Earthquake risk analysis on historical buildings in Istanbul

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Abstract

Historical structures in Istanbul, should be valued and preserved, since they are the most important part of cultural heritage of mankind. The typical historical structures and Byzantine and Ottoman buildings are very rigid. Earthquakes pose an everlasting danger to these historical structures, for they have destroyed so many historical structures in the past. Therefore, these Byzantine and Ottoman structures must be intensively studied for load carrying vulnerability against earthquakes. The ratio of load effects on structure and the strength capacity can represent a quantitative safety factor of historical structures against earthquakes. Therefore, an analytical risk analysis of the structure is performed in this paper, for a systematical restoration in future. All these Byzantine and Ottoman Buildings are the summit of mankind. Therefore, the prevention systems for these monuments against the hazardous future earthquakes must be urgently designed.

1 Introduction

İstanbul, the oldest metropolis, capital of the East Roman, Byzantine and Ottoman Empire is situated on an active seismic zone of Turkey and of the World.

During the last four thousand years (BC2000 – 1900 AD) approximately 1175 considerable earthquakes had occurred in Turkey and the surrounding area limited by the (22 – 45° E) longitudes and (33 – 45° N) latitudes [1].

Approximate 250 earthquakes in Istanbul caused serious damages on the numerous historical monuments during history. Since 212 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 in history [4].

Some numerous monuments are still the object of the risk of further damage as stated by various recent studies. According to the documents of Byzantine and Ottoman Empire, a chronological estimation of the earthquakes caused serious damages. show that long intervals of 150 – 250 years were followed four or five times by the intervals of 15 – 20 years. The last earthquakes which caused great damages occurred in 1894 and 1912 [1].

According to these findings, the next probable hazardous earthquake can occur between 2000-2050. The last earthquakes occurred in 17.08.2000. Therefore, an earthquake risk analysis on historical monuments is presented for a systematical restoration, in this paper.

Turkey is almost situated on one of seismic zones of the world; İstanbul is located on active seismic faults (Fig.1). A major system is the middle of Marmara Sea that is near the city makes a thorough assessment of the earthquake potential imperative for the safety of the historical monuments. A large number of Byzantine and Turkish Ottoman domed buildings created during many centuries are situated in this seismic zone. These prestige buildings with wide span have been subjected up today to several earthquakes with intensities greater than 6 in M.M. scale [2].

İstanbul needs a special mention as the world’s center of the dome and cupola tradition, dating back Byzantine with reference on the majestic presence of Hagia Sophia.

The intensity degrees of the earthquakes occurred in the past has been evaluated according to the (MSK-64) intensity scale [2]. The damages in İstanbul are characterized by statistical records for an interval of (212 – 1967) [2].

According the these findings a chronological estimation of the earthquakes caused serious damages show that long intervals of approximately (150 – 250) years were followed four or five times by the intervals of (15 – 20) years. The next earthquake can be between (2000 – 2050). And some Byzantine and Ottoman edifices are still the object of risk further damages. Therefore, the earthquake response of some domed buildings is analyzed taking into consideration their structural characteristics of architectural design, soil formations and foundation systems. An earthquake risk analysis on historical monuments is made for a systematical restoration.

These analysis will be the reason for urgent restoration of the Byzantine and Turkish Ottoman monuments which were repeatedly damaged due to older earthquakes. So a restoration team can be organized with almost all specialists needed for work.

According to the observations and analytical investigations made on some domed buildings which had no damages during earthquakes with intensities greater than 6 in M.M. scale lead to these conclusions that the stresses in the structural elements are all compression and it has bi-axial planes and elevations.
The analytical investigations and calculations made using the New Turkish Seismic Code (1997) and new geotechnical investigations show that all buildings which have tension stresses had cracked and collapsed several times by the earthquakes in the past. These edifices are now still under the risk of next earthquakes.

2 A Geotechnical Estimation of Soil Formation of İstanbul

The base of Northeastern area of ancient walls built by Byzantine is formed of greywaches and shales of upper devonian. Over this formation, there are lithological sarmation layers of sands and gravels clays and mactra limestone. The layer of artificial fill of the city remaining constitute the upper layer. Though the green clay of sarmation layer causes problems, especially on slopes. The over consolidated clays, sand and gravels are reliable as their load bearing capacities [3].

The soil of the Golden Horn coasts and Bosphorus is composed of natural alluvions brought by the rivers and the waste disposal of the city. Such a sedimentary soil and inclined bedrock of the area cause important settlement problems in which the damage due to the foundation failures of the buildings.

3 Foundation Systems

Inside the city walls area of İstanbul 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 is the Suleymaniye Mosque (1550-1557) is the greatest one of the Ottoman Mosques, constructed on one of the seven hills of İstanbul overlooking the Golden horn, has footings getting larger with depth and adapting to the 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 [3].

According to the investigations, the maximum stresses in the soil under the foundations are found about 4.5-11.5 kgf/cm² [6].

4. Structural Design Of Historical Buildings

The Byzantine and Ottoman Buildings in İstanbul have almost rigid domed structures. All buildings were planned rectangular with central dome flanking semi-domes and row of cupolas on two sides. The super structure was centered around the main dome. The main domes were supported by square, octagonal or hexagonal support system. The structural support systems transfers the load of the dome through various structural levels via auxiliary elements to the ground and is subjected to irregularities and complexities for both gravity effects and seismic actions.
These support systems consist of a series of structural measures ensuring its stability and stretching from the square or rectangular surrounding walls of structure to the building. The early Ottoman edifices with dome were constructed in Anatolia during the 14th and 15th centuries. These edifices were based either on the concept of a unique large dome covering the whole inner place or on the series of small domes one neighboring the other at the same level. Both thrust action and lateral seismic actions would thus be transmitted to massive exterior piers or walls. The progress in the late 15th and early 16th centuries brought secondary and partial domes surrounding the main dome at an interior level to resist thrust action. The control of this action is not sufficient to ensure the overall stability of the edifices formed by unusually sophisticated components, such as pendentives, planar, bowstring arches are subjected also too highly complex seismic forces. On the other hand, building techniques of Ottoman’s were also greatly improved during the 16th century allowing the construction of the masonry components in any curved geometry. The prestige buildings are of large dimensions. The central dome diameters are of 25 – 30 m. These buildings have bi-axial symmetry. The load transmission mechanism is still more complex and during especially with regard to the seismic conditions of the site [5].

5. Building Materials and Construction Technique

The Byzantine churches were built generally with bricks. The Ottoman Mosques were built both with stone and brick masonry. The walls and piers are always of stone. The covering part (domes, semi-domes) are built in brick masonry. The masonry covers should have curved geometry and consequently brick, especially shallow (or plate) brick was mostly preferred to stone. For the sake of practical use and flexibility, limestone had been used in both massive and powdered shapes and with addition of white of egg, a particular type of mortar was obtained, named Horasan. On the other hand iron rods and lead sheets were used perfectly [6].

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 the risk of further damages [6]. Therefore many prevention systems against to the hazardous future earthquakes must be designed and constructed. An earthquake resistant design of a prevention system needs a real earthquake risk analysis. Therefore, a study must involve the assessment of the basis elastic response spectra with the
operating basis earthquake and the safe shut down earthquake on the basis of the applicable specifications in order to evaluate the peak ground accelerations (PGA) to be expected at the site.

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

$$\text{PGA} = A_0 = (0.20 - 0.40)g$$

The new geotechnical investigations made at the site reveal that the site consists of sandstones with shear wave propagation velocities above approximate $V_s = 700\text{m/s}$.

All the historic buildings have the masonry rigid structures. They behave almost as a rigid body against seismic action. Their vibration periods are found $T = (0.39 - 1.1) \text{s}$ according to New Turkish Seismic Code (1997) (Table 1) [6].

Table 1. Vibration period of several important historical buildings in Istanbul

<table>
<thead>
<tr>
<th>BUILDINGS</th>
<th>VIBRATION PERIOD (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hagia Sophia (565)</td>
<td>1.01</td>
</tr>
<tr>
<td>Şehzade Mosque (1548)</td>
<td>0.54</td>
</tr>
<tr>
<td>Mihrimah Mosque (1548)</td>
<td>0.52</td>
</tr>
<tr>
<td>H. İbrahim Paşa Mosque (1551)</td>
<td>0.53</td>
</tr>
<tr>
<td>Süleymaniye Mosque (1557)</td>
<td>1.01</td>
</tr>
<tr>
<td>E. Kaptı Mihrimah Mosque (1568)</td>
<td>0.74</td>
</tr>
<tr>
<td>Zal Mahmut Paşa Mosque (1580)</td>
<td>0.52</td>
</tr>
<tr>
<td>Kılıç Ali Paşa Mosque (1558)</td>
<td>0.54</td>
</tr>
<tr>
<td>Kara Ahmet Paşa Mosque (1558)</td>
<td>0.46</td>
</tr>
<tr>
<td>Sokollu Mehmet Paşa Mosque (1571-2)</td>
<td>0.53</td>
</tr>
<tr>
<td>Rüstem Paşa Mosque (1562)</td>
<td>0.52</td>
</tr>
<tr>
<td>Piyale Paşa Mosque (1574)</td>
<td>0.39</td>
</tr>
<tr>
<td>Azapkapi Sokollu Mosque (1578)</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Using the formula $T_1 = C_t H_N^{3/4}$, $C_t = 0.05$, $H_N =$ Elevation of building. Natural period of ground for Istanbul is taken as $T = 0.10 - 0.90$, and for the spectrum coefficients, the formula is taken from Fig.2 using

$$S(T) = 1 + 1.5T/T_A \quad 0 \leq T \leq T_A$$
$$S(T) = 2.5 \quad T_A \leq T \leq T_B$$
$$S(T) = 2.5(T_B/T)^{0.8} \quad T > T_B$$
According to the New Turkish Seismic Code of 1997, for the rigid buildings the equivalent lateral seismic forces acting on building are found using the formula:

\[ V_t = A_0 w S(T) / R \]

where \( A_0 = PGA = 0.40 \) (peak ground acceleration), \( w \) = weight of the building, \( S(T) \) = spectrum coefficient, \( R = 4.5 \), a coefficient for rigid buildings according to the code.

Taking these forces into consideration, some results based on numerical analysis of some historical buildings are shown in Table 2. These 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 history.

Table 2. Results of numerical analysis on several important historical buildings

<table>
<thead>
<tr>
<th>BUILDINGS</th>
<th>MAX. COMPRESSION STRESS (KG/CM²)</th>
<th>MAX. TENSION STRESS (KG/CM²)</th>
<th>SAFETY FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hagia Sophia</td>
<td>28.90</td>
<td>22.70</td>
<td></td>
</tr>
<tr>
<td>Şehzade Msq.</td>
<td>17.70</td>
<td>3.16</td>
<td>3.16</td>
</tr>
<tr>
<td>Mihrimah Msq.</td>
<td>4.47</td>
<td>0.50</td>
<td>7.57</td>
</tr>
<tr>
<td>H. İbrahim Paşa Msq.</td>
<td>11.19</td>
<td>7.41</td>
<td>0.30</td>
</tr>
<tr>
<td>Süleymaniye Msq.</td>
<td>11.30</td>
<td>1.05</td>
<td>3.43</td>
</tr>
<tr>
<td>E.Kapı Mihrimah Msq.</td>
<td>12.53</td>
<td>4.38</td>
<td>1.29</td>
</tr>
<tr>
<td>Zal Mahmut Paşa Msq.</td>
<td>2.4</td>
<td>1.28</td>
<td>5.7</td>
</tr>
<tr>
<td>Kılıç Ali Paşa Msq.</td>
<td>9</td>
<td>2.13</td>
<td>3.71</td>
</tr>
<tr>
<td>Kara Ahmet Paşa Msq.</td>
<td>10.46</td>
<td>4.11</td>
<td>1.27</td>
</tr>
<tr>
<td>Sokollu Mehmet Paşa Msq.</td>
<td>17.6</td>
<td>1.85</td>
<td>1.85</td>
</tr>
<tr>
<td>Rüstem Paşa Msq.</td>
<td>55.4</td>
<td>1.11</td>
<td>4.29</td>
</tr>
</tbody>
</table>
Hagia Sophia (Fig. 3) with the first large dome of Christian dome had largely swaged, cracked, partially collapsed in 538, 960, 1766. H. Ibrahim Paşa Mosque (in 1648-1763), Edirnekapi Mihrimah Mosque (in 1719-1819), Kara Ahmet Paşa Mosque were damaged in the mentioned earthquakes. The buildings that suffer tensions are still the subject of the risk of further damages but there is the Süleymaniye Mosque (1549-1557)(Fig 4) which has been subjected up today to 89 earthquakes with intensities greater than 6 in M.M. scale, nevertheless has showed a perfect structural performance [2]. This mosque is wide spanned structure built with stone and brick masonry. Lime and powdered brisk with addition of white of egg giving a particular type of mortar (Horasan) had been used. This particular mortar make ductile connections to all the structural components that can absorb the seismic energy. In the other hand the connections of stone were perfectly designed by iron rods and sheets. The design and construction is in perfect media according to the seismic codes of our days. The buildings due to seismic actions that had not collapsed have axis symmetry. Four arches carrying the central dome have the same rigidity in two perpendicular direction. In addition, the columns carrying the arches have the same rigidity in these directions. The stiffness of the supporting system is same in longitudinal and lateral directions (Fig.5). According to the numerical analysis, the load transmission mechanism is perfect, especially with regard to the seismic conditions of İstanbul. In the domes, load transmission corresponds to the membrane theory of shells. Stresses are uniformly distributed. Loads flow in the arches is in perfect media according to the funicular polygon [6]. In Hagia Sophia, the central dome is not circular in current situation. The diameter in plane of the dome is 33m in one direction and 30.50m in the other. Load transmission is not so perfect with regard to the seismic conditions. Stresses in the central dome supports are uniformly distributed. Arches carrying the central dome and the columns carrying the arches do not have the same rigidity and consequently the load transmission mechanism is not perfect. The semi-cupolas 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]. According to the realized numerical analysis, it is shown that the distribution of the rigidity in plan and in elevation is uniform and perfect. The tenders used in the supports of arches are not only statics elements. They prevent the foundation settlements and numerous failures in the soil. Consequently the earthquake responses of these structures are perfect. The plane rigidity center and gravity center coordinates coincide approximately in the same point. All structural elements are dimensioned taking into consideration the behaviour of static system and the seismic conditions.
7. Conclusion

The analytical investigations made using the New Turkish Seismic Code, shown that all buildings which have tension stresses had been cracked, collapsed several times by the earthquakes in the history. These edifices are now still under the risk of further earthquake damages.

All these buildings are the summit of the mankind. The prevention systems for these monuments against the hazardous future earthquakes must be urgently designed.

According to the observations and analytical investigations made on the domed buildings of Istanbul which had no damages during historical earthquakes with intensities greater than 6 in M.M. scale lead to the following conclusions:

- In the domed buildings, there are biaxial symmetry,
- The arches carrying the central dome have the same rigidity in all directions,
- The distribution of rigidity in plan and in elevation is uniform,
- The plane rigidity center and gravity center coordinates coincide approximately at the same point,
- The elements and components of the structures have a large ductility and a great seismic energy absorption ability.

Taking these analysis results on masonry into consideration, a system can be developed to built on masonry the contemporary rural housing in the seismic zones of the Mediterranean area and new principles can be found for the elaborations of national seismic codes and the basis of prevention system for historical buildings against the hazardous future earthquakes.

References

Figure 1. Geological map of Istanbul

Figure 3. Hagia Sophia (565)
Figure 4 Suleymaniye Mosque (1557)

Figure 5 Şehzade Mosque (1548)