



# Earthquake risk analysis on historical buildings in Istanbul

N. Çamlıbel

*Yildiz Technical University,  
Beşiktaş-Istanbul, Turkey*

## SYNOPSIS

Istanbul, the oldest metropolis, capital of the East Roman, Byzantine and Ottoman Empire is situated on an active seismic zone of Turkey. Approximately 250 earthquakes occurred in Istanbul causing serious damage to the numerous historical monuments. Since 212, up to date many Byzantine and Turkish-Ottoman domed buildings collapsed and Hagia Sophia, with the first large dome had largely cracked and partly collapsed three times too in history [4].

Many other monuments are still the object of the risk of further damage as stated by various recent studies. Therefore, an earthquake risk analysis on historical monuments is presented, for a systematical restoration, in this paper. All these buildings are the summit of mankind. The prevention systems for these monuments against the hazardous future earthquakes must be urgently designed.

## INTRODUCTION

Turkey is one of the most active seismic zones of the world. Istanbul is situated on an active seismic zone Figure.1. A major fault system in the middle of the Marmara Sea, that is near the city, makes a thorough assessment of the earthquake potential imperative for the safety of the historical monuments. These prestigious buildings, with wide span, have been subjected until today, to several earthquakes with intensities greater than 6 (in M.M.Scale) [2].

Istanbul needs a special attention as the world's center of dome, and coupola tradition dating back to Byzantines with reference to the majestic presence of Hagia Sophia. During the last four thousand years (B.C. 2100-1900 A.D.) 1175 earthquakes had occurred in Turkey and the surrounding areas limited by the (22-45° .E) longitudes and (33-45° .N) latitudes [1].

The intensity degrees of the earthquakes occurred in the past have been evaluated to the (MSK-64) intensity scale [2]. The damages in Istanbul are characterized by statistical records to the interval of (212-1967) years [2].

According to these findings, a chronological estimation of the earthquakes causing serious damage show that, long intervals of approximately (150-250) years were followed four or five times by intervals of (15-20) years. The last damage causing earthquakes occurred in 1894 and 1912. According to this estimation, the next probable hazardous earthquakes can be anytime



between the years (2000-2500). Some Byzantine and Ottoman edifices are still the object of risk of further damages. Therefore, the earthquake response of some domed buildings is analysed, taking into consideration their structural characteristic architectural design, soil formation and foundation system. An earthquake risk analysis on historical monuments is made for a systematical restoration.

According to the observations and analytical investigations, made on some domed buildings, which had no damage during earthquakes with intensities greater than 6 (in M.M.Scale), lead to conclusions that the stresses in the structural elements are compression and they have bi-axial planes and elevations.

The analytical investigations and calculations made using the Turkish Seismic codes and new geotechnical investigations show that all buildings which have tension stresses had been cracked, collapsed several times by the earthquakes in the past. These edifices are now still under the risk of damage by earthquakes.

#### A GEOTECHNICAL ESTIMATION OF THE SOIL FORMATION OF ISTANBUL

The base of Northern area of the ancient walls built by Byzantines is made of greywackes and shales of Upper Devonian. Over this formation, are lithological sarmation of sands and gravels, clays and maetra limestones. The layer of artificial fill of the city remains constitute the upper layer. Though the green clay of the sarmation layer causes problems, especially on slopes, the over consolidated clays, sand and gravels are reliable as to their settlement and their load bearing capacities.

The soil of the Golden Horn coasts and Bosphorus is composed of natural alluvial soil brought by the rivers and the waste disposal of the city. Such a sedimentary soil and inclined bedrock of the area cause major settlement problems in which the damage due to the foundation failures of the buildings often results in the impossibility of restoration [3].

#### FOUNDATION SYSTEMS

Inside the city walls area of Istanbul, wooden grillage could be found under the foundations of old masonry buildings constructed on greywackes. Hagia Sophia, Byzantine churches and Ottoman Mosques are situated in this area. One of these, the Süleymaniye Mosque (1550-1557), the greats of the Ottoman Mosques, constructed on one of the seven hills of Istanbul overlooking the Golden Horn, has footings getting larger with depth and adapting to rock via a wooden grillage filled with mortar. Along the coasts of Golden Horn and Bosphorus, all old buildings have the foundations of wooden grillage and short wooden piles Figure.2. [3].

According to the investigations, the maximum stresses in the soil under the foundations are found to be  $(4.5-11.5) \text{ kgf/m}^2$  [6].

#### EARTHQUAKE RISK ANALYSIS ON HISTORICAL BUILDINGS

The proximity of the site to a major fault system in the Marmara Sea makes a thorough assessment of the earthquake potential imperative for the safety of the historical buildings. These historical edifices are important structures.



Earthquake risk analysis must be governed by a special criteria similar to those for Nuclear Power plants. These buildings have been subjected to many earthquakes with intensities greater than 6 (in M.M.Scale) that caused serious damages [1]. These edifices are still the object of further damage [6].

According to the probabilistic and deterministic analysis for the historical buildings in Istanbul, the magnitude must be taken between  $7.0 < M < 7.5$  and the peak ground acceleration of the bedrock under the soil material can be taken as

$$(PGA) = Co = (0.20-0.30)g$$

(g: gravity acceleration, Co: peak ground acceleration)

The new geotechnical investigations made at the site, reveal that the site consists of sandstones with shear wave propagation velocities above  $V_s = 700$  m/sec.

All the historical buildings have the masonry rigid structures. They behave as a rigid body against seismic action. Their vibration periods are found to be  $T = (0.27, -0.45)$  sec, according to the Turkish National Seismic codes (Table.1.) [6]

Taking the seismic codes into consideration, some results based on numerical analysis of some historical buildings are shown in (Table.2.)

The numerical results on some buildings show that all the structural components are generally in compression and tension media. The fact is that the buildings that suffer tensions were damaged several times during the history.

The buildings that suffer tensions are still the object of risk of further damage. There were no earthquake damages in all edifices that suffer tensions.

One of these, Süleymaniye Mosque (1549-1557) figure.4, has been subjected, until today, to 89 earthquakes with intensities greater than 6 (in M.M.Scale), nevertheless has showed a perfect structural performance [2]. This mosque is a wide spanned structure built with stone or brick masonry. The walls and piers are of stone. Covering parts (domes, semidomes) were built of brick masonry. Lime and powdered brick mixed with the white of egg, giving a particular type of mortar (Horasan), had been used. This particular mortar makes ductile, all the structural components that can absorb the seismic energy. On the other hand, the connections of the stones were perfectly designed by iron rods and sheets. The design and construction is in perfect media, according to the seismic codes of today.

The buildings that had not collapsed, due to seismic actions were designed axisymmetrically. Four arches carrying the central dome have the same rigidity in two perpendicular directions. In addition, the columns carrying the arches have the same rigidity in these directions. The stiffness of the supporting system is the same in the longitudinal and lateral directions Figure.5.

According to the numerical analysis, the load transmission mechanism is perfect especially with regard to the seismic conditions of Istanbul. In the domes, load transmission corresponds to the Membrane theory of shells. Stresses are uniformly distributed. Loads flowing in the arches are in perfect media according the funicular polygon [6].



In Hagia-Sophia, the central dome is not circular. The diameter in the plane of the dome is 33 m. in one direction and 30.50 m. in the other direction. Load transmission is not perfect with regard to the seismic conditions. Stresses in the central dome support are not uniformly distributed. Arches carrying the central dome and the columns carrying the arches have not the same rigidity and consequently the load transmission mechanism is not perfect. The semicoupolas were loaded by arches and one of these in sea direction is cracked. Therefore this edifice must be repaired urgently and reinforced against the future seismic actions [4].

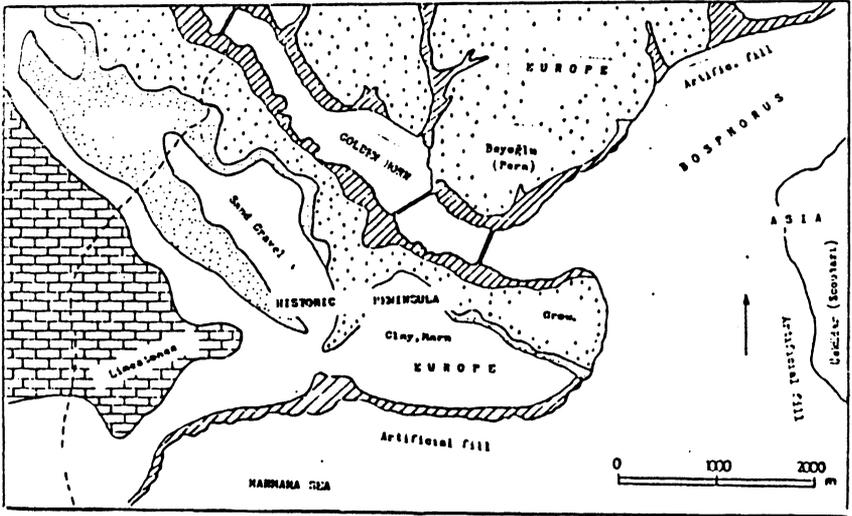
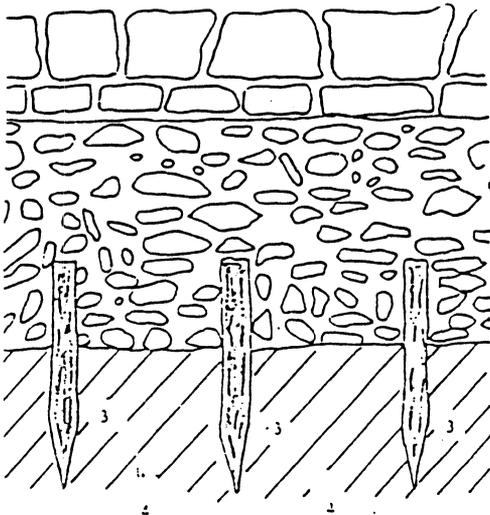


Figure.1. Geological Map of Istanbul (8)



1. Foundation system (ston or brick)
2. Sub-foundation (Horasanmortar-brick)
3. Wooden pears (in clays) : ( wooden griages in growaycs)
4. Soil (crawaycs, clays)

Figure.2. Foundation System of Mosques.



Table.1. Vibration period of several important Historical Buildings in Istanbul.

<u>Buildings</u>	<u>Vibration period (Sec.)</u>
Hagia-Sophia (532-565)	0.28
Şehzade Mosque (1546)	0.38
Mihrimah Mosque (1548)	0.29
H. İbrahim Paşa Mosque (1551)	0.33
Süleymaniye Mosque (1557)	0.36
E.Kapı Mihrimah Mosque (1568)	0.45
Zal Mahmut Paşa Mosque (1580)	0.27
Kılıç Ali Paşa Mosque (1558)	0.30
Kara Ahmet Paşa Mosque (1558)	0.27
Sokullu Mehmet Paşa Mosque (1571)	0.39
Rüstem Paşa Mosque (1562)	0.34

Table.2. Results of numerical Analysis on several important Historical Buildings in Istanbul

<u>Buildings</u>	Max. (kgf/cm <sup>2</sup> ) <u>Compression stress</u>	Max. (kgf/cm <sup>2</sup> ) <u>Tension stress</u>
Hagia Sophia (532-565)*	28.9	22.7
Şehzade Mosque (1546)	10.92	2.8
Mihrimah Mosque (1548)	28.21	15.44
H.İbrahim Paşa Mosque (1551)*	21.22	24.36
Süleymaniye Mosque (1557)	22.49	2.7
E.Kapı Mihrimah Mosque (1568)*	37.77	13.14
Piyale Paşa Mosque (1573-1579)	20.10	13.90
Zal Mahmut Paşa Mosque (1580)	16.90	6.00
Kılıç Ali Paşa Mosque (1558)	12.31	0.54
Kara Ahmet Paşa Mosque (1558)*	42.29	20.52
Sokullu Mehmet Pş. Mosque (1571)	29.20	14.30
Rüstem Paşa Mosque (1562)	7.46	1.49

\* - These mosques have been damaged several time in history.

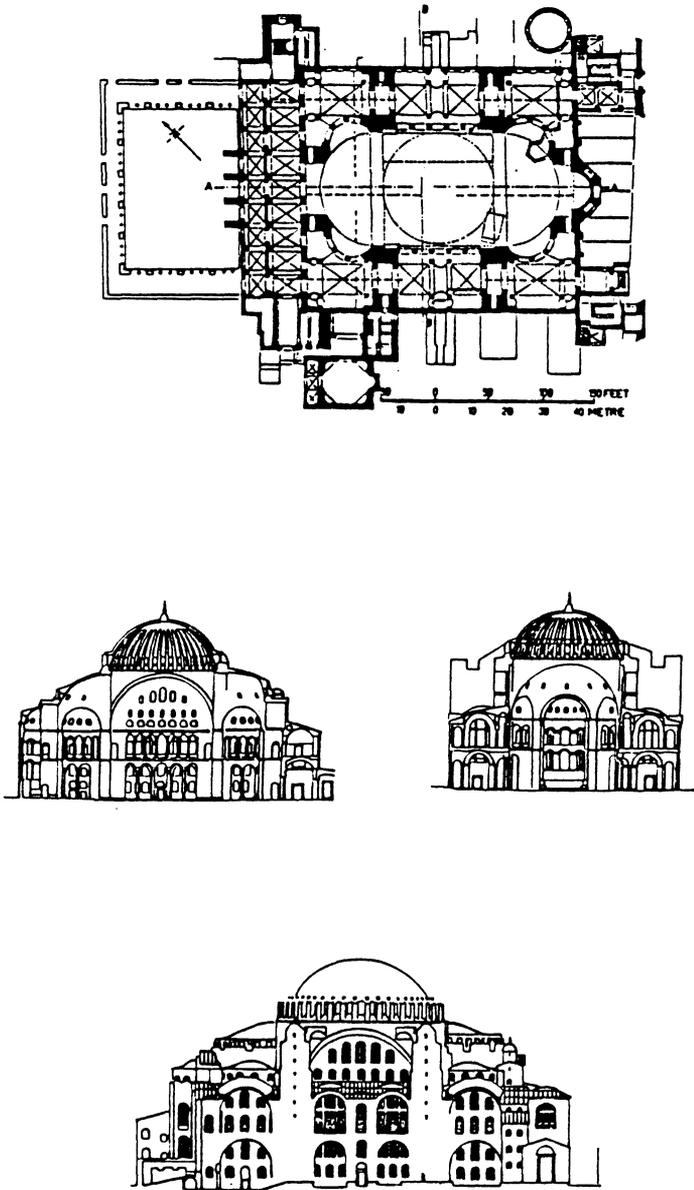


Figure.3. Hagia-Sophia (532-537)

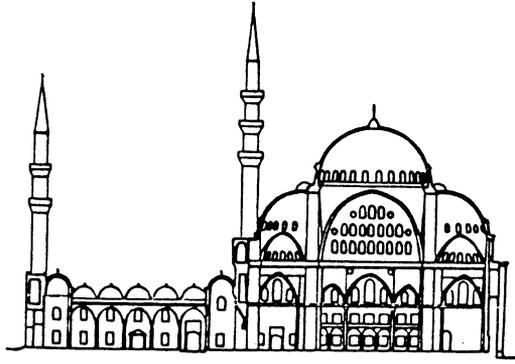
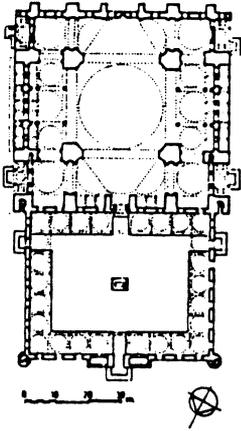


Figure.4. Süleymaniye Mosque, 1550-1556

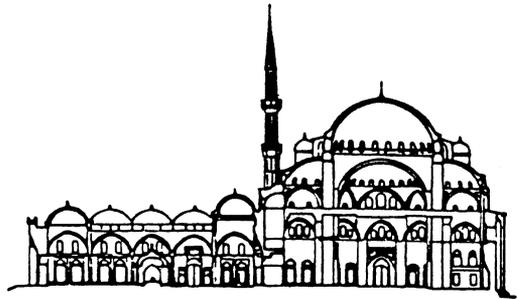
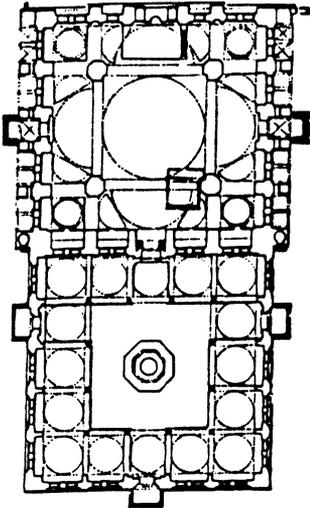


Figure.5. Mehmed Mosque, 1543-1548



## CONCLUSIONS

- 1- The analytical investigations made using the Turkish Seismic Codes, show that all buildings which have tension stresses had been cracked, collapsed several times by the earthquakes in history. These edifices are now still under the risk of further earthquake damage.
- 2- All these buildings are the summit of mankind. The prevention systems for these monuments against the hazardous future earthquakes must be urgently designed.
- 3- According to the observations and analytical investigations made on the domed buildings of Istanbul which had no damage during historical earthquakes, with intensities greater 6 (in M.M.Scale) lead to the following conclusions:
  - 3.1 In the domed buildings, there is bi-axial symmetry.
  - 3.2 The arches carrying the central dome have the same rigidity.
  - 3.3 The distribution of rigidity in plane and in elevation is uniform.
  - 3.4 The plane rigidity center and gravity center coordinates coincide approximately at the same point.
  - 3.5 The elements and components of the structures have a large ductility and a great seismic energy absorbtion ability.
- 4- Taking these risk analyses and results on masonry into consideration a system can be developed on masonry, to build contemporary rural housing in the seismic zones of the Mediterranean area. The new principals for the elaborations of national seismic codes and the basis of prevention systems for historical buildings against the hazardous future earthquakes, can be found in this system.

## REFERENCE

- 1- TUBITAK, The earthquake catalog of Turkey and its arounds, Istanbul, 1961
- 2- ARIOĞLU, E. and ANADOL , K., Earthquake Resistance of Süleymaniye Mosque in the Historical Perspective (1557-1973) Proceeding of the World Congress of Earthquake Engineering Roma. (2309-2312)
- 3- AKSOY, I.H., Istanbul'da Tarihi Yapılarda Uygulanan Temel Sistemleri (Foundation Systems of Historical Buildings in Istanbul), Istanbul Technical University, 1982.
- 4- MUNGAN, I., On the Structural Development of the Ottoman Dome with Emphasis on Sinan Domes From Antiquity to the Present, Proceedings of IASS-MSU Symposium, Istanbul, 1988
- 5- KARAESMEN, A. and UNAY, A.I., A Study of Structural Aspects of Domes From Antiquity to the Present, Proceeding of IASS-MSU Symposium, Istanbul, 1988.
- 6- ÇAMLIBEL,N., Sinan Mimarlığında Strüktürün Analitik İncelenmesi (Analytical Investigation of Sinan's Structures), Yıldız University, Istanbul, 1988.