	Histori cal Sou rce
557 AD	7.0 -7.5 magnitude	One of the most destructive <i>events</i> after construction. Caused serious damage on the original dome. Estimated	NO INFO RMA TION PRO VIDE D	Wikidat a

		around		
558 AD	NO INFORMATION PROVIDED	Corruption of the original dome	NO INFORMATION PROVIDED	NO INFORMATION PROVIDED

Table 3. Earthquakes during Middle Ages – Byzantium and Ottoman period

Date	Estimated Magnitude/Intensity	Reported Damage to Hagia Sophia	Intervention/Repair	Historical Source
26 October 869 AD	Mw: 7.5	Part of the semi-dome collapsed, and repairs were carried out	Repairs/Restorations	Boğaziçi Digital Archive
989 AD	Mw: 7.0	Major reconstruction required and a part of dome collapsed.	The restoration was carried out by the Armenian architect Tyred.	NO INFORMATION PROVIDED

18th October 1344 AD	Estimated Magnitude: 6.5-7.0	Extensive cracks in the dome and the arches.	NO INFORMATION PROVIDED	Historical seismic records – Boğaziçi Digital Archive
1346 AD	NO INFORMATION PROVIDED	Collapse of the southeastern/eas tern section of the dome and the eastern arch.	Large flying buttresses are being constructed in four directions.	Diker, Günel & Güzelbulut, (2023)Ejourn als

Table 4. Earthquakes during Ottoman and Modern Era

Date	Estimated Magnitude/Inte nsity	Reported Damag e to Hagia Sophia	Intervention/Rep air	Historic al Sour ce
Septem ber 14th 1509 AD	“Little Apocalypse” Estimated Magnitude: 7.2 – 7.6	It caused a lot of damage, but the building held up. Detachm	Repairs and maintenance	Historical earthq uake dama ges

		ent of plaster. Collapse of a minaret is also reported.		
March 5th 1556 AD	Mw: 6.7 – 7	Some damage to the dome	Localized repairs	Historical Earth quake Studie s

28 or 22 of 1776 AD	Mw 7.0-7.2	Cracks in the dome and need for further reinforcement . Significant less damage than the earthquake of 1754.Strong sea disturbances were observed in the waters of Bosporus.	Repairs and maintenance.	Historical Earth quake studie s
July 10th	Mw 7.0	Damage to the	Extensive repairs	Historical

1894 AD		wall, the arches and the mosaics.	were carried out. Monitoring of the monument was increased.	earthquake damages
9th August 1912 AD	Mw 7.4	Strong earthquake in the western Marmara region. No significant structural damage.		Modern palaeoseismological studies.
17th August 1999 Izmit	Mw 7.4	Although Hagia Sophia was recorded as having been shaken by the earthquake, it sustained no significant structural damage	UNESCO approved a conservation program for mosaics damage	BSSA/ UNESCO
12th November 1999 Düzce	Mw 7.2	The monument registered the strong seismic motion	Monitoring/Seismic recording	BSSA C CiteSeerX
26th Septe	Mw 5.8	The earthquake was felt in	No significant structural	Modern seism

mber 2019		Istanbul	damage to Hagia Sophia has been documented	ologic al recor dings
6th Febr uary 2023 Kahram anma raş	Mw 7.8/7.5	Major earthquake in Turkey but not close to Istanbul.	No recorded seismic damage	Modern seism ologic al recor dings
April 23 2025	Mw 6.2 – 6.3	Although no significant damage was recorded, a major issue regarding its future maintenance and preservation was raised.	2025-present: A period of restoration and seismic strengthening of the dome, including maintenance of the lead coverings and work on the metal framework.	Modern seism ologic al studie s and Reute rs/AP

The following map shows some of the most significant earthquakes that were recorded in the Constantinople region, which consequently affected Hagia Sophia. The locations of older earthquakes are marked only approximately, as their exact coordinates were not historically recorded. The map also illustrates the intensity of the earthquakes and their dates.

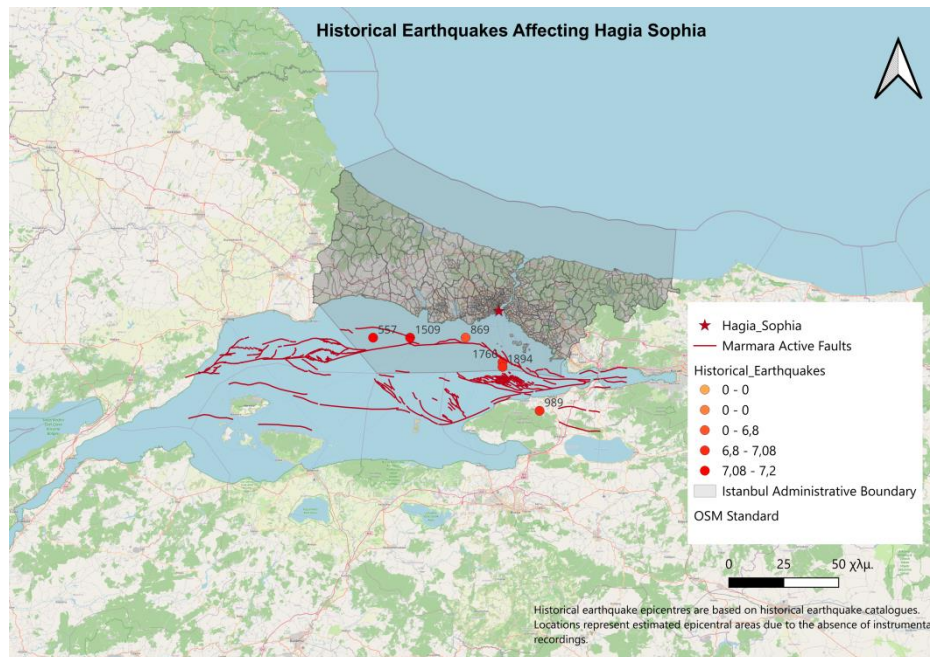


Figure 19. Historical Earthquakes affecting Hagia Sophia. Source: Maria Karkali, producing in qgis, 2026

3.2 Seismic Vulnerability of Hagia Sophia

The seismic vulnerability of Hagia Sophia is a major concern for structural engineers and conservation architects, given its location in one of the world’s most active seismic regions, close to the North Anatolian Fault.

While these materials have an impressive compressive strength, they generally have a very low tensile strength and limited energy dissipation capacity compared to modern reinforced concrete or steel structures. While such masonry structures have withstood structural damage from various hazards for a long time, they are more vulnerable to horizontal seismic forces.

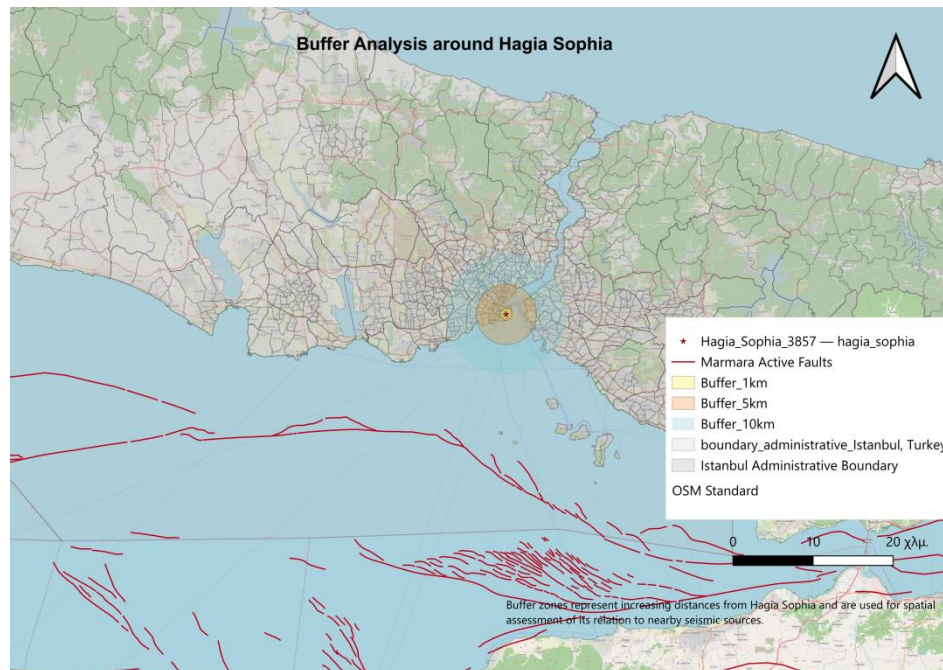


Figure 20. Buffer Analysis around Hagia Sophia Source: Maria Karkali using qgis

Despite having stood for roughly 1,500 years and withstood earthquakes, this makes the monument high-risk. This demonstrates considerable structural resilience. However, its vulnerability is due to the old, deteriorated materials, the heavy dome and its proximity to an active fault line. Dr. Efthymios Lekkas, Professor of Dynamic Tectonics, Applied Geology and Natural Disaster Management, and President of Greece's Earthquake Planning and Protection Organization, warned that a stronger tremor could cause seriously damage the structure from the Byzantine era. He explained that an earthquake measuring 7.0 on the Richter scale could have catastrophic consequences for Hagia Sophia (Erdogan K., 2025). Of particular concern is the main dome, which has a diameter of around 31 meters. It transfers substantial vertical loads and horizontal thrusts four to the massive support piers via the pendentives and four main arches. Previous historical earthquakes have demonstrated the dome and supporting arches vulnerability to partial and complete collapse, as well as to the effects of previous repairs. During an earthquake, the building's substantial weight creates a considerable amount of inertial force, and the limited tensile strength of historic brickwork makes it particularly vulnerable to cracking. Overall, the Hagia Sophia can be considered a monument that is structurally vulnerable yet historically resilient. According to the latest restoration work being

carried out on the Hagia Sophia, modeling and structural analyses show that the eastern half dome is considered the most vulnerable part of the structure (Daily Sabah, 2026). Another threat is the interaction between the dome and semi-domes, and the risk of 'hammering', a phenomenon that occurs during an earthquake when two adjacent buildings collide due to insufficient space between them. According to Diker, this may have happened because, when the dome and arches were rebuilt after historic collapses, they were made thinner than they should have been (Sevencan, 2025).

3.3 Geology and soil morphology

The geological foundation of Constantinople is particularly complex. Situated between tectonic zones, the city comprises rock formations ranging from the Paleozoic to the Quaternary period. The Paleozoic rocks that make up the oldest basement layer consist primarily of schist's, sandstone and limestone. These compact rocks provide a stable base for heavy structures. *"Key characteristics of the Paleozoic sequence include horizontal and vertical transitions, alternations of different rocks types, and lenticular structures"* (S. Eroskay, 1985). Additionally, Mesozoic units overlie them in an unconformable manner. These outcrops are mainly found in the northern part of Istanbul, on both the Asian and European sides.

In contrast, Quaternary deposits consist of more recent materials, such as sand and gravel, which are found in valleys, along the coast, and around the Golden Horn. Unlike Paleozoic formations, these deposits are unconsolidated and pose a high risk of subsidence.

In recent years, increasing evidence has emerged suggesting the existence of an extensive underground space beneath the floor of the Hagia Sophia. Despite investigations beginning in 1935, little is known today about what exactly what lies beneath the monument. However, it has long been known that crypts dating back to the early Christian period are present. Various natural underground water flows have recently been discovered. In 2005, for examples, studies were conducted to examine the operation of the tunnel network. Nine wells were identified in the area surrounding the church. Anthemios and Isidoros addressed these natural underground

flows by constructing the network of galleries, to control the flow away from the foundations and prevent the buildup of hydrostatic pressure. For practical purposes, clay pipe conduits were constructed to house the building's water supply and drainage systems. They allowed for ventilation between interior and exterior spaces, as well as the diversion of rainwater to external systems. The narrow passages often required crawling to navigate and were primarily designed for maintenance work (Daily Sabah, 2025).

4. Earthquake damages and repairs

4.1 Earthquake damages and repairs during Byzantine period

One of the most significant years in the temple's history was 557 AD, when the capital of Byzantium was struck by three major earthquakes. The first earthquake, on 6 April, caused no particular problems or damage. The second, and largest, earthquake occurred on 6 October, causing significant damage, primarily to buildings that had already been weakened by the previous quake. This earthquake was more intense than the first, and most importantly it caused a tsunami that reached Thrace. The third and largest earthquake of that year occurred on 14 of December, measuring 7 on the Richter scale. It was later characterized as one of the strongest earthquakes to ever hit Istanbul since its foundation. According to contemporary records, Constantinople was "almost completely leveled" (Agathias the Scholastic, c. 530–582). However, the dome of Hagia Sophia collapsed during repair work in May 558 AD due to earthquake-related damage, rather than during the earthquake itself. More specifically, the dome collapsed because it had been built too narrowly. Despite the pendentives, loads were transferred to the walls, causing the supporting structures to crack, shift and weaken. The addition of more lateral forces, such as those experienced during an earthquake, proved to be the final straw.

Another powerful earthquake struck Constantinople during the Byzantine period on 9 January 869 AD. According to seismologists, it had an estimated to have had a magnitude of 6.6 on the Richter scale, resulting in significant destruction and loss of life. Described as 'horrific', many houses and churches collapsed and Hagia Sophia was left with numerous cracks (Paflagon, N.D.). The Orthodox Church commemorates the memory of the earthquake on 9 January each year.

The devastating earthquake that struck Constantinople on 26 October 989 caused massive damage to the Byzantine capital. The tremor brought down numerous buildings and destroyed many churches. The most iconic collapse was that of the dome of Hagia Sophia, whose repairs took approximately 6 years to complete under the direction of the architect Tridates. The earthquake also caused severe damage along the eastern coast of the Sea of Marmara, significantly affecting Nicomedia.

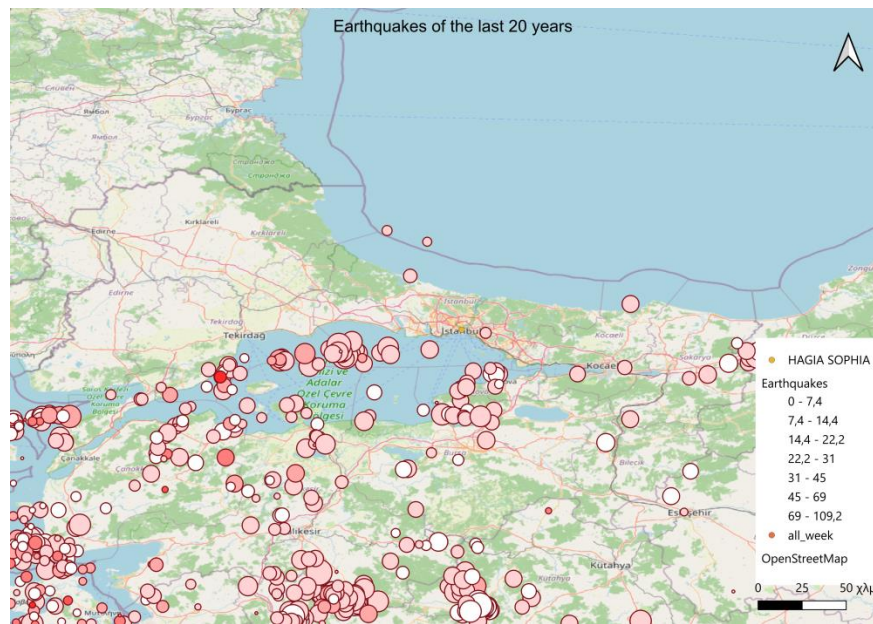


Figure 21. Earthquakes of the last 20 years. Source: Maria Karkali using qgis

4.2 Structural Failures

The building has had earthquake monitoring sensors in place for over 20 years.

Records of measurements and vibrations have been kept in order to understand the building's general structural behavior. While the building appears to have withstood them well, its structural integrity remains uncertain. A strong future earthquake could cause damage.

Many simulation and testing models have been created to strengthen the structure and improve its earthquake resistance. The key question was how the arches could support the dome. The amount of stress an arch is under depends on the weight it is bearing. Another issue was how to position the circular base of the dome on the square shape defined by the four corners. The second dome was steeper, taller, and more pointed, adding roughly six to seven meters to its height.

It was not until the late 1990s that a more precise explanation emerged, when modern structural analysis was used to explain the process in detail. A flatter dome concentrates its outward thrust at the base in a narrow horizontal band. This thrust has nowhere to go but straight outwards, meaning the walls below must absorb it entirely. A larger dome exerts a greater proportion of its weight in downward compression.

The thrust at the base is reduced. The load is shared more broadly (completed in 562 CE), as it has been ever since.

Four pendentives were inserted into the each corner to complete the structure, creating a harmonious transition from circle to square.

The first construction failure of the Hagia Sophia occurred around 558 AD, 20 years after it opened. The original dome was relatively flat, with shallow curvature and a low profile, and a large portion of it, along with sections of the eastern arch, was destroyed, while the interior sustained severe damage. The dome subsequently collapsed partially on two other occasions: in 989 and 1346. The damage was later repaired by reconstructing the affected sections. The dome consists of three sections from the 6th century, one from the 10th century, and one from the 14th century (G. Lialios, 2024).

4.3 Dynamic characteristics of Hagia Sophia

Hagia Sophia provides its own explanation for its existence, the interior of the monument is characterized by a profound sense of dematerialization. This must have been a particularly striking impression for faithful in the middle Ages. This dematerialization is evident in both small-scale details, such as the capitals, and the building's principal architectural principal, the dome (Dr. William Allen, n.d.).

Two features of the temple stand out in particular: its architecture, which evokes a sense of visual dynamism and grandeur, and its revolutionary construction, which continues to inspire admiration to this day. The greatest achievement in conveying a sense of movement is undoubtedly the massive central dome, spanning 32 meters in diameter and rises 56 meters high. It captivates the viewers by evoking a powerful sense of soaring height. Furthermore, forty windows at the base of the dome admit natural light into the interior, constantly shaping the atmosphere. This also creates the impression that the dome is hovering above the space, lending it a majestic appearance. Another dynamic feature is the structure itself, which rests on four large spherical triangles and massive piers- an engineering feat that was revolutionary for its time.

4.4 Observed damage patterns related to seismic action

For many years, patterns of damage resulting from seismic activity have been observed, focusing on specific structural weakness inherent in the ambitious architecture of Hagia Sophia. Lateral forces were strongly transmitted to the supporting walls, causing displacement. Subsequently, in 558, the dome collapsed completely due to earlier earthquakes. The dome was then rebuilt with a higher crown and a series of ribs to ensure that forces were distributed directly to the structural supports (Savage, 2026). However, powerful earthquakes caused partial collapses of the dome during the 10th and 14th centuries. Even today, after enduring years of seismic stress, the dome is no longer perfectly circular, but appears more elliptical.



Figure 22. The dome. Source: Theothertour August 2026, Edited by Maria Karkali

The central dome collapsed in 558, and was subsequently rebuilt in 989 and again in 1346. Although the dome has remained intact since then, past reconstruction efforts resulted in the construction of four asymmetrical arches. According to Dikes, these arches are thinner than optimal, making the dome more fragile (Sevencan, 2025).

Furthermore, the arches slenderness makes them vulnerable to future event. Years of seismic activity have also caused cracks to appear at the ends of the arches. Notably, the four massive central piers, which support the entire weight of the structure, are now visibly titling. This phenomenon, resulting from historical earthquakes and lateral thrust forces, has been observed for many years.

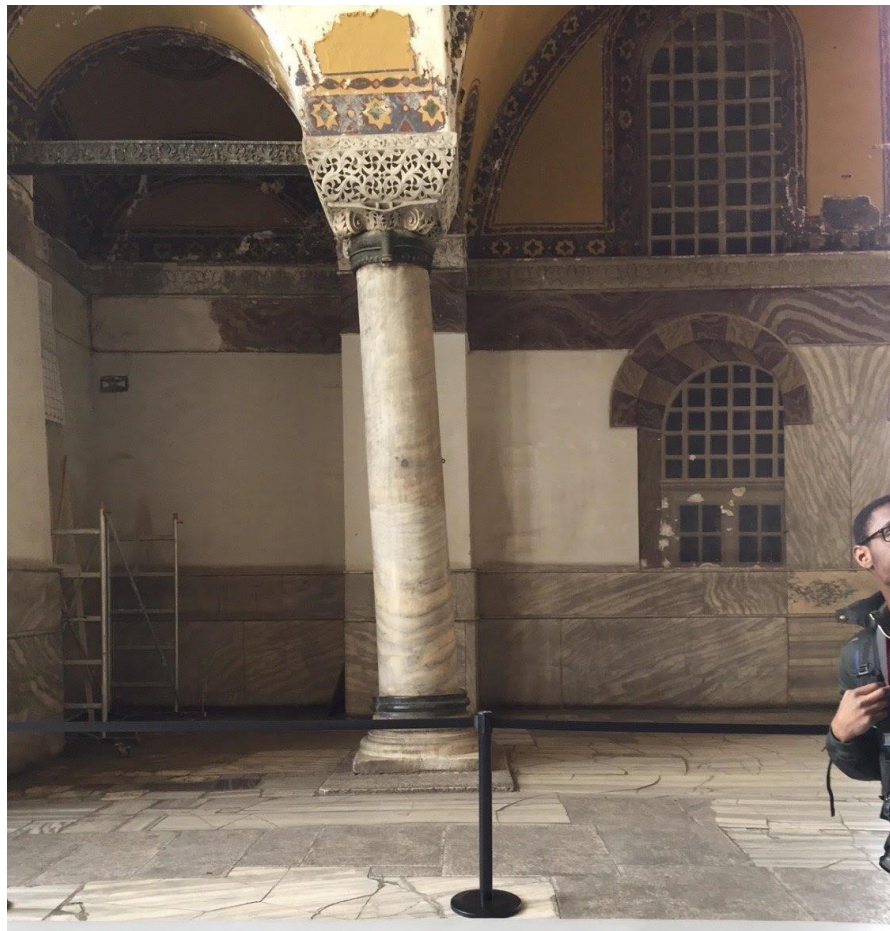


Figure 23 Central pier. Source: eileenstephenson.com, leaning Column of Hagia Sophia

Hammering is also a significant risk during earthquakes. This phenomenon occurs when the central dome and the two semi-domes, which were built to absorb lateral thrusts, collide due to there being insufficient space between them during powerful earthquakes (Sevencan, 2025).

During an earthquake, the two semi-domes, which were built to support the main dome, can start to sway. This movement can create hammering which risks damaging the main dome instead of protecting it' said Dicker. (Sevencan, 2025).

The semi-domes of the Hagia Sophia are among the structure's most heavily stressed elements. A revolutionary engineering feat for their time, they were designed to distribute the weight of the central dome, and create the vast, unobstructed interior space for which the building is renowned, by channeling the dome's lateral thrusts outwards. The structural weaknesses of the entire building are located in the east and west arches, as well as the two half domes (T. Aoki et al., 1997).

Minarets are feature of Islamic religious architecture. As slender structures, minarets are generally highly vulnerable to earthquakes (Nur Avci et al., 2026). During the Ottoman period, four external minarets were added to Hagia Sophia, this function as independent structures. During an earthquake, they oscillate intensely, resulting in horizontal shear cracks appearing between their sections.

4.5 Current restoration techniques

Hagia Sophia is currently undergoing a major, multi-year conservation and restoration program, with a particular focus on structural and seismic safety. The risk of a major earthquake is a concern for many institutions, governments and ministries. This is one of the most significant upgrades in its long and eventful history. Great care is being taken to ensure that the restoration is as non-intrusive as possible. One of the most significant aspects of the restoration is the temporary covering of the dome with a steel structure to protect the building from the elements, as anything could potentially damage to the dome or the mosaics beneath it. Four large steel piers have been installed under the dome to support the entire structure and prevent additional weight being added to it. They also provide workers with access to the inside. As part of the restoration, the lead covering of the main dome is being carefully removed and replaced. Work is primarily carried out from the outside to minimize the risk of damaging the historic interior surfaces and mosaics (Daily Sabah, 2026).

Maria Karkali, “Hagia Sophia in urgent need of protection From the effects of seismic activity”

According to the architect Hasan Firat Diker, “*The main dome is completely covered on the outside. We will continue this process in the eastern half-dome and observe the interventions that need to be made*”.



Figure 24. Photo taken on April 14, 2025 shows Hagia Sophia under restoration in Istanbul, Türkiye. Türkiye on Monday started the first-ever comprehensive restoration work on the main dome of Hagia Sophia, one of the most important historical sites in Istanbul. (Xinhua/Liu Lei)



Figure 25. Construction techniques Source: Hispanatolia.com

A multi-layered temporary flooring system was installed in all areas through which construction machinery was to pass. This ensured both load distribution and protection of the marble slabs. To prevent damage to the original marble flooring, a complete protective system comprising the following layers was applied:

- A vapor-permeable membrane
- Felt
- Sand
- 18mm plywood
- A 10 x 10 cm wooden frame
- XPS insulations boards placed between the frames
- A sound-absorbing underlay on top
- Finally, a diamond-patterned steel sheet is placed on top (Republic of Turkey/Ministry of Culture and Tourism)



Figure 26. Ongoing works at the Hagia Sophia Grand Mosque continue under the decisions of the scientific committee and the conservation board. Source: Republic of Turkey, Ministry of Culture and Tourism



Figure 27. Ongoing works at the Hagia Sophia Grand Mosque continue under the decisions of the scientific comitee and the conservation board. Source: Republic of Turkey, Ministry of Culture and Tourism



Figure 28. Ongoing works at the Hagia Sophia Grand Mosque continue under the decisions of the scientific comitee and the conservation board. Source: Republic of Turkey, Ministry of Culture and Tourism



FIGURE 29 ONGOING WORKS AT THE HAGIA SOPHIA GRAND MOSQUE CONTINUE UNDER THE DECISIONS OF THE SCIENTIFIC COMMITTEE AND THE CONSERVATION BOARD Source: Republic of Turkey, Ministry of Culture and Tourism

Instead of replacing everything with modern materials, damaged masonry and structural components are repaired using carefully selected compatible materials. A priority was the northeast minaret of Hagia Sophia. In April 2026, the Turkish Ministry of Culture officially announced the completion of the restoration work on the minaret. In line with the Scientific Committee’s decision, the upper sections, were partially dismantled and reconstructed, while the lower sections were strengthened. During this process, 411 stones and 26 rows of steps were carefully dismantled and categorized.



Figure 30 Minaret of Hagia Sophia. Source: tgrthaber.com



Figure 31 Minaret of Hagia Sophia. Source: tgrthaber.co

5. Conservation strategies and seismic risk mitigation

The detailed methods and proposals for a comprehensive conservation strategy are outlined below. The analysis covers past methods employed, examining how they might be reused, as well as new measures proposed to protect against ongoing seismic activity.

5.1 Principles of cultural heritage conservation

The Hagia Sophia is one of the world's most significant cultural monuments. It is protected by internationally recognized principles for safeguarding cultural heritage, which aim to preserve its historical, architectural and cultural value. Furthermore, the Hagia Sophia is protected by UNESCO'S fundamental international regulations. It was added to the protection list in 1985 as part of the historical areas in Istanbul. As previously noted, Hagia Sophia is a complex monument. It embodies not just a single history, but various historical eras and functions. Its evolution from a Byzantine church to a mosque and then to a museum reflects the multifaceted nature of history and transformation. In this context, the Venice Charter highlights the importance and respecting the valuable contributions from all these periods.

As the monument is located in a highly seismic area, any intervention must balance seismic protection with respect for its historical integrity. As this thesis focuses on the seismic strengthening of monuments, a key factor to consider is how such reinforcement could affect the monuments authenticity. Specialized interventions and works are often required to ensure optimal protection, particularly in the case of the Hagia Sophia. However, international charters (such as those of ICOMOS) stipulate that authenticity and integrity must be preserved. Examples of such interventions include spurs, tie rods and buttressing arches (Pecchioli, Cangi, 2023). The most important principle of conservation is protecting the monuments authenticity. Any intervention must preserve the monument's original structural elements and materials, while avoiding alterations that would affect its historical character. For this reason, the least possible intervention should be carried out, involving only those measures

that are absolutely necessary for the monument's optimal preservation (The Burra Charter, 1979/2013).

Material compatibility is also of particular importance. The materials used in restoration work must have physical, chemical and mechanical properties that are compatible with those of the original structure. This prevents incompatibilities that could deteriorate the monument's condition (The Nara Document on Authenticity, 1994). A significant issue that arises in this case, for example, concerns the management of brickwork and mortar, which is a complex aspect of monument conservation. Since mortars are composite materials, a specially designed mortars with specific characteristics are needed to ensure compatibility with existing historical materials and optimal mechanical performance (Apostolopoulou ,Moropoulou, 2022). Where possible, modern intervention should be reversible to allow for the future procedures, such as removal of materials, can be carried out at any time without damaging the structure. One particularly challenging aspect is ensuring that the new interventions can be distinguished from the original construction without disrupting the monument's aesthetic unity (The Venice Charter, 1964).

Last but not least are preventive maintenance and continuous monitoring. The modern approach to preserving cultural heritage places great emphasis on preservation. Monitoring the monument's structural behavior using measuring instruments, geodetic surveys and digital models enables damage to be detected early and facilitates the implementation of appropriate measures before serious structural failure occurs.

Conservation work has been required on the exterior and interior of the monument several times in the past. Given the ongoing efforts to preserve its historical form to the greatest extent possible, a recurring concern is how to protect both the structure and the decorative features, such as the mosaics, simultaneously. In this case, ICOMOS is attempting to preserve the integrity of the entire monument. They are proposing an on-site examination and measurement of the monument, and if necessary, the use of non-invasive methods, before any intervention. In fact, UNESCO has previously funded work on the mosaics and parallel studies on the structure (UNESCO, 1994).

5.2 Non-Destructive Testing (NDT)

Historical structures are investigated according to the principal of minimal intervention, whereby information about a monument’s condition is gathered without damaging its original structural elements. Non-destructive testing (NDT) and minimally invasive techniques are therefore essential for assessing the structural condition and seismic vulnerability of monuments such as Hagia Sophia.

5.2.1 Geometric Documentation

Geometric documentation is the first and most fundamental stage in investigating a historical monument, as it provides accurate and reliable data on the structure’s morphology, geometry and current condition. This is particularly important for cultural heritage monuments, where any intervention must be based on detailed understanding of the structure and be scientifically substantiated. The scope of geometric surveying extends beyond the production of drawings to include the precise recording of all structural elements, deformations, cracks, and forms of deterioration that have developed throughout the monuments history.

In the context of seismic protection, geometric documentation is essential for developing reliable numerical models that simulate seismic behavior and assess a structure’s vulnerability. Furthermore, taking repeated measurements at different times enables the results to be compared and potential displacements or deformations associated with seismic events or the natural ageing of the monument to be detected.

4 Terrestrial Laser Scanning – TLS

In recent years, non-destructive methods had become widely adopted for the preservation of cultural monuments. The most significant feature of these advanced technological methods is that they allow for the non-invasive evaluation of a

building’s condition and the implementation of innovative technological and material solutions.

Historic buildings are often characterized by complex geometry and numerous small-scale architectural features, decorative elements and reliefs. This necessitates the use of technology for thorough and comprehensive data collection, an area in which TLS (Terrestrial laser scanning) method offers optimal capabilities (A. Gardzińska, 2021). More specifically, is a form of terrestrial Lidar technology. It operates by emitting laser pulses towards the structures surface and measuring the time required for them to return. This process enables highly accurate 3D coordinate calculations for millions of points, creating a dense point cloud that faithfully represents the monuments geometry. In the context of cultural heritage, this technology can successfully capture the current state of monuments, facilitating structural assessments and the production of materials for interpretation and presentation.

One of the most significant advantages of this method is its compatibility with tools such as photometric instruments. Furthermore, its high accuracy and rapid data acquisition make it indispensable for monuments such as Hagia Sophia. Finally, it enables the documentation of complex geometries without the need for physical contact with the structure.

At Hagia Sophia, TLS is used to precisely document the central dome, the semi-domes, arches and piers. It can also detect minor deviations from the original geometry that may be associated with seismic stresses or long-term deformations.



Figure 32 TLS technology and its application in heritage documentation (a) Principle of TLS. (b) A resultant point cloud of TLS survey. Source: MDPI

5 Digital Photogrammetry

Digital photogrammetric is a method of measurement and 3D imaging that uses digital photographs. It is employed for the documentation, conservation and digital preservation of cultural heritage monuments. The fundamental principle of photogrammetric is using images to measure distances and generates geometric representations. This involves capturing one or more photographs from different angles and using them to derive information about the distance and shape objects. Modern photogrammetric techniques employ high-resolution digital cameras and computer vision software for image processing and analysis (M. Tsagkarakis, 2024). This method has many applications, but is particularly important for monuments as it enables them to be documented and preserved precisely without the need for physical presence. The main advantages of this method are its low implementation cost and its ability to cover large areas while producing high-resolution, photorealistic 3D models. It can be also capture cracks, signs of deterioration and other structural defects in great detail. In the case of Hagia Sophia specifically, photogrammetry can complement laser scanning by enriching the 3D model with information about the texture of structural materials and the condition of surfaces.

One of the most notably applications of the method to the monument occurred in 1992 as part of a UNESCO program. Photogrammetric surveys were crucial for its preservation. Recently, laser scanning and photogrammetry methods were employed to document the condition of the mosaics in the central dome. The resulting data revealed traces of earlier interventions from different periods that had been incorporated into the current designs (Daily news, 2026).

In the case of seismic phenomenon in particular, this method can contribute directly to the detailed and precise documentation of a monument by capturing all forms of damage and cracking. This allows various data records to be monitored for a comprehensive assessment of crack development. Since the method requires no direct contact, it is one of the most useful modern monitoring tools. It can also serve as a valuable diagnostic step prior to any intervention, as comparing pre- and post-earthquake records provides a clear picture of geometric changes.

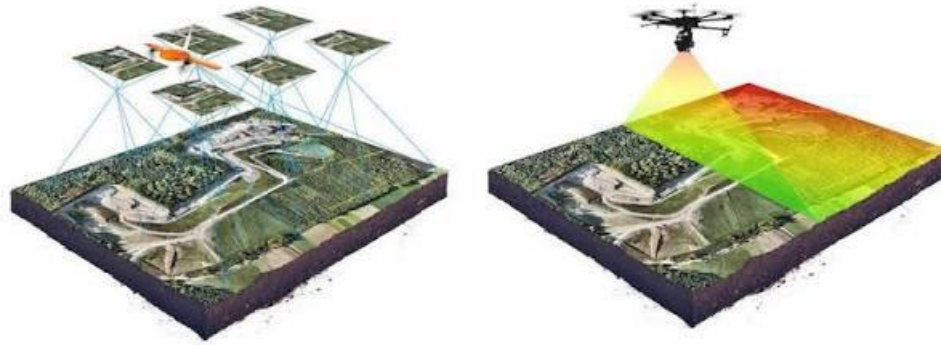


Figure 33 3Dmapping via drone photogrammetry. Source: Michalis Tsagkarakis

6 UAV (Drone)

In recent years, there has been a significant increase in the use of unmanned aerial vehicles (UAVs) for the geometric documentation of historical monuments. UAVs can capture high-resolution images of hard-to-reach areas, such as domes, roofs and the upper sections of facades, thus eliminating the need for scaffolding. Although UAVs were initially appeared and evolved for military purposes, their use has rapidly expanded in various fields, including science, agriculture, policing, product delivery and aerial photography (kartsakli N., 2018).

This technique can be particularly useful, as it provides high precision, detailed orthophotos, and safe access to hard-to-reach areas, such as the domes and the facades.

5.2.2 Geophysical and non-destructive testing

7 Ultrasonic Pulse Velocity (UPV)

This method is now one of the most widely used non-destructive techniques worldwide. It facilitates the quality assessment and internal analysis of structural materials. It operates by measuring the speed at which sound waves travel through stone, marble or concrete. The use of non-destructive and non-invasive techniques generally has many advantages for diagnosis the sustainability of existing buildings. Moreover, they are essential with respect to conservation constraints when dealing with historical and architectural heritage. In the case of Hagia Sophia, for example, this technique would be highly useful for detecting internal cracks and structural failures, evaluating the homogeneity of construction materials, and assessing their quality.

Due to the monument’s complex masonry and age, this method could provide a clearer picture of areas with reduced cohesion and damage resulting from the area’s continuous seismic activity. Another advantage of this technique is that the measurement results can be combined with those from other invasive methods, which would be analyzed below, to provide a better picture of the monument’s structural condition.

In practice, the Ultrasonic Pulse Velocity method was employed at Hagia Sophia as part of a study into the mechanical properties of its historic cultural materials.

Yüzügüllü, Durukal and Byen took in-situ ultrasonic readings of the monument’s bricks and mortar and combined with Schmidt Hammer tests, to evaluate the quality of the materials and the dynamic modulus of elasticity. This research demonstrated that the UPV method can provide reliable information on masonry homogeneity and contribute to calibrating numerical models for the monument’s seismic assessment, eliminating the need for destructive testing (Yuzugullu et al., 1995).

8 Ground Penetrating Radar (GPR)

It is one of the most important non-destructive testing methods in use today. It is primarily used in archeological investigations and for assessing historical structures. The method involves transmitting radio wave pulses at select centre frequencies into the ground for subsurface study, and is safe. When these waves encounter interfaces between materials with different electromagnetic properties, some of the energy is reflected back to the receiving antenna. Recording the record time and intensity of these signals makes it possible to identify internal structures. This allows voids, cracks and other features to be identified without intervening in the monument (Daniels, 2004).

The method also offers high spatial resolution and rapid data acquisition. It is particularly well-suited to monuments such as Hagia Sophia because it is one of the few non-destructive techniques that does not damage or alter the object under examination. This enables a safer assessment of its condition prior to any restoration work, which is crucial for a 1,500-year-old monument that has suffered significant wear and tear over the centuries and could be compromised by even minor damage. Specifically, continuous monitoring of the structural condition is essential due to the cumulative impact of repeated earthquakes.

This method has previously been used extensively to evaluate structural behavior and issues that were not readily visible. A highly significant Ground Penetrating Radar (GPR) application was carried out on the gallery floor at Hagia Sophia, where extensive cracking and localized subsidence were observed. By employing various frequencies, dense scan lines could be conducted to map the internal structure of the flooring and the vaults situated directly beneath it (Yalçın et al., 2017). The resulting data revealed the presence of voids and structural alterations within the vaults, as well as evidence of previous intervention methods and previously installed metal elements. Ultimately, it was determined that the visible surface cracks were linked to deeper internal discontinuities. These findings provided significant insight into the monument's structural behavior. At the same time, the data informed the design of new conservation measures that minimized the need for further invasive interventions, thus helping to preserve the monument's authenticity.

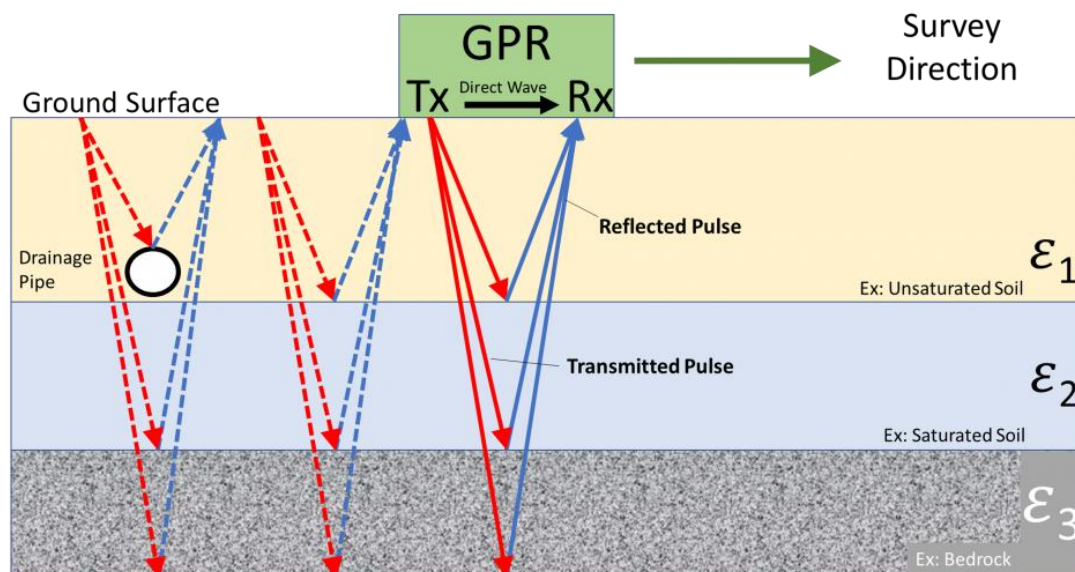


Figure 34. Schematic diagram of a GPR survey. Reflected waves penetrating the subsurface travel at different velocities based on the dielectric permittivity (ϵ) of the media in which they encounter. All subsurface anomalies, such as the draining pipe, are observed by the GPR. The progression of the survey is represented by dashed lines. (Source: Brett Trotter, USGS)

Table 5. Studies and interventions carried out at Hagia Sophia using Non-destructive testing (NDT) methods since 2000.

Year	NT method	search
2000	○ Ultrasonic's ○ Ground Penetrating Radar (GPR) ○ Infrared Thermography ○ Microwaves Reflectometry ○ Fibre Optic Microscopy	investigation for the compatibility of conservation interventions on Hagia Sophia mosaics using NDT techniques (oropoulou, Kouli et al.)

2003	○ Ambient vibration survey ○ Microtremor method	<i>Dynamic Response of Hagia Sophia and Suleymaniye: Analysis of Data from the Kocaeli and Duzce Earthquakes (Serkan Milli)</i>
2004(revised edition)		<i>Architectural-structural survey of Hagia Sophia (Hidaka and Sato)</i>
2009	○ Ambient vibration ○ Earthquake-induced vibrations ○ Natural frequencies ○ Mode shapes ○ FDD ○ EFDD ○ SSI	<i>System identification for 4 types of structures in Istanbul by Frequency Domain Decomposition and Stochastic Subspace Identification Methods. (Dominik Stengel)</i>
2009	○ Ambient vibration dataset	<i>Tools and Techniques for Real Time Modal Identification (Yavyz Kaya).</i>
2010	○ Infrared Thermography ○ GPR ○ Fiber-Optics Microscopy	<i>Multispectral Applications of Infrared Thermography in the Diagnosis and Protection of Built Cultural Heritage (Moropoulou et al.)</i>
2014		<i>Preliminary report of non-destructive investigation of plaster-covered mosaics</i>

		(Hitoshi Tajabezawa).
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5.3 Structural Analysis regarding seismic loading

Structural analysis is important for protecting and preserving monuments. Such studies examine factors such as self-weight, compressive stresses, deformations, and load paths. Since the 1990s, research papers and measurement studies on the structural and seismic behavior of Hagia Sophia have been published. For example, in 1993 researchers at Princeton University conducted field measurements to estimate the structure's mode shapes and natural frequencies using the finite element method (Cakmak et al., 1993). Furthermore, microseismic vibration measurements were carried out at the monument in the same year as part of another study. The fundamental frequency was estimated to be 2Hz (T. Aoki et al., 1993). The aim was to determine the monument's dynamic characteristics experimentally. Generally, greater emphasis is placed on the behavior of the dome, the four central piers and the main arches.

Table 6. Significant structural analyses

Year	Title	Researchers
1993	Dynamic analysis and earthquake response of Hagia Sophia	A.S. Cakmak, R. Davidson, C.L. Mullen, M. Erdik
1993	Structural characteristics of the dome of Hagia Sophia from	T. Aoki, S. Kato, K. Ishikawa

	measurement of micro tremor	
2007	Structural characteristics of Hagia Sophia: I – A finite element formulation for static analysis	T. A. Ozkul and E. Kuribayashi

A more detailed investigation into soil-foundation interaction could initially be proposed as an area for future research. Furthermore, repeated micro-tremor and ambient vibration measurements could be taken to evaluate the monument's dynamic characteristics and determine if they have changed over time. Finally, the impact of historical earthquakes on the monument could be investigated. Additional scenarios could be examined relating to major historical earthquakes (e.g. in 557, 989 and 1509 etc.) could be examined to see how they correlate with results derived from current structural analysis.

5.4 Proposed action plan for Hagia Sophia.

The fundamental principle of a monitoring plan is the continuous observation and assessment of structural behavior, with a primarily focus on damage detection. For this specific monument, a monitoring strategy designed for high-risk structures must be implemented. The monument has sustained significant damage over the years, largely due to earthquakes. Given that an earthquake of a similar magnitude is anticipated in the coming years, a 24-hours monitoring system with an immediate response to any changes is essential. The following outlines a comprehensive monitoring plan, an immediate assessment plan, and a post-earthquake recovery plan. It is important to note, due to its historical significance and location in a seismically active area, a monitor plan for the monument has been in place for years. Indeed, the monument's successful monitoring and inspection were demonstrated following the last major earthquake to strike the region in April 2025. According to a study by Bogazici University researchers Eser Cakti and Embrullah Dar, Hagia Sophia has been monitored using a structural health system since 1991. Upgraded in 2008, the system has since recorded over 100 seismic events. The researcher's findings revealed slight angular displacements in the main dome, suggesting that the arches and dome shift minutely relative to the main piers during tremors (Erdogan K., 2025). In order to develop a well-structured action plan, it is essential to define its purpose and the ultimate goal. This action plan aims to improve the monitoring and assessment of the structural condition of the Hagia Sophia in the context of seismic activity. In today's world, such a plan could play a pivotal role in preserving this magnificent building.

5.4.1 Pre-earthquake stage/ preparedness

The first step is to document the monument's initial condition by maintain a detailed record of its structural state at regular intervals. This will make easier to compare the conditions after an earthquake occurs, and assess any potential displacement or change. This is a fundamental step in the protection plan. Furthermore, continuous assessment helps to ensure authenticity and historical accuracy. In this case, geometric documentation could be carried out using 3D laser scanning to capture highly detailed data, as well as, photogrammetry via terrestrial or aerial (UAV/Drone) methods. Subsequently, crack mapping provides a detailed record of the building's structural pathology, enabling the design of appropriate interventions. Once crack mapping has been completed, sensors can be installed to establish baseline conditions (e.g. crack meters or displacement sensors). To better assess seismic vulnerability, non-destructive testing (NDT) methods specifically Ground-penetrating radar (GPR), could be employed here to understand the internal masonry structure (e.g. thickness and internal voids). Ambient Vibration Testing would play an equally important role here, as it allows for a focus on dynamic testing. This is particularly significant for an action plan, as the use of various sensors enables the recording of natural micro-vibrations and the immediate identification of potential asymmetries or natural frequencies. Environmental monitoring is indispensable, particularly in the context of current climate change trends, which are causing significant shifts in weather patterns, such as extreme temperatures. This makes environmental monitoring a critical process, especially when dealing with cultural heritage monuments. Proactive monitoring establishes a baseline of environmental and structural data prior to any seismic event. Consequently, should any displacement or new cracking be observed, it will possible to determine whether the change is due to environmental factors or structural alterations. Due to monument's large size, several sensors would need to be places inside to ensure comprehensive data collection. Furthermore, in view of climate change and fluctuating weather conditions, a small weather station could be installed in the outdoor area of the monument. This would enable real-time monitoring of phenomena such as humidity, wind speed, fog and temperature variations. With regard to temperature specifically, sensors could be placed at various

points inside the structure, as well as two or three outdoor locations, to enable comparisons to be made and temperature differentials to be assessed. This approach facilitates immediate data collection and decision-making, enabling the rapid remediation of any potential material degradation. Therefore, it is essential to prioritize vulnerable areas and points, such as vaults, that are more likely to sustain damage in the event of an earthquake. This approach provides a more comprehensive understanding of the structural system. In the case of Hagia Sophia in particular, the building’s weakest elements are the east and west arches. International scientific studies using digital models have demonstrated that these arches are subject to the greatest stresses and are most vulnerable to structural loads. Historical evidence corroborates this, as these precise sections partially collapsed during the earthquakes of 989 and 1346. Additionally, due to its size and the continuous pressure exerted by the arches and piers, the dome itself is considered one of the structure’s most vulnerable points. Finally, the issue of the building’s foundations has engaged scientists particularly in recent years. Ongoing research is being conducted into the network might pose during a major earthquake in the future, and its impact on the monument’s structural integrity. In order to better assess the seismic behavior of the foundation and soil, it is essential to identify potential asymmetries and geotechnical conditions. This could be achieved by excavating exploratory trial pits on a sampling basis.

Table 7. NDT Methods

Method	Research Field
Visual inspection	Cracks/deterioration/ deformation
Photogrammetry	Superficial damages
3D laser scanning	Precise 3D geometry
GPR (Ground penetrating radar)	Internal Masonry
Crack mapping	Crack location/ width/orientation

Ambient vibration testing	Dynamic behavior
Geotechnical Investigation	Soil properties/Foundation
Displacement sensors	Movements

5.4.2 Immediate post-earthquake response

A comprehensive record of the monument has now been created, providing a valuable baseline. In the event of an earthquake in the Istanbul area, the monument must be inspected immediately. It is essential to have a protocol in place for the initial hours following an earthquake, in order to that priorities and inspection procedures are handled correctly. The first crucial step is to ensure the safety of the site and the public. This involves inspecting the site immediately for any visible signs of structural failure and cordoning off potentially hazardous areas. Once safety has been ensured, the next step is to assess the dome, walls, and openings. A direct comparison will then be made between the monument's current state and its pre-seismic condition, based on the detailed baseline data that has already been established. Direct mapping of defects via photographs can also be carried out at this initial stage. Once the initial assessment is complete, a second protocol covering procedures and investigations for the days immediately following the earthquake may be implemented to facilitate updated documentation and subsequent tasks. Following an extensive inspection of critical structural elements, such as the dome and arches, new photogrammetric mapping and 3D scanning should be performed, as the baseline conditions will have changed. From the outset, it will also be necessary to conduct targeted non-destructive testing (NDT) will also be necessary to investigate internal wall damage that cannot be detected through visual inspection alone. A change in dynamic behavior is also a distinct possibility, so conducting new dynamic measurements and comparing the results would be prudent. It is equally important to perform a structural assessment by updating the digital model during the initial days to verify the building's load-bearing capacity. Subsequently, protective measures and repairs for any damage can be

undertaken. Additionally, temporary restrictions should be imposed in high-risk areas to prevent further damage. A schedule spanning weeks or months must also be developed over time for a detailed assessment and comprehensive investigation into the site's restoration.

5.4.3 Recovery/ Long-term Conservation

The long-term conservation protocol requires closer examination. The challenge of proper maintenance and restoration primarily lies in the building's structural integrity and the need for continuous monitoring. This is particularly pertinent given that it is a 1,500-year-old monument which has withstood hundreds of earthquakes over the centuries. As a historic cultural monument, it requires historic preservation, which entails adherence to strict international charters, such as those championed by ICOMOS, which emphasize minimal intervention and reversibility. This means that all restoration techniques must be selected with great care to avoid compromising the building's authenticity. Given the constant threat of earthquakes, laboratory testing offers a viable solution, particularly for high-risk monument's featuring complex structural elements, such as arches. Specifically, a replica could be constructed on a laboratory scale using the same materials found in the original structure (e.g. the Hagia Sophia) and subjected to stresses simulating those experienced during an earthquake. This would enable reactions and pressures to be recorded in order find a long-term solution and prevent further damage or collapse. Engineers have been conducting such tests for years as this issue has long been a cause for concern and division. Following an inspection of the sensors already installed at the monument, additional locations will be added or existing ones adjusted, depending on the identified weak points, to monitor seismic activity. Real- time recording will ensure an immediate response and enable data logging. Even if existing information and previous studies are already available, the foundation and the soil may still be inspected. This is particularly important following a major earthquake, as ground alterations or foundation issues may have occurred. Such an inspection could involve excavating exploratory soil sections (approximately 10 mm in sizes) to assess soil quality.

6 Discussion

This study reveals a link between the need to protect Hagia Sophia from seismic activity in the region and the importance of raising awareness of its historical significance. Researchers from various disciplines have long been engaged by this issue, and the preservation of the monument is now considered a matter of global concern. While its unique structural design is impressive, it is complex to maintain. Given the unpredictability of the structural stress that a natural phenomenon might impose, an action plan for seismic events, incorporating a specific strategy and protocol, can facilitate the effective management of such situations. Furthermore, past non-destructive testing (NDT) applications, particularly those stemming from research initiatives, demonstrate the significant contribution these methods have made to detailed studies of the monument without compromising its structural integrity. These methods can contribute to a comprehensive monitoring and control plan to ensure the monument's protection. While previous research has largely focused on NDT, this action plan and the use of these techniques demonstrate a more holistic approach. Further research is needed to optimize the organization and study of the monument and its surroundings.

7 Conclusion

The aforementioned thesis provided a thorough analysis of the seismic behavior of the Hagia Sophia, taking into account its intricate and pioneering structural design, as well as its current state. The analysis highlights that seismic activity in the region is one of the most significant factors affecting the monument's stability and historical integrity. By incorporating historical sources and records, a correlation is established between the building's observed structural deterioration and damage to the building's structure and the region's seismic activity. Repeated seismic tremors over time reduce the monument's reduced load-bearing capacity and further cracking and damage. As it is a World Heritage Site, greater care must be taken in the selecting intervention and conservation methods that preserve its authenticity. Any interventions on the building must be kept to an absolute minimum and be compatible with the monument's existing materials. In conclusion, this thesis presents the protection of monuments against seismic activity as an ongoing process of monitoring and documentation aimed at optimal prevention and safeguarding, not merely as an act of intervention. Effective risk management relies on accurately identifying seismic hazards and vulnerable points. This enables the implementation of an appropriate action plan for earthquake preparedness and response, helping to preserve the monument for years to come and safeguard its remarkable history.

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