Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1187

DYNAMIC BEHAVIOR OF HACHINOHE CITY HALL BUILDINGS EXAMINED BASED ON STRONG-MOTION DATA

T. Kashima[1]

ABSTRACT

The Building Research Institute (BRI) of Japan operates its nationwide strong-motion network in Japan. Currently, we run more than 70 strong-motion stations deployed in major cities throughout Japan.

The Hachinohe City Hall is one of the stations in the BRI network. Known as one of the most earthquake-prone areas, Hachinohe City is located in the northern portion of the largest one (Honshu) of main islands of Japan. Actually, the city has suffered disastrous earthquakes several times. In consideration of such a situation, we installed two sensors on the top and basement floors of the main building of the Hachinohe City Hall in 1993. The five-story main building, which is made of steel-framed reinforced concrete (SRC), was slightly damaged by the 1994 Far Off Sanriku Earthquake. Strong-motion data recorded in the building clearly showed a change in dynamic characteristic during strong shaking.

In addition, BRI installed three sensors in the annex building and three borehole sensors in the ground in 1999. The ten-story annex building adjacent to the main building is made of SRC and equipped with a base-isolation system. Two sensors are placed on the upper and lower sides of the base-isolated story, and another is located on the top floor of the annex building. Borehole sensors are set up at the underground sites of 1 meter, 30 meters and 105 meters in depth.

A number of strong-motion records have been collected from the Hachinohe City Hall station. Among recent records, the most remarkable is one obtained from the earthquake on the Northern Coast of Iwate Prefecture of July 24, 2008, with a magnitude of 6.8. 0.78 g of peak ground acceleration was observed on the ground surface. The effects of the base-isolation system were examined through the analysis of the strong-motion records.

Introduction

The Building Research Institute (BRI) of Japan is a national research institute specialized in the field of architecture, building engineering, and urban planning. Seismic safety of buildings

---

[1] Senior Research Engineer, International Institute of Seismology and Earthquake Engineering (IISEE), Building Research Institute, Tsukuba, 305-0802, Japan

and houses is one of the most important research targets. BRI operates a nationwide strong-motion network as one of its research activities. Most of the targets of instrumentation are building structures. Currently, we manage more than 70 strong-motion stations deployed in major cities throughout Japan.

The Hachinohe City Hall, one of the stations in the BRI strong-motion network, has brought valuable strong-motion records so far. The Hachinohe station has eight acceleration sensors set up in two buildings and in the ground. One of the target buildings is an ordinary five-story SRC building and another is a base-isolated ten-story SRC building.

This paper will introduce the BRI strong-motion network and the Hachinohe station, and discuss the dynamic behavior of the two buildings with reference to strong-motion data.

BRI Strong-Motion Network

BRI operates a strong-motion network composed of 75 monitoring stations. The network aims at obtaining information on the dynamic behavior of various buildings during earthquakes. Consequently, most of the targets of instrumentation are buildings. About one third of the stations are located in Tokyo and its surrounding areas, while the remaining ones are located in major cities throughout Japan as shown in Fig.1. All stations equipped with digital strong-motion instruments are connected to BRI via telephone lines to maintain the instruments and to collect strong-motion records immediately after an earthquake.

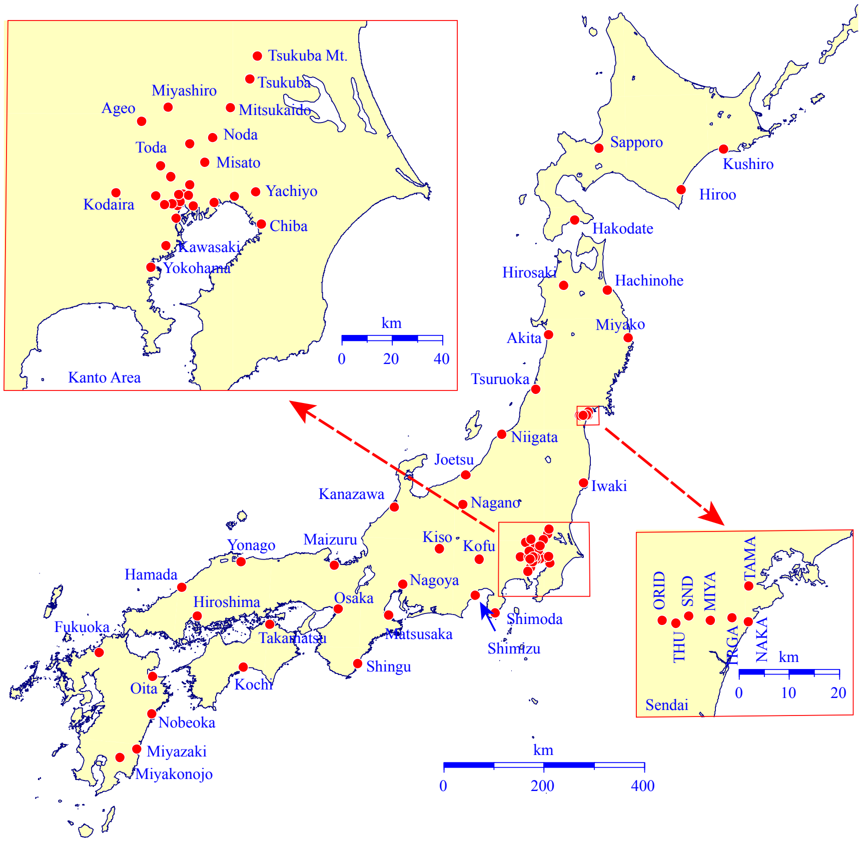


Figure 1. Monitoring stations of the BRI strong-motion network (red circles).

Instrumentation at Hachinohe City Hall

Hachinohe City lies on the coast of the Pacific Ocean in the Aomori prefecture situated in the northernmost part of Honshu of Japan. The city has often suffered damages due to big earthquakes occurring off the shore and on the coast. For example, an earthquake with a JMA (Japan Meteorological Agency) magnitude of 7.9, which occurred off Tokachi on May 16, 1968, contributed to 19 fatalities and 212 collapsed houses in Hachinohe city (Hachinohe City 2009). During the Far Off Sanriku Earthquake of December 28, 1994, two people were killed and 61 houses were destroyed in the city.

Considering such circumstances, BRI set up a strong-motion station at the Hachinohe City Hall in 1979. The original strong-motion instrument was replaced with a digital type and moved from the old building to the new building in 1993. The new building completed in 1980 is currently called the main building. The old building, which had been seriously damaged by the 1994 Far Off Sanriku Earthquake, was reconstructed as a base-isolated building. In 1999, BRI has installed an additional instrument for the base-isolated building, referred to as the annex building. The building layout and the sensor locations are shown in Fig. 2 and the sensor configuration in section is plotted in Fig. 3.

The five-story main building with one basement floor is made of steel-framed reinforced concrete (SRC). BRI installed a 16-bit digital strong-motion instrument with two acceleration sensors placed on the basement floor (M.B1F) and at the penthouse (M.06F) in 1993.

The ten-story annex building with one basement floor is made of SRC. The base-isolation device composed of 14 lead rubber bearings (LRB) was installed between the basement and the first floors. The strong-motion instrument in the annex building has three acceleration sensors inside the building and three sensors in the ground. The sensors inside the building are placed on the basement (A.B1F), the first (A.01F), and the tenth (A.10F) floors, respectively. The base-isolation device is placed between the sensors on A.B1F and A.01F. The three borehole sensors are laid at underground sites of 1 meter (GL), 30 meters (G30) and 105 meters (G105) in depth.

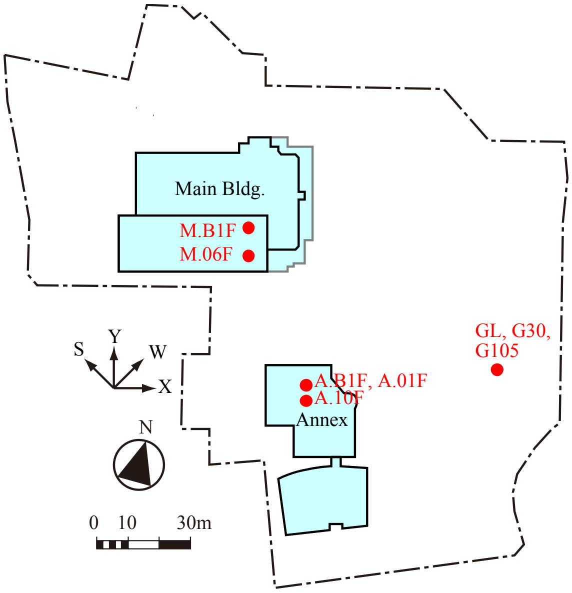


Figure 2. Layout of the buildings and the sensor locations at the Hachinohe city hall.

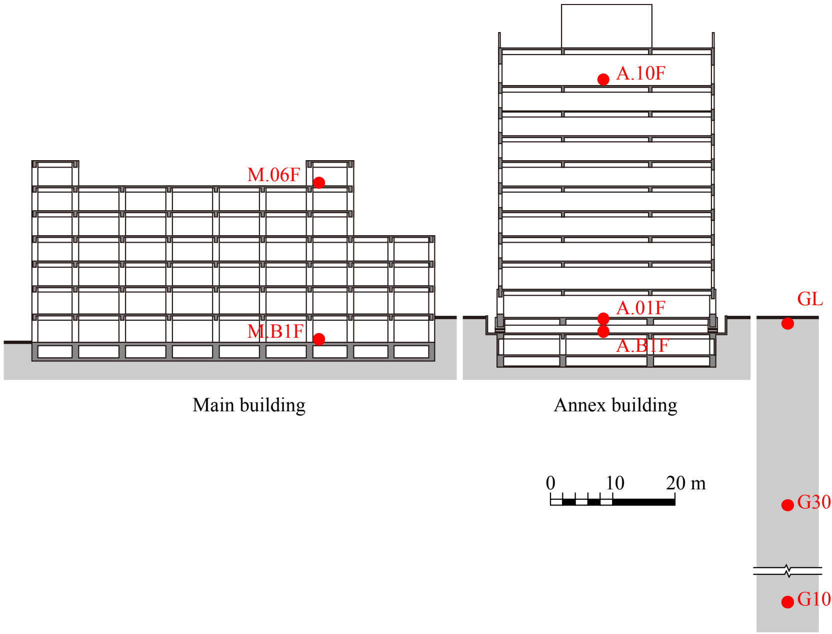


Figure 3. Sectional view of sensor configuration at the Hachinohe city hall.

Strong-motion Records

77 strong-motion records have been collected at the main building in the period from 1994 to 2009. On the other hand, the instrument of the annex building has been triggered by 83 earthquakes in the period from 2000 to 2009. The difference in the number of strong-motion

Table 1. Major strong-motion records observed at the Hachinohe City Hall.

#	EQ1			EQ2			EQ3		
Date and time	1994/12/28 21:19			1995/01/07 07:37			2008/07/24 00:26		
Epicenter	Far Off Sanriku			Off Iwate Pref.			N Coast of Iwate Pref.		
JMA magnitude	7.6			7.2			6.8		
Focal depth (km)	0			48			108		
Epicentral distance (km)	191			76			87		
Peak accelerations (m/s^2)	X	Y	Z	X	Y	Z	X	Y	Z
Main M.B1F	3.20	4.16	1.19	2.81	2.25	1.29	1.98	1.59	1.27
Main M.06F	7.18	9.62	2.27	7.97	6.13	2.97	9.83	5.85	3.56
Annex A.B1F							2.28	2.07	2.34
Annex A.01F							1.67	1.37	1.37
Annex A.10F							2.02	1.39	5.70
Annex GL							7.63	3.32	2.12
Annex G30							1.38	1.53	0.84
Annex G105							1.67	0.79	0.85

records between the main and annex buildings attributes to triggering conditions of the individual instruments. The instrument of the annex building can be more sensitive because the triggering is determined by the 105 meter-deep sensor (G105).

Table 1 lists the strong-motion records whose peak accelerations on the basement floor of the main building (M.B1F) exceeded 1 m/s^2. The strong-motion record of the 1994 Far Off Sanriku Earthquake (EQ1), which is the biggest one at the main building, has the peak acceleration of 4.16 m/s^2 on M.B1F. At the annex building, the biggest peak acceleration on GL was 7.63 m/s^2 from the earthquake occurring on the northern coast of Iwate prefecture of July 24, 2008 (EQ3). The epicenters of the three earthquakes are plotted in Fig. 4.

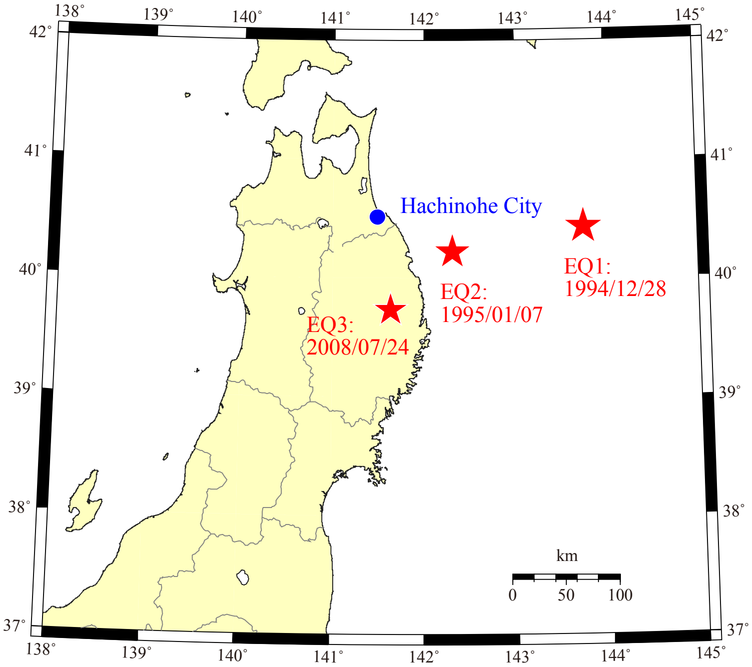


Figure 4 The epicenters of the earthquakes listed in Table 1 and Hachinohe City.

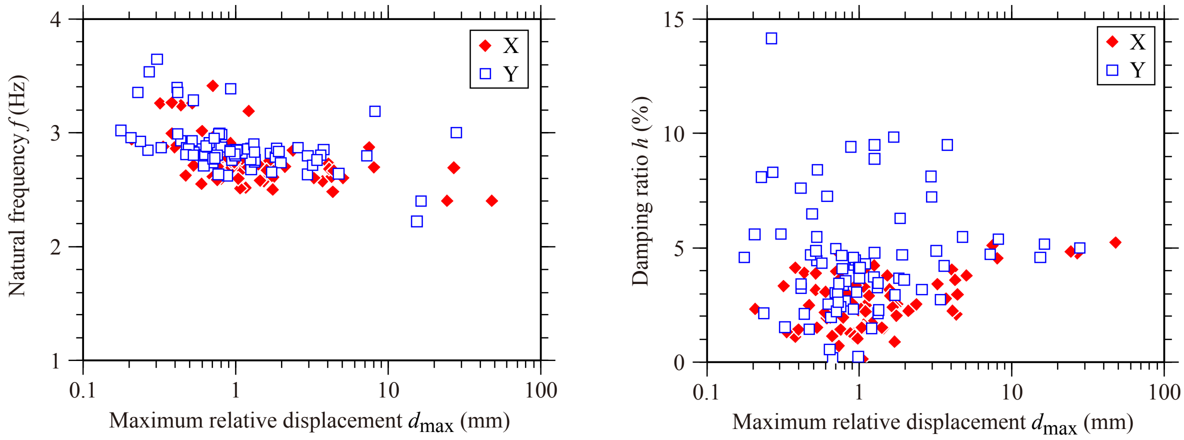
Dynamic Characteristics of Main Building

In order to discuss the dynamic characteristics of the main building, the fundamental natural frequencies and the damping ratios are estimated from 77 strong-motion records in two horizontal directions. The longitudinal direction is represented as X and the transverse direction is Y as shown in Fig. 2. M.B1F and M.06F acceleration records are regarded as the input and response (output) of the single-degree-of-freedom system, respectively. Then the fundamental natural frequency f and the damping ratio h that have the best fit to the observed response are searched using the steepest descent algorithm on the assumption that the system response is linear (Kashima and Kitagawa 2006a).

Figure 5 shows the estimated natural frequencies and the damping ratios as the relationship with the maximum displacements ($d_{\max}$) of M.06F relative to those of M.B1F. Looking at the relationship between the natural frequencies and the maximum relative displacements in Fig.5 (a), the decreasing trend in the natural frequencies with increase of the displacement can be observed.

The estimated damping ratios vary widely as shown in Fig.5 (b), and no clear dependence on the maximum relative displacement is recognized. Larger values were estimated for the damping ratios, especially in the Y-direction. Torsional movements may have an influence on the damping ratios in the Y-direction because the sensor M.06F is placed in the eastern part of the building as shown in Fig. 3.

Figure 6 shows time-course changes in the fundamental natural frequencies *f* and damping ratios *h* of the main building. The sizes of symbols correspond to the maximum relative displacement d_{max}. The natural frequencies in the both directions were around 3.3 Hz at the beginning of the observation in 1994. The 1994 Far Off Sanriku Earthquake of December 28, 1994 (EQ1) slightly damaged the main building and the natural frequencies were estimated to be 2.4 to 2.6 Hz during the earthquake shaking. After the Far Off Sanriku Earthquake, the natural



(a) Natural frequency

(b) Damping ratio

Figure 5. Estimated natural frequencies and damping ratios of the main building.

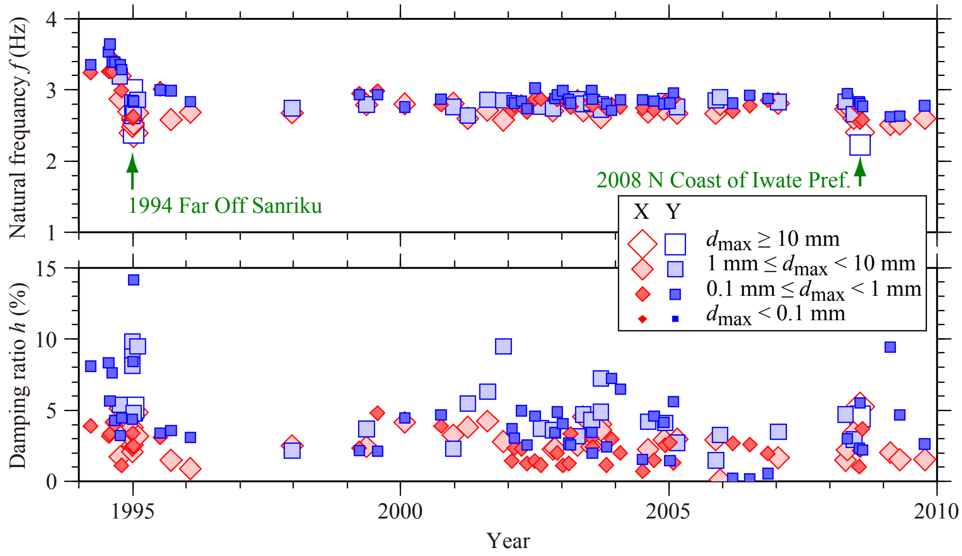


Figure 6. Time-course transition of the natural frequencies and damping ratios of the main building.

frequencies damped to 2.6 to 2.8 Hz from those before the earthquake. The natural frequencies of the 2008 Northern Coast of Iwate Prefecture Earthquake (EQ3) were estimated to be at the same level as those of the 1994 Far Off Sanriku Earthquake. The natural frequencies after the 2008 earthquake have been recovered to 2.6 to 2.8 Hz; therefore it is suggested that the building structure was not damaged by this earthquake.

Dynamic Characteristics of Annex Building

Figure 7 shows horizontal acceleration waveforms recorded on the tenth (A.10F), the first (A.01F), and the basement (A.B1F) floors, as well as on the ground (GL) during the earthquake of July 24, 2008 (EQ3). Red and blue lines indicate X- and Y-directions, respectively. Although the accelerations on the ground (GL) were very large, those on the building basement (A.B1F) decreased obviously. Looking at the waveforms on A.10F, A.01F, and A.B1F, the amplification of vibration in the building is not apparently observed on the accelerations.

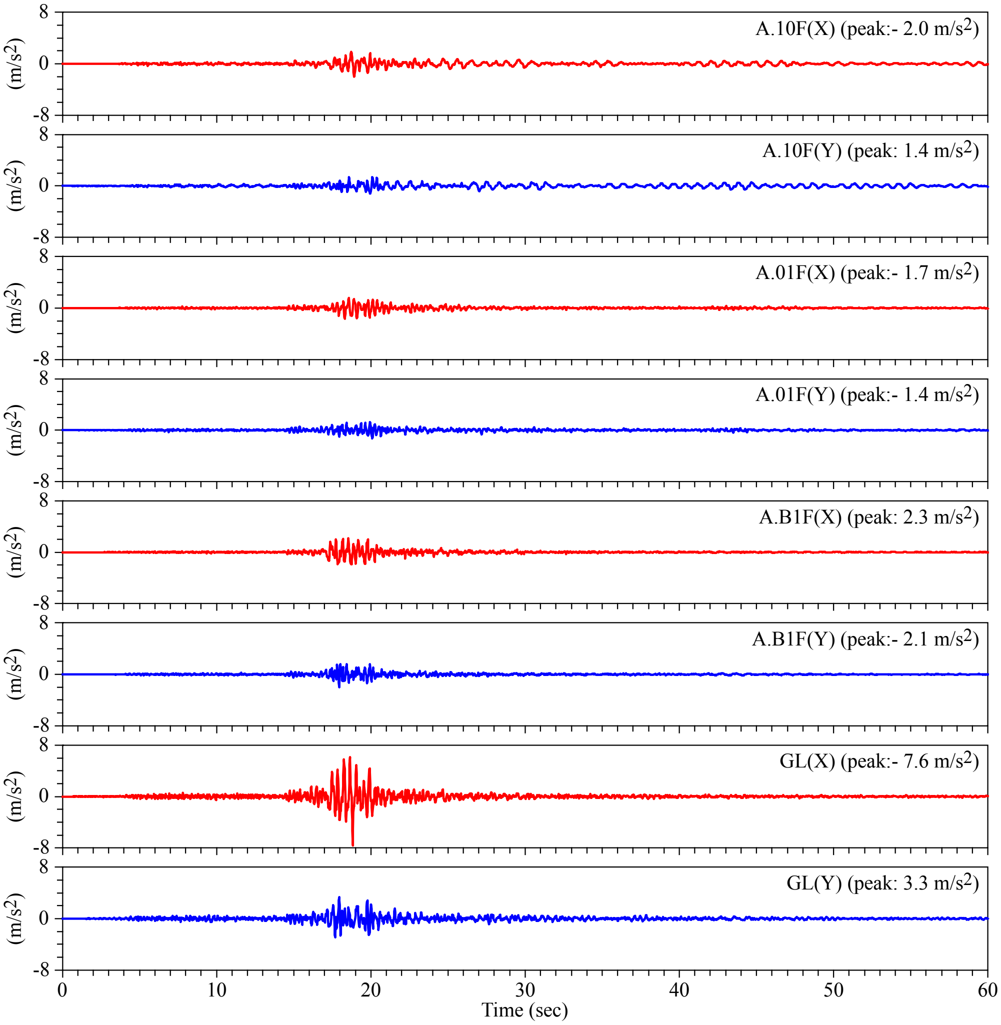


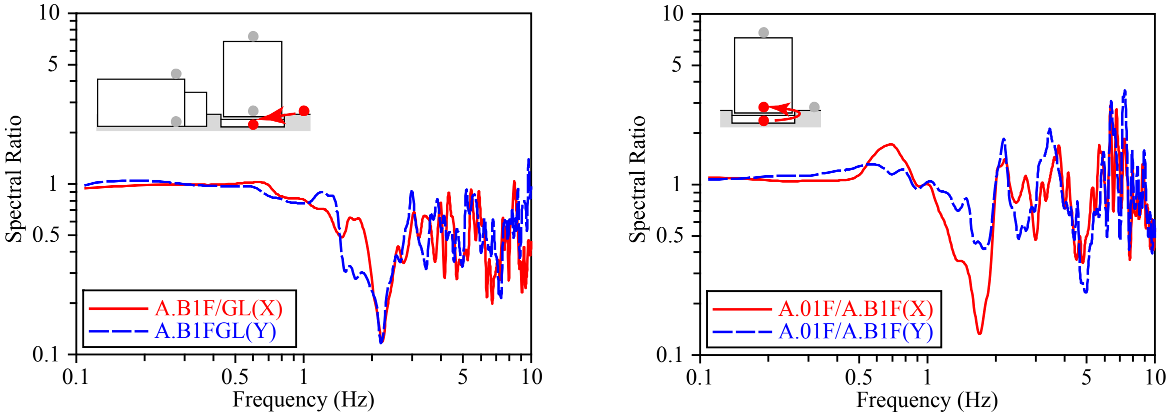
Figure 7. Acceleration records at the annex building for the earthquake of July 24, 2008 (EQ3).

Figure 8 illustrates Fourier spectrum ratios of acceleration records on A.B1F to GL, A.01F to A.B1F, A.10F to A.01F, and A.10F to GL in the horizontal directions for the earthquake of July 24, 2008 (EQ3). All the Fourier spectra were smoothed using the Parzen window with a frequency width of 0.2 Hz. The spectrum ratios of A.B1F/GL in Fig. 8 (a) represent a loss of the seismic input motion from the ground surface to the building foundation. Deep notches appear in the frequency range of 2 to 2.5 Hz and the spectrum ratios are smaller than 1.0 at high frequencies.

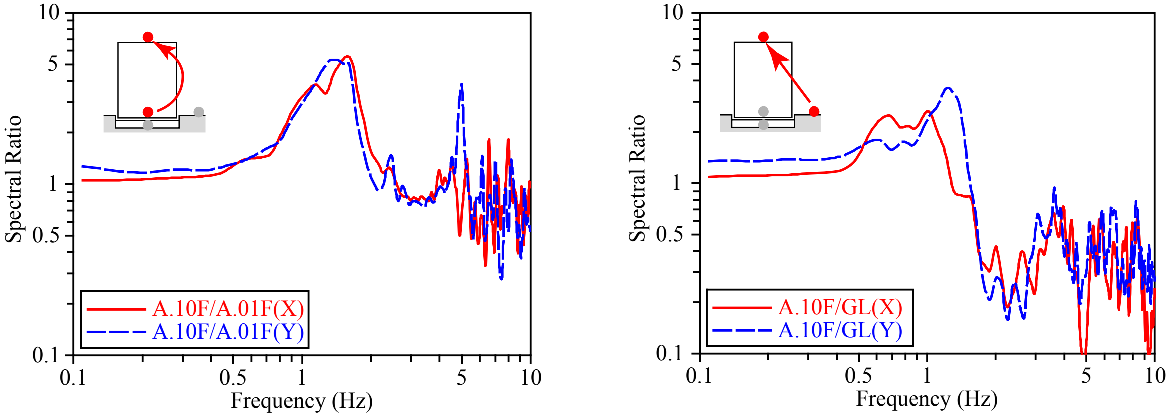
The spectrum ratios of A.01F/A.B1F in Fig. 8 (b) are influenced by the dynamic characteristics of both the base-isolation device and the building. Notches at the frequencies of around 2 Hz and 5 Hz correspond to the natural frequencies of the superstructure. The dynamic properties of the base-isolation device may appear in the frequency range lower than 1 Hz, however the peaks are not clearly observed.

The spectrum ratios of A.10F/A.01F in Fig. 8 (c) are dominated by the characteristics of the superstructure. Clear but low-in-height peaks are observed at the frequencies of 1.4 Hz and 1.6 Hz in the X- and Y-directions, respectively.

The spectrum ratios of A.10F/GL in Fig. 8 (d) indicate the overall characteristics of the base-isolated building from the ground surface to the building top. The spectrum ratios have low



(a) A.B1F/GL (b) A.01F/A.B1F



(c) A.10F/A.01F (d) A.10F/GL

Figure 8. Fourier spectrum ratios of acceleration records of (a) A.B1F to GL, (b) A.01F to A.B1F, (c) A.10F to A.01F, and (d) A.10F to A.B1F for the earthquake of July 24, 2008 (EQ3).

peaks at the frequencies of 1.0 Hz and 1.2 Hz in the X- and Y-directions, respectively and damped to 0.2 to 0.5 in the frequency range higher than 2 Hz. Thus, it is demonstrated that the base-isolation system properly decreased the natural frequencies, enhanced the damping function, and reduced the high frequency components transmitting from the input motion to the superstructure.

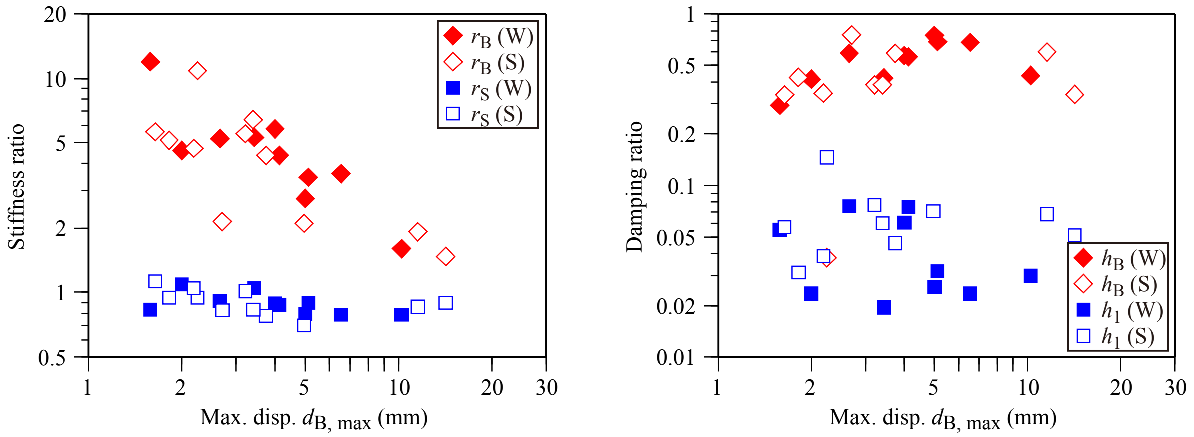
The stiffness levels and the damping ratios of the base-isolation device and the superstructure are estimated based on strong-motion records. The following four parameters of a linear system with multi-degree of freedom are optimized using the Evolutionary Strategies (T. Kashima and Kitagawa 2006b).

- Stiffness ratio of the base-isolation device: $r_{\mathrm{B}} = k_{\mathrm{B}}^{\mathrm{A}} / k_{\mathrm{B}}^{\mathrm{D}}$
- Damping ratio of the base-isolation device: h_{B}
- Stiffness ratio of the superstructure: $r_{\mathrm{S}} = k_i^{\mathrm{A}} / k_i^{\mathrm{D}}$
- First modal damping ratio of the superstructure: h_1

Where, $k_{\mathrm{B}}^{\mathrm{A}}$ is the stiffness of the base-isolation device of the analytical model, $k_{\mathrm{B}}^{\mathrm{D}}$ is the stiffness of the base-isolation device used at the design stage, k_i^{A} is the stiffness of the i-th story of the superstructure of the analytical model, and k_i^{D} is the stiffness of the i-th story used at the design stage. The fitness of the analytical model is determined based on response accelerations on A.01F and at A.10F for 10 seconds around the peak time of the acceleration on A.10F.

The major axis of vibration of the superstructure in the horizontal plane is turned at an angle of 45°. Therefore, the weak (W-) and the strong (S-) directions were adopted as the analytical axes (cf. Fig. 2). The strong motion records that plotted displacements more than 1.5 mm (0.5% in share strain) of the base-isolation device were selected for the analysis. The number of analytical records was ten and eleven in the W- and the S-directions, respectively.

The relationship between the stiffness ratios and maximum displacement of the base-isolation device ($d_{\mathrm{B,max}}$) are shown in Fig. 9 (a). Diamonds indicate the stiffness ratios of the base-isolation device and squares represent the stiffness ratios of the superstructure. Solid and



(a) Stiffness ratio

(b) Damping ratio

Figure 9. Estimated stiffness ratios and damping ratios of the base-isolation device and the superstructure. $d_{\mathrm{B,\,max}}$ is the maximum displacement of the base-isolation device.

hollow symbols correspond to the W- and the S-directions, respectively. The stiffness ratios of the base-isolation device clearly decrease with an increase in device displacement. The stiffness of the base-isolation device in design $k_{\mathrm{B}}^{\mathrm{D}}$ is the initial stiffness of the tri-linear hysteresis model considering the large displacement; therefore it does not represent the stiffness in small displacement range. So the stiffness ratio may be large values in the small displacement range as in Fig. 9 (a). The stiffness ratios of the superstructure show stable values around 1.0.

Figure 9 (b) illustrates the relationship between the damping ratios and maximum displacement of the base-isolation device. The damping ratios of the base-isolation device, which are relatively stable, are distributed between 0.3 and 0.7. The damping ratios of the superstructure with minor variations are estimated around 0.04 in average.

Conclusions

The dynamic characteristics of the main and annex buildings at the Hachinohe City Hall were examined based on the strong-motion records. The main building suffered severe shaking during the Far Off Sanriku Earthquake of December 28, 1994. A change of the natural frequencies before and after the earthquake was clearly identified from the strong motion records. The earthquake of July 24, 2008 again attacked the building, but structural damage was not recognized from the analysis of the strong-motion data.

The stiffnesses and damping ratios of the base-isolation device and the superstructure are also assessed based on the strong-motion records. The maximum displacement of the base-isolation device was 15 mm during the earthquake of July 24, 2008. The stiffness of the base-isolation device decreased obviously with an increase in device displacement. The damping ratio of the base-isolation device was stably estimated to be 0.3 to 0.7.

As the result of the analyses in this paper, I would like to conclude that the strong-motion observation is useful in monitoring the healthiness of the building structures.

References

Hachinohe City Web Site, 2009. *http://www.city.hachinohe.aomori.jp/*

Kashima, T. and Y. Kitagawa, 2006a. Dynamic Characteristics of Buildings Estimated from Strong Motion Records, *Proceedings of the 8th U.S. National Conference on Earthquake Engineering*, Paper No. 1136.

Kashima, T. and Y. Kitagawa, 2006b. Dynamic Characteristics of An 8-storey Building Estimated from Strong Motion Records, *Proceedings of the First European Conference on Earthquake Engineering and Seismology*, Paper No. 1005.