Dynamic Characteristics of Colosseum at Northern Wall and Western Buttress Valadier based on the Microtremor Measurements in 1998, 2013 and 2015

Yutaka Nakamura[1], Jun Saita[1], Tsutomu Sato[1] and Gianfranco Valente[2]

Abstract

The dynamic characteristics of the vertical line at the pillar #40 of Colosseum from the 2013 measurement shows unexpectedly large change from the result of the 1998 measurement. A maintenance work for the floor and fences was done at 3F and 4F around the measurement point during summer of 2010, and it may be considered as one of the contributing factors. Meanwhile, it is difficult to lose the potential that it was caused by the statistical or physical fluctuation. So the 2015 re-measurement was conducted to investigate the change situation of the dynamic characteristics. The vertical lines not only at the pillar #40, but also at the pillars #44 and #37 were measured and compared with the result of the 1998 measurement. As a result, there becomes a high possibility that the maintenance work in 2010 causes the change of the dynamic characteristics. Additionally in 2015, microtremor was measured from the top to 15m beneath of the western buttress Valadier. The dynamic characteristics through the ground to the top were estimated combined with the measured data between 2F and GF in 1998, and as a result, it is quantitatively confirmed that the edge of the buttress Valadier is one of the weakest points.

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1 System and Data Research, Tokyo, Japan.

2 University of l'Aquila, Italy.

1. Introduction

The vertical line at the pillar #40 of Colosseum shows unexpectedly large change of the dynamic characteristics from the result of the 2013 measurement at GF to 4F as the re-measurement of the 1998 dense microtremor measurement before 15 years. A maintenance work for the floor and fences was done at 3F and 4F around the measurement point during summer of 2010, and it may be considered as one of the contributing factors. Meanwhile, it is difficult to lose the potential that it was caused by the statistical or physical fluctuation.

So the 2015 re-measurement was conducted to investigate the change situation of the dynamic characteristics. The vertical lines not only at the pillar #40, but also at the pillars #44 and #37 were measured and compared with the result of the 1998 measurement.

Additionally, microtremor was also measured around the top of the western buttress Valadier.

The date of the past measurement at and around Colosseum is listed below.

[*The date and the target of the measurement*]

Preliminary measurement: some measurement points at BF, GF and 1F on November 22, 1997 ([1])

1st full-scale measurement: measurement at each floor of three rings at every five pillars on July 6-7, 1998 ([2])

Extra measurement: surrounding ground on March 21, 2010 ([3])

2nd measurement: underground measurement points and the vertical line at the pillar #40 on December 13, 2013 ([6]), and southern and western ground on December 15, 2013 ([7])

3rd measurement: pillars #57 (partially), #44, #40 and #37 on November 11, 2015 (this article), and northern ground on November 14, 2015 ([7])

2. Background

At the time of DISS_13 on November 2013, some organizations conducted microtremor measurement and other investigation of Colosseum. We investigated the earthquake motion characteristics of the vertical line at the pillar #40 (hereinafter “the vertical line #40”) as the center of the northern wall on Colosseum with microtremor measurement. It is found that the predominant frequency shifted about 10% in maximum comparing with the result of the 1998 measurement.

Confirming the difference for the both measurement with the photographs, it was found that there is a change as a different appearance of the floor and fences at 3F and 4F. The work for changing the appearance of the floor and fences is estimated to be done between spring and autumn of 2010. Among the change of the appearance, the change from a concentric floor joint to a radial floor joint is qualitatively harmonious to the change of the earthquake response characteristics cleared by the comparison between the both measurements.

Various kinds of the maintenance and management are estimated to be adopted in the future, and it is necessary to grasp quantitatively and precisely the impact to the dynamic characteristics of cultural heritage to avoid degradation of the heritages caused by the changing situation. Therefore it is desirable to perform regularly the dynamic characteristics investigation, as same as the performing the maintenance work regularly.

Eventually it should be necessary to consolidate the systems of grasping the condition in realtime, and re-measurement was tentatively conducted in 2015 with adding some measurement points for the 2013 measurement to grasp the change of condition from the 1998 measurement.

3. Measurement in 2015

Figure 1 shows the overview of measurement points at Colosseum main body for the 2015 measurement. A part of the northern wall and the buttress Valadier around the pillar #57 are investigated. Figure 2 shows the photographs of measurement point with its measuring condition. Figure 3 indicates the distribution of the points at the pillar #35, #37, #40, #44 and #45 on the cross-section.

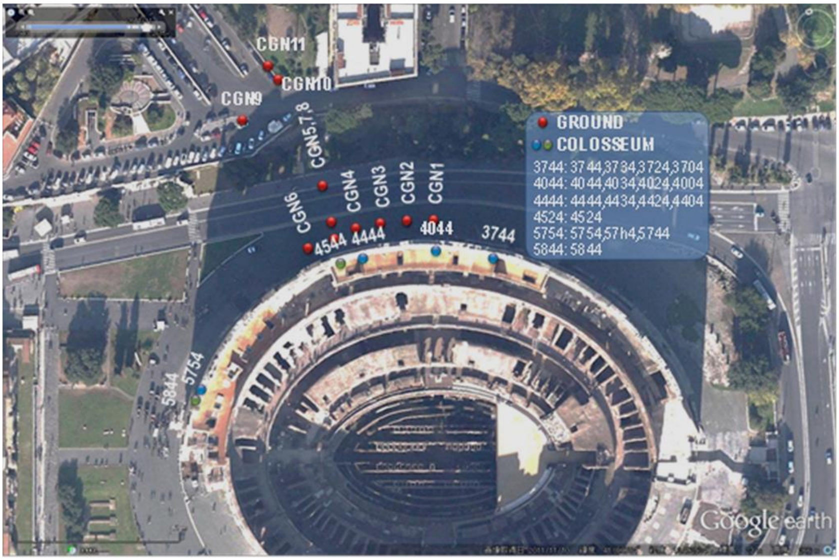

Figure 1. Measurement points in 2015

Figure 2. Measurement points at the pillars #37, #40 and #44 in 2015

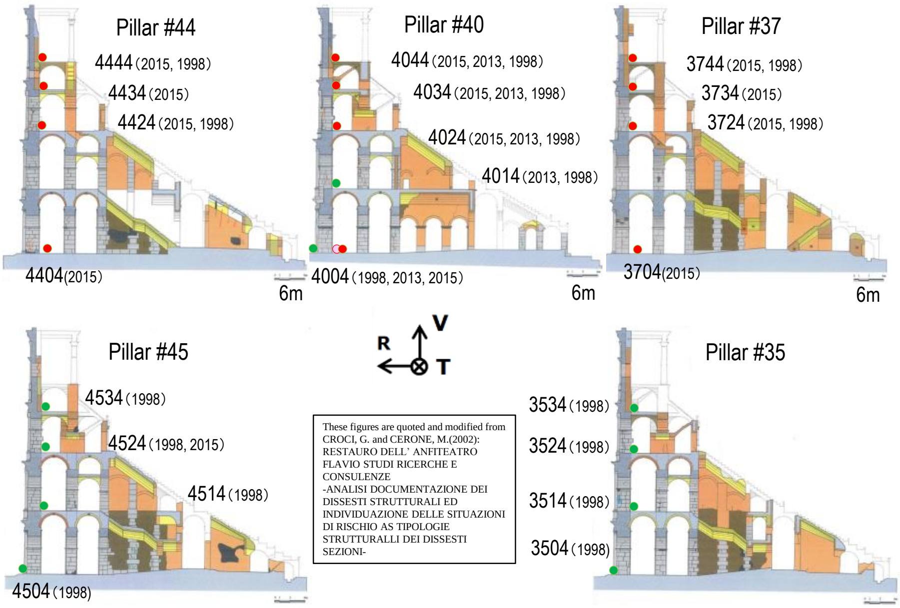

Figure 3. Measurement points at the pillars on cross-section

However the pillars #35, #40 and #45 were generally measured in 1998, there was no floor at 4F of the pillar #35 and #45 and the measurement was conducted at the pillar #37 and #44. In case of the measurement in 2015, the measurement was conducted at the same location of the pillar, #37, #40 and #44, from 4F to GF. Measurement at the northern wall was conducted at 4F, 3F, 2F, 1F and GF, but the 2015 measurement was not conducted at 1F because of a commercial facilities around the past measurement points.

On the other hand, the measurement point GF was set at slightly different for each measurement. It was the outside of the outmost column in 1998, the inside of the same column in 2013 and the deeper inside on the floor in 2015 because an entrance was constructed around the past points.

Figure 4 shows the reinforcement condition of the western buttress Valadier with distribution of the measurement points around the pillar #57 in 1998. Because the reinforced part of Valadier was cleaned in 2015 with scaffold, the measurement was conducted using this scaffold.

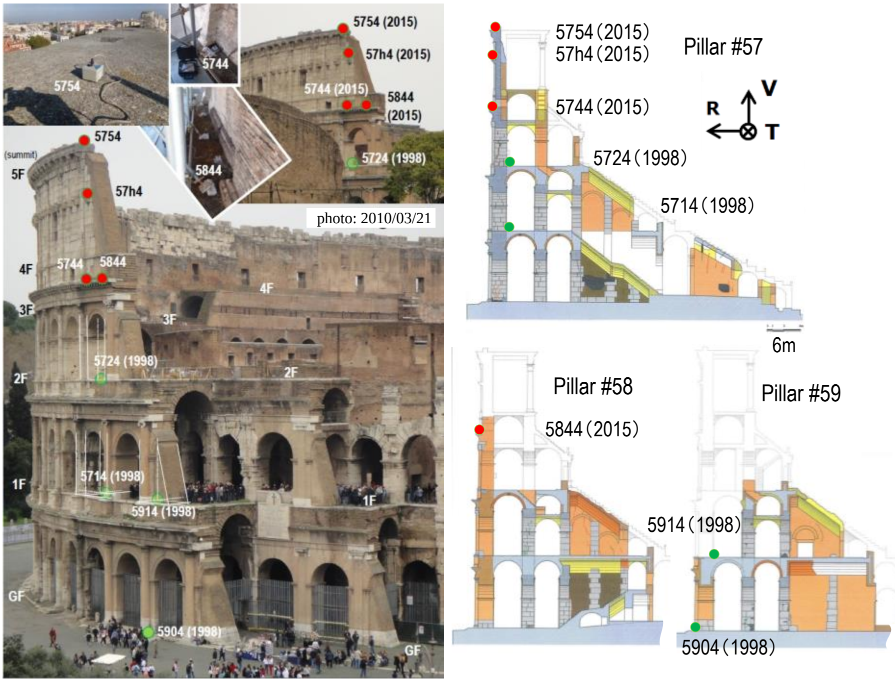

Figure 4. Measurement points around the western buttress Valadier

At Valadier, during continuous measurement at the point 5754 on the top as the fixed measurement point, microtremor was recorded for five minutes at the points 57h4, 5744, and 5844 in series.

At the northern wall, during continuous measurement at the two points at 4F, 4044 for the pillar #40 and the point 4404 for the pillar #44, as the fixed measurement points, microtremor was recorded for five minutes at other measurement points including the fixed points in series.

Frequency analysis with FFT is adopted for measured data and then the transfer function till 4F based on GF and other items are derived.

For the pillar #57 of the western buttress Valadier, because it was able to measure only at the top and down below about 15m, totally three points in 2015, the transfer function based on GF for the vertical line at the pillar #57 through the ground to the top was estimated combined with the measured data between 2F and GF in 1998.

4. Comparison between the 2015 and past measurement

4.1. Northern wall

Figures 5 to 11 are the transfer spectrum for transvers (T), radial (R) and vertical (V) directions of the vertical lines #37, #40 and #44. The left and right diagrams show the amplification characteristics and the phase difference characteristics against GF, respectively. These transfer spectra show several peaks at common frequencies for some of R, T and V directions and it suggests that they are interconnecting. The main peak frequencies of the R direction removing that of the T direction are put in order approximately as 1:3:5 based on the first peak frequency 1.6 Hz. It suggests that this is a simple wave field as SH wave in a vertical cantilever. Each three vertical line shows similar spectrum shape for each direction. The spectrum corresponding to the vertical line #40 at the symmetry center shows rather simple shape than the other spectrum. The phase of the V direction of the vertical line #37 becomes the opposite phase over 10 Hz against that of the other pillar, and it suggests the existence of a vibration as a rocking vibration on T-V plane.

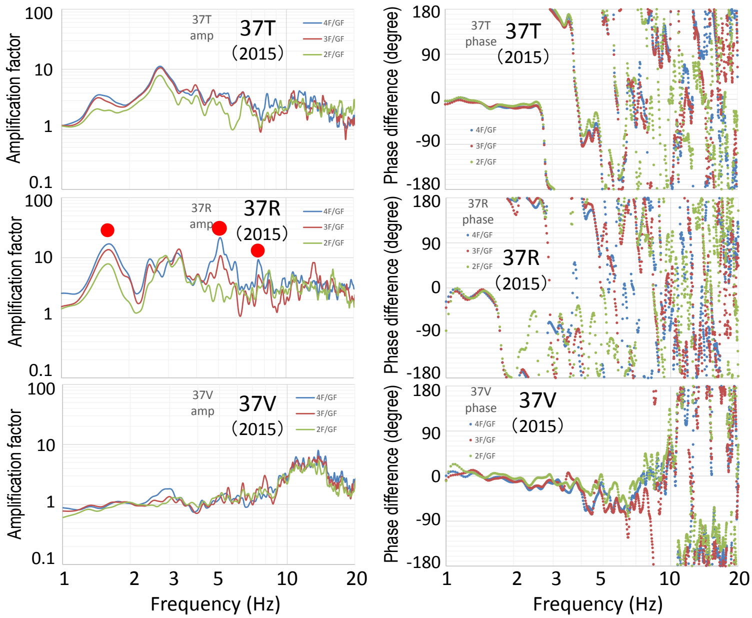

Figure 5. Transfer spectra between each floor and GF at the pillar #37 in 2015

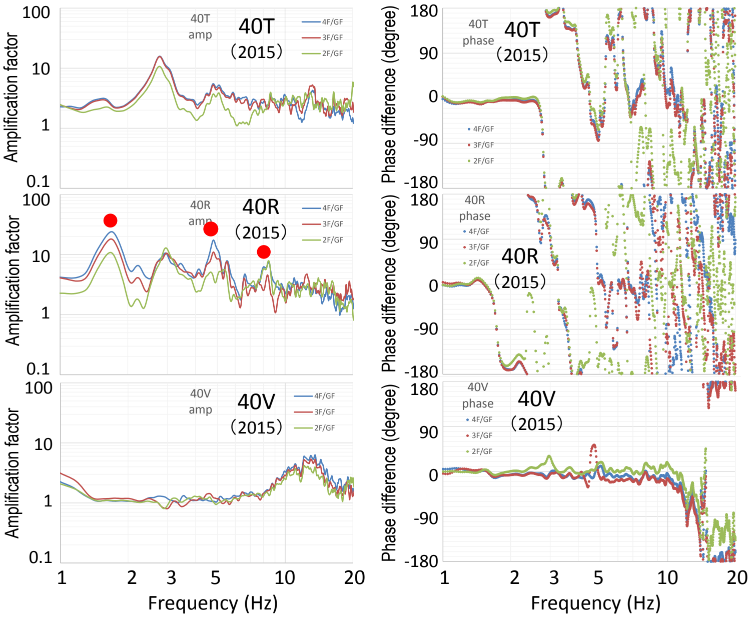

Figure 6. Transfer spectra between each floor and GF at the pillar #40 in 2015

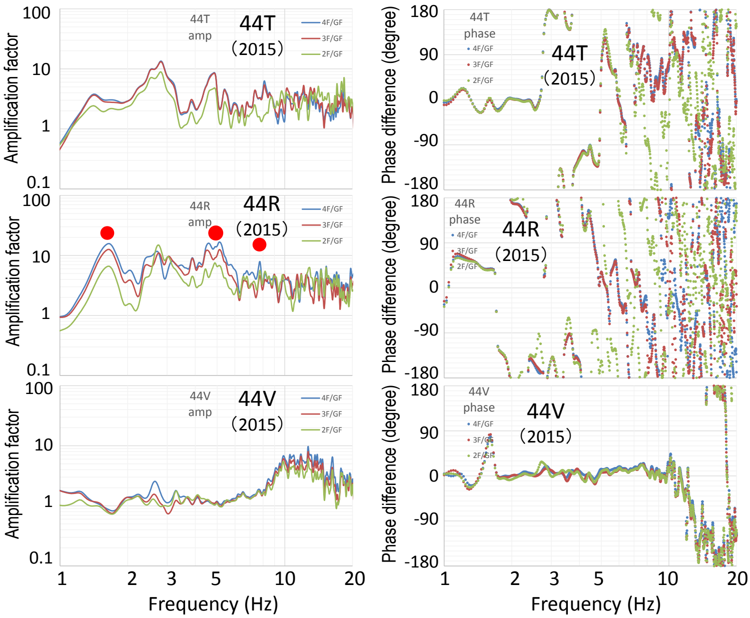

Figure 7. Transfer spectra between each floor and GF at the pillar #44 in 2015

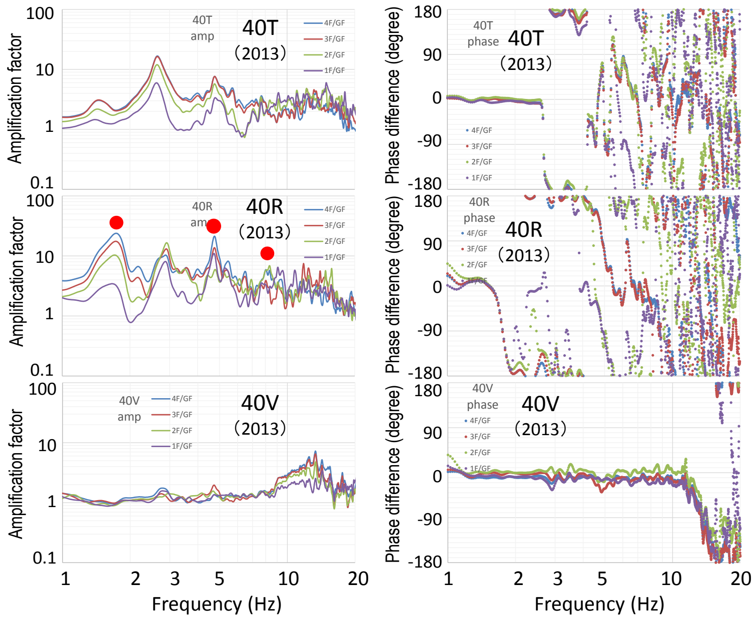

Figure 8. Transfer spectra between each floor and GF at the pillar #40 in 2013

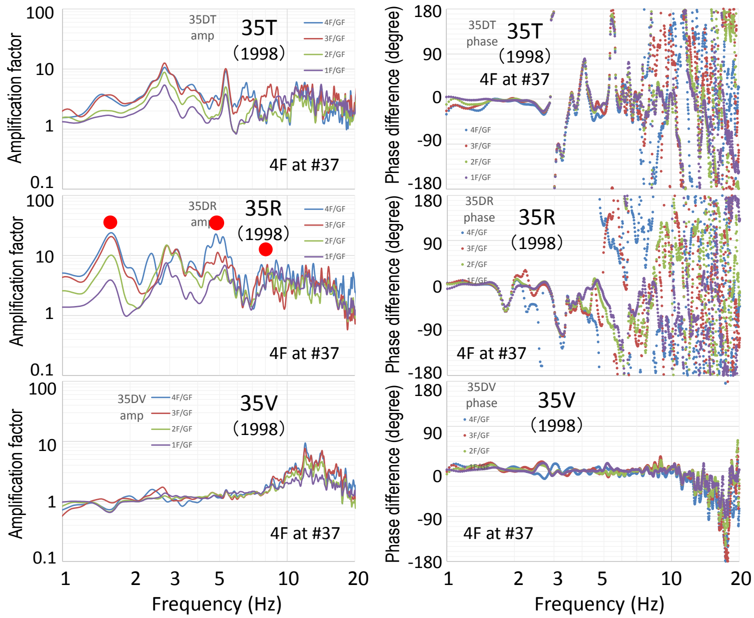

Figure 9. Transfer spectra between each floor and GF at the pillar #35 in 1998

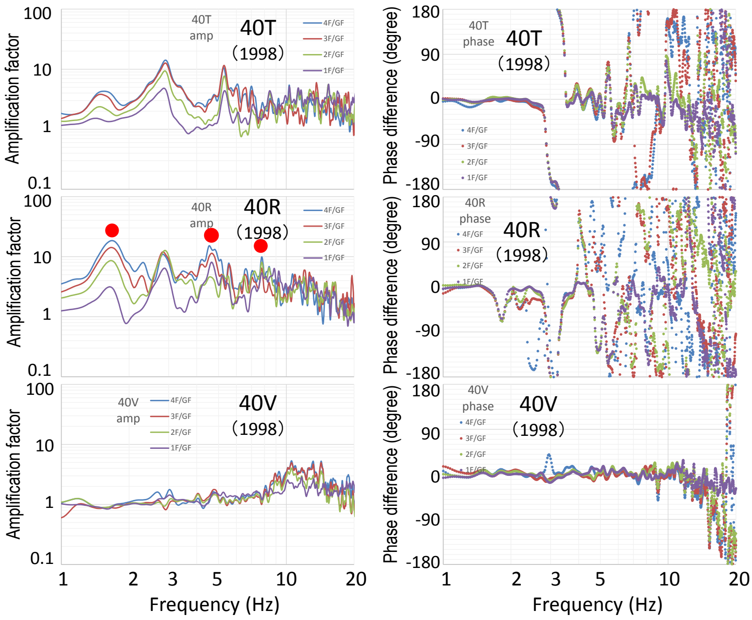

Figure 10. Transfer spectra between each floor and GF at the pillar #40 in 1998

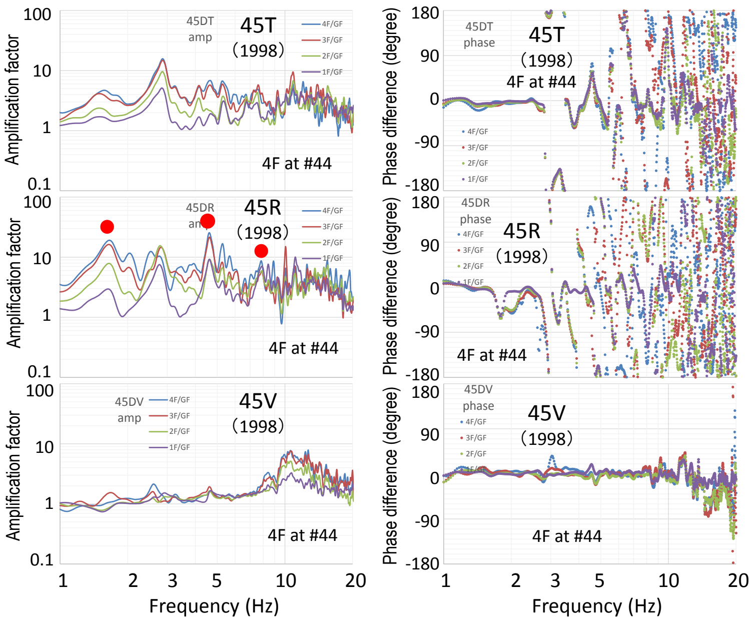

Figure 11. Transfer spectra between each floor and GF at the pillar #45 in 1998

Figure 12 indicates the change of the predominant frequency against the measurement year for each vertical measurement line and for each direction. The predominant frequency becomes lower for the T direction of the vertical lines #37 and #40, becomes higher for the R and V direction of the vertical lines #37 and #40 and remains unchanged for each direction of the vertical line #44. The change of the frequency is 10 % at a maximum.

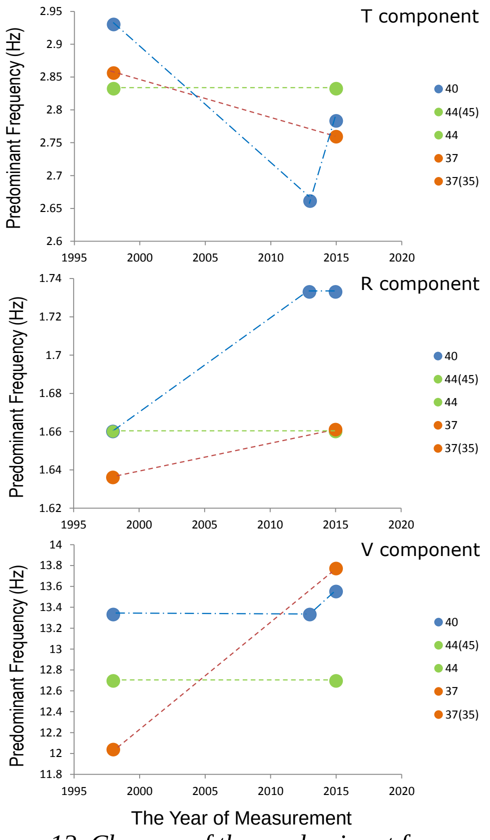

Figure 12. Changes of the predominant frequency

Figure 13 shows the mode of the amplification factor at the predominant frequency. Amplification factor for both T and R direction of the vertical line #40 was relatively small in 1998 and almost same in 2013 and 2015. On the other hand, that of the vertical lines #37 and #44 at both sides was smaller than that of the vertical line #40 in 2015

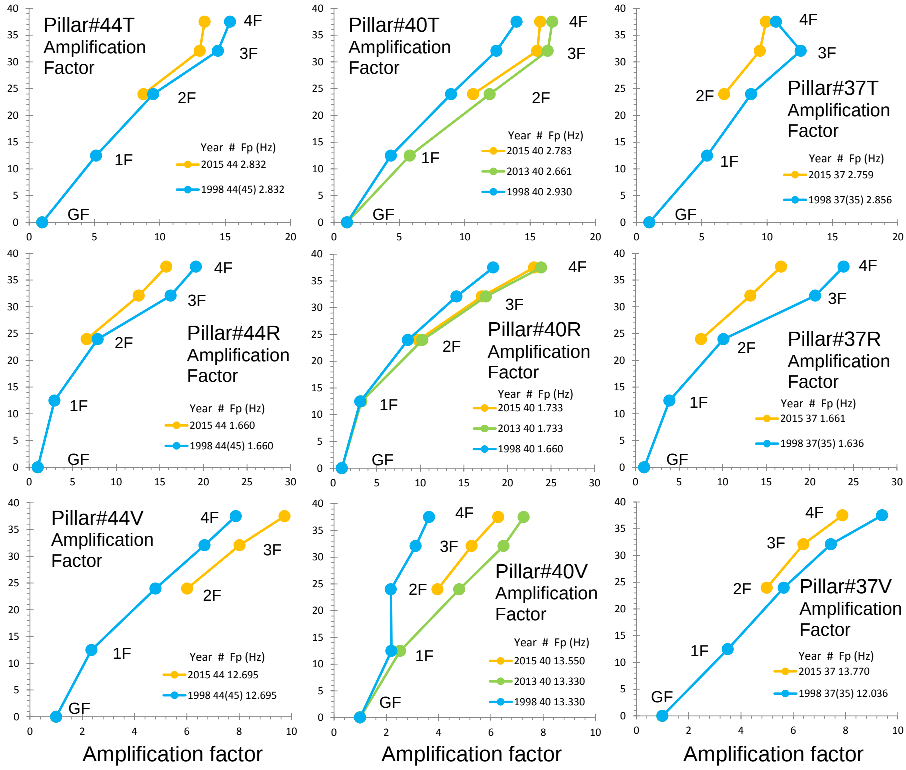

Figure 13. Mode shapes at predominant frequency

in contrast to 1998. This makes an impression that the vibration is leveled for three vertical lines. In case of R direction, the amplification factor over 2F became discontinuously large at the vertical lines #37 and #44 in 1998, and becomes smooth for the changing situation till 2F in 2015. In case of the V direction, the amplification factor becomes larger at the vertical lines #37 and #44 at both sides than that of the vertical line #40, and it suggests the existence of a rotation motion along the T-V plane with considering the phase characteristics mentioned above.

Kb value is an index to estimate roughly a strain with multiplying to the earthquake acceleration ([2]). Figure 14 shows the *Kb value* of the columns or the wall for each floor derived from the estimated vibration mode. The strain becomes larger mostly at 2F for the T direction. On the other hand, for the R direction, it was small at the central

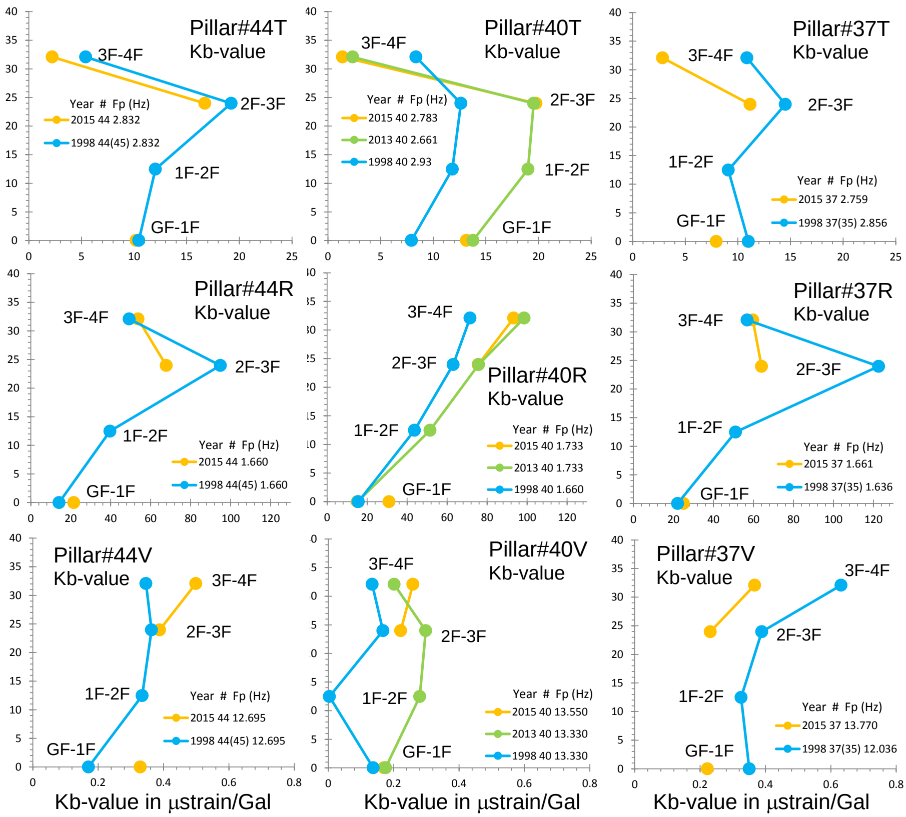

Figure 14. Kb-values at predominant frequency

vertical line #40 and considerably large at 2F of the vertical lines on the both side in 1998 and it becomes larger at the central vertical line #40 in 2013. *Kb value* of the vertical line #40 in 2015 is almost same for that in 2013. *Kb value* of the R direction in 2015 becomes about 30 % more of that in 1998 at the wall of 3F at the central vertical line #40 same as in 2013, but it becomes significantly small at the column of 2F of the vertical lines on the both side where gives the maximum value in 1998. It is considered that the distribution of *Kb value* changes especially in the R direction after 1998.

Kb value was relatively small at the vertical line #40 in 1998 and a maximum of 70 μstrain/Gal at 3F, but that was large as 1.4 times (95 μstrain/Gal) to 2 times (123 μstrain/Gal) against that of the vertical line #40 at 2F of the vertical lines #37 and #44 on the both side. However in 2015, although Kb value became considerably large as about 93 μstrain/Gal at 3F of the central vertical line #40, the values became almost half as 65 μstrain/Gal in maximum for the vertical lines #37 and #44 on the both side, and *Kb value* seems to be leveled for each vertical line.

According to *Kb value*, there is a great change in the dynamic characteristics between in 1998 and after 2013. However the value in 1998 had been larger on the both side than that in the center, the value after 2013 became larger in the center than that on the both side. Consequent change of the distribution or maximum value of *Kb value* was found for each measurement point after 1998. However the value itself for each vertical line became modestly small and seems to be not a change for more dangerous, the distribution of *Kb value* is unknown in 2015 because of unable to measure at 2F. It is expected to measure completely.

As mentioned above, it is confirmed that the change of the dynamic characteristics caused by the maintenance work in 2010 can be almost certainly grasped as a result of the repeated measurement at the northern wall in 2013 and 2015. After this, it is expected to develop strategy to utilize the regular microtremor measurement for the maintenance.

4.2. The buttress Valadier

Figure 15 indicates the amplification factor characteristics of the vertical line #57 at the buttress Valadier from the top to 1F based on GF. The measurement in 2015 was conducted from the top to 4F, 15m beneath, along the pillar #57, and the measurement in 1998 conducted simultaneously at 2F and 1F of the pillar #57 and at 1F and GF of the pillar #59. The result of the T, R and V directions are figured and the peak at 1.25 Hz is commonly found on each direction. Figure 16 shows a vibration mode at this frequency. Although the vibration of 1.25 Hz is a vibration mainly caused by the R direction, coherence between the T and R direction components is extremely high as around 0.99 and it suggests that this vibration is including the T direction component. *Kb value* distribution derived from the result above is shown in Figure 17. *Kb value* is about 280 μstrain/Gal at the top for the T and V directions in maximum, and reaches over 500 μstrain/Gal

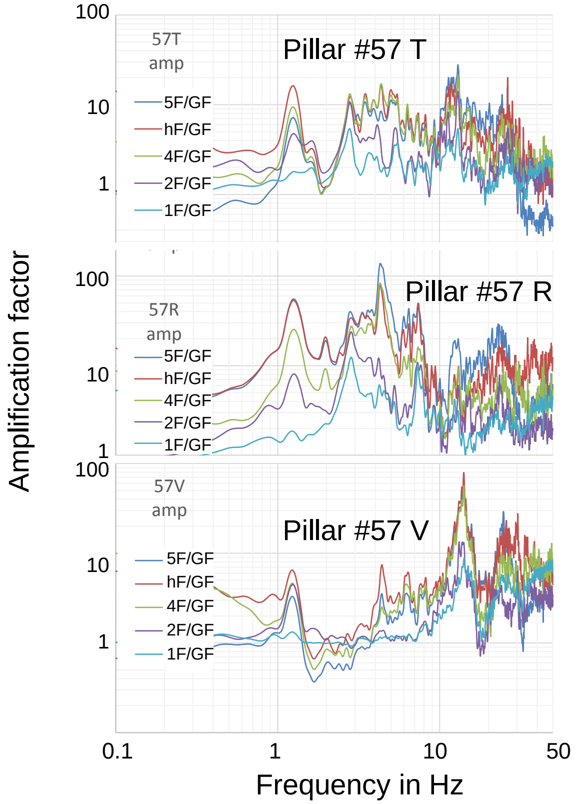

Figure 15. Transfer spectra based on GF at the pillar #57

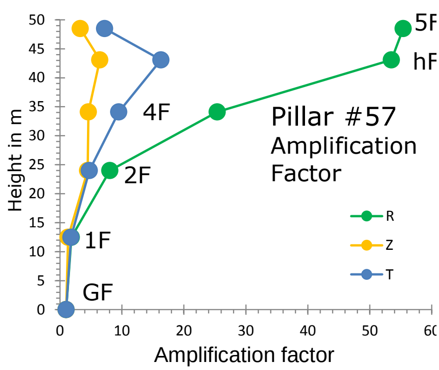

Figure 16. Mode shape of the pillar #57at 1.25Hz

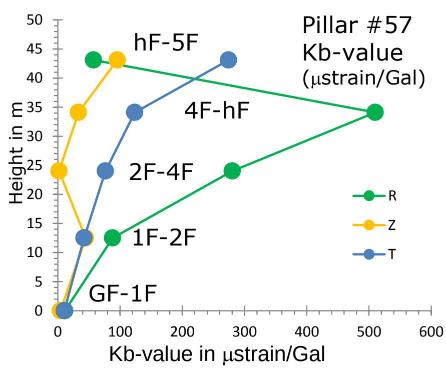

Figure 17. Kb-value of the pillar #57at 1.25Hz

in maximum around 4F for the R direction. It means that this part is vulnerable enough to reach a shear strain of 1/50 when acceleration value is about 40 Gal at ground surface (corresponding roughly to *RI* 4 or *MMI* 7) if the dynamic characteristics is remained during a strong motion. It is expected that this large shear strain is not occurred in practical because of the non-linearly or other reasons, however the fact remains that the wall at upper buttress Valadier is weak point against earthquake motion.

Figure 18 shows the result of the measurement of the eastern buttress Stern in 1998 at GF and 1F of the pillar #25, and 1F and 2F of the pillar #26, as the vertical line #25, although this part is not a measuring object in 2015. From the result of the measurement at the pillar #26 in 1998, an amplification factor difference between 2F and 1F is approximately 4.8 times for the predominant frequency 1.025 Hz, and *Kb value* is derived as about 94 μstrain/Gal from this. This is larger than that as approximately 80 μstrain/Gal measured at 1F column of the vertical line #57 corresponding to the measurement point at the pillar #26. Not only the large *Kb value* but also the predominant frequency of the vertical line #25 as 1.025 Hz is lower than that of the

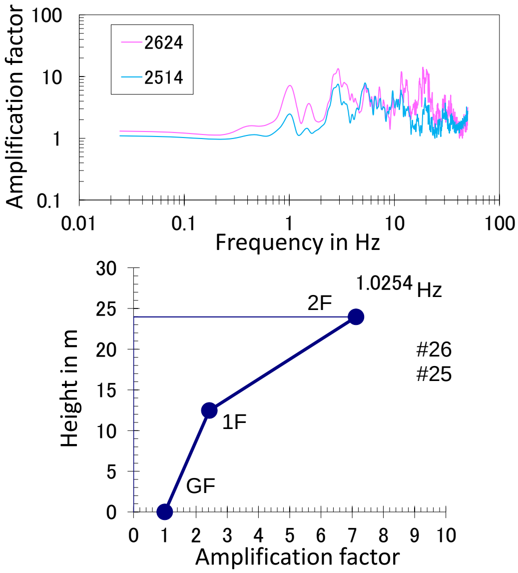

Figure 18. The result of the measurement of the eastern buttress Stern in1998

vertical line #57 as 1.25 Hz. It suggests that the part of the buttress Stern is more vulnerable. It is expected for the buttress Stern to take necessary countermeasures and reinforcements with investigating completely from the top to GF and making clear the vulnerability of this part same as the buttress Valadier. An elevator facility for visitors has been installed around the buttress Stern after the 1998 measurement and it is considered to be urgent to confirm the vulnerability with this new facility.

5. Conclusion

Colosseum had been investigated preliminarily in winter of 1997 and practically in summer of 1998, and then the pillar #40 of the northern wall was re-measured in winter of 2013. As a result, an unexpectedly large change of the earthquake motion characteristics is found as the shift about 10 % of the predominant frequency and so on.

The maintenance work between spring and autumn in 2010 is concerned to be the reason. After this, we had a chance to measure again in 2015. Consequently there was no significant difference between the result of the 2013 and 2015 measurements at the pillar #40, and difference between the result of the 1998 and 2015 measurements at the closed to the pillar #37 and #44. This means that the impact of the maintenance work in 2010 is likely to be found as the change of the dynamic characteristics. We would like to suggest establishing a framework for a rational maintenance and management of a cultural heritage utilizing the result of the regular investigation as a material for the future.

In 2015, additional first measurement around the top of the outer wall was conducted at the pillar #57, the end of the buttress Valadier. Although the measurement was conducted only around the top because of time requirement, it is possible to obtain comfortable and reasonable transfer spectrum from the result of this measurement connecting that of the 1998 measurement. It is possible from this result to point out the vulnerability of the buttress Valadier. Meanwhile, comparing this result with the result measured up to 2F of the buttress Stern in 1998, it is hard to eliminate doubt that the buttress Stern is

more vulnerable as pointed out after the measurement ([2]).
Additionally, an elevator facility for visitors has been installed around the buttress Stern after the 1998 measurement and it is considered to be urgent to confirm the vulnerability with this new facility.

On the other hand, recently it is being revealed that the dynamic characteristics of structures demonstrates daily or seasonally variation and it is pointed out that there is a good correlation on the dynamic characteristics of structures between the daily or seasonally variation and temperature variation ([3]). According to [3], the change of the predominant frequency caused by these variations is mostly about 10 % and less than 20 % in maximum.

From the viewpoint of earthquake disaster prevention, it is necessary to reveal quantitatively the change why and how the reason. Although, it is impossible for short time measurement to analyze even the daily variation as well as the seasonally variation, it is considered to investigate from this aspect in the future. It seems to be also necessary for Colosseum to investigate with high-accuracy microtremor measurement continuously to confirm the daily or seasonally change of the earthquake motion characteristics. This should be possible to grasp even the behavior of Colosseum itself precisely caused by the rather distanced damage earthquake. It is possible to establish rational countermeasures from exposing the weakness with precise response analysis along with understanding the earthquake motion characteristics. It is expected to be a contribution for bequeathing the treasurable cultural heritage to posterity better.

Acknowledgement

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