LONG-TERM SEISMIC MONITORING OF MIDDLE-RISE SRC BUILDINGS

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Abstract

The Building Research Institute (BRI) of Japan operates a strong motion network consisting of over 80 observation stations in major cities across Japan. One of the stations is in the BRI site in Tsukuba, Japan, and two office buildings and the surrounding ground are the targets of monitoring. One building is a 7-storey steel-framed reinforced concrete (SRC) building constructed in 1979 and called the main building. The other is an 8-storey SRC building built in 1998 and called the annex building. The seismic monitoring started in 1998 just after the completion of the annex building. Four acceleration sensors are placed in the main building, 11 sensors in the annex building, and 7 sensors in the ground. Nearly 1800 sets of strong motion data have been accumulated to date. Various findings on the dynamic characteristics of the buildings and ground have been obtained through the analysis using the numerous strong motion data from this instrumentation.

The fundamental natural frequencies of the annex building gradually decreased for 7 years after the completion. The natural frequencies in both the horizontal directions were about 1.8 Hz in 1998 and decreased to about 1.4 Hz in 2005. Thereafter, the decrease in natural frequencies halted until 2011. The natural frequencies of the main building were stable from 1998 to 2011. The 2011 Great East Japan (Tohoku) Earthquake caused slight damage to both buildings. As a result, the natural frequencies of the annex building decreased to about 1 Hz. The natural frequencies of the main building also decreased from 1.6 Hz to 1.2 Hz in the Y-direction, and from 2.3 Hz to 1.6 Hz in the X-direction. Although the damping ratios of both the buildings widely varied throughout the observation period, the values after the 2011 Tohoku Earthquake were bigger than those before the earthquake.

The dynamic soil-structure interaction is one of the key issues to discuss the seismic response of building structures. The optimization analysis of the dynamic parameters of the annex building was conducted using a simplified rocking-building mode,. Through the analysis, it was confirmed that the decrease in the natural frequencies was caused by the decrease in the stiffnesses of the superstructure.

The amplitude-dependence of the natural frequencies in the two buildings was minutely discussed as well. Although the amplitude dependence of the natural frequencies of the buildings was not remarkable, it showed different trends before and after the 2011 Tohoku earthquake. The cause of the difference is examined from the analysis of strong motion observation records. As a result, the change of the structural characteristics could be considered as the main cause of the difference.

The paper concludes that the seismic monitoring with the densely equipped instrument for over 20 years has provided new and precious findings on the dynamic behaviour of the ground and buildings.

Keywords: Strong motion observation; structural health monitoring, soil-structure interaction

1. Introduction

The Building Research Institute (BRI) of Japan is a national institute engaged in research and development in the fields of architecture, building engineering, and urban planning. As one of its research activities, the BRI operates a strong motion network that covers buildings in major cities across Japan.

As one of the BRI strong motion stations, the main building and annex building of BRI were densely equipped with accelerometers. In the past two decades, many researchers have obtained various findings from diverse viewpoints using the strong motion data recorded at this station. This paper reviews the transition of the dynamic characteristics of two BRI buildings considering the soil-structure interaction effect.

2. Outline of buildings

BRI is situated in Tsukuba City, approximately 60 km north-northwest of Tokyo. BRI has two office buildings consisting of the main building, a 7-storey steel-framed reinforced concrete (SRC) structure completed in 1979, and the annex building, an 8-storey SRC structure built in 1998 that is connected to the main building by a passageway having expansion joints. Each building is supported by a spread foundation at a depth of about 8 m. The building features are summarised in Table 1, and the external appearance of the buildings is shown in Fig. 1.

Table 1 Outline of BRI buildings

Building	Main building	Annex building
Year of completion	1979	1998
Number of floors	7 with 1 basement	8 with 1 basement
Structure	SRC	SRC
Foundation	Spread	Spread
Building area	3,403 m^2	637 m^2
Total floor area	13,467 m^2	5,050 m^2

Fig. 1 – BRI main building (right) and annex building (left)

3. Strong Motion Instrumentation

Strong motion recording in the BRI buildings was started in 1998 [1, 2]. The strong motion instrumentation comprises four sensors in the main building and eleven sensors in the annex building. The sensor configuration is illustrated in Fig. 2. In addition, seven sensors are installed in the surrounding ground. A sensor labelled GL(A01) is set 1 m deep in the ground at a distance of 20 m from the annex building. The installation azimuths of all sensors are N180°E (180° clockwise from the north) and N270°E, being along the building axis. Hereinafter, the N180°E and N270°E directions are referred to as the Y- and X-directions, respectively.
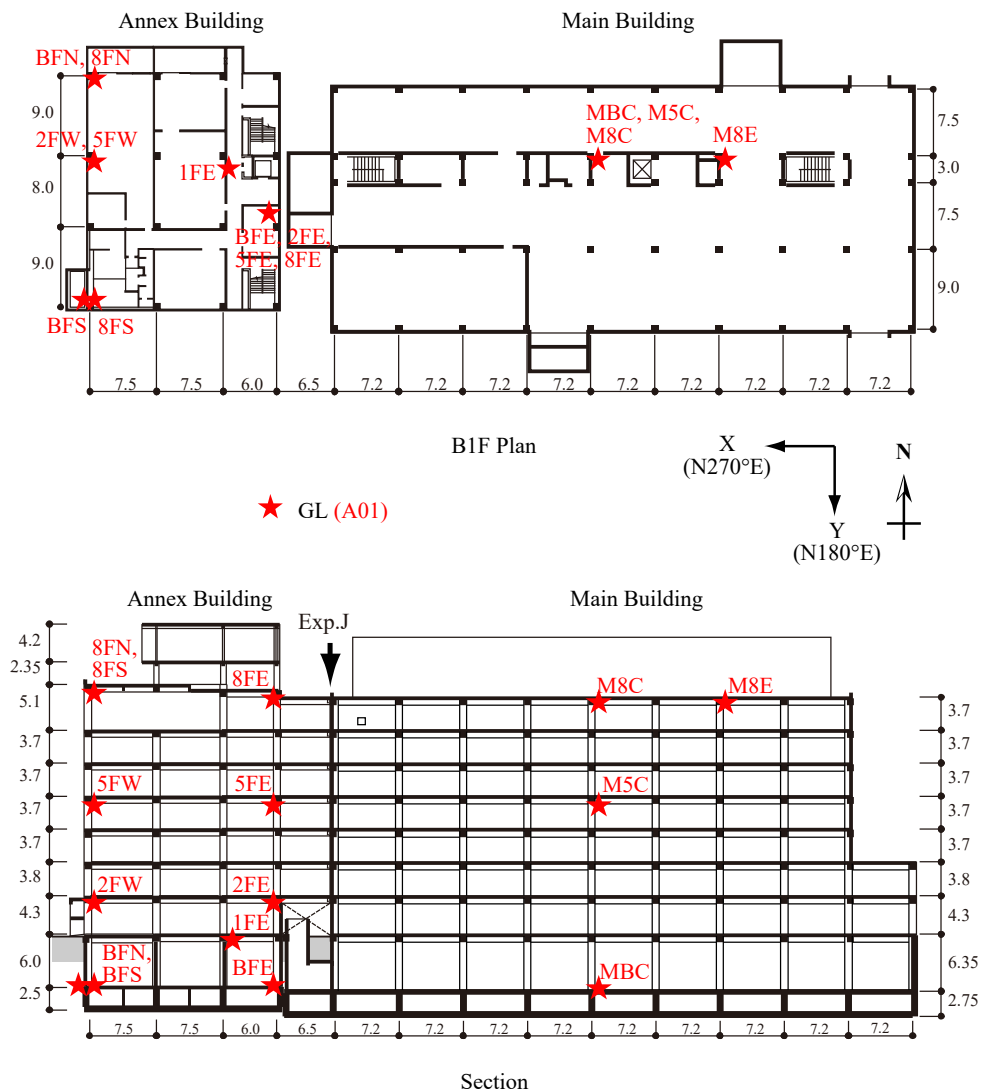
Fig. 2 – Sensor configuration in the main and annex buildings

4. Strong Motion Records

Nearly 1800 sets of strong motion data have been accumulated to date. Epicentres of recorded earthquakes are plotted in Fig. 2.

　　The severest ground motion was obtained during the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011. The earthquake, hereinafter referred to as the Tohoku earthquake, with a moment magnitude (Mw) of 9.0 caused a monstrous tsunami and massive damage to eastern Japan. Seventy-nine stations of the BRI strong motion network were running at the time of the earthquake. Among them, 61 stations

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were triggered [3]. Although the epicentre was 330 km away, the BRI buildings suffered some structural damage [4]. Restoration work on both buildings was carried out in 2012. Cracks on the concrete walls and slabs were filled with epoxy resin and splits on the partitioned walls were repaired.
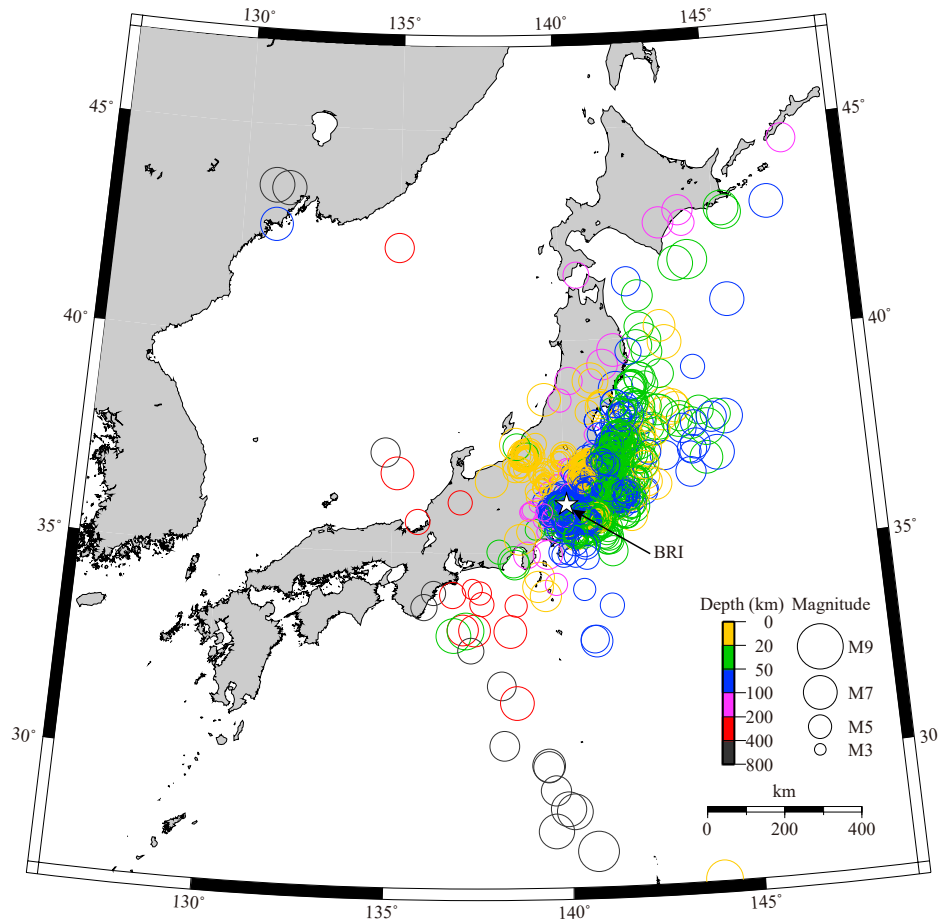

Fig. 3 – Epicentres of recorded earthquakes

5. Transition of the Dynamic Characteristics of the Buildings

The fundamental natural frequencies and damping ratios of both buildings were estimated using the acceleration data having Japan Meteorological Agency (JMA) seismic intensity scales are 2 and higher. As the fundamental frequency and damping ratio, a frequency, and a damping ratio of a single-degree-of-freedom system that can simulate an actual response having the best fitness were determined using the grid search method [5]. Figure 4 illustrates the change in natural frequencies and damping ratios in the horizontal directions of both buildings for more than 20 years from the start of monitoring. The upper (a) and lower (b) plots represent the main building and annex building, respectively. Red circles (○) and blue triangles (△) indicate the values in the Y- and X-directions, respectively.

In the case of the main building, the natural frequencies in both horizontal directions were generally stable until the time of the Tohoku Earthquake. The natural frequencies in the Y- and X-directions before the Tohoku Earthquake were 1.6 Hz and 2.3 Hz on average, respectively. The damage by the earthquake reduced the natural frequencies to about two-thirds. The damping ratios in the Y- and X-directions were about 2 % and 4 % before the Tohoku Earthquake, respectively. The damping ratios of the main building after the Tohoku Earthquake have not changed significantly.

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The natural frequencies in both horizontal directions of the annex building gradually decreased from 1.8 Hz to 1.4 Hz during the first seven years. The cause of the decrease is not clear, but the natural frequencies seemed to be stable for the next six years. The natural frequencies dropped to about 1 Hz due to the damage by the Tohoku Earthquake, and have not yet been recovered. Compared with the main building, the annex building has a significant variation in the damping ratios.
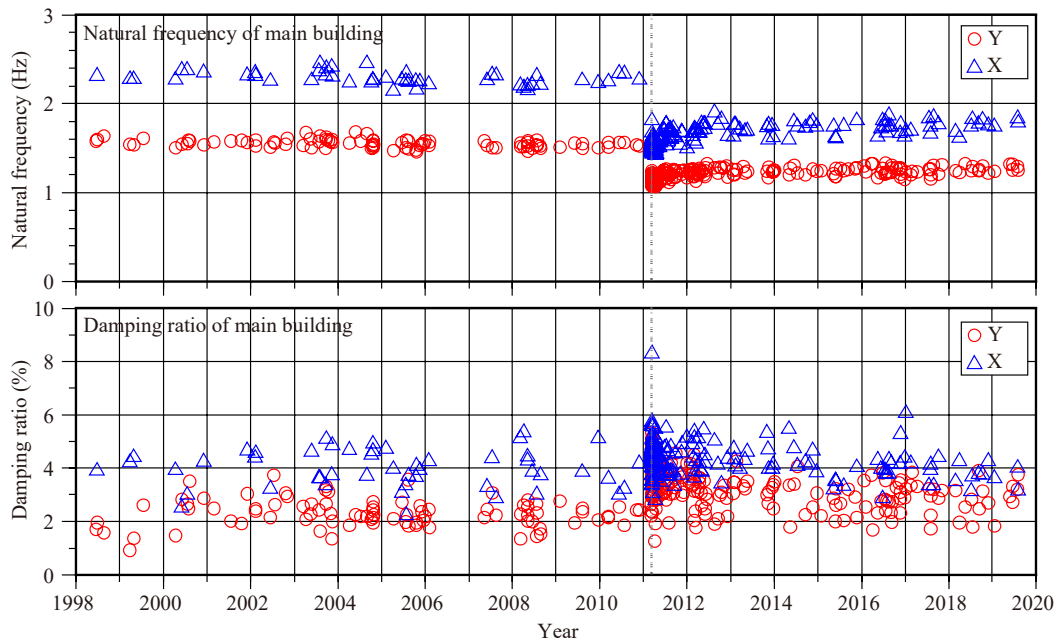
(a) Main building
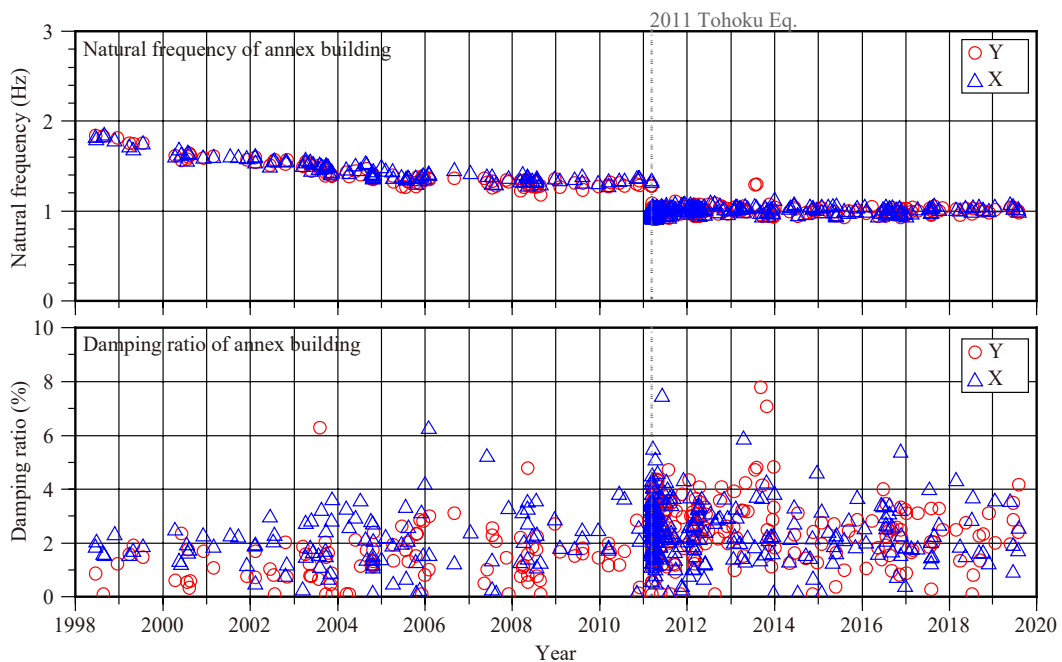
(b) Annex building

Fig. 4 – Change in natural frequency and damping ratio of the main and annex buildings with time

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In order to discuss the amplitude-dependence of the dynamic characteristics, the maximum displacement angle $\theta_{\max}$ defined by Eq. (1) is adopted to represent the seismic response amplitude.

$$\theta_{max} = |x_{\mathrm{T}}(t) - x_{\mathrm{F}}(t)|_{max}/H \tag{1}$$

where, $x_{\mathrm{T}}(t)$ and $x_{\mathrm{F}}(t)$ are the time histories of the displacements on the eighth and basement floors, respectively (see Fig. 7), and H is the height of the eighth floor from the first floor level.

The relation of the natural frequency and damping ratio to the maximum displacement angle $\theta_{\max}$ of the main building is plotted in Fig. 5. In the figure, (a) and (b) indicate the results in the Y- and X-directions, respectively. In each of (a) and (b), the upper and lower plots correspond to the natural frequency and damping ratio, respectively. In all the plots, red, pale red and white circles (●, ◉ and ○) indicate values before, during, and after the Tohoku Earthquake. For values during the Tohoku Earthquake, the system identification was made for every 20 seconds. The natural frequencies in the Y- and X-directions of the main building were about 1.6 Hz and 2.2 Hz in the small amplitude range, respectively. Structural damage by the Tohoku Earthquake reduced the natural frequencies of the main building to 1.2 Hz and 1.6 Hz. The natural frequencies before the Tohoku Earthquake are stable and the amplitude dependence can be recognised slightly. The natural frequencies after the earthquake vary, especially in the X-direction. The damping ratios in the Y-directions are generally between 2% and 4%. The damping ratios in the X-direction are larger than those in the Y-direction and distributed between 3% and 6%. Generally, the damping ratios after the Tohoku Earthquake are slightly larger than before the earthquake. In addition, damping ratios tend to increase as the response amplitude increase.
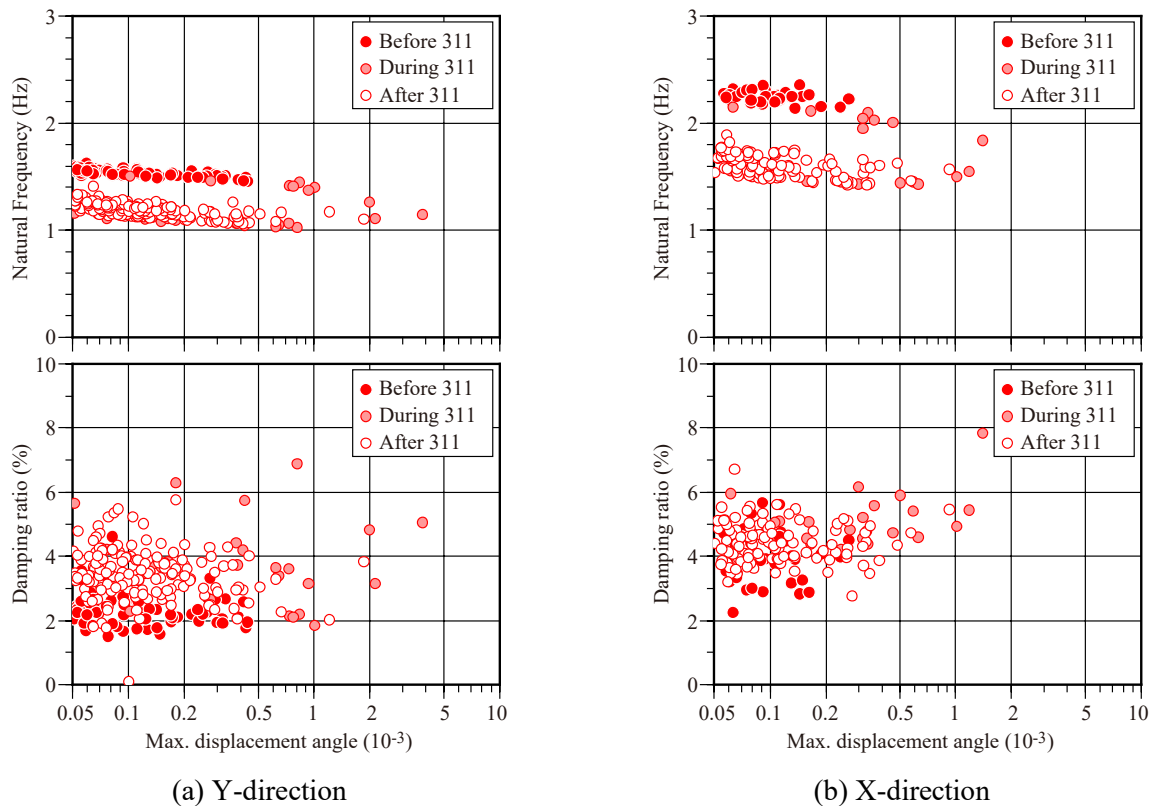

(a) Y-direction

(b) X-direction

Fig. 5 – Relations of natural frequency and damping ratio to maximum displacement angle ($\theta_{\max}$) of main building

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The relations of the natural frequency and damping ratio to the maximum displacement angle θ_{max} of the annex building is plotted in Fig. 6. The arrangement of the plots and the meaning of the symbols are the same as in Fig. 5. The natural frequencies in the X- and Y-directions are close and were distributed between 1.2 Hz and 1.8 Hz before the Tohoku Earthquake. The cause of the fluctuation is thought to be a decrease in the natural frequencies for seven years after the completion as shown in Fig. 4. After the Tohoku Earthquake, the natural frequencies in both directions dropped to about 1.0 Hz, and the variation became very small. Although the damping ratios vary widely, there is a tendency for the damping ratio to increase after the Tohoku Earthquake and to increase as the response amplitude increases.
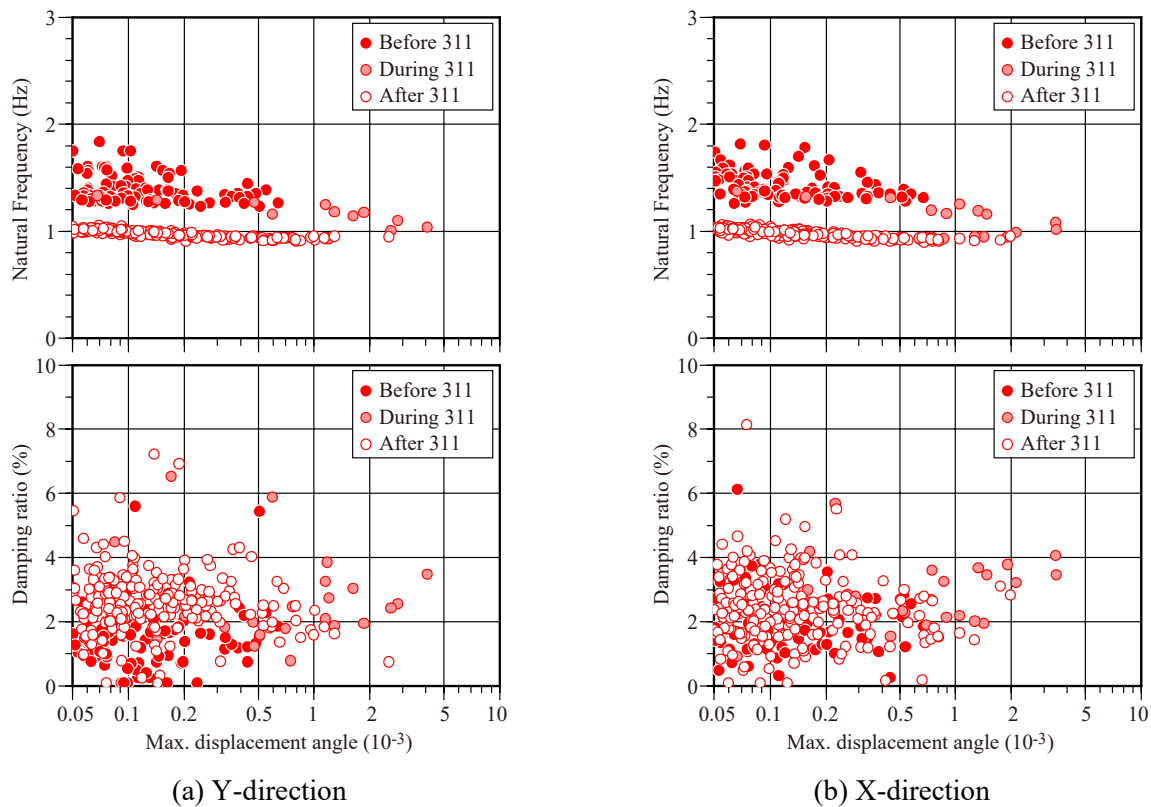

(a) Y-direction   (b) X-direction

Fig. 6 – Relations of natural frequency and damping ratio to maximum displacement angle (θ_{max}) of the annex building

5. Effect of Soil-structure Interaction

Soil-structure interaction is one of the key issues to discuss the seismic response of buildings. The actual phenomenon of the annex building considering the soil-structure interaction effect is investigated using strong motion data in this chapter. The effect of the soil-structure interaction is often represented as the horizontal and rotation movements of a foundation. Since it is known that the horizontal translation of the annex building to be small [2], only the rotational movement is dealt with herein. A simple model having a spring and a damper of rocking (rotation) between the ground and foundation is illustrated in Fig. 7. The superstructure is modelled as an equivalent single-degree-of-freedom system. In this model, strong motion data at four measuring points (z_L, z_R, x_F and x_T) enable to separate the total displacement at the top floor into those caused by rocking (u_R), and building deformation (u_B) as shown in Eqs. (2) and (3). Based on this model, stiffnesses of the rocking and building (k_R and k_B) and damping coefficients of those (c_R and c_B) are identified from the strong motion data. To identify the parameters, the Evolution Strategies (ES) is adopted as an optimization algorithm. The ES algorithm, which simulates natural evolution, can be a powerful algorithm in nonlinear optimization [6].

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The targets of the optimization are four parameters, k_R, k_B, c_R and c_B, and the fitness of the simulation is evaluated from the difference of displacements, u_R and u_B, to the observed ones.

$$u_R = (z_L - z_R)H/W \tag{2}$$
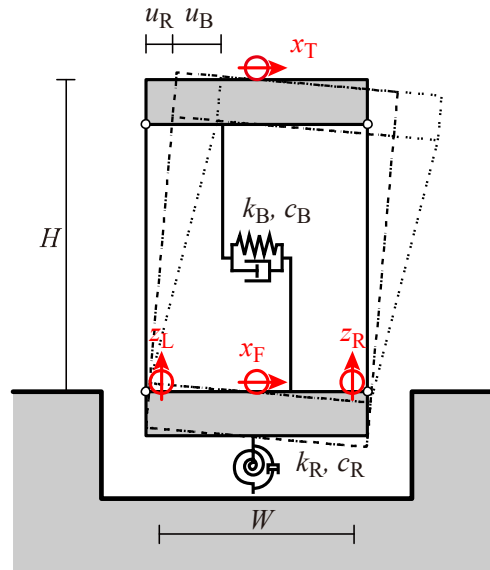
$$u_B = x_T - x_F - u_R \tag{3}$$

Fig. 7 – Rocking-building model

The parameter identification of the rocking-building model focuses on the Y-direction of the annex building using strong motion data having the maximum relative displacement ($u_R + u_B$) of 2.5 mm and larger. The optimised parameters are plotted in Fig.8 as a relation to time. In Fig.8(a), red circles and blue triangles correspond to the natural frequencies of the rocking-building model (f_{RB}) and building (f_B), respectively. The natural frequencies are calculated from the optimized stiffnesses k_R and k_B. Fig.8(b) and (c) show the stiffnesses of the rocking and building (k_R and k_B), respectively. Fig.8(d) and (e) show the damping coefficients of the rocking and building (c_R and c_B), respectively. The natural frequency ratio of the rocking-building model to the building model (f_{RB}/f_B) is plotted in Fig.8(f). The rocking ratio r_R is given by $r_R = u_R/(u_R + u_B)$ is shown in Fig.8(g).

The rocking stiffness k_R can be considered as a constant value throughout the monitoring period, although there is some variation. The building stiffness k_B gradually decreased for seven years after the completion, and notably dropped by the Tohoku Earthquake. There has been no significant change in the building stiffness since the Tohoku Earthquake.

The rocking damping coefficient c_R varies greatly but does not seem to change significantly over the monitoring period. The variation in the damping coefficient of the building is smaller than that of the rocking, and there is no change during the monitoring period as well.

The natural frequency ratio (f_{RB}/f_B) increased from 0.93 to 0.97 in the first seven years and is around 0.98 after the Tohoku Earthquake. The rocking ratio r_R decreased from 0.1 to 0.07 in the first seven years and is around 0.04 after the earthquake. Both parameters indicate that the effects of the soil-structure interaction became smaller.
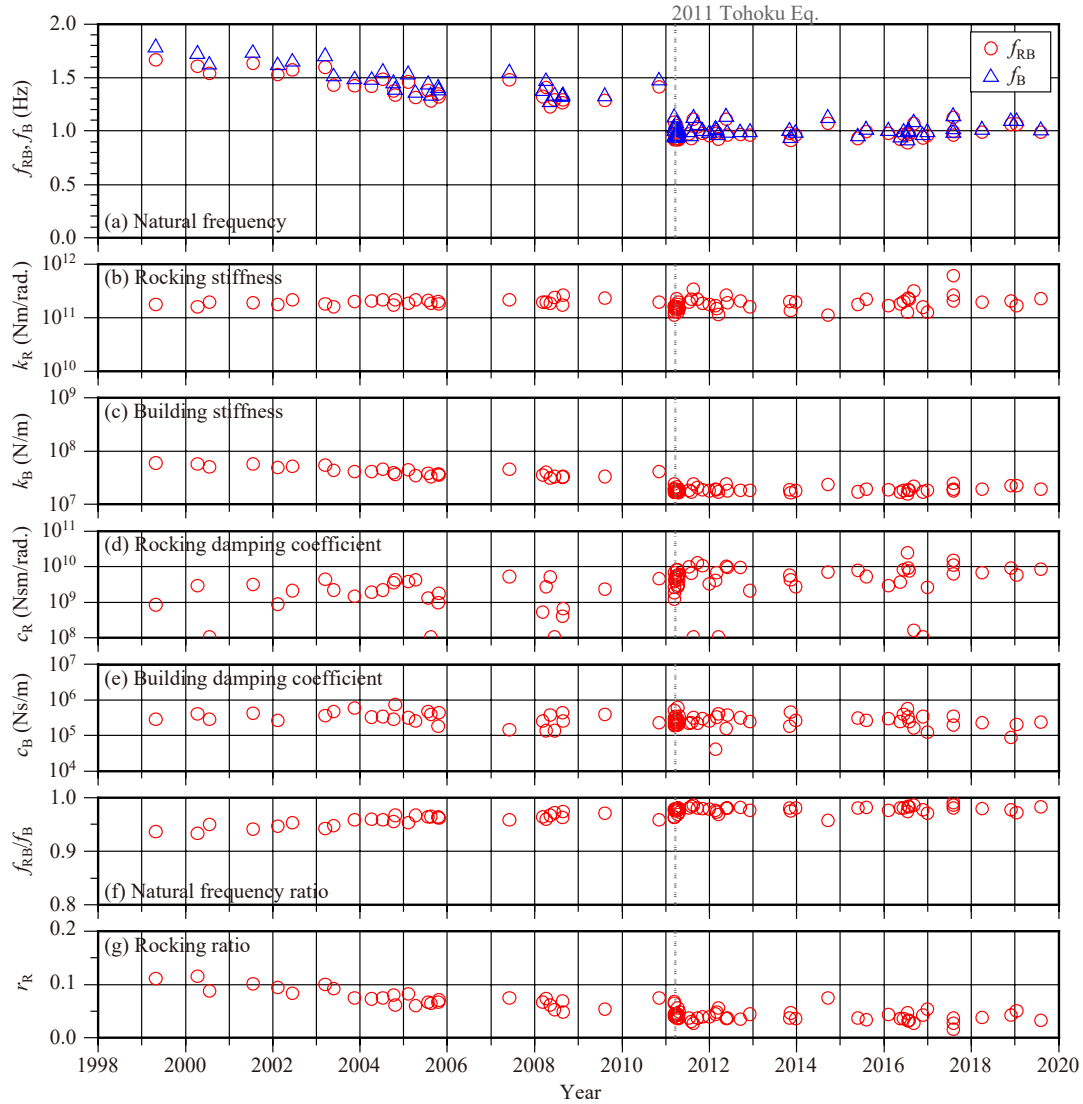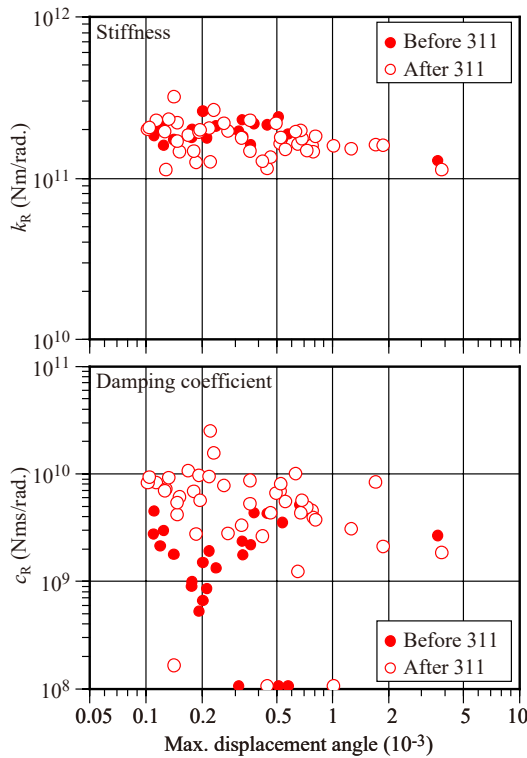
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Fig. 8 – Change in natural frequencies (f_{RB}, f_B), stiffnesses (k_R, k_B), damping coefficients (c_R, c_B), natural frequency ratio (f_{RB}/f_B), and rocking ratio (r_R) with time

Fig. 9 shows the relations of the stiffness and damping coefficient to the maximum displacement angle. Fig. 10 shows the relations of the natural frequency ratio and displacement ratio to the maximum displacement angle. Solid and hollow circles (● and ○) in both figures indicate the values before and after the Tohoku Earthquake, respectively.

The rocking stiffness k_R varies somewhat and appears to decrease with increasing amplitude. The relation between the building stiffness k_B and maximum displacement angle θ_{max} is similar to the relation between the natural frequency and the maximum displacement angle shown in Fig. 6(a). The changes in the building stiffness before and after the Tohoku Earthquake are apparent.

The damping coefficients c_R and c_B widely vary, and there is no change due to the response amplitude. The natural frequency ratio (f_{RB}/f_B) ranges from 0.93 to 0.97 before the Tohoku Earthquake. On the other hand, the natural frequency ratio after the Tohoku Earthquake is stable at an average of about 0.98. The rocking ratio (r_R) before the Tohoku Earthquake varies widely between 0.06 and 0.12. The rocking ratio after the Tohoku Earthquake is about 0.04 on average, and there is some amplitude dependence. From the above results, it can be concluded that the decrease in natural frequency for several years after the completion and due to the Tohoku Earthquake was caused by the decrease in the building stiffness.
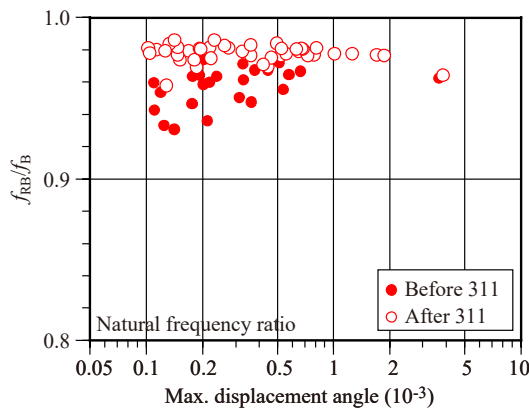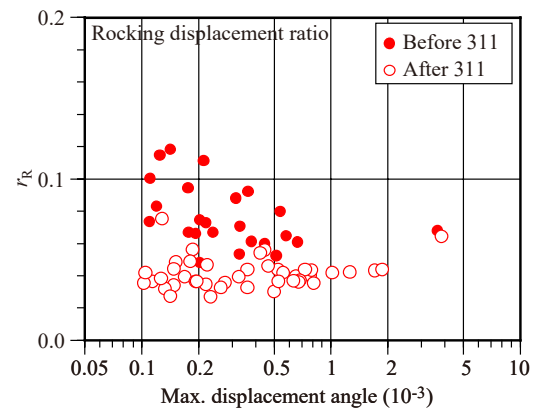
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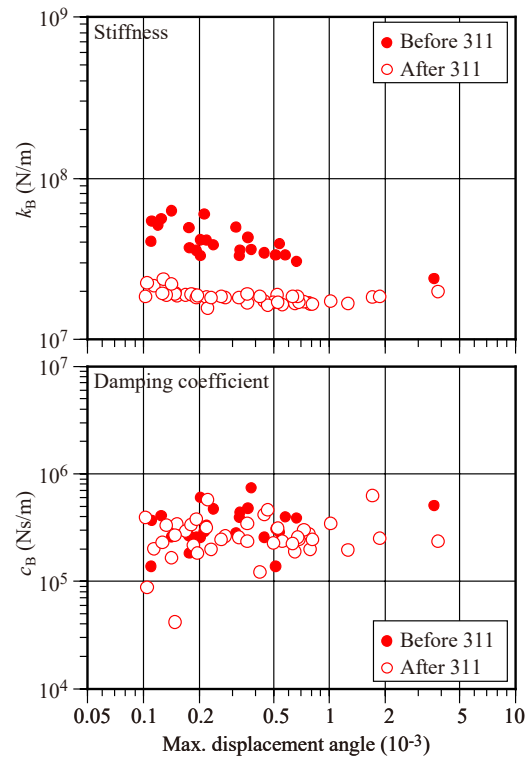
(a) Rocking (b) Building

Fig. 9 – Relations of stiffnesses (k_R, k_B) and damping coefficients(c_R, c_B) to maximum displacement angle (θ_{max})

(a) Rocking (b) Building

Fig. 10 – Relations of natural frequency ratio (f_{RB}/f_B), and rocking ratio (r_R) to maximum displacement angle (θ_{max})

6. Conclusions

The long-term seismic monitoring of the two buildings provided useful findings. The natural frequencies of the annex building were gradually decreased for seven years after the completion. Thereafter, the natural frequencies stopped decreasing. Although the cause is unclear, such phenomena should be kept in mind.

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The 2011 Tohoku Earthquake caused some structural damage to both buildings and reduced those stiffnesses. As a result, the natural frequencies of the buildings dropped to about two-thirds. It can be pointed out that the stiffness of a building is considerably reduced due to the extent of damage that the structural members are cracked. Damping ratios of damaged buildings often increase slightly.

The amplitude dependence of the dynamic characteristics is an interesting phenomenon. In general, as the response amplitude increases, the natural frequency decreases. The degree of reduction depends on the structure. On the other hand, the damping ratio may increase or decrease as the amplitude increases. In the case of the BRI buildings, the damping ratios seem to increase slightly with the increase of the response amplitude.

The findings obtained above are considered useful for improving the accuracy of seismic structural health monitoring of buildings.

7. References

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