ON THE EARTHQUAKE RESISTANCE OF THE SULEYMANIYE MOSQUE (ISTANBUL) IN THE HISTORICAL PERSPECTIVE (1557-1973)

Ersin ARIOGLU [I] **Köksal ANADOL** [II]

SYNOPSIS

The Suleymaniye Mosque was built in Istanbul during the reign of Magnificent Suleyman, by the head architect of the period, Mimar Koca Sinan, between the years 1549-1557. The mosque up today has been subjected to 89 earthquakes with intensities greater than VI (in MM scale) and showed a perfect structural performance. In the paper the successful earthquake response of the structure is analysed and discussed in function of its determined structural and dynamic characteristics .

INTRODUCTION

The Suleymaniye Mosque having plane dimensions of 63x69 meters and a volume of about $18x10^4$ m^3, is situated at the center of a Kulliye (an assembly of educational, social and religious buildings), spread out on an area of 108.000 m^2. In addition to its structural characteristics resisting capacity to earthquakes with accelerations greater than 0,20g., the mosque with its functional, aesthetic and acoustic properties, is one of the masterpieces of the classical period of Turkish architecture. The construction has been completed in 4 millions working days, costing about 60 millions in today's days currency ($) (5).

STRUCTURAL CHARACTERISTICS

A. Sub-ground : The mosque is built on a sedimentary graywacke-shale layer of Paleozoic origin. The mechanical and dynamic properties of the ground and the geological structure of the region are given in Fig. 1,2.(1).

B. Foundation System: The mosque is constructed on stone foundation with wooden piles of 6,20 m. dept (Fig. 7-E).

C. Structural System: The loads are transferred to foundations by means of 4 main frames and side walls, bounding the main hall (Fig. 7-A) The vertical load of 976 tons, coming from the main dome, is taken to the pillars through arches. The lateral thrust in the x-x direction is carried by half-domes to the side walls, whereas in the y-y direction it is transformed into vertical direction by means of hinged buttresses, specially designed by Sinan, and transferred to arches. Side walls and 4 pillars are carrying to foundations, loads in the order of 36.000 and 32.000 tons, respectively. The uniform distribution of the stiffness in the structural system, dimensioning, connection technology of structural elements and material selection are perfectly achieved. Mathematical models of the mosque for static and dynamic analysis are given in Fig. 5, 6 and 7-C.

D. Materials and Construction Technology: Material properties and outstanding construction stages are represented in Fig. 5 and 6.

I. Dipl. Ing. (ITU) Head of Structural Design Dept. Yapı Merkezi-Istanbul
II. Dipl. Arch. (DGSA) Head of Research Dept. Yapı Merkezi-Istanbul

EARTHQUAKES EFFECTING THE MOSQUE

Istanbul and its surroundings (39^o- 43^oN ; 25^o-31^oE) are situated on a highly active earthquake zone, the seismic activity of which can be expressed by the formula $\log_{10}N= 5.5 -0.64$ M, derived using the statistical data obtained between the years 11 and 1964 (In this formula, N denotes the total number of earthquakes occurred in 1953 years, having a magnitude greater or equal to M) (2). The most destructive earthquakes effecting the city are summarized in Table I. The information, given in the table on the earthquakes occurred after 1912, are based on instrumental records. The intensities of these earthquakes felt in Istanbul, are obtained using the $I= f (I_o, \Delta)$ relation given at the end of the table (2).

The information provided for previous earthquakes are based on the historical documents of the Ottoman Empire (5). It is possible to estimate accurately, the intensities in Istanbul and epicenter coordinates of these earthquakes, using the very detailed information about earthquake damages, given in these documents. The spectral accelerations are also presented; the theoretical calculations being based on the detailed descriptions of earthquake damages (collapsed minarets, failed columns, etc.) given in the above mentioned documents (5).

The mosque has resisted successively all of these destructive earthquakes without any damage. Furthermore, theoretical analyses show that the Suleymaniye Mosque can even resist, within the elastic limits, earthquakes with accelerations in the order of 0,3g. This statement is approved by the perfect engineering discipline of the structure, the highlights of which are summarized below.

CONCLUSION

1) The natural periods of the structure are made greater than the predominant period of the ground (Fig. 1, 5) ($T_x= T_y= 0.76$ sec., $T_o=0.42$ sec.).

2) The stiffnesses are uniformly distributed in the horizontal and vertical planes. The geometric center, the center of gravity and the center of stiffness nearly coincide (Fig. 4).

3) The lead and iron-sheet joints and the special mortar "Horasan" used to connect structural elements, increase the energy absorption capacity and the ductility of the structure.

4) The discipline in the selection of the constructional material and the construction technology are perfect.

The resistance of the mosque against earthquake forces is certainly not a coincidence but the result of great insight and mathematical concept.

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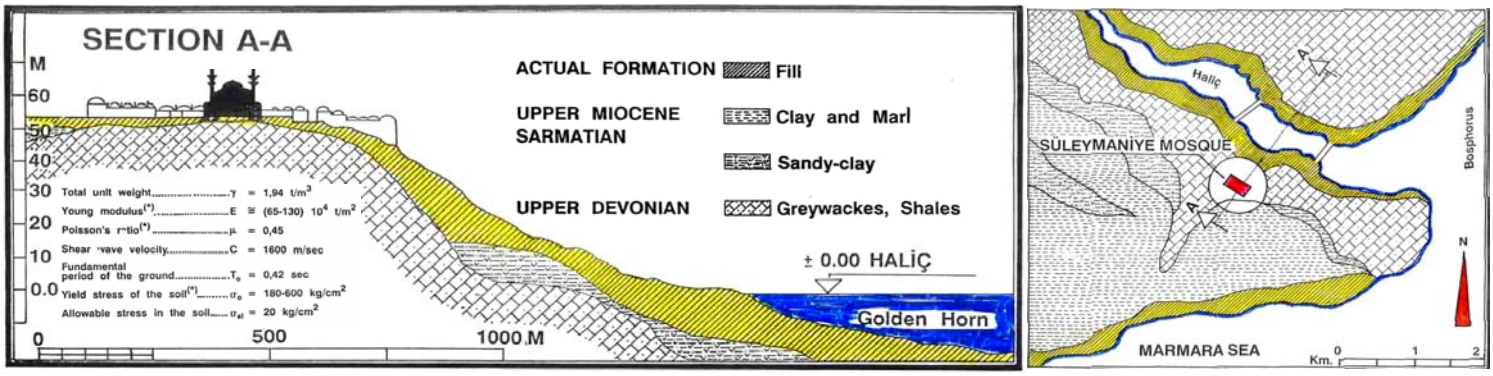


Fig.1 -Characteristics of the Subground and the Geologic Structure

No	Date	Epicenter N	Epicenter E	Magnitude	Intensity (MM) (at epicenter)	Distance from Epicenter(Km)	Intensity (MM) in Istanbul	Acc. %g
1	30.04.1557	41.0	29.0	6.4	VIII	0	VIII	12
2	30.07.1633	41.0	29.0	5.5	VII	0	VII	-
3	28.06.1648	41.0	29.0	7.0	IX	0	IX	18
4	.1718	41.0	29.0	6.2	VII	0	VII	-
5	25.05.1719	40.8	29.4	7.3	X	25	IX	18
6	03.09.1763	41.0	29.0	5.8	VII	0	VII	-
7	23.04.1766	40.8	28.2	7.6	X	72	IX	17
8	28.02.1855	40.2	29.1	7.7	X	90	VIII	14
9	10.07.1894	40.6	28.7	7.8	X	54	IX	21
10	09.08.1912	40.5	27.0	7.8	X	177	VII	-
11	04.01.1935	40.5	27.5	6.9	IX	137	VI	-
12	18.03.1953	40.0	27.3	8.0	XI	182	VII	-
13	06.10.1964	40.3	28.2	7.0	IX	102	VI	-
14	22.07.1967	40.7	30.8	7.2	IX	150	VI	-

$M = 0.592\ I_o + 1.63$ $\quad I = I_o + 3.58 - 3.33 \log \Delta$

M = Magnitude I = Local Intensity I_o = Epicenter Intensity Coord. of Istanbul : (41.04N-28.98E)

Table I -Destructive Earthquakes in Istanbul

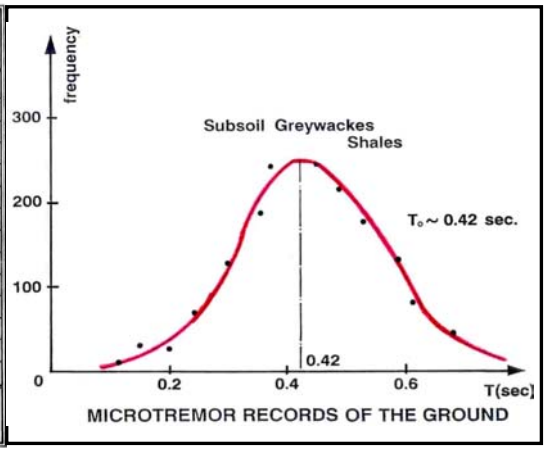


Fig. 2

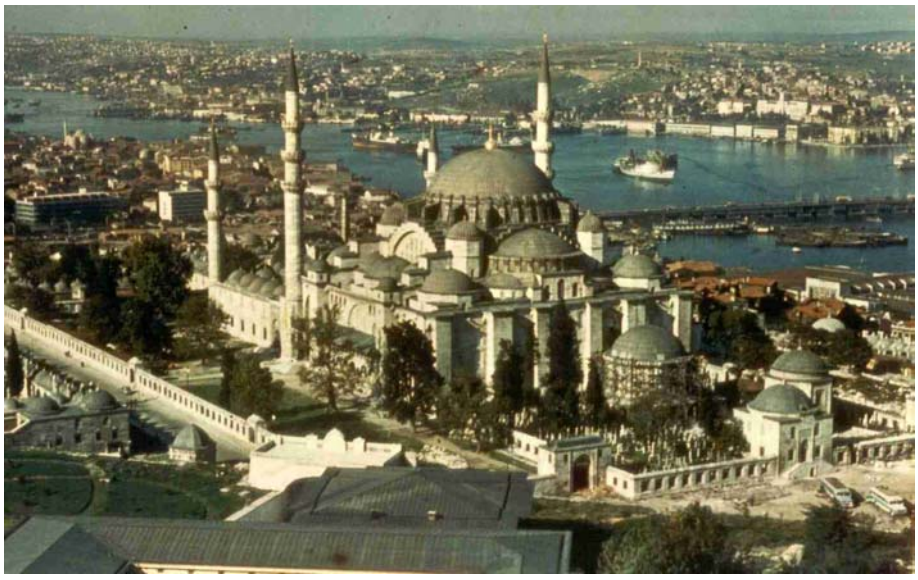
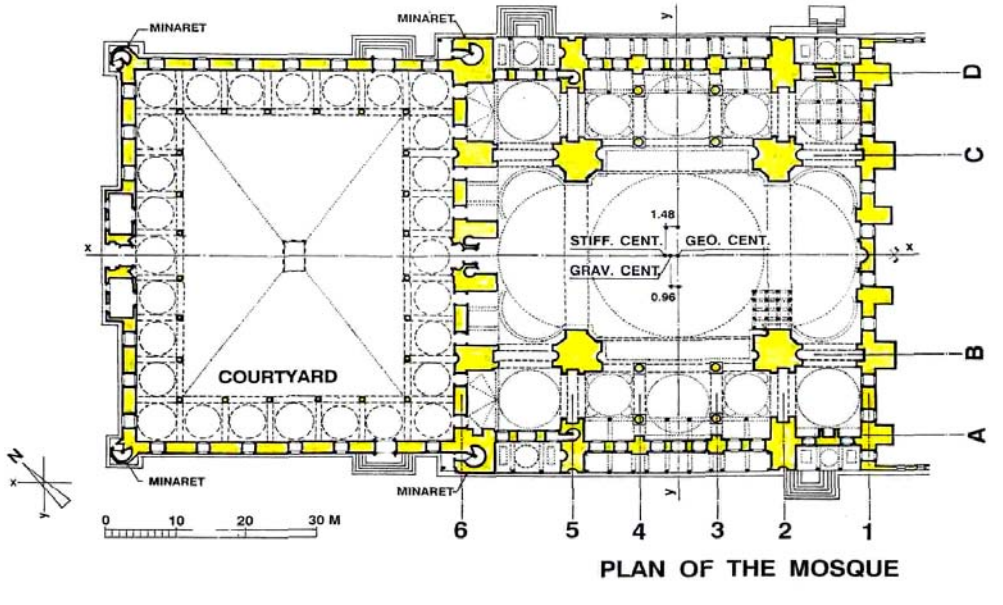


Fig. 3 (Above) General View - Fig.4 (Below) Plane of the Mosque



DYNAMIC CHARACTERISTICS

Natural greatest period of Mosque
Tx = Ty = 0.76 sec.
(Mathematical Model Fig.7C without damping)
Critical Damping : h ~ 0.06
Ductility factor : D ~ 1.40
Periods of Minarets : (sec)

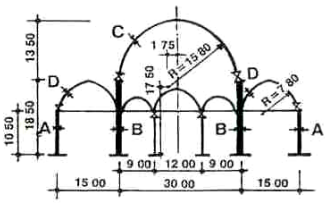
	$T_{experiment}$	$T_{theoretical}$
Short	0.93	0.88
Long	0.95	0.91

	x m	y m	z m
Coor. STIFFNESS Center	1.48	0	-
Coor. GRAVITY Center	0.96	0	15.82

MATERIAL CHARACTERISTICS				
	γ t/m^3	E kgf/cm^2	Yield stress kg/cm^2	
			TENSION	COMPRS.
Limestone	2.6	26x10^4	30	600
Marble	2.8	49x10^4	40	1000

	Excavation Foundations & Sidewalls	Waiting for Settlement of Foundations	Minarets					Oct 15th
			Sidewalls & Ext. Arches	Piers	M.Arch Hf.Dome	Main Dome	Others	
years	1549	1550 1551 1552 1553	1554		1555	1556	1557	

CONSTRUCTION STAGES



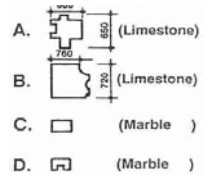


Figure 5 -Section x-x

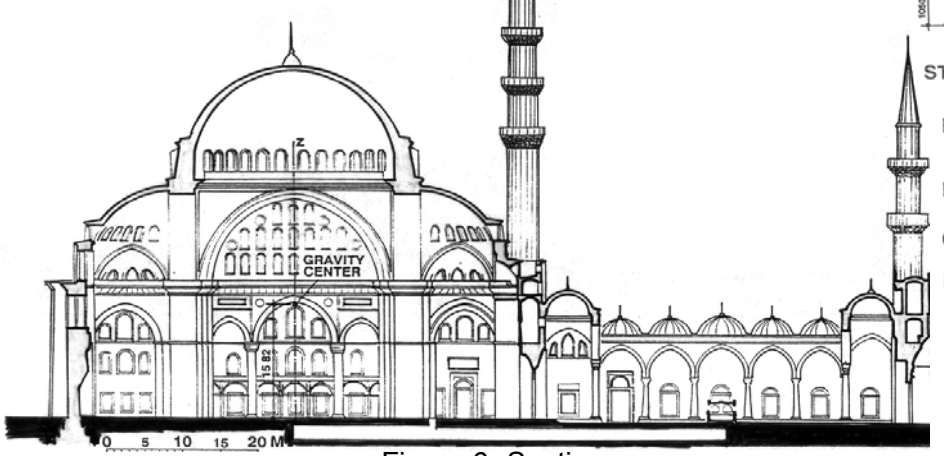
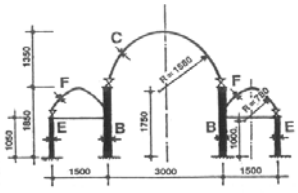
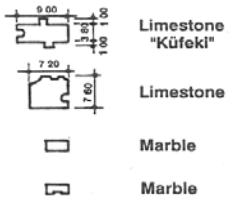


Figure 6 -Section y-y





A. LOADING FLOW SCHEME

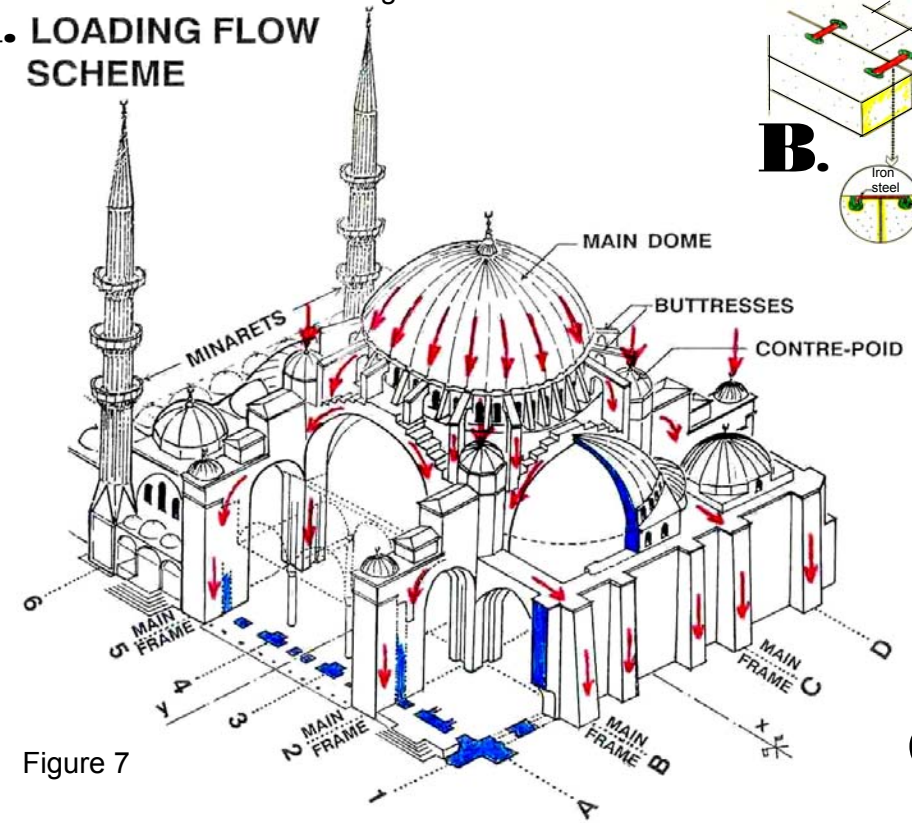
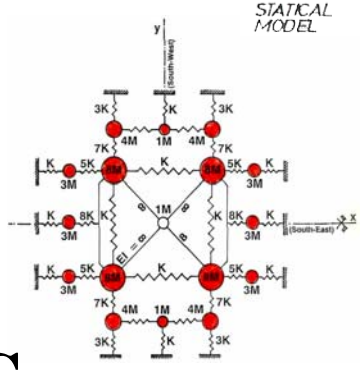


Figure 7

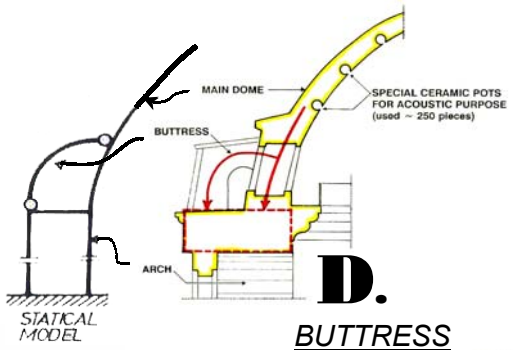
NOTE : In the whole struc. 44,085 pieces of iron tiebars are used.

B. DETAIL OF IRON TIEBARS

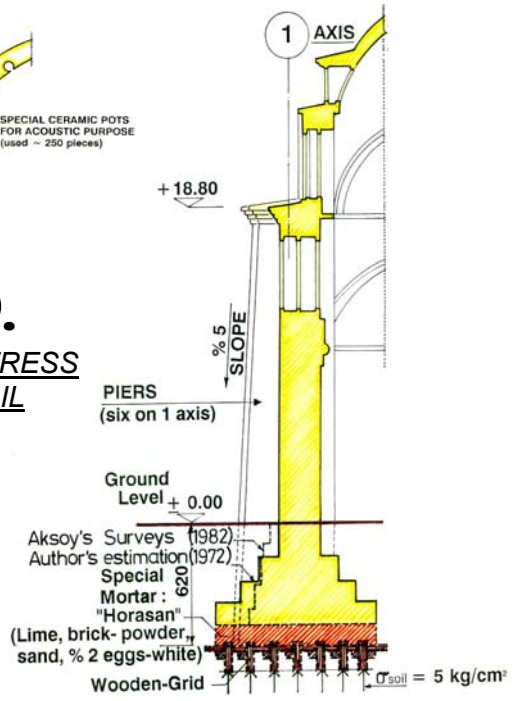


C. *MATHEMATICAL MODEL (In plan)*

(for dynamic analysis)



D. *BUTTRESS DETAIL*



E. *WALL AND FOUNDATION DETAIL*