THE CHANGE OF THE DYNAMIC CHARACTERISTICS USING MICROTREMOR

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ABSTRACT :
Considering the geotectonic environment and the historical importance, it is necessary to investigate the dynamic characteristics of the historical constructions in the city for rational and effective countermeasures against earthquake disasters. Since autumn 1998, microtremor measurements had been started to investigate the dynamic characteristics of several structures in Istanbul. In 17th August 1999 the Kocaeli Earthquake (Mw7.6, maximum PGA for rock site in Istanbul was 41 Gal) occurred and caused severe damage in the epicentral area. Microtremor measurements were conducted for few structures including historical monuments such as Suleymaniye mosque, Hagia Sophia museum, Sehzade mosque, and a newly constructed 14 stories office building, before the earthquake. In order to assess the earthquake's aftermath on the measured structures in Istanbul, microtremor measurement was again conducted. The result of the measurement before and after the earthquake shows the change of natural frequencies decreasing after the earthquake up to about 8.9% for Hagia Sophia Museum.

The ${}_{av}K_b$ value, averaged K_b value was proposed by Nakamura et al. (2000) as vulnerability index for buildings. Because the averaged drift angle of the buildings can be estimated by multiplying the ${}_{av}K_b$ value and the maximum input earthquake acceleration, the ${}_{av}K_b$ value was proposed to assess the possibility of building damage. The ${}_{av}K_b$ values before the Kocaeli earthquake are corresponds to the change of natural frequencies. Thus, it is expected that the danger of a structure can be assessed by the ${}_{av}K_b$ in advance.

KEYWORDS:
microtremor, dynamic characteristic, vulnerability index, historical structure, damage

1. INTRODUCTION

During its long history, Istanbul has been damaged by many earthquakes. Considering the geotectonic environment and historical importance of Istanbul, it is necessary to investigate the dynamic characteristics of the historical structures in the city and to work out rational and effective countermeasures to earthquake disasters. Since the autumn of 1998, microtremor measurements have been carried out to investigate the dynamic characteristics of several structures in Istanbul.

In 17th August 1999 the Kocaeli Earthquake (Mw=7.6) occurred and caused severe damage in the epicentral area. Although Istanbul is approximately 100km away from the epicenter and did not suffered serious damage, this earthquake might have affected some old structures. With this concern, the structures investigated before the earthquake was re-investigated in September 1999. The impact of the Kocaeli earthquake was analyzed, focusing on the shift of the natural frequency of structures. In Istanbul, although only 41Gal in PGA was observed at YPK station (Yapi Kredi Plaza strong motion station of Kandilli observatory), comparison of the results of an investigation before and after the earthquake has shown that the natural frequency shifted lower by several percent for both old and new structures. This frequency shift corresponds to the vulnerability index against the earthquake disaster for structures proposed by Nakamura et al.(2000).

2. OUTLINE OF MEASURED STRUCTURES

Microtremor measurement was conducted for historical structures as Suleymaniye mosque, Hagia Sophia museum, Sehzade mosque, and newly constructed office building. Figure 1 shows the overview of these structures. Figures 2 to 5 show the floor plan and elevation with measurement points, and Table 1 shows the detail of the structures such as height, structural type, established year and the date of measurement.

Measured historical structures have a main dome supported by four arches on four big piers. In case of Suleymaniye mosque and Hagia Sophia museum, a pair of opposite arches are reinforced by two semi-domes. In case of Hagia Sophia museum with a main dome of diameter of 31 m, the spaces beneath the arches are filled as a wall and the dome appears as though it is supported by the walls instead of arches. The internal space is 30 m width x 80 m length. The main dome has been partially affected by earthquakes several times and was restored each time. On the whole, the structure has deteriorated considerably and a certain countermeasure has been required.

The four arches of Sehzade mosque supporting main dome are reinforced by four semi domes. Sehzade mosque is an etude of an architect Sinan (1490-1588), and he adopted the structure for the main dome to be supported by four semi domes. And also the Suleymaniye mosque is one of the highest masterpieces of his maturity.

The basement grounds for historical structures mentioned above are firm and are in good condition. An Office Building made by Reinforced Concrete (RC) structure is a 14-story building with 5 underground levels and will be used for shopping centers and business offices. Each floor has the 57 m x 16 m rectangular section, and in the central part of the south side, facilities of utility such as elevators, stairs and etc. are equipped. This building was constructed on the firm ground, and is situated near the YPK station, which recorded maximum acceleration 41Gal at the time of the Kocaeli earthquake.

(a) Suleymaniye Mosque

(b) Hagia Sophia Museum

(c) Sehzade Mosque

(d) An Office Building

Figure 1. Overview of Measured Structures

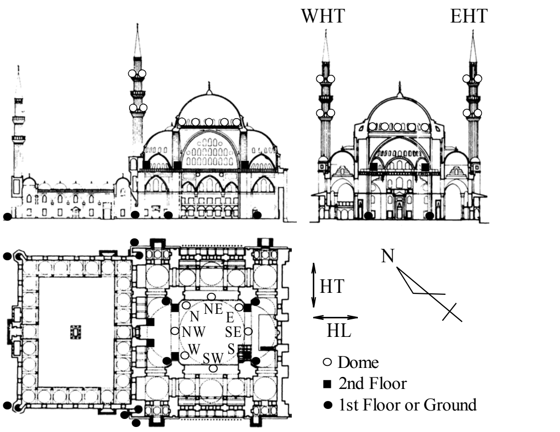

Figure 2. The elevation and floor plan with measurement points in Suleymaniye mosque. (○,■,●:Measurement points)

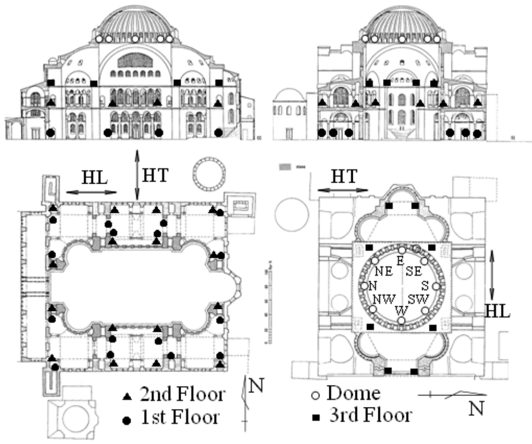

Figure 3. The elevation and floor plan with measurement points in Hagia Sophia museum. (○,●,▲,■:Measurement points)

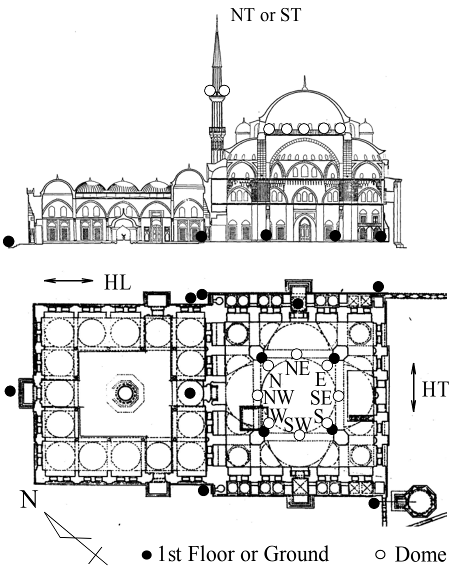

Figure 4. The elevation and floor plan with measurement points in Sehzade mosque. (○,●:Measurement points)

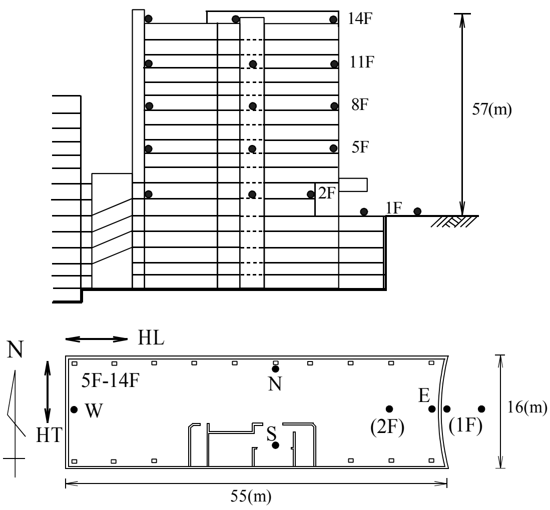

Figure 5. The elevation and floor plan with measurement points in a newly constructed office building. (●:Measurement points)

Table 1. Dimensions, Completion year and etc. of Measured Structures

Name of building	Suleymaniye Mosque	Hagia Sophia Museum	Sehzade Mosque	an Office Building
Height	53 m	56 m	37 m	57 m
Dimensions of a plane	68 m × 63 m	95 m × 70 m	50 m × 43 m	57 m × 16 m
Diameter of main dome	27 m	31 m	18 m	-
Structural type	Stone	Stone and Brick	Stone	RC(14F+5BF)
Completion year	1550AD	512AD	1543AD	1999AD
Date of measurement before the earthquake	19th and 21st October, 1998	8th and 9th June, 1999	6th June, 1999	11th June, 1999
Date of measurement after the earthquake	7th September, 1999	3rd and 4th September, 1999	10th September, 1999	2nd September, 1999
Measured floors	1F, 2F, DM	1F, 2F, 3F, DM	1F, DM	1F, 2F, 5F, 8F, 11F, 14F

3. OUTLINE OF MEASUREMENT AND ANALYSIS

Microtremor measurement was simultaneously conducted at one or two points of whole points on each floor shown in Table 1. Measurement points were set to grasp the dynamic behavior of these structures.

About minaret, two minarets of both Suleymaniye and Sehzade mosque were measured. Suleymaniye mosque has two high minarets and two low minarets. High minarets (WHT and EHT) were measured at the highest and lowest balcony of three balconies. Every balcony has four measurement points and a pair of them was measured simultaneously. On the EHT minaret, however, only s-side point of highest balcony was measured because of the failure of instrument at the time of before the earthquake.

Sehzade mosque has two minarets with two balconies each other. Measurement was conducted at four measurement points only on the upper balcony. Moreover, for the base ground, measurement points were situated around the structure.

A velocity sensor for microtremor measurement is a geophone GS-11D of GeoSpace. Although the natural frequency of the sensor is 4.5 Hz originally, it is 1 second in this time because of astatization. A recorder is PIC91 of SDR. This instrument has a 16bit A/D converter, and it can connect 2 sets of three components of the modified GS-11D. The characteristic of the sensor is adjusted so that three axes may be assembled, and the spectrum ratio can be used effectively in the frequency range between 0.3 Hz and 30 Hz.

At every measurement point, microtremor was recorded three times with 1/100 second sampling rate and 40.96 second data length. After measurements, Fourier spectrum for each component is calculated from the waveform of whole length and three records are averaged. Fourier spectrums are smoothed by Hanning spectral window repeated twenty times as bandwidth to be approximately 0.2Hz before averaging.

For representative spectra of the historical structures, these calculated spectra related to the four supporting columns for each floor and these calculated spectra for eight points on the corridor of main dome (DM) for every component are averaged. And these spectra of minarets are averaged for representative spectra. In case of an office building, every three floor has four measurement points at the center of the each side of the floor, and these spectra are averaged for representative spectra.

The transfer function of structures and minarets shall be presumed by the ratio of a representation spectrum between the top floor and the ground floor. In addition, the ground floor is set to first floor (1F).

4. VULNERABILITY INDEX AGAINST EARTHQUAKE DISASTERS FOR STRUCTURES (Nakamura et al., 2000)

It is considered that the vulnerability of structures against earthquake disasters can be estimated by the drift angle, related to the input earthquake acceleration a in cm/s^2. Here, a is a portion which affects this structure among whole earthquake motion a, namely,

$$\alpha = e \times a \tag{4.1}$$

where e shows the efficiency of earthquake motion working for this structure.

A deformation performance and the degree of earthquake motion amplification can be estimated from the dynamic characteristic of structures. Here, the primary natural

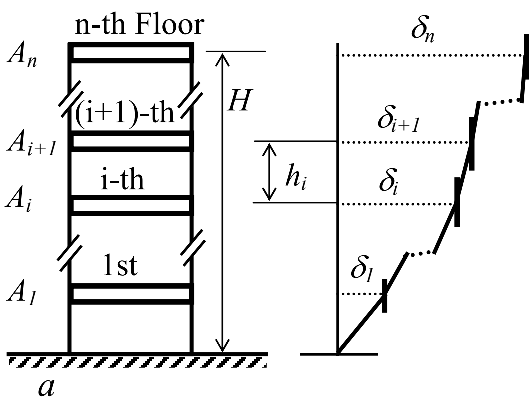

Figure 6. Schematic model of n-th floor structures and its mode shape. δ_i is the horizontal displacement, h_i is the height, A_i is amplification factor of i-th story column, H is the height of the n-th floor structure, and a is the horizontal acceleration of foundation ground.

frequency of the structure that seems to have influence on earthquake damage is considered. Displacement δi of i-th floor is estimated from this primary natural frequency F and amplitude Ai of i-th floor as followings (See figure 6).

$$\delta i = Ai \times \alpha / (2\pi F)^2 \tag{4.2}$$

So, the drift angle γ_i of i-th floor is shown as,

$$\begin{aligned} \gamma_i &= (\delta_{i+1} - \delta_i) / h_i && (4.3) \\ &= \Delta A_i \times \alpha / (2\pi F)^2 / h_i && (4.4) \\ &= e \times K_{bi} \times a && (4.5) \end{aligned}$$

where,

$$K_{bi} = \Delta A_i / (2\pi F)^2 / h_i \times 10000 \tag{4.6}$$

ΔA_i : difference of amplification of the i-th floor, ($=A_{i+1}-A_i$), and
h_i : the height of i-th floor in m.

Thus, the drift angle γ_i for each floor is estimate from vulnerability index K_{bi} multiplied by the maximum acceleration on the surface ground a in cm/s^2 and the efficiency e of earthquake motion.

Here, ${}_{av}K_b$ value is derived as averaged K_{bi} for each structure for the discussion followings.

$${}_{av}K_b = A / (2\pi F)^2 / H \times 10000 \tag{4.7}$$

where,
A : amplitude of the top floor, and
H : height of the structure in m.
In addition, when ${}_{av}K_b$ is substituted for K_{bi} of formula (4.5), averaged drift angle γ_{av} will be calculated. K_{bi} and ${}_{av}K_b$ are expressed in unit of 10^{-6}, 10000 in Eqs. (4.6) or (4.7) is multiplied for adjustment.

5. RESULT OF ANALYSIS

Figure 7 shows the velocity locus of microtremor at every measurement point on Sehzade mosque. It shows

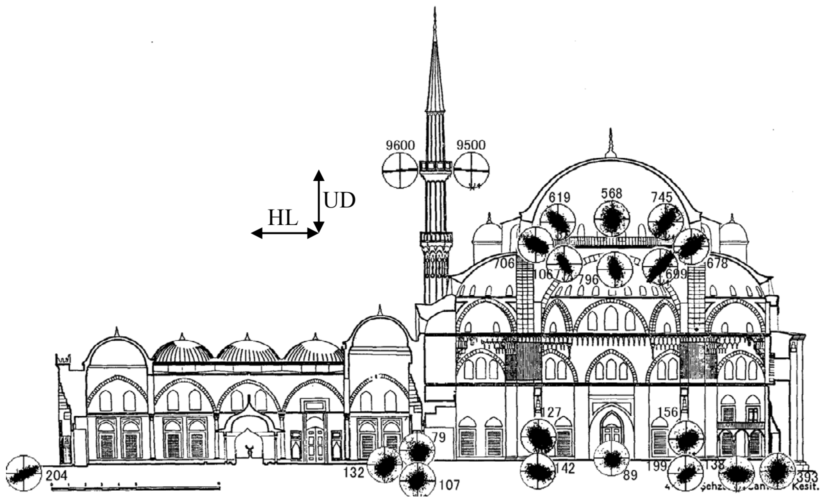

Figure 7. Normalized Loci of Microtremors in HL-UD Plane for 40.96 second at each Measurement Points of Sehzade Mosque (non-simultaneous measurement). Dots in circle indicate the normalized locus, and the number near the circle means maximum value of microtremor in unit of 10^{-8} m/s.

the locus of microtremor for 40.96 seconds in the circle to the position corresponding to every measurement point, and the number near the circle means maximum amplitude in 10^{-8} m/s. This figure shows that minarets are vibrating more intensely than the structures. The state of the vibration for main dome can also be grasped by this figure.

Figure 8 shows the transfer functions of four structures before and after the earthquake estimated from the result of microtremor measurement. Figure 9 shows examples of the transfer functions for minarets.

In case of Suleymaniye mosque, the peak frequency near 0.8 Hz is significant on the corridor of the main dome (DM) only before the earthquake. And in case of Sehzade mosque, the peak amplification factor near 1.2 Hz increased after the earthquake. These peak frequencies may correspond to the peak frequencies of minarets. Tables 2 to 5 shows the shift of the natural frequencies and amplification factor of the estimated transfer functions before and after the earthquake for both horizontal components and torsion component, except the peak frequencies mentioned above. Measurement before the earthquake of a Suleymaniye mosque was performed in two days on alternate days. The day WHT minaret was measured was not windy and was a quiet day. However, the day DM and EHT minaret was measured was windy. So the amplitude of EHT minaret was ten times or more compared with that of WHT minaret. Therefore, neither 0.8 Hz vibration of Suleymaniye mosque nor 1.2Hz vibration of Sehzade mosque was transmitted from the foundation; it is speculated that minarets were excited by the wind and then the vibration was transmitted to the main dome.

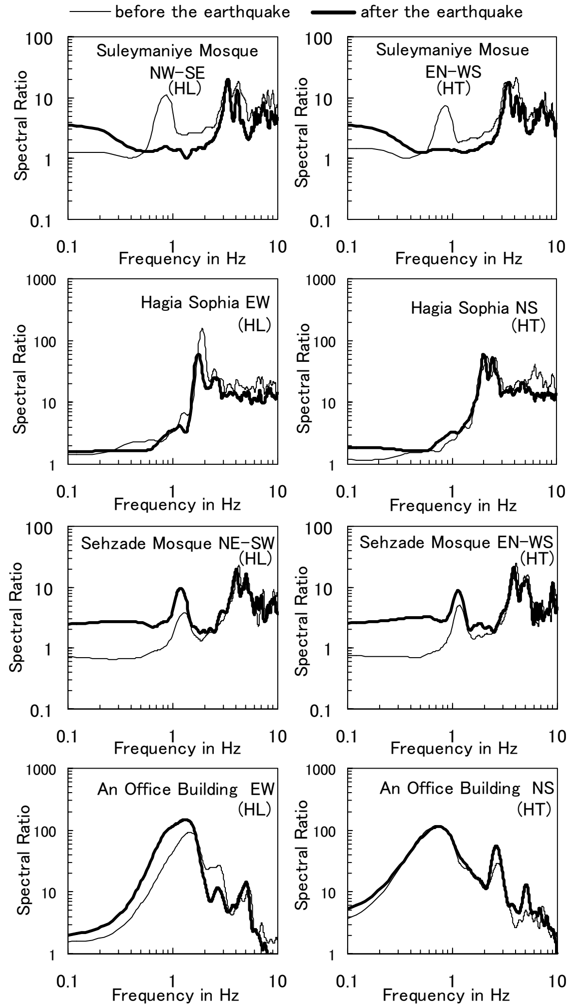

Figure 8. Estimated transfer functions of the highest floor of structures.

Tables 2 to 5 shows the natural frequencies estimated from the transfer function of structures for horizontal and torsional vibrations. From these table, the vibration that is assumed to be affected by the vibration of minarets are ignored. Additionally, these tables include the amplification factor.

Because the data length of microtemor measurement is 40.96 seconds, the frequency resolution ΔF on Fourier analysis become 0.025 (=1/40.96) Hz. In Tables 2 to 5, the shift of natural frequency is also shown in a unit of frequency resolution on analysis. According to Tables 2 to 5, there are some cases that the shift of frequencies are smaller than the resolution. The natural frequency of a peak is estimated using the data of four samples around peak. Therefore, the reading error should be less than a half of the resolution. Moreover, a spectrum is computed by averaging 12 times of measurement data (corresponding to 8 minutes approximately) or 24 times of measurement data (corresponding to 16 minutes approximately), and the reliability appear to be satisfactory. Thus, if the shift of frequency is below the resolution, this

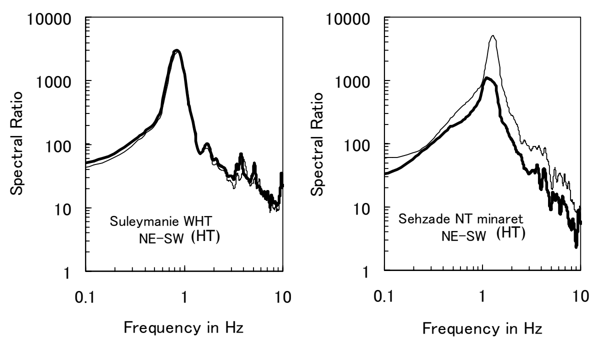

Figure 9. Examples of Estimated Transfer Function of Minaret

Table 2. The Dynamic Characteristics of Suleymaniye mosque before and after the 1999 Kocaeli earthquake

Main body		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	3.43	3.36	2.21	3.11
	A	20.5	20.2		
	${}_{av}K_b$ (10^{-6})	**11.0**	**11.4**		
HT: NE-SW	F(Hz)	3.55	3.46	**2.78**	4.04
	A	18.6	17.5		
	${}_{av}K_b$ (10^{-6})	9.3	9.3		
Torsion	F(Hz)	6.69	6.45	3.59	9.83
Minalet WHT		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	0.843	0.819	**2.86**	0.987
HT: NE-SW	F(Hz)	0.867	0.842	2.79	0.991
Torsion	F(Hz)	9.69	9.59	1.03	4.10
Minalet EWT		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	0.842	0.842	-0.01	-0.003
HT: NE-SW	F(Hz)	0.842	0.842	**0.08**	0.028
Torsion	F(Hz)	9.36	9.33	0.32	1.23

Note: dF is frequency shift in unit ΔF, ΔF = 1/40.96 Hz

Table 3. The Dynamic Characteristics of Hagia Sophia museum before and after the 1999 Kocaeli earthquake

Main body		Before	After	dF/F (%)	dF
HL: EW	F(Hz)	1.92	1.75	**8.92**	7.00
	A	156	60.5		
	${}_{av}K_b$ (10^{-6})	**261**	**122**		
HT: NS	F(Hz)	2.16	2.01	6.82	6.04
	A	54.6	59.6		
	${}_{av}K_b$ (10^{-6})	72.0	90.5		
Torsion	F(Hz)	3.32	3.10	6.63	9.01

Note: dF is frequency shift in unit ΔF, ΔF = 1/40.96 Hz

Table 4. The Dynamic Characteristics of Sehzade mosque in before and after of the 1999 Kocaeli earthquake

Main body		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	4.06	3.87	**4.78**	7.96
	A	24.3	21.5		
	${}_{av}K_b$ (10^{-6})	**14.3**	**14.0**		
HT: NE-SW	F(Hz)	4.26	4.07	4.56	7.96
	A	23.0	20.2		
	${}_{av}K_b$ (10^{-6})	12.3	11.9		
Torsion	F(Hz)	5.25	5.00	4.76	10.2
ST		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	1.13	1.14	-0.12	-0.06
HT: NE-SW	F(Hz)	1.33	1.31	**1.97**	1.08
Torsion	F(Hz)	11.8	11.6	1.69	8.19
NT		Before	After	dF/F (%)	dF
HL: NW-SE	F(Hz)	1.15	1.10	4.26	2.00
HT: NE-SW	F(Hz)	1.27	1.12	**11.5**	6.00
Torsion	F(Hz)	11.4	11.0	3.51	16.4

Note: dF is frequency shift in unit ΔF, ΔF = 1/40.96 Hz

Table 5. The Dynamic Characteristics of An Office BLDG in before and after of the 1999 Kocaeli earthquake

Main body		Before	After	dF/F (%)	dF
HL: EW	F(Hz)	1.45	1.33	**8.38**	4.99
	A	91.6	147		
	${}_{av}K_b$ (10^{-6})	**217**	**414**		
HT: NS	F(Hz)	0.720	0.745	-3.38	-0.999
	A	118	114		
	${}_{av}K_b$ (10^{-6})	1138	1029		
Torsion	F(Hz)	1.037	0.964	7.05	2.994

Note: dF is frequency shift in unit ΔF, ΔF = 1/40.96 Hz

would be the shift within the error range, and it would be proper to judge that the natural frequency did not shift before and after the earthquake.

6. DISCUSSION

At the time of the Kocaeli Earthquake, maximum PGA in Istanbul for hard rock site was only 41 Gal at YPK station. It is interesting to occur the shift of the natural frequency under such a weak seismic motion.
Before and after the earthquake, the transfer functions kept their shapes as shown in Figure 8, but the peak frequency has slightly shifted to lower, except the lowest peak frequency seen in Suleymaniye and Sehzade mosques.

For minarets, the shift rate of the frequency is smaller than that of the main structures except the NT minaret of Sehzade mosque and WHT minaret of Suleymaniye mosque. This means that minarets are in better condition than main structures.

However, it is thought that the minarets themselves vibrated quite intensely during the earthquake. Especially in the case of WHT minaret of Suleymaniye mosque, damage as shown in Figure 10 has appeared in incidental facilities such as a roof. That is, buckling arise in the west side of a lower part of a conic roof, and the ornament at the top of the conic roof is crooked on the east side.

The shift of the natural frequency for WHT minaret is larger than others. As a result, the shift rate of the natural frequency correspond to the damage grade of incidental facilities.
Hereafter, the measurement result for every structure is examined.

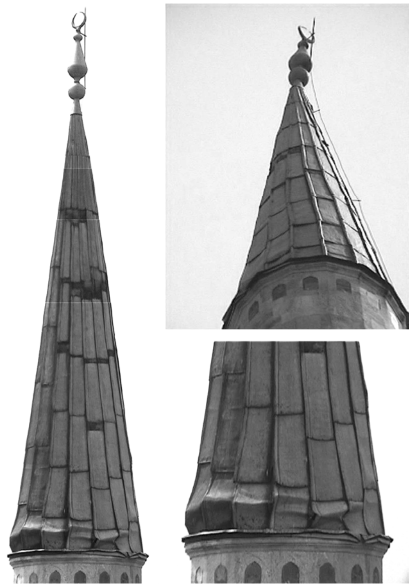

Figure 10. Damage of WHT minaret of Suleymaniye Mosque

6.1. Suleymaniye mosque
This mosque was designed after the model of the Hagia Sophia museum and has similar dimensions and structure. It is considered as the masterpiece of an architect Sinan's maturity term. Although 500 years have passed, it dose not seem to be in good condition.

As shown in Table 2, a natural frequency of HL (NW-SE) component of the main body was decreased to 3.36 Hz after the earthquake from 3.43 Hz before the earthquake. And that of HT (NE-SW) component was decreased to 3.46 Hz from 3.55 Hz. These changes correspond to 3 – 4 ΔF and are considered a significant change. These rates of change are 2.2 – 2.8 %, and are equivalent to approximately 5 % of rigidity lowering. It is presumed that this is the reason for slight damage.

The ${}_{av}K_b$ value is also shown in Table 2. If effective seismic motion is assumed to be approximately 1/3 of the maximum acceleration (approx. 15 Gals), averaged drift angle will be presumed to be approximately 1/6000, and this drift angle is far from collapse.

6.2. Hagia Sophia museum
Hagia Sophia museum was constructed at a beginning of sixth century with four arches on the four huge main piers, which the main dome is supported. A pair of opposite arches is reinforced with the wall, and the other pair is reinforced with semi dome. Moreover, there are two layers of large scale corridor around the four main piers.

As shown in Table 3, a natural frequency of HL (EW) component was decreased to 1.75 Hz after the earthquake from 1.92 Hz before the earthquake. And that of HT (NS) component was decreased to 2.01 Hz from 2.16 Hz. These frequency shifts correspond to 6 – 7 ΔF and are considered a significant change. These rates of shift are 6.8 % (HT component) to 8.9 % (HL component), and are equivalent to approximately 13 – 17 % of rigidity lowering. As a result, this might have been affected not a little.

The ${}_{av}K_b$ value is also shown in Table 3. If effective seismic motion is assumed to be approximately 1/3 of the maximum acceleration (approx. 15 Gals), averaged drift angle would be presumed to be approximately 1/250. Generally it is thought that a structure begins to collapse on 1/100 – 1/200 of drift angle. It is considered that it stood against this earthquake motion without great margin. For this reason, it is thought that the significant decrease of natural frequency occurred.

6.3. Sehzade mosque
Sehzade mosque is an etude of architect Sinan. Although 500 years have passed, it dose not seem to be in good condition. According to the result of the measurement at the base of the four main piers and the dome corridor equivalent to the upper part, natural frequencies shifted from 4.06 Hz and 4.26 Hz before the earthquake to 3.87 Hz and 4.07 Hz after the earthquake for HL (NW-SE) and HT (NE-SW) component, respectively. These shifts correspond to 8 – 9 ΔF and are considered a significant change. These rates of

shift are approximately 5 %, and are equivalent to approximately 10 % of rigidity lowering. If effective seismic motion is assumed to be approximately 1/3 of the maximum acceleration (approx. 15 Gals), the ${}_{av}K_b$ value in Table 4 shows that the averaged drift angle will be presumed to be approximately 1/5000, and this drift angle is far from collapse.

Moreover, it is confirmed that natural frequency shifts were quite remarkable in NT minaret of Sehzade mosque and that the damage from the earthquake was relatively larger than ST minaret. In addition, it is said that NT minaret have been slightly damaged when the measurement before the earthquake was done.

6.4. An office building

In case of the office building, on the vibration of NS component, the shift of predominant frequency correspond to less than 1 ΔF and is not considered a significant change. Considering that the floor shape of this building is flat and extremely short in the NS component as shown in Figure 5, its rocking vibration excels in vibration of the NS direction. And it is thought that the rigidity of a base is more strongly reflected rather than the rigidity of a building itself. The fact that the natural frequency of the NS component did not change before and after the earthquake suggests that the earthquake did not influenced the base at all.

On the other hand, it is supposed that the vibration of EW component reflects the rigidity of the building itself. The shift of natural frequency correspond to 5 ΔF and is considered a significant change. These rates of shift are approximately 8.4 % and are equivalent to approximately 15 % of rigidity lowering.

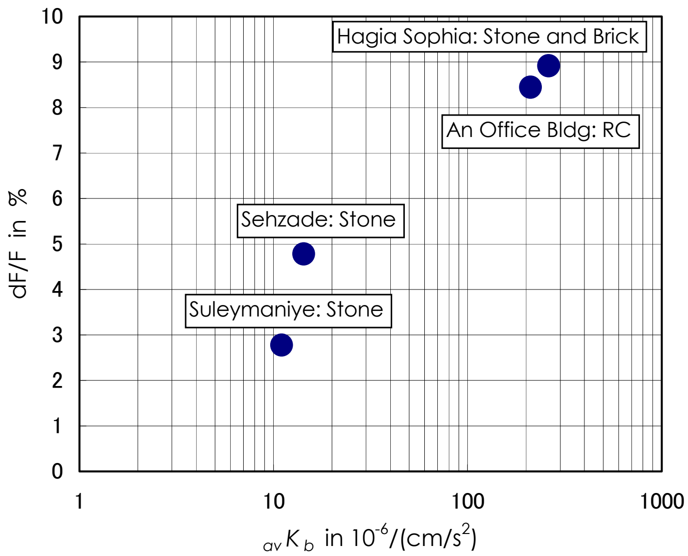

Figure 11. Relationship between ${}_{av}K_b$ and dF/F for Measured Structures

Natural frequency shift can be considered as an expression of the degree of damage. Figure 11 shows the relationship between ${}_{av}K_b$ value and the rate of natural frequency shift. The relation between ${}_{av}K_b$ and the frequency shift rate suggests that ${}_{av}K_b$ can be given as damage degree before the earthquake.

Figure 11 shows large ${}_{av}K_b$ correspond to larger damage in general. Both Suleymaniye and Sehzade mosque have the same type of structure, and Hagia Sophia museum has a structure type of similar to them. On the other hand, the office building has different characteristics as RC structure.

In addition, the ${}_{av}K_b$ value for an office building was examined using the EW direction considered to reflect the rigidity of the building itself.

7. CONCLUSION

At the time of the Kocaeli earthquake, the seismic motion in Istanbul was relatively small because of the hard base ground. For some structures measured before the earthquake, it was possible to measure after the earthquake again to investigate the shift of the natural frequency. As a result, the shifts of natural frequency were 2.8 %for Suleymaniye mosque built 500 years ago, 8.9 % Hagia Sophia museum built 1500 years ago, 4.8 % for Sehzade mosque built 500 years ago and 8.5% for an office building newly built. It seems that the impact of the earthquake is small; thus the change of the natural frequency is also small. For the measured structures, they were affected by the Kocaeli earthquake as 7 – 16 % of rigidity lowering. The change of natural frequency also corresponds well to the vulnerability index against earthquake disasters for structures. This suggests that the proposed index ${}_{av}K_b$ value is appropriate.

8. ACKNOWLEDGEMENT

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