VIBRATION CHARACTERISTICS OF A HIGH-RISE BUILDING IN JAPAN UNDER LONG-PERIOD SEISMIC GROUND MOTION

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ABSTRACT: In the Mw9.0 2011 Tohoku, Japan earthquake, high-rise buildings located in Tokyo and Osaka, far from the source zone, were shaken by long-period ground motion and some of them were suffered from damages to interior objects and fire-protecting doors as well as malfunctions of elevators. In this study, vibration characteristics of a high-rise building in Osaka were investigated using seismic records obtained in the foreshock, mainshock, and aftershock of the Tohoku event and other earthquakes. The natural periods, participation functions and damping ratios were identified based on the fitting of observed transfer function.

KEYWORDS: long-period ground motion; high-rise building; the 2011Tohoku earthquake

1. INTRODUCTION

In the last few decades, a large number of high-rise buildings have been built in large cities in Japan, especially in three metropolitan areas: Tokyo, Osaka, and Nagoya. These metropolises are located on large sedimentary planes having long natural periods. Thus high-rise buildings in the metropolises may be affected by long-period seismic ground motion due to resonance. In fact, in the Mw9.0 2011 Tohoku earthquake, high-rise buildings located in Tokyo and Osaka, far from the source zone, were shaken by long-period ground motion and some of them were suffered from damages to interior objects and fire-protecting doors as well as malfunctions of elevators (Takewaki et al. 2011).

There is a 60-70 % probability that a Nankai-trough megathrust earthquake of Mw8.5-9.0 occurs within the next 30 years. Since the population exposed to the future Nankai-trough earthquake is more than that of the 2011 Tohoku earthquake, the preparedness and mitigation measures to the mega-quake are one of the most urgent issues in disaster mitigation in Japan (Cabinet Office of Japan 2015).

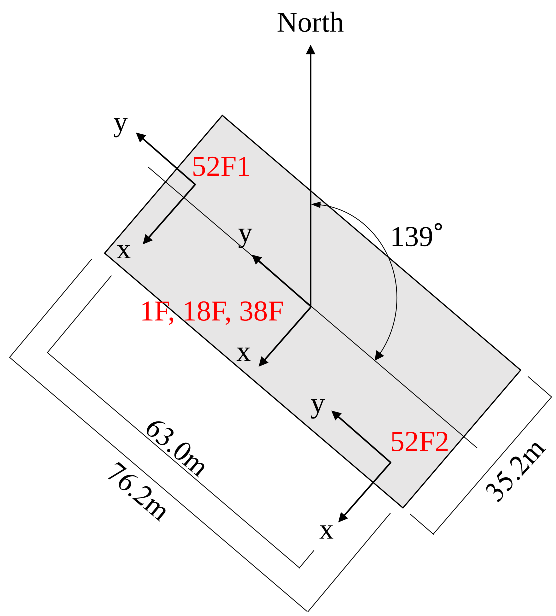
Celebi et al. (2014) evaluated the vibration characteristics of a high-rise building located in the Osaka-bay coast, based on system identification using the ARX model. Yamashita et al. (2012) grasped the changes in building vibration characteristics before and after the 2011Tohoku earthquake for a 29-storied high-rise building in Shinjuku, Tokyo. In this study, the vibration characteristics of the high-rise building located in Osaka-bay coast are investigated using seismic records obtained in the Tohoku earthquake and other events. The system parameters, such as natural periods, participation functions and damping ratios, are identified based on the method proposed by Yamashita et al. (2012), but by a different calculation procedure.

2. EARTHQUAKE RECORDS AND THE TARGET BUILDING

A 55-storied high-rise building located in the Osaka-bay coast was selected as the target of this study. The basement of the building is made by a steel-RC (reinforced concrete) construction, and its upper stories are steel construction. Three-component accelerometers were installed on the 1st, 18th, 38th and 52nd floors. The two horizontal components were measured to the x-axis (transverse, 229° clockwise from the north) and the y-axis (longitudinal, 319° clockwise from the north). **Figure 1** shows the location of accelerometers on the 1st, 18th, 38th and 52nd floors. Note that the accelerometer donated 52F1 was used as the representative one of the 52nd floor in this study.

The list of earthquakes used in this study is shown in **Table 1**. As a record before the main-shock of the Mw9.0 Tohoku event, the foreshock occurred Off-the-Sanriku coast on March 9, 2011 was selected. Five records were selected after the main-shock including the largest aftershock 30 min after the main-shock. **Figure 2** shows the velocity response spectra with 2 % damping of the accelerograms to the two building-axes recorded at the first-floor. The response spectra indicate that these records have different predominant periods and amplitude levels.

(a)



(b)

Figure 1. Appearance of the 55-storied building (a) and the location of accelerometers on 1st, 18th, 38th and 52nd floors (b). The accelerometer 52F1 represents the record of the 52nd floor in this study.

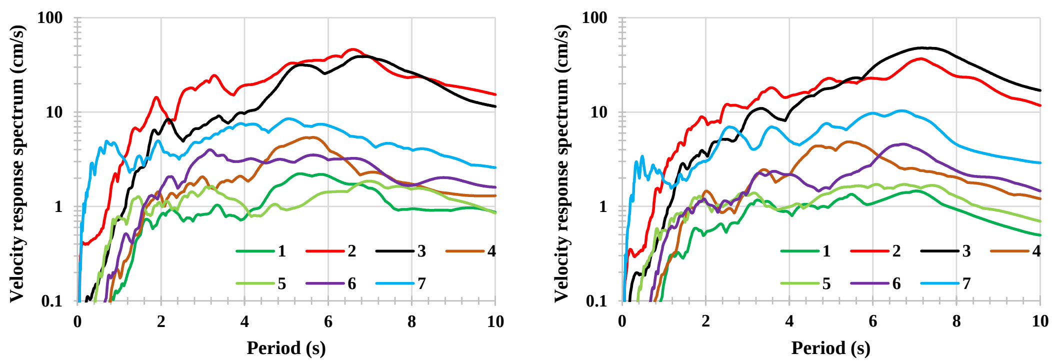
Table 1. List of the observation records at the target building

Event	Date	Time	M_{JMA}	Location of epicenter	Distance (km)	Max. Acc. at 1F (cm/s²)	
						x-axis	y-axis
1	2011/3/9	11:45	7.3	Off Sanriku coast	813	0.8	0.7
2	2011/3/11	14:46	9.0	Off Sanriku coast	769	34.3	33.5
3	2011/3/11	15:15	7.6	Off Ibaraki Pref	555	8.9	9.2
4	2011/3/12	3:59	6.7	Northern Nagano	387	1.5	1.2
5	2011/3/15	22:31	6.4	Eastern Shizuoka	309	1.6	5.3
6	2011/4/7	23:32	7.2	Off Miyagi Pref	704	2.2	1.5
7	2013/4/13	5:33	6.3	Near Awaji Island	59	23.2	15.2

To confirm vibration characteristic of the Osaka plain, the time history records obtained at the KiK-net station near the target building were used. **Figure 3** shows acceleration time histories at the surface and in the borehole of the KiK-net OSKH02 station during the mainshock (Event 2), rotated to the building axes. **Figure 4** shows the Fourier spectrum ratio of acceleration records at KiK-net OSKH02 station between the surface and downhole during the mainshock (Event 2). In each axis, the spectral ratio indicates that the first mode of the site is in the range 0.16-0.17 Hz (5.9-6.3 s). This value will be used to investigate the resonance between the target building and the ground of the site.

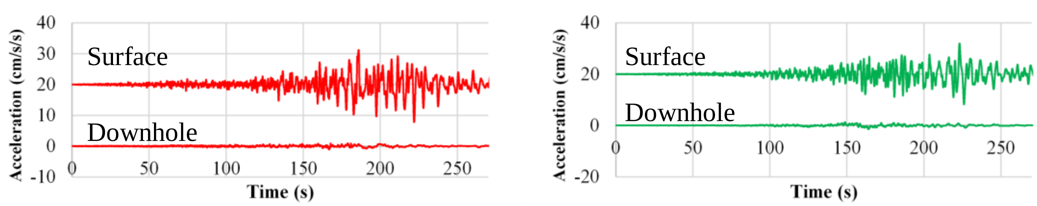
Figure 5 shows the acceleration time histories at the four instrumented floors of the 55-storied building during the mainshock (Event 2). As a floor goes up, an increase of response is seen in the two horizontal axes. In the two directions, the response accelerations show some differences.

Figure 6 shows the Fourier spectrum ratios of acceleration between the upper floors and the 1st floors during the mainshock (Event 2). From these ratios, the natural frequencies to the two building axes could be determined. Identified frequencies (periods) are 0.15, 0.48, and 0.91 Hz (6.6, 2.1, 1.1 s) for the first three modes in the x-axis; 0.14 0.43, 0.71 Hz (6.9, 2.3, 1.4 s) for the first three modes in the y-axis. These first-mode values are similar to the predominant frequencies (periods) of the site, 0.16-0.17 Hz (5.9-6.3 s), which were indicated earlier. Due to this close values, the resonance between the target building and the site might be caused.



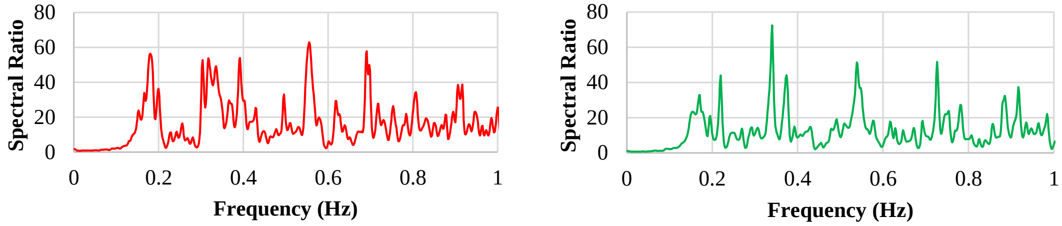
(a) x-axis (b) y-axis

Figure 2. Velocity response spectra of seven earthquake records at the 1st floor of the 55-storied building (h=0.02)



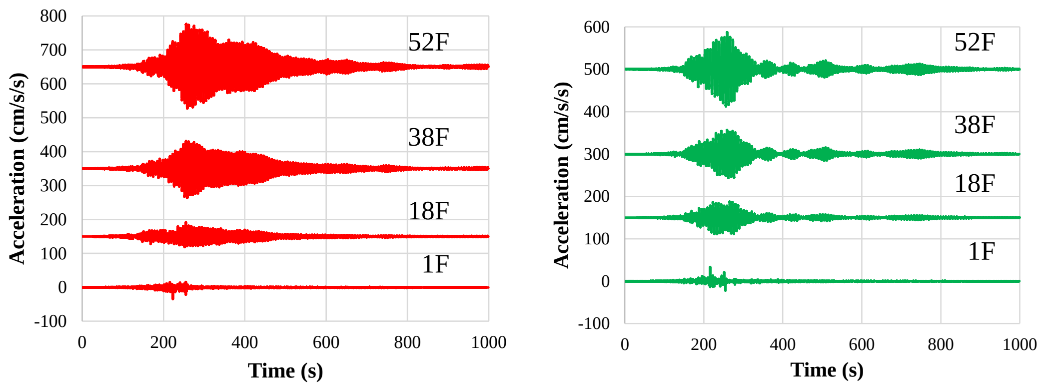
(a) x-axis (b) y-axis

Figure 3. Acceleration time histories at the surface and downhole of KiK-net OSKH02 station during the mainshock (Event 2) rotated to the building axes



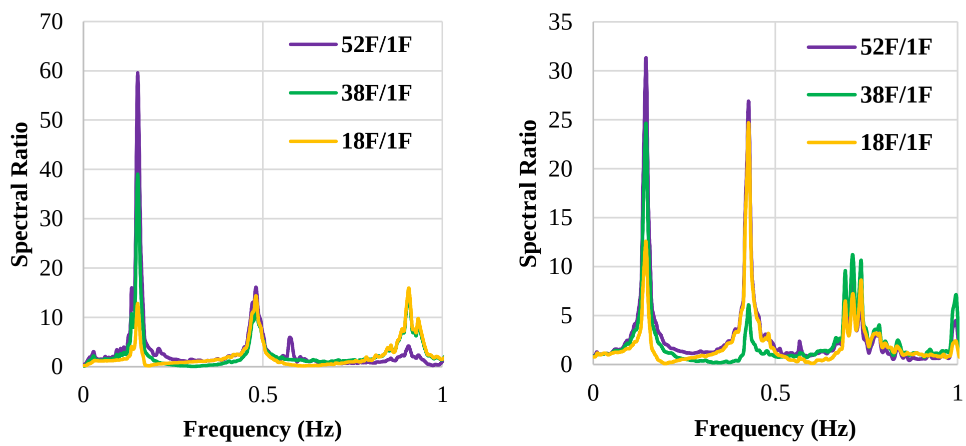
(a) x-axis (b) y-axis

Figure 4. Fourier spectrum ratio of acceleration records at KiK-net OSKH02 station between the surface and the downhole during the mainshock (Event 2)



(a) x-axis (b) y-axis

Figure 5. Acceleration time histories at each floor of the 55-storied building during the mainshock (Event 2)



(a) x-axis (b) y-axis

Figure 6. Fourier spectrum ratios of acceleration records between the instrumented floor with respect to the 1st floor during the mainshock (Event 2)

3. SYSTEM IDENTIFICATION METHOD

To identify the parameters such as the natural periods, participation functions and damping ratios, curve-fitting for the transfer function proposed by Yamashita et al. (2012) was employed. In this method, the Fourier spectral ratio between an upper floor (k) and the 1st floor was used as the observed transfer function. The calculated Fourier spectrum was smoothened by a rag-window of 0.01-Hz bandwidth.

First, from the dominant frequencies of the Fourier spectral ratio, first three natural periods were determined. Second, using the least-squares method, the amplitudes of analytical model were determined to fit the observed Fourier spectral ratio. As the analytical model, the amplitude $|G_k(\omega)|$, shown in Equation (1) from the modal expansion, under a harmonic ground motion $e^{i\omega t}$ with the period T ($=2\pi/\omega$) was used. The parameters of the analytical model were determined for mode-number j and floor k, such as participation function $\beta_j\varphi_{j,k}$ and damping ratio h_j.

$$\left.\begin{aligned} |G_K(\omega)| &= \sqrt{G_{KR}(\omega)^2 + G_{KI}(\omega)^2},\ B_j = \frac{\omega}{\omega_j} \\ G_{KR}(\omega) &= \sum_{j=1}^{N} \frac{1+(h_jB_j)^2 - B_j{}^2}{(1-B_j{}^2)^2+(2h_jB_j)^2} * \beta_j\varphi_{j,k} \\ G_{KI}(\omega) &= \sum_{j=1}^{N} \frac{-2h_jB_j{}^3}{(1-B_j{}^2)^2+(2h_jB_j)^2} * \beta_j\varphi_{j,k} \end{aligned}\right\} \quad (1)$$

The participation function for the first-mode was searched by 0.01-interval, from 0.00 to 3.00. Those of the second and third modes were searched by 0.01-interval, from -1.00 to 1.00. The damping ratios for the first three modes were searched by 0.001-interval, from 0.000 to 0.100. The first three modes were thought to be enough in evaluating the response characteristics for the target building.

In this study, a different calculation procedure from Yamashita et al. (2012) was introduced for Equation (1). Specifically, the identifications for the first to third modes were not conducted simultaneously. Instead, the identification was performed mode by mode, which means the amplitude of the best-fit analytical transfer function was determined one by one to reduce the calculation time.

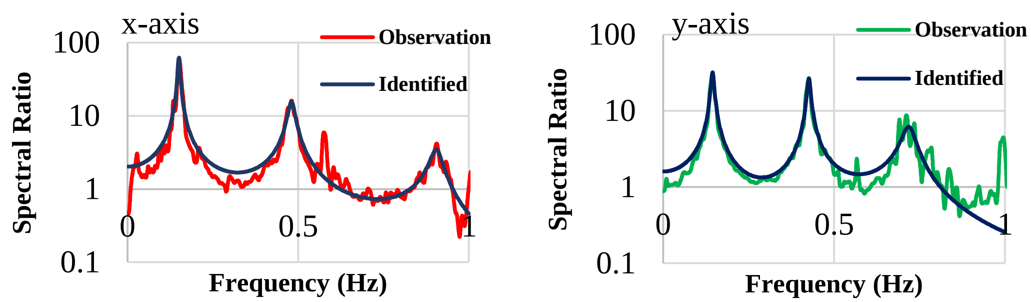
First, the parameters for the first-mode were identified. Next, using these parameters, the second-mode's parameters were determined. Finally, using all these parameters, the parameters for the third-mode were determined. By this procedure, the number of calculation steps was increased, but the calculation time was reduced.

In order examine the accuracy of the method employed in this study, a comparison of identified parameters was carried out with the identification result by Yamashita et al. (2012) for the damping ratio in 29-storied high-rise building in Shinjuku, Tokyo. From this comparison, the difference was less than 0.5 % and hence the method used in this study was proved to have enough accuracy with a much shorter calculation effort.

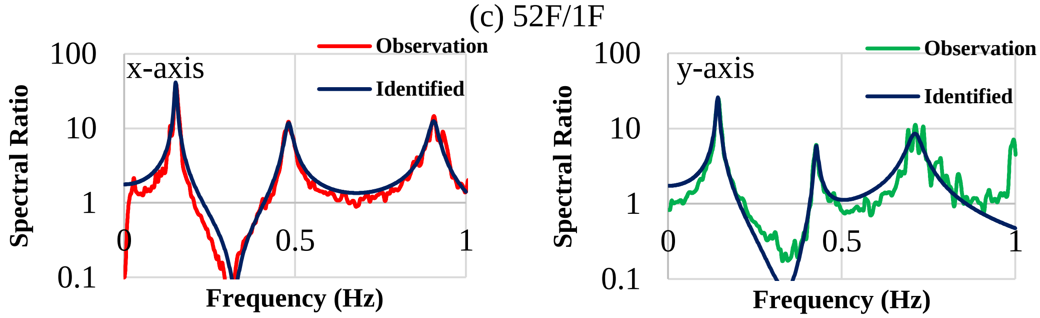
4. THE RESULT OF SYSTEM IDENTIFICATION

According to the curve-fitting for the transfer function, the parameters such as natural periods, participation functions and damping ratios were identified. **Figure 7** shows the comparison of the observed and identified participation functions for the mainshock (Event 2). In the figure, the degree of agreement looks quite good for the first, second and third modes for the two building axes at the three floor levels with respect to the first floor.

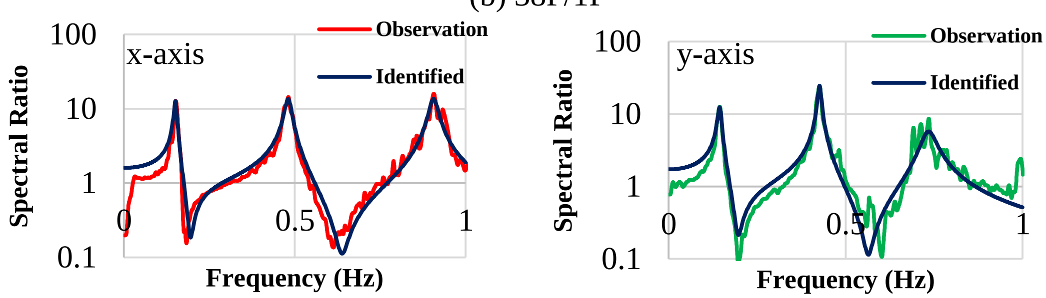
Table 2 shows the series of change in the identified natural periods. In the table, an elongation of the natural period from the foreshock (Event 1) to the mainshock (Event 2) is confirmed in the two building axes. The ratio of identified natural periods between foreshock (Event 1) and aftershock (Event 3) was examined. In the x-axis, the natural periods got longer 1.03, 1.04, and 1.06 times for the first, second and third modes, respectively, while those ratios are 1.08, 1.08, and 1.17 in the y-axis.



(c) 52F/1F



(b) 38F/1F



(a) 18F/1F

Figure 7. Comparison of observed and identified Fourier spectral ratios in the mainshock

In the 2011 northern Nagano earthquake (Event 4), 13 hours after the aftershock (Event 3), the most of the natural periods decreased but still larger than those in the foreshock (Event 1). In the 2013 Awaji Island earthquake (Event 7), the natural periods did not recover to the levels of the foreshock for the two building axes, especially to the y-axis. This observation indicates that the stiffness of structural frames have been softened or the contacts between non-structural elements have been loosened due to large deformation in the mainshock.

Figure 8 shows the relationship between the identified damping ratios and natural frequencies for the 7 earthquakes for the two building axes. By selecting the natural frequency instead of the natural period as the abscissa, the tendency for different modes could be grasped easily. To the x-axis, the damping ratios for different modes are similar for the foreshock (Event 1) and mainshock (Event 2), and also the damping ratios among different events are not so large. On the contrary, the variation of the damping ratios for different events look much bigger to the y-axis, especially for the second and third modes.

Figure 9 shows identified participation functions for the first three modes in the two building axes. In general, the first and second modes were identified reasonably well, consistent with these theoretical mode shapes. On the contrary, the third mode shape could not be obtained, probably due to the lack of accelerometers to observe this mode. The straight line connecting the 18th and 38th floors may not be correct.

To examine the validity of the identified parameters, a modal composition using these values was carried out and the result was compared with the observation records. As an

Table 2. Identified natural periods (s) for the 7 events for the two building axes

Axis	mode	Event Number						
		1	2	3	4	5	6	7
x	1	6.32	6.62	6.51	6.51	6.42	6.62	6.56
	2	2.01	2.08	2.09	2.04	2.06	2.07	2.06
	3	1.07	1.10	1.13	1.10	1.09	1.09	1.10
y	1	6.49	6.90	7.02	6.62	6.69	6.95	7.01
	2	2.18	2.31	2.36	2.27	2.23	2.29	2.35
	3	1.20	1.40	1.40	1.35	1.29	1.34	1.32

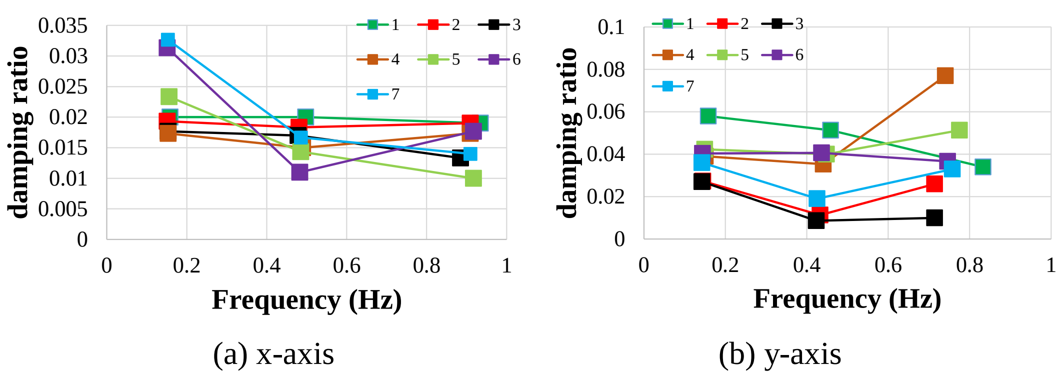
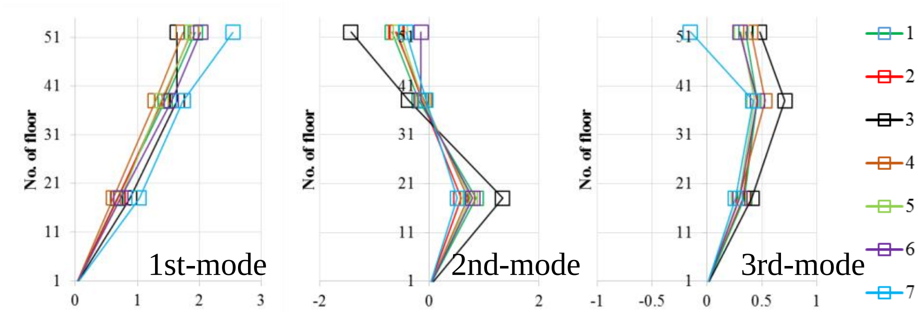


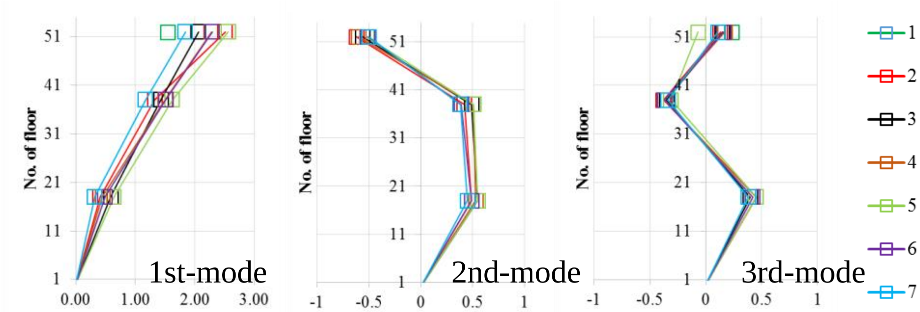
Figure 8. The relationship between identified damping ratios and natural frequencies for 7 earthquakes to two building axes

example, the acceleration responses of the 52nd floor to the two building axes were shown in **Figure 10** for the mainshock (Event 2). To the x-axis, the response using the identified values exhibits somewhat larger than the observed one before reaching the maximum response, but the modal composition becomes smaller than the observed one after the peak. To the y-axis, however, a good agreement is seen before reaching the maximum value. But after reaching the peak, the modal composition gives smaller response. These observations indicate that the system parameters of the building changed during the mainshock and thus the simulation using the constant parameters for all the time steps had limitation. But generally speaking, the identified structural parameters from the fitting of the observed Fourier spectral ratios performed well in estimating the response of the building under seismic excitations.

Finally the relationship between the identified system parameters and the amplitude of the input motion was investigated. **Figure 11** shows the relationship between the identified natural period of each mode and the maximum velocity at the 1st floor (the resultant of the two horizontal components). The elongation trend of the natural periods as the increase of

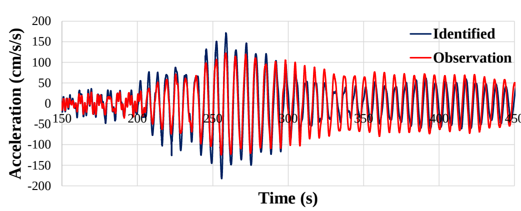


(b) y-axis

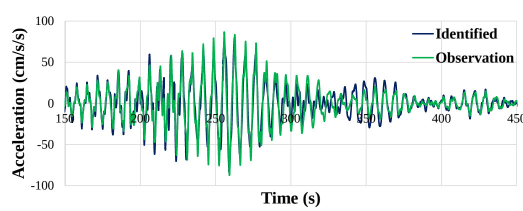


(a) x-axis

Figure 9. Identified participation functions for the 7 events

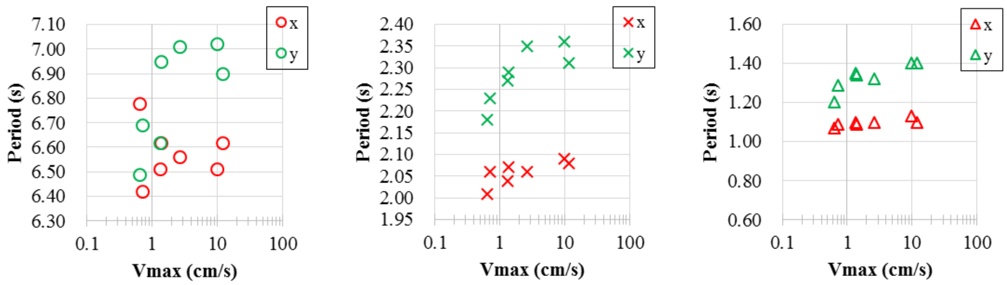


(a) x-axis



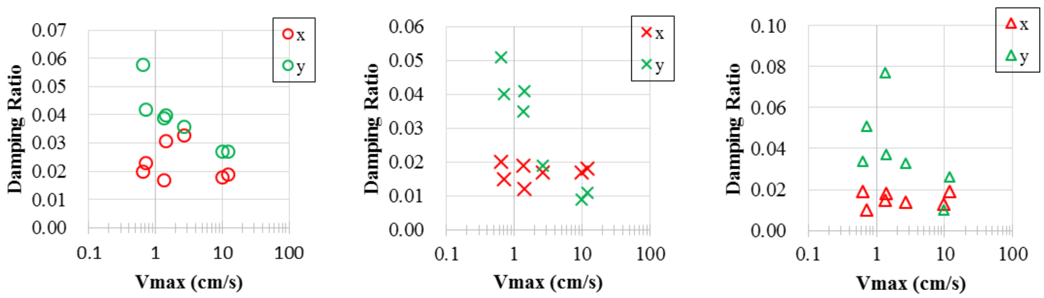
(b) y-axis

Figure 10. Comparison between acceleration time histories between by mode composition and from observation



(a) first-mode (b) second-mode (c) third-mode

Figure 11. The relationship between the identified natural period of each mode and the maximum velocity at the 1st-floor



(a) first-mode (b) second-mode (c) third-mode

Figure 12. The relationship between the identified damping ratio of each mode and the maximum velocity at the 1st-floor

the velocity can be observed. **Figure 12** shows the relationship between the identified damping ratio of each mode and the maximum velocity at the 1st floor. The damping ratios look almost constant in the x-axis while a decreasing trend is seen in the y-axis as the velocity gets larger. The damping ratios for the x-axis were generally smaller than those for the y-axis, and thus showing the different vibration characteristics of this building to the two axes.

5. CONCLUSION

In this study, the vibration characteristics of a high-rise building located in the Osaka-bay coast were investigated using acceleration records in the foreshock, mainshock, and aftershock of the Mw9.0 2011 Tohoku earthquake and other earthquakes. The parameters such as the natural periods, participation functions and damping ratios were identified by fitting for the Fourier spectral ratios with a different calculation procedure from a previous study. As a result, an elongation of the natural period from the foreshock to the mainshock was observed to the two building axes. The first three mode shapes were estimated, and the relationship between the identified system parameters and the amplitude of the input motion was examined.

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