Dynamic Characteristics of Hagia Sophia in Istanbul before and after the 1999 Kocaeli Earthquake by Microtremor Measurements

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Abstract

Hagia Sophia is a huge structure rebuilt in 537AD with a big dome. It has been suffered accidents as collapsing the dome repeatedly by earthquakes but the original shape has been remained miraculously. A Mw7.4 earthquake about 100 km away attacked and affected Hagia Sophia in 17th August, 1999. We had measured microtremor of some structures in Istanbul including Hagia Sophia two months before the earthquake by chance. Two weeks after the earthquake, we had measured at almost same place again. Hagia Sophia was affected severely estimated from the shifted predominant frequency. This fact has been already reported and this time the situation of the changing dynamic characteristics before and after the earthquake is reanalysed at 48 points from the response spectra, vibration locus, mode and so on. As a result, the response spectra of the main structure shows many peaks, mainly one clear peak for EW component and two peaks for NS component. Amplification factors of EW component are larger than that of NS component and both of them at south side are larger than that at north side. Amplification factors decreased obviously after the earthquake for entire the EW component. But for NS direction, it was almost same at the dome cornice, increased at southern side of 2nd cornice or gallery level (hereafter 3F or 2F respectively) and decreased drastically at northern side of 3F or 2F. The torsional vibration in the horizontal plane can be detected by the simultaneous measurement at east and west main piers on 2F and 3F. It shows complexities as some is confirmed in a south-north couple and the other is confirmed only at

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the one part. It shows that each part moves with a certain level of degree of freedom and suggests the progress of degradation.

1. Introduction

Figure 1 shows a view of Hagia Sophia from the west.
Hagia Sophia construction begun in 532, dedicated in 537 and received its definitive form in 562, as a principal church of Byzantine empire and converted to a royal mosque in 1453. It contains four brick arches from stone piers that offer primary support for a 31 m diameter central dome and two semi-domes. It has four main piers supporting the corners of the dome base and four main arches that spring from these piers and support the edges of dome base [1]. It has a dimension of free internal space 30 m wide, 80 m long, 56 m high. During its history it was affected by many earthquakes resulting in several reconstructions of different parts of the main dome and repair of some structural elements [2]. Structure exhibits large deformations in its piers and arches resulting from the material properties. Main piers inclined away from vertically 45 cm along the short axis and lean backward an average of 15 cm along the long axis.

A Mw7.4 earthquake about 100 km away attacked and affected Hagia Sophia. We had measured microtremor of some structures in Istanbul including Hagia Sophia two months before the earthquake by chance. Two weeks after the earthquake, we had measured at almost

Figure 1 *Hagia Sophia, view from the west before the event*

same place again. The result of these measurements has been reported [3], and it suggest that Hagia Sophia was affected severely estimated from the shifted predominant frequency.

In this paper, it will be described that the result of the microtremor measurement at Hagia Sophia in Istanbul conducted at 8th and 9th June, 1999 and at 3rd September, 1999, before and after the Kocaeli earthquake, occurred in 17th August, 1999, with a focus on the change after the earthquake.

2. Locations of Microtremor Measurement and Procedures of Measurement and Analysis

Figures 2-1 and 2-2 show measurement locations on the plane, the side and front cross sections of Hagia Sophia. Outside Hagia Sophia,

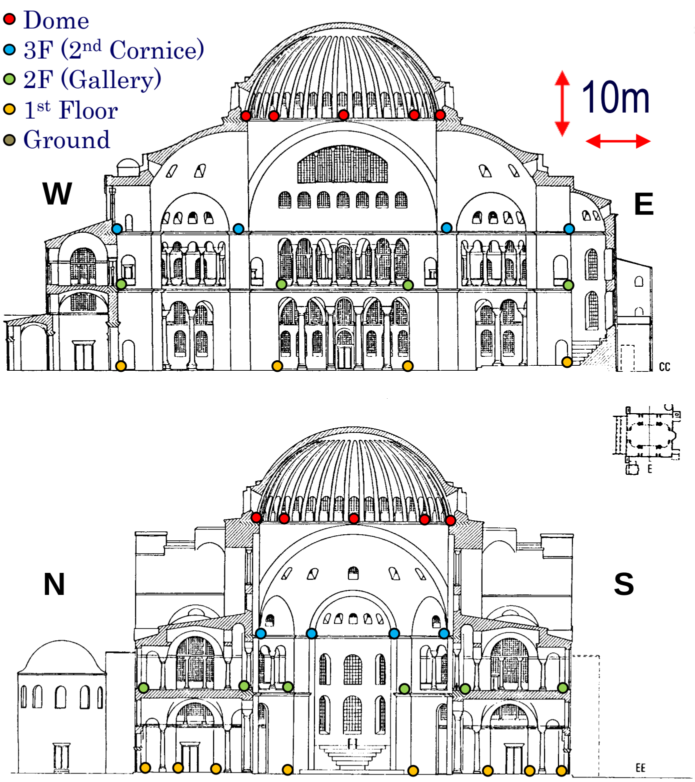


Figure 2-1 *Measurement locations in Hagia Sophia*

measurement points were set 7 points on the ground. And inside Hagia Sophia, measurement points were set 16 points at the first floor (1F), 16 points at the gallery level (2F), 8 points at the second cornice (3F) and 8 points at main dome cornice (D). Total number is 48 inside.
However microtremor measurement was conducted simultaneously at two points with same color enclosed by pink long circles using two instruments with a three-direction sensor, it was considered as basically individual measurement because simultaneous measurement could to be conducted in the same level.
At each site microtremor were recorded three sets of 40.96 seconds, 4096 data as a sampling time of 1/100 seconds, selecting low noise condition. Velocity locus of 40.96 seconds data was drawn using stable record of three data. Averaged Fourier spectra of each site were

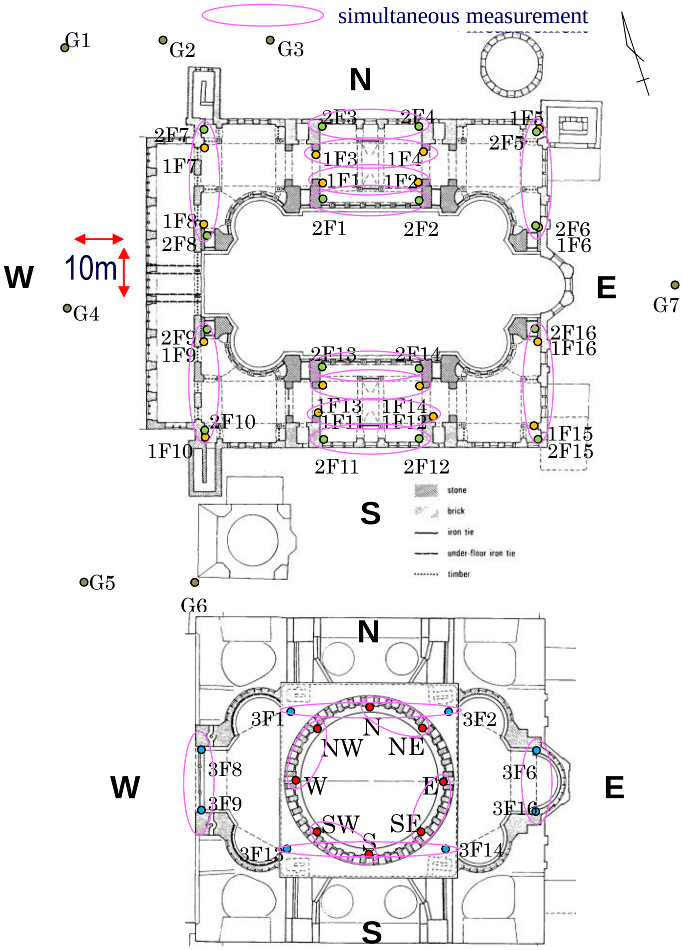


Figure 2-2 *Measurement locations in Hagia Sophia*

derived from the average of three spectra of 40.96 seconds data. Response spectra of each site were derived as a spectral ratio divided by an averaged Fourier spectra corresponding to site at 1F.

3. Results of Analysis

3.1. Velocity loci of microtremor before and after the event

It is easy to grasp visually the dynamic behavior of each site using locus. Figure 3 shows the loci of the 40.96 seconds data corresponding to the measured location before and after the Kocaeli earthquake on the plan and the elevation. Please notice that these loci were not measured simultaneously.

Loci are extremely small with almost same level at all the points at the 1F, however on the 2F, they are small at the points at the corner of southeast or north and large at the center. The extent of loci over 2F is almost same and loci on the dome cornice locate radially and the east-west motion is predominated at the west end. Before the earthquake, the loci are predominantly large at south of the dome cornice. After the earthquake, the loci are averaged especially at the dome cornice and they become large at the northern side and relatively large at western side as the building motion. Additionally, the north-south motion predominates at the center of the gallery level 2F. The vertical motion predominates on the east and west half dome, and the vibration seems to be rocking vibration on the north-south arch.

Mentioned above are the results on the analysis of velocity locus, and then in the next section the results of the frequency analysis will be described.

3.2. Transfer functions of horizontal component after the event

Figures 4 are the transfer functions of the EW and NS components for each point on each level measured after the earthquake, and these figures indicate the response for each component layered at the 16 points corresponding to the location on the plain. The measurement points on the dome are indicated at the location of the corresponding pier.

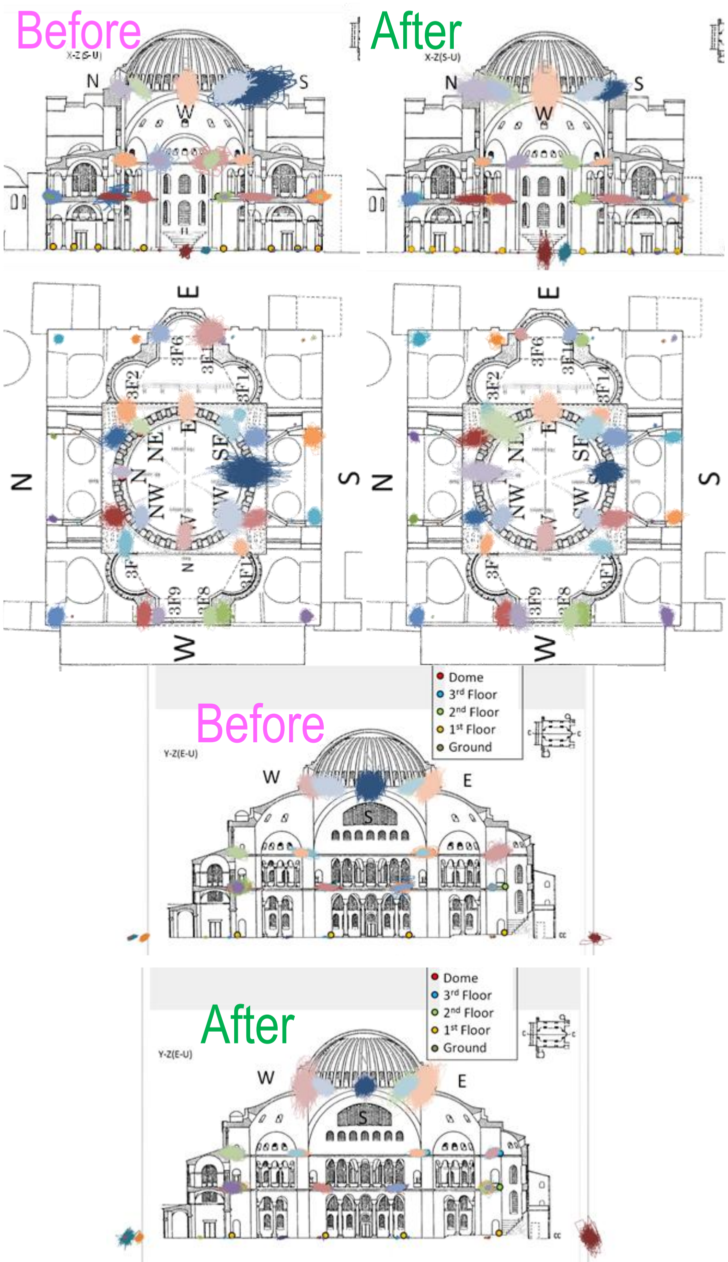
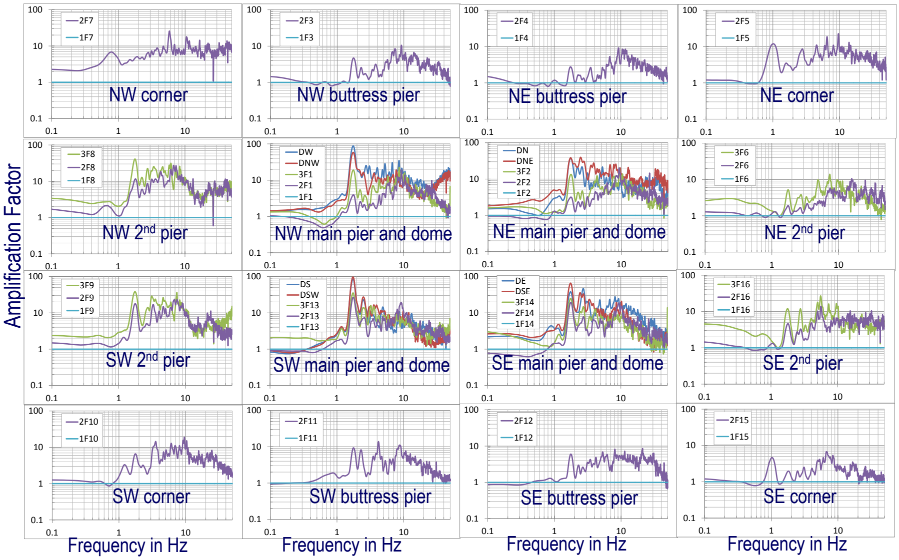
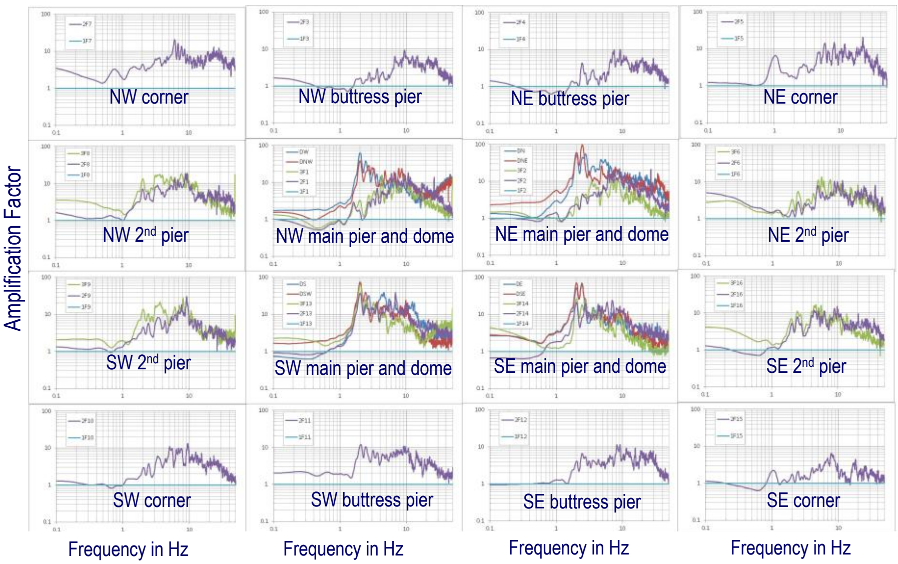


***Figure 3** Microtremor loci in velocity amplitude of before and after the Kocaeli earthquake*

These figures indicate roughly the dynamic characteristics of the structure. However the response spectra at gallery level against 1F



(a) *Transfer functions of EW component after the event*



(b) *Transfer functions of NS component after the event*

Figure 4 *Transfer functions of horizontal component after the event* shows similar shape, it can be seen that the vibration around 1 Hz predominates at the corner of the structure and that more than 2 Hz predominates at the other site with large response at western side of the structure, and the vibration around 10 Hz is a similar level but becomes large around 2 Hz in south-north side. A large response around 2 Hz is seen at the four main piers in the center or the dome with tendency to become lager in west or south side. A vibration around 1 Hz at the corner may be a predominant frequency of the additional minarets at the time of diversion to a mosque and seems to be a vibration unrelated to the structure itself.

Torsional vibration will be described in the next section.

3.3. Phase difference in north-south direction from simultaneous measurement of east and west side points of 3F and 2F

Because the simultaneous measurement was conducted at the places separated east and west, it is possible to derive the torsional vibration component from the north-south direction vibration. Figure 5

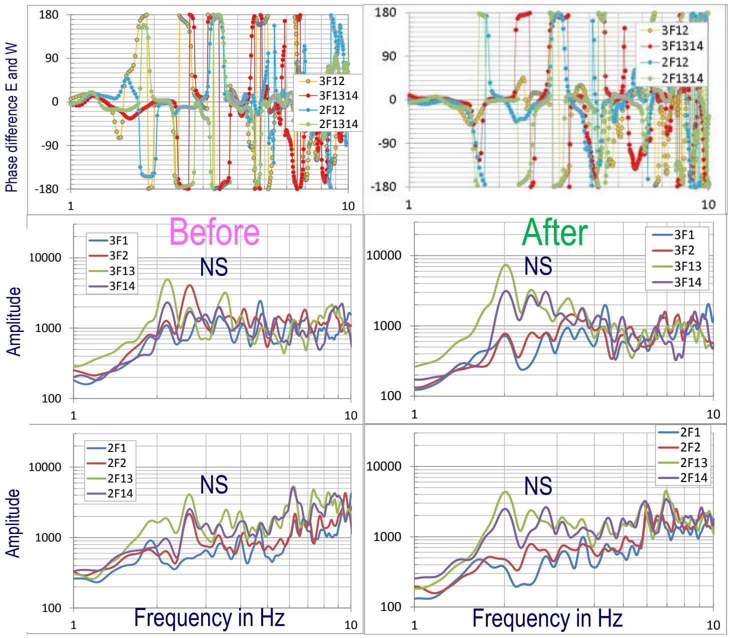


Figure 5 *Phase difference in NS component*

shows the spectrum and its phase difference from microtremor measured at the main piers of 2F and 3F. Top of the figure indicates the phase difference and the figures below indicate the spectrum amplitude of 3F and 2F. Although the phase difference becomes 180 degrees at all the points at the frequency range over 3 Hz, the spectrum amplitude does not indicates clear peaks after the earthquake. Before the earthquake, three points among four points with clear peak have a frequency with the phase difference 180 degrees, but all of them do not indicate a clear peak after the earthquake. In any case, only the south part becomes to be easy to vibrate after the earthquake.

3.4. Transfer functions of main dome and piers, before and after the earthquake

Figure 6 shows the change of the response characteristics of main piers and dome cornice before and after the earthquake. At the dome cornice, there are one clear peak as first modal frequency at EW component and two peaks as second and third modal frequencies at NS component. However peaks at EW component can be recognized at all the piers before the earthquake, they can be recognized only at the southern side after the earthquake. This trend is also seemed at the two peaks of NS component and the southern side becomes to be relatively easy to vibrate after the earthquake.

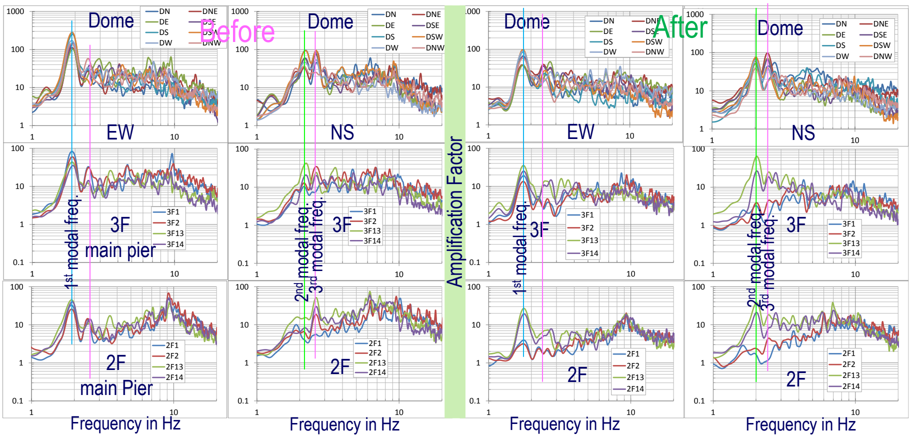


Figure 6 *Transfer functions of main dome and piers*

The peak at high frequency range of NS component is considered corresponding to the torsional vibration and it is recognized clearly at the NS component of the dome cornice. After the earthquake, the torsional vibration component becomes relatively large because the peak of EW component becomes small. However the torsional vibration predominates at NS component at the dome cornice, which can be seen only at the southern side without the dome.

4. Discussion

4.1. Change of the predominant frequency

Table 1 show the changes of the first and the second predominant frequencies of Hagia Sophia before and after the Kocaeli earthquake based on the microtremor measurements and earthquake observations on the basis of past research results. The predominant frequency during earthquake event is between 1.38 Hz and 1.61 Hz for EW component and between 1.53 Hz and 1.79 Hz for NS component after [4]. Contrary to this, that of microtremor is rather high. It is considered that the predominant frequency during the Kocaeli earthquake decreased more than 25 % against that of microtremor, and the change of the predominant frequency remained at around 8 % by the microtremor measurement just after this earthquake. And the result of the analysis on the earthquake motion records [4] suggests the possibility of the quickly decrease and restitution of the predominant frequency by the earthquake motion.

Table 1 *Change of the predominant frequency*

date	1991	12-Dec-93 Mb4.8, Δ=59km	1999.6	17-Aug-99 Mw7.4, Δ=97km	1999.9	Sep. to Dec. M4.4 – M7.2	2000
MT or EQ	microtremor	Eq.	microtremor	Kocaeli Eq.	microtremor	Eqs.	microtremor
EW	1.85	1.56	1.90	1.41?	1.76	1.38-1.61	1.75
NS	2.10	1.77	2.20	1.62?	2.03	1.53-1.79	2.10
unit	Hz	Hz	Hz	Hz	Hz	Hz	Hz
	Durukal et.al.(2003)					Durukal et.al.(2003)	

4.2. Amplification mode of the first modal frequency (EW component)

Figure 7 shows the amplification mode of the first modal frequency derived from the amplification spectrum corresponding to the location on the plane. Vertical axis is height of the location, and horizontal axis is amplification factor. The amplification characteristics show that it is large not only at the southern side but also at western side. Especially it becomes large at the main pier and the dome cornice at south-west part. Although the amplification factor becomes totally small after the earthquake, these characteristics are not changed.

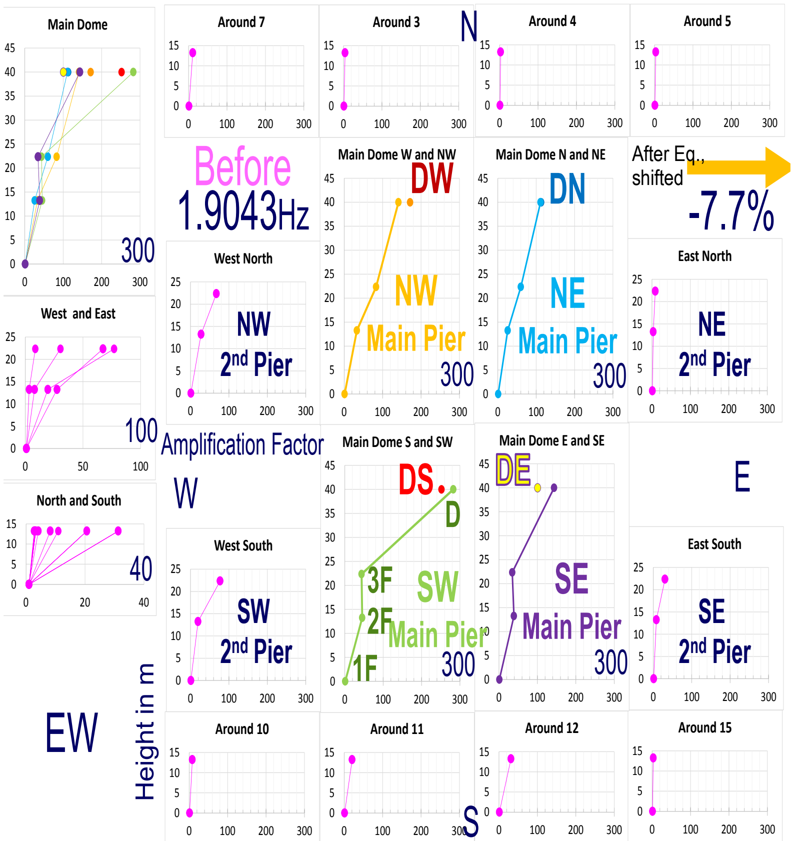


Figure 7-1 *Amplification mode of the first modal frequecy (EW): before the event*

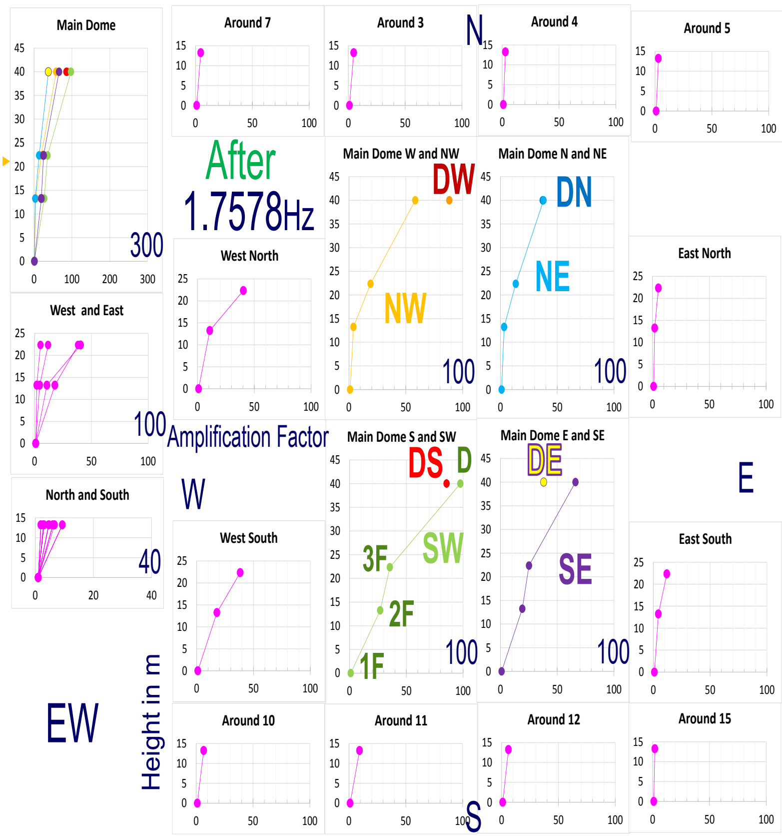


Figure 7-2 *Amplification mode of the first modal frequency (EW): after the event*

4.3. Amplification mode of the second modal frequency (NS component)

Figure 8 shows the amplification mode of the second modal frequency and the characteristics do not differ from that of the first modal frequency as a trend. The characteristic point of the first and the second mode is large amplification related to the SW main pier, and it is obvious especially for the NS component. This problem on the SW main pier has been already pointed [4] based on the analysis of the earthquake motion records, and is also clearly appeared on the characteristics of microtremor.

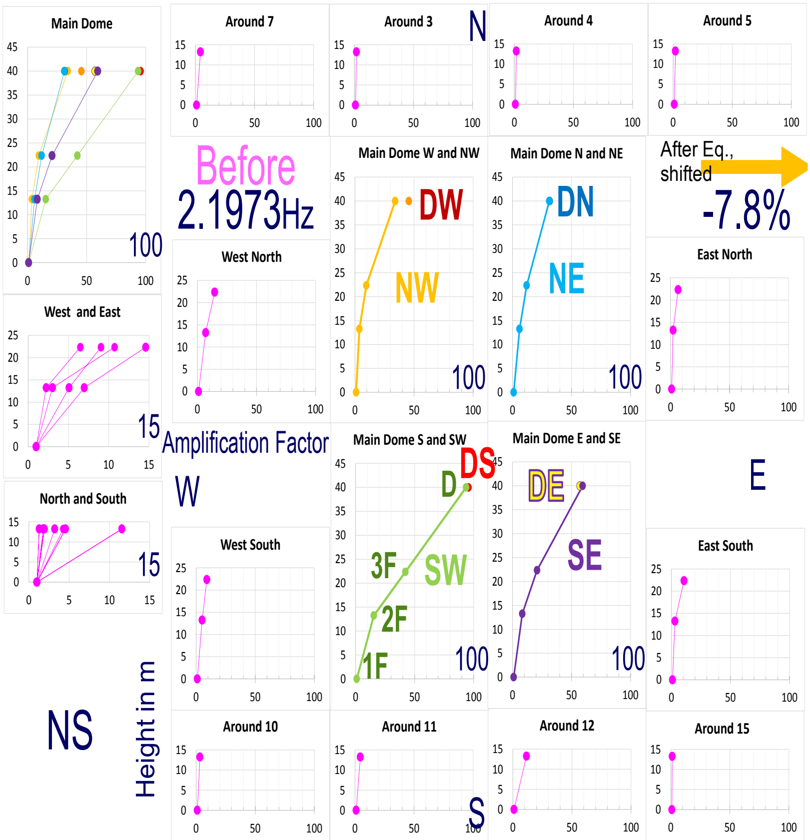


Figure 8-1 *Amplification mode of the second modal frequency (NS): before the event*

4.4. On the Kb-value, a destructive index

Figure 9 is an explanation of Kb value. It can be used for the estimation of the drift angle for each floor by multiplying Kb value by PGA, peak ground acceleration.
Please refer the detail of Kb value on Reference [5] as a name of KT or Reference [6] in this proceeding.

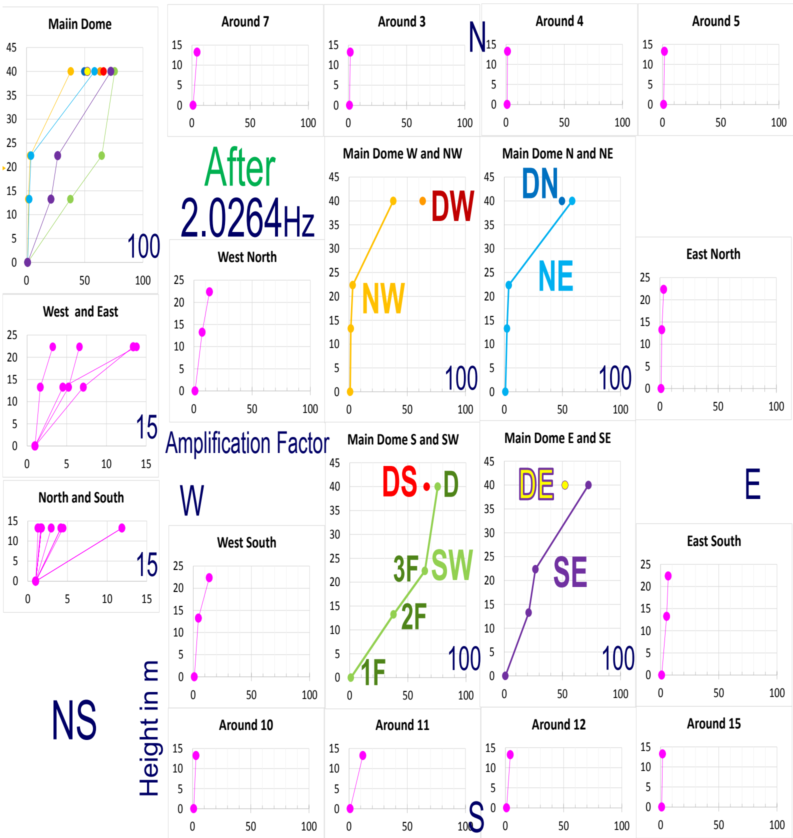


***Figure 8-2** Amplification mode of the second modal frequency (NS): after the event*

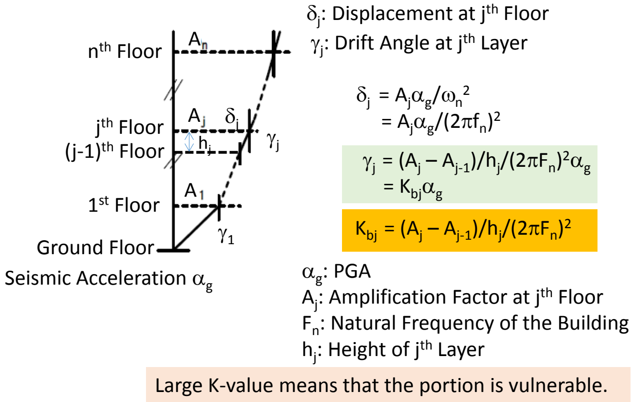


***Figure 9** Explanation of Kb value*

4.5. Kb values at the first modal frequency (EW component)

Figure 10 shows the Kb value distribution on a plane corresponding to the first modal frequency indicating the difference of the level for the vertical direction by the color of the circle. As you can find by the scale at the center of the figure, although Kb value becomes small after the earthquake, the trend to be large at west or south side has not changed. It is obvious that west or south part is weak point from the past earthquake damage or other deformation situation, and it is possible to say that the microtremor reflects the structural characteristics well. Points with large Kb value after the earthquake are at two sub piers and two main piers of the west side and the dome cornice at west side. It considerably becomes larger at the points on the western half dome related to the damage for the half dome of west side and west part of the main dome caused by the earthquake in 10th century.

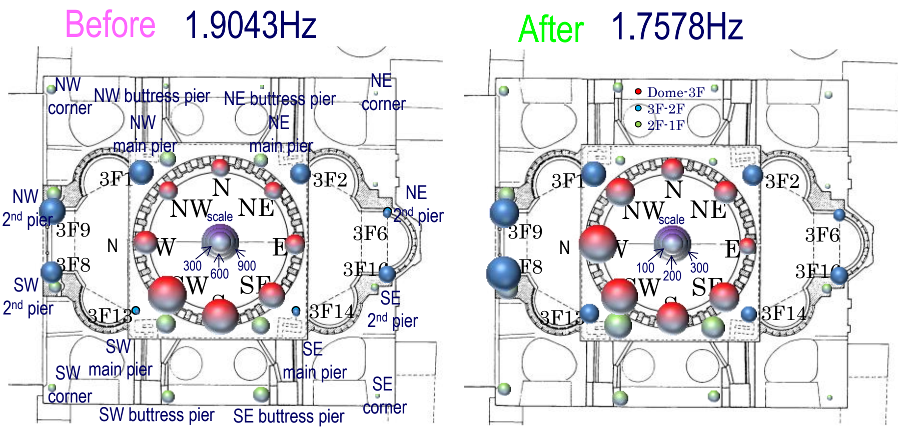


Figure 10 *Kb values at the first modal frequency (EW)*

4.6. Kb value at the second modal frequency (NS component)

Figure 11 shows the Kb value distribution by the second modal frequency on the plane as Figure 10. Kb value of the second modal frequency becomes large at south side, west side and the dome. It suggests that there must be a weak point from the characteristics of NS component. Especially the Kb value of the main pier at south-west part becomes larger after the earthquake for both EW and NS component, and it indicates a possibility to be suffered some damage. And the Kb value becomes dominantly small after the earthquake for the NS component at south-west and south side of the dome, and it is because the difference for the response of the dome becomes small by enlarged response of the south-west main pier.

These suggest that a large strain between the main pier of south-west and the dome cornice before the event concentrates to the main pier of south-west part itself after the event.

It is necessary to notice that these analytical results are estimated from the individual measurement having a trend of overestimation against the simultaneous measurement. Then we consider that it is necessary to conduct the simultaneous measurements at some vertical levels to verify the results above.

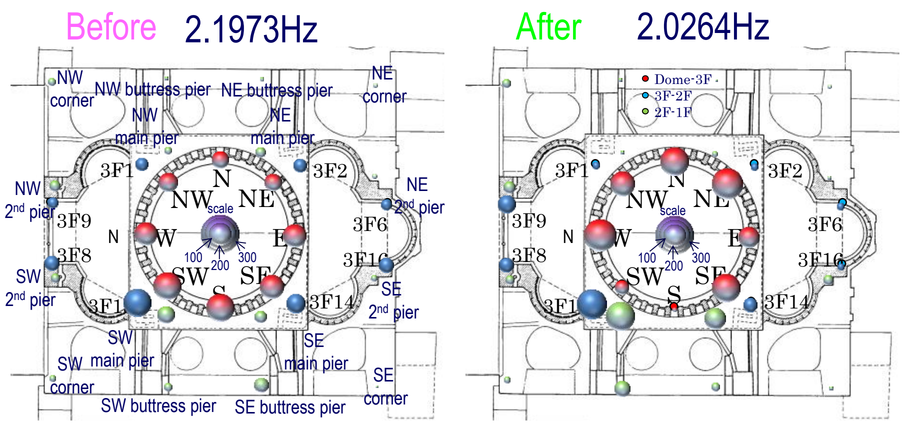


Figure 11 *Kb values at the second modal frequency (NS)*

5. Concluding Remarks

We had an opportunity to measure microtremor at Hagia Sophia before and after the Kocaeli earthquake in 1999. As a result of the comparison of the characteristics by microtremor before and after this earthquake with a focus on the microtremor characteristics after this earthquake, it was found as follows;

i) The vibration predominates toward to the east-west direction as the main axis of the building.
ii) Although this building has almost symmetrical structure for north, south, east and west as a center of the center dome, the vibration mode shows that it is easy to vibrate at the west and south sides.
iii) Vulnerability index for structures Kb value suggests that the west and south parts may be weakened.
iv) From the change before and after the earthquake, although the amplification factor decreased remarkably for the EW component, the trend to vibrate easily around the west side of the dome does not change.
v) The SW main pier has a possibility to be suffered some damage by the Kocaeli earthquake.
vi) As a result of our microtremor measurement two months before and three weeks after the Kocaeli earthquake, the predominant frequency decreased about 8 % after this earthquake.

The result of the microtremor measurement suggests being high risk around the west half dome and it agrees with the past researches. It is expected to expose the weakness of the building by the characteristics derived from the microtremor measurement.

Acknowledgement

On the measurement of Hagia Sophia, we feel we owe a great deal for Prof. M. Erdik, Kadilli Observatory and Earthquake Research Institute of Bogazici University, director of Hagia Sophia museum and other concerned personnel. We greatly appreciate their help.

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