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DYNAMIC CHARACTERISTICS OF SUPER-HIGH-RISE RC BUILDINGS BASED ON LONG TERM EARTHQUAKE RECORDS

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Abstract

Japan has been hit by several large earthquakes in the past three decades, including the 1995 Hyogoken-Nanbu earthquake (the Kobe earthquake), the 2011 off the Pacific coast of Tohoku earthquake (the Great East Japan earthquake), the 2016 Kumamoto earthquake, the 2018 Osaka North earthquake, and 2018 Hokkaido Eastern Iburi earthquake, etc. A huge number of super-high-rise residential buildings were constructed during this period, mainly in the urbanized areas in the Kanto and Kansai regions. Strong motion records in the buildings are indispensable to investigate dynamic characteristics of the structural responses during massive earthquake, as has been reported and emphasized in many papers. In addition, the resilience of buildings has attracted attention from the standpoint of the seismic design of the upper structure along with the piles and foundation. Therefore, it is expected to grasp the dynamic characteristics of the pile-building system based on the earthquake observation records. However, there are few cases where strong motions of ground-foundation-building are observed simultaneously, and furthermore, it is necessary to grasp the dynamic characteristics of the pile-building system and to grasp the characteristic fluctuation by long-term earthquake observation records.

In this study, earthquake observation records obtained from three super-high-rise RC buildings equipped earthquake observation systems that have simultaneously monitored the pile tip, ground surface, and upper building for more than 10 years were used. These buildings incorporate moment resistance frames using high-strength materials. Based on these records, we examined the dynamic characteristics and long-term characteristic fluctuations. The target buildings are located in the Kansai and Kanto regions, and have been obtained from small and medium-scale earthquakes to relatively large earthquakes It is possible to analyze with Long-term earthquake observation records for small-, medium-, and large-scale earthquakes were analyzed.

The large earthquakes in the long-term earthquake observation records were used to clarify the dynamic characteristics of the pile-building system and the upper structure. The records for a building in the Kansai region that was hit by the 1995 Hyogoken-Nanbu Earthquake were analyzed in detail the large fluctuations in dynamic characteristics caused by the 1995 Hyogoken-Nanbu earthquake and subsequent earthquakes, and the records for buildings in the Kanto region that were hit by the 2011 off the Pacific coast of Tohoku earthquake were analyzed in detail the large fluctuations in dynamic characteristics caused by the 2011 off the Pacific coast of Tohoku earthquake and the earthquakes before and after it.

Keywords: Earthquake observation, Super-high-rise reinforced concrete (RC) building, Long-term earthquake records, Dynamic characteristics

1. Introduction

Japan has been hit by several large earthquakes in the past three decades, including the 1995 Hyogoken-Nanbu earthquake (the Kobe earthquake), the 2011 off the Pacific coast of Tohoku earthquake (the Great East Japan earthquake), the 2016 Kumamoto earthquake, the 2018 Osaka North earthquake, and 2018 Hokkaido Eastern Iburi earthquake, etc. A huge number of super-high-rise residential buildings were constructed during this period, mainly in the urbanized areas in the Kanto and Kansai regions. Strong motion records in the buildings are indispensable to investigate dynamic characteristics of the structural responses during massive earthquake. The dynamic characteristics of high-rise reinforced concrete (RC) buildings and their fluctuations have been extensively reported [1, 2, 3]. The resilience of buildings has attracted attention from the standpoint of the seismic design of the upper structure, piles, and foundation. It is expected that the dynamic characteristics of the pile-building system can be determined based on earthquake observation records. However, there are few cases where the strong motions of a ground-foundation-building system have been observed simultaneously. It is necessary to determine the dynamic characteristics of the pile-building system and the long-term temporal variation based on earthquake observation records.

In this study, the vibration characteristics in earthquake observation records are investigated for three super-high-rise RC buildings equipped an earthquake observation system that has simultaneously monitored the pile tip, ground surface, and upper building for more than 10 years. Based on these records, we examined the dynamic characteristics and long-term characteristic fluctuations. The target buildings are in the Kansai and Kanto regions. Long-term observation records obtained for small-, medium-, and large-scale earthquakes were analyzed.

2. Profiles of Buildings

The investigated structures were three super-high-rise RC buildings, two in the Kanto region and one in the Kansai region. Fig.1 shows the location of these buildings. These buildings are located within the Kanto and Osaka plains, in which thick sedimentary layers overlie seismic bedrock.

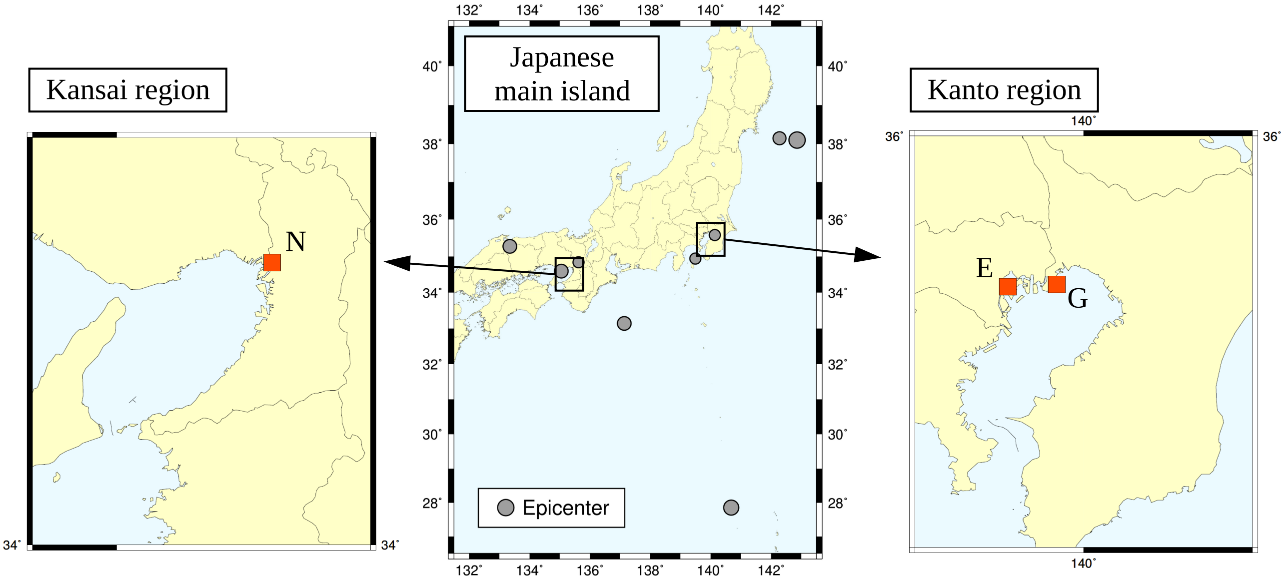


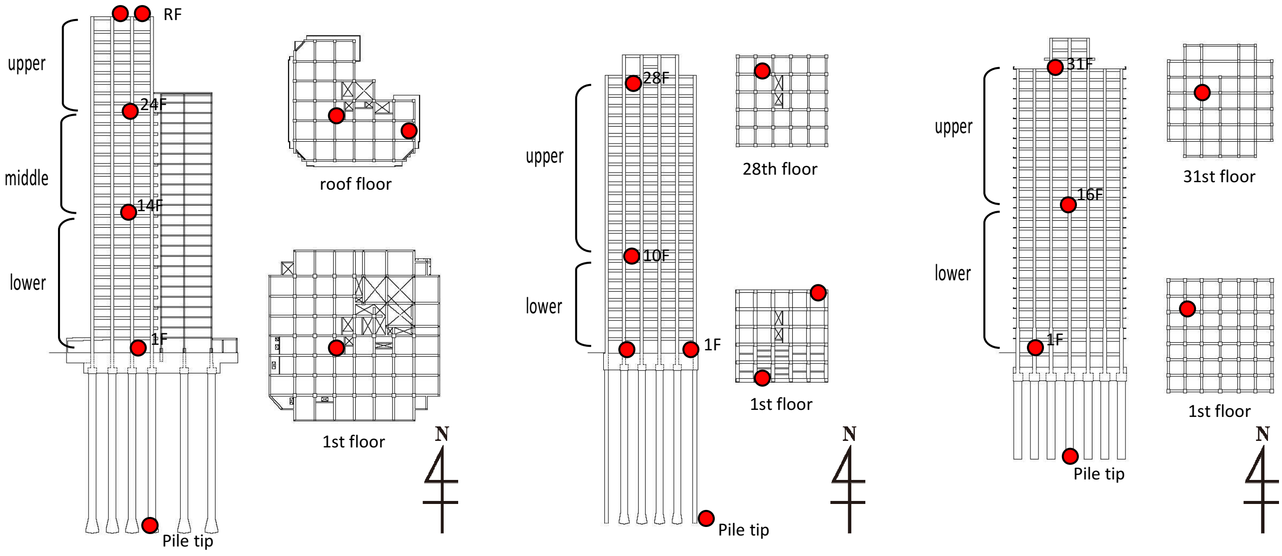
Fig. 1 – Construction site maps of buildings in the Kanto and Kansai regions investigated in this paper. Plots E,G,N indicate the building names listed in Table 1

These buildings are equipped with strong-motion observation systems. Seismic accelerometer records were simultaneously obtained at multiple locations, namely the pile tip, the ground surface, and the top and first or basement floors, including any mid-level floors. Table 1 lists the profiles, names, number of stories, structural type, and strong-motion observation floors for the buildings. Fig. 2 shows the locations of seismometers in each building.

Buildings E, G, and N were constructed in 2000, 1996, and 1989, respectively. They incorporate moment resistance frames using high-strength materials.

Table 1 – Profiles of buildings examined in this study

Building	Region	No. of stories	Pile type (pile/wall length)	Strong-motion observation location
E	Kanto	33	Steel pipe-concrete hybrid belled pile (47.0 m)	Pile tip, ground surface, 1F, 14F, 24F, and RF
G	Kanto	28	Cast-in-place concrete belled pile (44.9 m) and continuous underground wall (45.2 m)	Pile tip, 1F, 10F, and 28F
N	Kansai	31	Cast-in-place concrete pile (23.0 m)	Pile tip, ground surface, 1F, 16F, and 31F



(a) building E (b) building G (c) building N

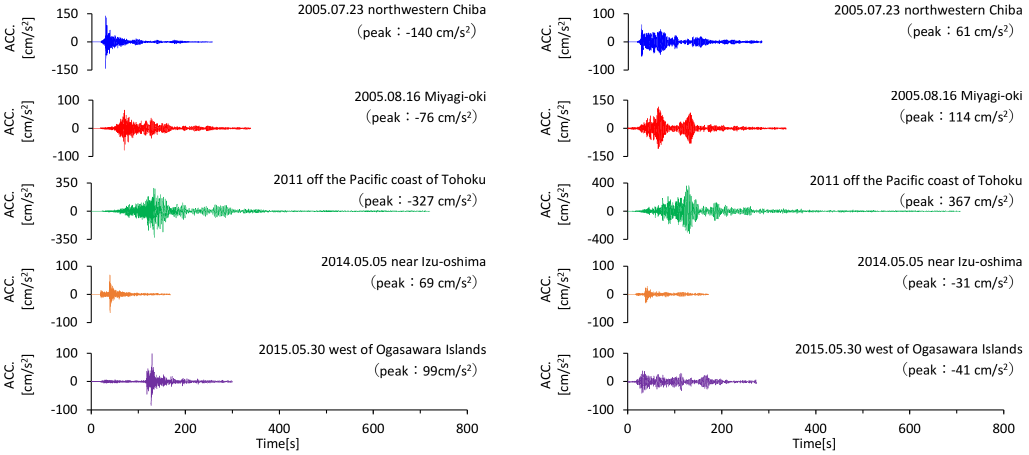
Fig. 2 – Profiles of buildings and locations of strong motion observation

3. Strong-motion Records

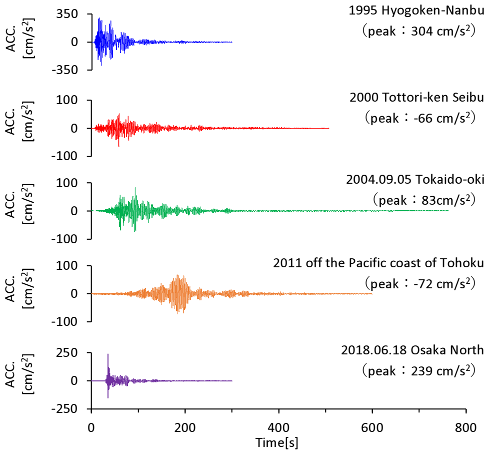
3.1 Accelerograms and response spectra

Fig. 3 shows the accelerograms obtained at the top floors of the three buildings during major earthquakes. The maximum values for buildings E and G (Kanto region) were recorded during the 2011 off the Pacific coast of Tohoku earthquake and those for building N (Kansai region) were recorded during the 1995 Hyogoken-Nanbu earthquake (measured peak acceleration: >300 cm/s^2).

Fig. 4 shows pseudo-velocity response spectra based on the ground surface records in the EW direction with a damping factor of h = 5%. For buildings E and G, the spectral amplitudes are 40-80 cm/s for the period range of 1-2 s, which is near the natural period, during the 2011 Tohoku earthquake. For building N, the spectral amplitudes are 80-120 cm/s for the period range of 1-2 s, which is near the natural period, during the 1995 Hyogoken-Nanbu earthquake.

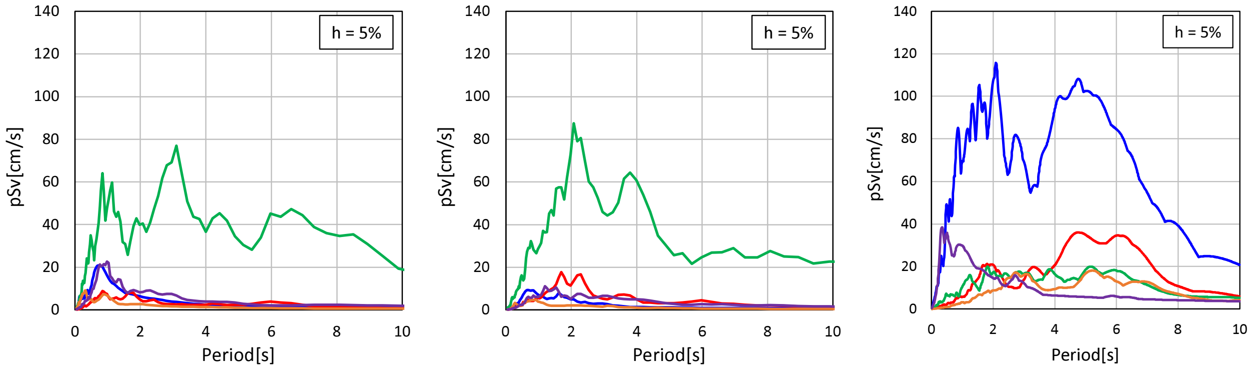


(a) building E (NS dir.)　　(b) building G (NS dir.)



(c) building N (EW dir.)

Fig. 3 – Accelerograms of recorded motions at top floors

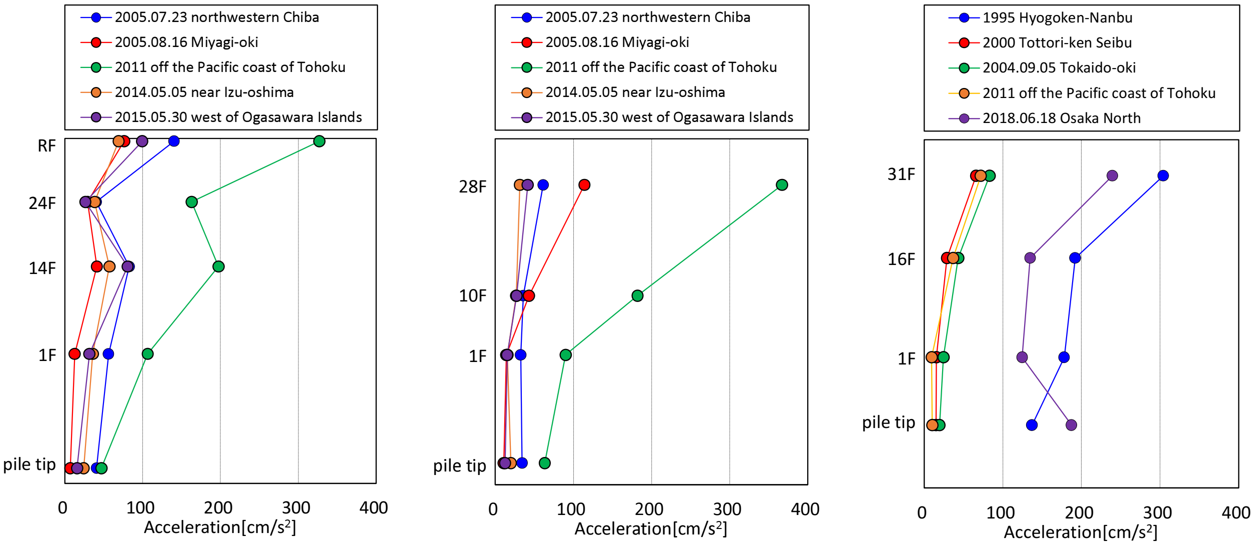


(a) building E (NS dir.)　　(b) building G (NS dir.)　　(c) building N (EW dir.)

Fig. 4 – Pseudo-velocity response spectra of recorded motions on the ground surface where colors of lines correspond to those in Fig. 3

3.2 Peak floor responses

The distributions of the peak floor accelerations are plotted in Fig. 5 for five earthquakes. Buildings G and N generally show first-mode vibration. For building E, for which seismograms were recorded at the level of the fourth floor, the effect of second-mode vibration can be seen. This indicates that the amplitude of the short-period components of ground motion was significant.



(a) building E (NS dir.) (b) building G (NS dir.) (c) building N (EW dir.)

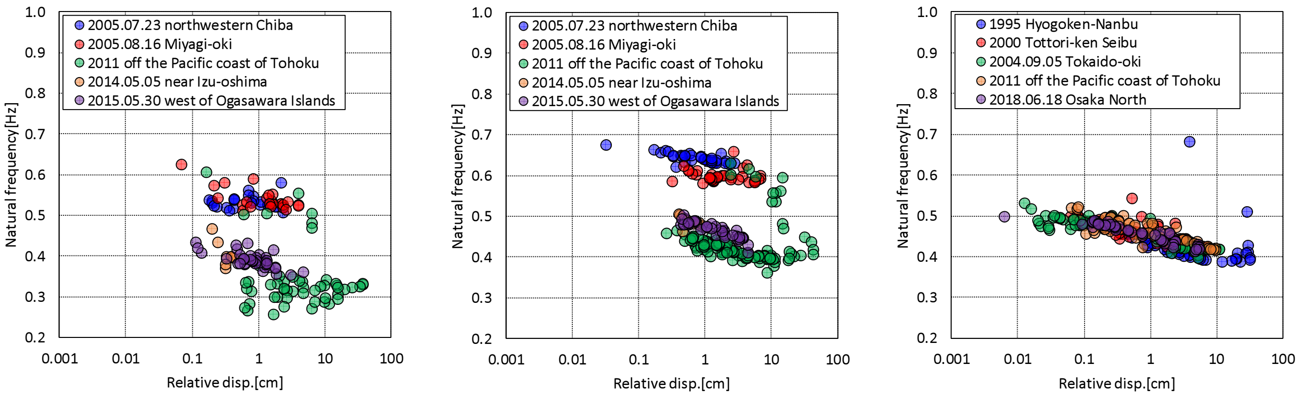
Fig. 5 – Peak floor responses

4. Temporal variation of dynamic characteristics

4.1 Temporal variation of natural frequencies and natural modes

The dynamic characteristics (i.e., natural frequencies) of super-high-rise RC buildings are known to vary according to the level of input earthquake excitation [2]. The temporal variation of the natural frequencies and natural modes of the RC buildings was investigated using motion recorded at several floor levels. The multivariable output-error state-space (MOESP) method was used to identify the dynamic characteristics of the buildings during an earthquake [4]. Motions recorded at the pile tips were used as input data. Motions recorded at the bases and upper floors of the buildings, including the top, were used as output data. Signals with a 10-s duration were used for system identification with multiple 5-s intervals.

Fig. 6 shows the variation of natural frequencies during major earthquakes observed at each building. The horizontal axis shows maximum relative displacement at the top from the pile tips within a 10-s duration. For buildings E and G, the natural frequencies drastically decreased during the 2011 Tohoku earthquake. For building N, the natural frequencies similarly decreased during the 1995 Hyogoken-Nanbu earthquake. The decrease in the natural frequencies was due to the nonlinear behavior of the upper floors of the buildings

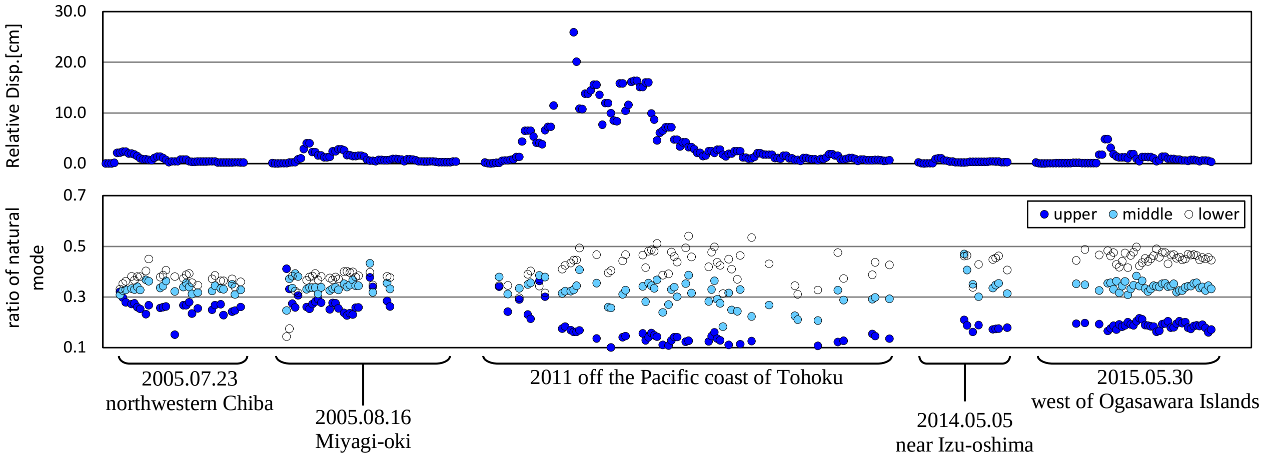


(a) building E (b) building G (c) building N

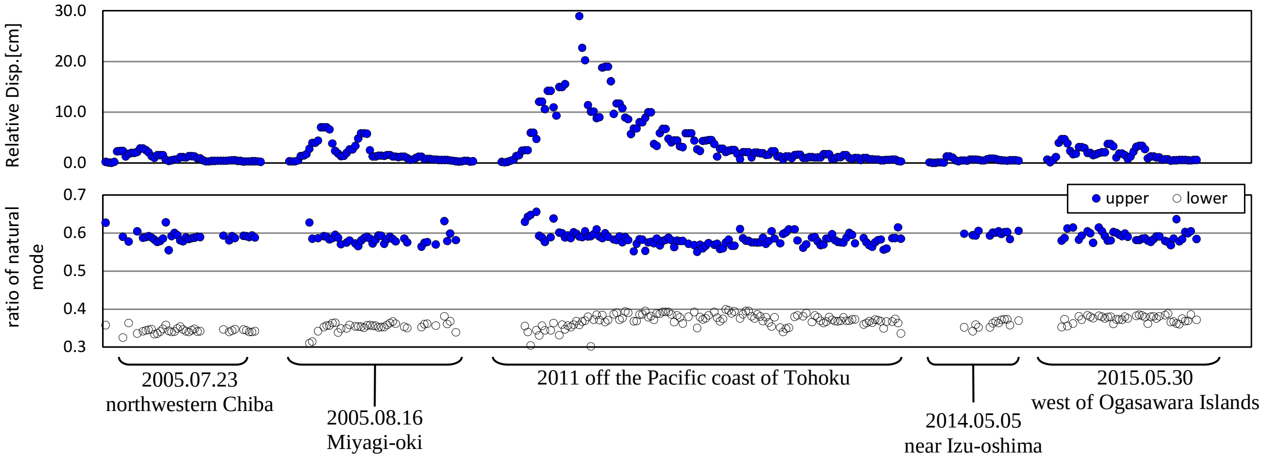
Fig. 6 – Variation of natural frequencies of buildings

(e.g., cracking of the structural members of the moment-resisting frame). The natural frequencies of each building decreased by about 20-30% when the relative displacement reached its peak. This result is consistent with a previous study [2].

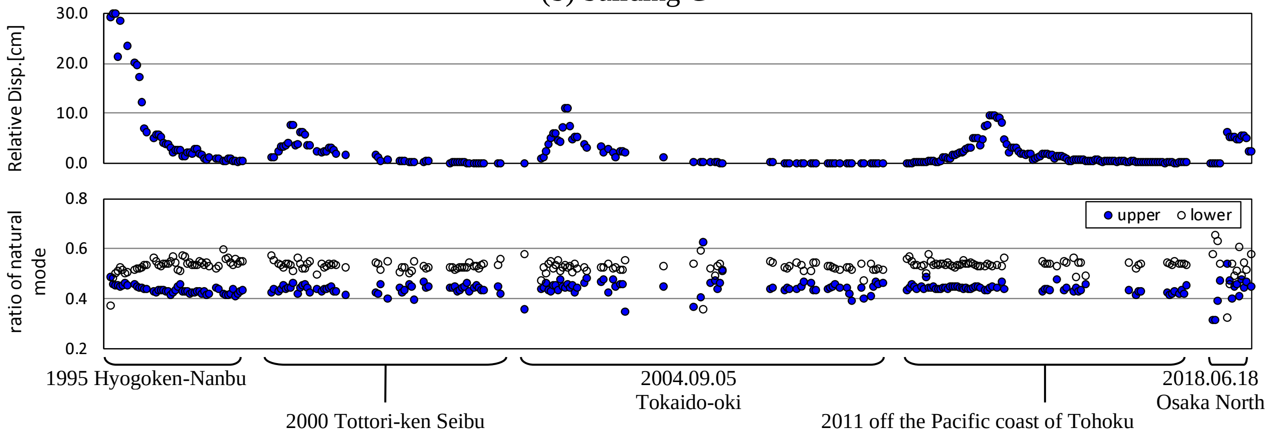
Fig. 7 shows the temporal variation of the relative displacement at the top and the natural mode ratios. The natural mode ratios are shown for each section (in the height direction) of the buildings. Each section was set at the top, bottom, or middle according to the arrangement of the sensors shown in Fig. 2. For each building, the ratio of the natural mode greatly changed when the relative displacement reached about 30 cm



(a) building E



(b) building G



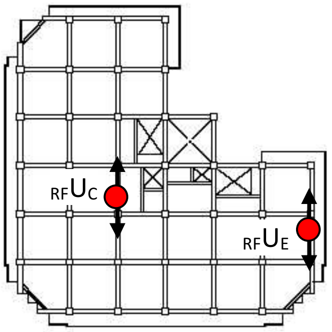
(c) building N

Fig. 7 – Temporary variation of natural mode ratio of buildings

on the top floor. The ratio of the lower section increased and that of the upper section decreased, which is considered to be affected by the degree of nonlinearity (e.g., that caused by the cracking of structural members in the building height direction). During earthquakes with a relatively small displacement, the variation of natural mode ratios was not distinct.

4.2 Variation of torsional response

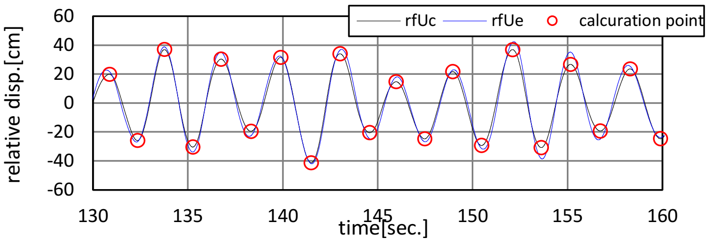
The torsional response of building E was calculated from the acceleration record for the top floor and the variation for each earthquake was investigated. Fig. 8 shows the definition of the torsional response rate [5, 6], which was calculated from the relative displacement between the center and the east side of RF (Fig. 8 (a)). The torsional response rate was calculated using a 0.5-Hz low-pass-filtered waveform. Fig. 8 (b) shows a part of the waveform of the relative displacement of the RF center and the RF east side subjected to the low-pass filter processing. The torsional response rate was calculated based on the time at which the phase matched among the peaks whose absolute values of the local maximum and minimum values were 0.1 cm or more, as indicated by red circles.



torsional response rate
= abs ($_{RF}U_E$ - $_{RF}U_C$) / abs ($_{RF}U_C$)

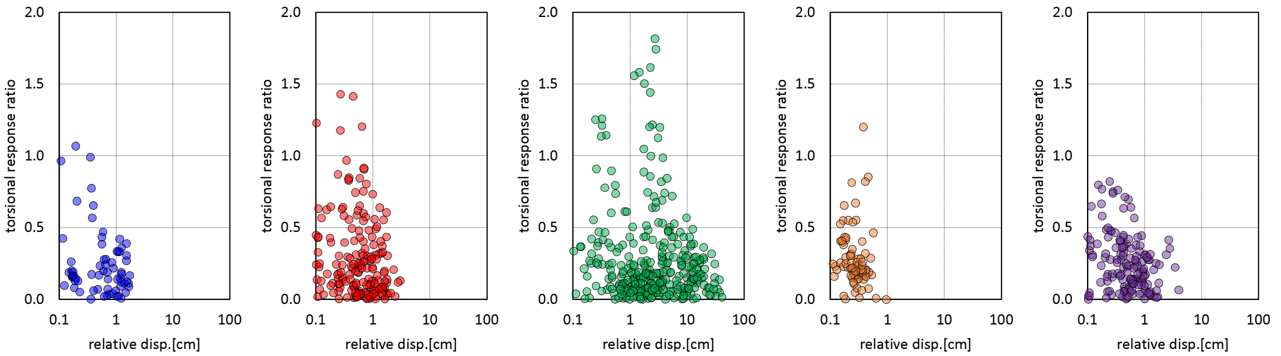
$_{RF}U_C$: relative displacement of RF center
$_{RF}U_E$: relative displacement of RF east side

(a) Torsional response rate



(b) Example of torsional response rate calculation

Fig. 8 – Definition of torsional response rate



(a) 2005.07.23 northwestern Chiba

(b) 2005.08.16 Miyagi-oki

(c) 2011 off the Pacific coast of Tohoku

(d) 2014.05.05 near Izu-oshima

(e) 2015.05.30 west of Ogasawara Islands

Fig. 9 – Variation of torsional response rate

Fig. 9 shows the variation of the torsional response rate. Because of the L-shaped plan of building E, a torsional response was induced; the values are mostly less than 0.5. In addition, the torsional response rate did not show a clear variation due to the change in building stiffness seen in the natural frequency and natural mode ratio, and the trend did not change after the 2011 off the Pacific coast of Tohoku earthquake, which induced the maximum relative displacement.

4.3 Variation of swaying and rocking ratios

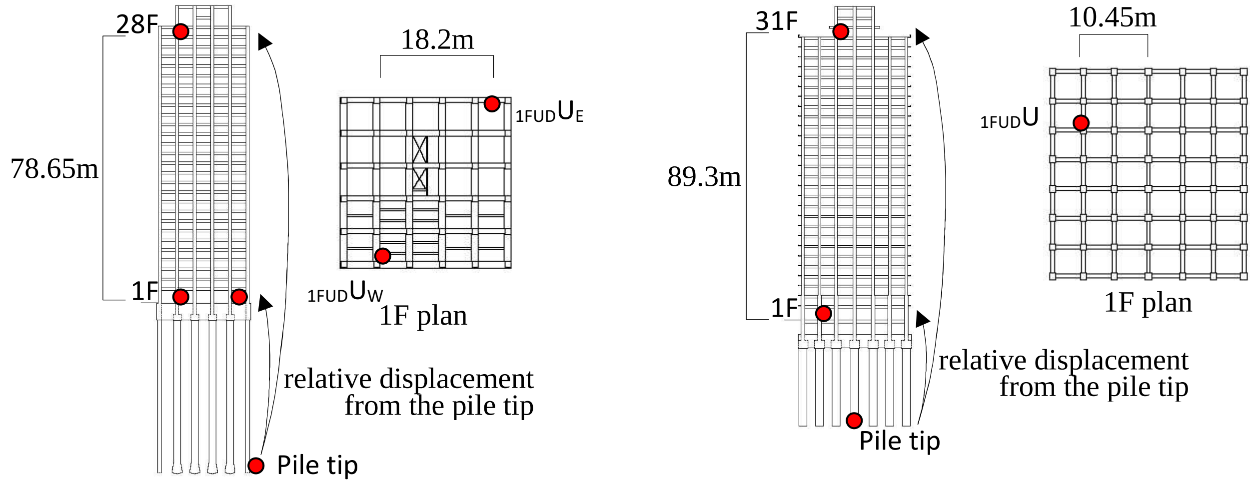
The swaying and rocking ratios due to soil-structure interaction were examined for buildings G and N. The sway deformation was obtained using the horizontal relative displacement of 1F from the pile tip. Fig. 10 shows the definition of the rocking ratio. The rocking deformation was calculated by multiplying the rotation angle calculated from one or two 1F vertical relative displacements from the pile tips by the building height. The swaying and rocking ratios were calculated using a 0.8-Hz low-pass-filtered waveform to extract the behavior of the translation first natural mode. Fig. 10 (c) shows a part of the waveform of the horizontal displacement of the top floor and the vertical displacement of 1F subjected to the low-pass filter processing. The ratio was calculated based on the time at which the phase matched among the peaks whose absolute values of the local maximum and minimum values were 2 cm or more, as indicated by red circles.

displacement by rocking
$= ({}_{1FUD}U_W - {}_{1FUD}U_E) / 18.2\ \text{m} \times 78.65\ \text{m}$

${}_{1FUD}U_W$: relative UD displacement of 1F west side
${}_{1FUD}U_E$: relative UD displacement of 1F east side

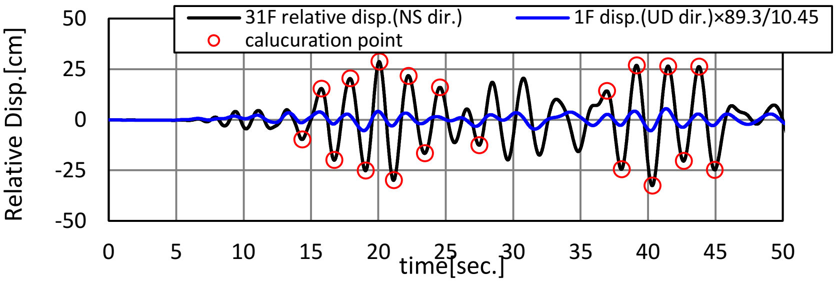
displacement by rocking
$= {}_{1FUD}U / 10.45\ \text{m} \times 89.3\ \text{m}$

${}_{1FUD}U$: relative UD displacement of 1F



(a) building G

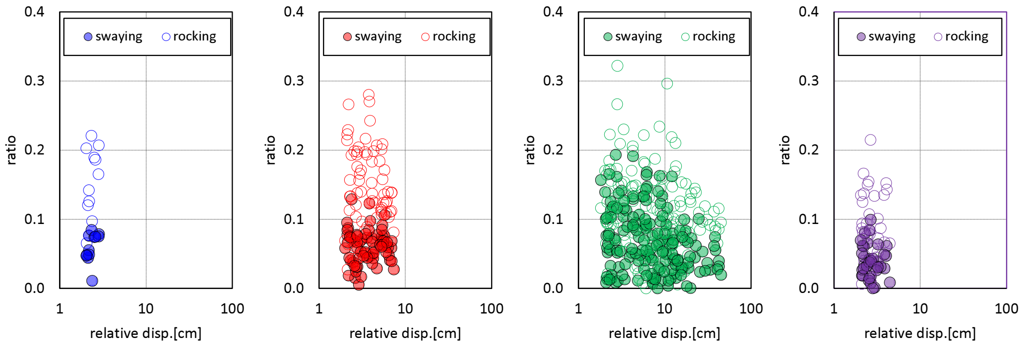
(b) building N



(c) Example of rocking ratio calculation

Fig. 10 – Definition of swaying and rocking ratio

Figs. 11 and 12 show the variation of swaying and rocking ratios for buildings G and N. For each building, the swaying ratio was about 10% or less and the rocking ratio was about 30% or less. Even after the 1995 Hyogoken-Nanbu earthquake and the 2011 off the Pacific coast of Tohoku earthquake, the general trend did not change. The nonlinearity of the pile and the deformation of the ground were not distinct.



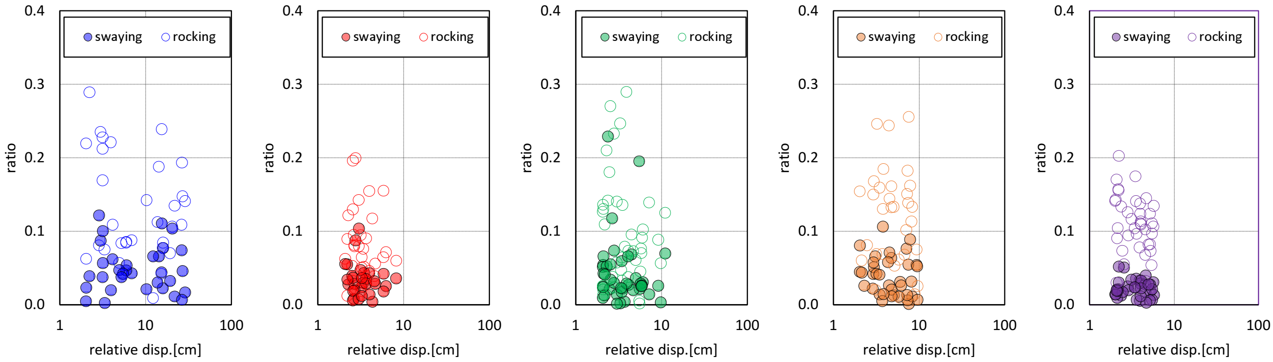
(a) 2005.07.23 northwestern Chiba

(b) 2005.08.16 Miyagi-oki

(c) 2011 off the Pacific coast of Tohoku

(d) 2015.05.30 west of Ogasawara Islands

Fig. 11 – Variation of swaying and rocking ratios (building G)



(a) 1995 Hyogoken-Nanbu

(b) 2000 Tottori-ken Seibu

(c) 2004.09.05 Tokaido-oki

(d) 2011 off the Pacific coast of Tohoku

(e) 2018.06.18 Osaka North

Fig. 12 – Variation of swaying and rocking ratios (building N)

5. Conclusions

The dynamic characteristics and long-term characteristic fluctuations for three high-rise RC buildings equipped with seismic observation systems were investigated using long-term seismic records. The natural frequencies decreased significantly in the Kanto region buildings during the 2011 off the Pacific coast of Tohoku earthquake and in the Kansai region building during the 1995 Hyogoken-Nanbu earthquake. The decrease in the natural frequencies was due to nonlinear behavior, such as that caused by the cracking of the structural members of the moment-resisting frame. The natural frequencies of each building decreased by about 20-30% when the relative displacement reached its peak. The natural mode ratio for each section (in the height direction) changed significantly when a relative displacement of about 30 cm occurred on the top floor. The ratio of the lower section increased and that of the upper section decreased, which is considered to be affected by the degree of nonlinearity (e.g., that caused by the cracking of structural members in the building height direction). A torsional response was generated in the L-shaped building; however, the calculated torsional response did not show a clear variation due to the change in building stiffness seen in the natural frequency and natural mode ratio. The swaying ratio was about 10% or less and the rocking ratio was about 30% or less. Even after earthquakes with large amplitudes, the general trend did not change, and the nonlinearity of the pile and the deformation of the ground were not distinct.

AKCNOWLEDGMENT

The seismic observation records used in this study were obtained through joint observation with the Urban Renaissance Agency. The system identification tool developed by Mr. Takenori Hida, the University of Tokyo, was used. Some of the figures in this paper were created using the software GMT version 5 (Wessel and Smith, 1998).

REFERENCES

[1] Nagano M., Hida T., Watanabe K., Tanuma T., Nakamura M., Ikawa N., Yasui M., Sakai S., Morishita T., Kawashima M. (2012): Dynamic Characteristics of Super High-Rise Residential Buildings in Kanto and Kansai Areas Based on Strong Motion Records during The 2011 Off The Pacific Coast of Tohoku Earthquake, *Journal of Japan Association for Earthquake Engineering*, Japan Association for Earthquake Engineering, Vol. 12, No.4 (Special Issue), 65-79. (in Japanese)

[2] Morishita T., Saito Y., Ryujin H., Tanuma T., Watanabe K. (2014): Dynamic Properties for the Super-high-rise RC Structure Buildings Based on Long Term Earthquake Records, *AIJ Journal of Technology and Design*, Architectural Institute of Japan, Vol. 20, No.45, 527-532. (in Japanese)

[3] Yamamoto T., Yasui M., Nagano M., Hida T., Tanuma T. (2016): Replication of Seismic Response of High-Rise Residential Building During the 2011 Off the Pacific Coast of Tohoku Earthquake Based on Simulation Analyses Considering Dynamic Soil-Structure Interaction, *Journal of Japan Association for Earthquake Engineering*, Japan Association for Earthquake Engineering, Vol. 16, No.8, 75-81. (in Japanese)

[4] Hida T., Nagano M. (2014): Estimation Accuracy of Natural Frequency and Damping Factor of Building by System Identification Based on Three Subspace Methods, *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, Vol. 79, No.701, 923-932. (in Japanese)

[5] Yamazaki Y. (1986): Lateral Torsional Response of Buildings during Earthquake, *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, No.369, 31-41. (in Japanese)

[6] Tobita Y., Nagano M., Kitamura H., Sato T., Suzuki K., Matsuda Y., Yamauchi T. (2017): Study on Torsional Response of Seismically Isolated Building on Soil with Inclined Bedrock using Strong Motion Records, *AIJ Journal of Technology and Design*, Architectural Institute of Japan, Vol. 23, No.54, 409-414. (in Japanese)