Proceedings Third UJNR Workshop on Soil-Structure Interaction, March 29-30, 2004, Menlo Park, California, USA.

Dynamic Behavior of a 9-Story Base-Isolated Building during the 2003 Off Tokachi Earthquake, Japan

Toshihide Kashima,[a] Akihiro Itou[b] and Hisashi Fujita[c]

On 26th September, 2003, a disastrous earthquake occurred in the northern Japan. The strong motion network of Building Research Institute (BRI) has obtained precious strong motion records at stations in Hokkaido and Tohoku areas. The Kushiro Governmental Office building, which is a nine-story base-isolated building, is instrumented with six acceleration sensors as one of the strong motion stations. The record observed in this building and in its site showed that the base-isolation devices effectively performed. This report summarizes the results of strong motion observation from the 2003 Off Tokachi Earthquake and discusses characteristics of the strong-motion records and dynamic behavior of the Kushiro Governmental Office Building.

INTRODUCTION

For the purpose of development of seismic safety for buildings, it is necessary to understand the characteristics of earthquake ground motions and the behavior of buildings during earthquakes. Building Research Institute (BRI) is in charge of strong motion observation in order to investigate actual dynamic behavior of buildings and is conducting research projects concerned.

The Off Tokachi Earthquake of September 26, 2003, was one of the biggest earthquakes that are expected around Japan. The earthquake caused serious damage to cities in the south-western Hokkaido area. BRI strong motion network has gathered a number of records from 12 stations in northern Japan. Especially, records at the Hiroo Town Office and the Kushiro Governmental Office Building are precious in terms of research on input earthquake motion and seismic response of buildings.

[a] Building Research Institute, 1 Tachihara, Tsukuba, Ibaraki 305-0802, Japan
[b] Kushiro Development and Construction Department, 10-3 Saiwai-cho, Kushiro, Hokkaido 085-8551, Japan
[c] Hokkaido Development Agency, Nishi 2-chome,Kita 8-jo Kita-ku, Sapporo, Hokkaido 060-8511, Japan

OUTLINE OF BRI STRONG MOTION NETWORK

Building Research Institute (BRI) is a national institute that is engaging in researches on architecture, urban planning and building engineering. BRI has started the installation of strong motion instruments more than 40 years ago. The aim of the observation is to contribute to the advance of earthquake-resistant design technology for buildings by means of experimental investigation of strong ground motion characteristics and seismic response of buildings. We are now operating 75 stations as shown in Figure 1.

Figure 1. Disposition of strong motion observation stations operated by Building Research Institute (BRI)

STRONG MOTION RECORDS FROM THE 2003 OFF TOKACHI EARTHQUAKE

On 26th September, 2003, a disastrous earthquake occurred in the northern Japan. The JMA magnitude was 8.0 and cities and towns in the south-eastern Hokkaido suffered damage by the earthquake. The BRI strong motion network has obtained precious strong motion records at stations in Hokkaido and Tohoku (northern main island of Japan) area. Peak accelerations of major records are listed in Table 1. The epicenter of the main shock is plotted on the map with locations of the strong motion stations in Figure 2.

The most intensive strong motion was recorded at the Hiroo Town Office that was 84 kilometers away from the epicenter. A strong motion instrument is placed at the first floor of the 2-story (partially 3-story) reinforced concrete building. The peak acceleration was 564 cm/s^2 and the building was somewhat damaged.

The Kushiro Government Office Building is a base-isolated building with nine stories above ground and one below. Although the peak ground acceleration was 260 cm/s^2, peak accelerations at the ninth floor were not so large (Kashima et al. 2004). It can be regarded that the base isolation system effectively worked. Detailed discussion about the records at the Kushiro Government Office Building is made hereinafter.

Table 1. Peak accelerations of strong motion records from the 2003 Off Tokachi Earthquake

Code	Station	Δ (km)	I_{JMA}	Loc.	Peak Acc. (cm/s^2)		
					H1	H2	V
HRO	Hiroo Town Office	84.2	5.7	01F*	564.0	367.0	242.8
KGC	Kushiro Government Office Bldg.	136.2	5.4	GL*	210.2	259.8	106.3
				B1F	154.1	192.4	76.4
				01F	70.3	80.6	85.1
				09F	93.8	120.6	183.6
HCN2	Annex, Hachinohe City Hall	258.5	4.1	GL*	69.8	85.3	27.2
				B1F	28.7	27.7	25.0
				01F	43.8	33.3	20.4
				10F	53.4	56.6	51.6
HCN	Hachinohe City Hall	258.6	3.5	B1F*	27.3	24.8	13.4
				06F	83.5	105.9	21.9
HKU	Hokkaido University	266.3	4.1	GL*	66.9	50.0	25.4
HKD	Hakodate Development and Construction Department	276.9	4.3	GL*	43.2	57.1	28.7
MYK	Miyako City Hall	297.5	2.8	GL*	12.3	12.0	9.8
				01F	10.4	11.5	5.4
				06F	20.2	17.0	6.4
HRH	Hirosaki Legal Affairs Office	329.5	3.2	01F*	21.3	21.2	9.3
THU	Tohoku University	479.4	2.3	01F*	5.7	6.5	4.0
				09F	35.7	21.6	5.7

Δ: Epicentral distance, I_{JMA}: JMA instrumental seismic intensity calculated from record at the location with an asterisk (*), Loc: sensor location, H1, H2: horizontal components, V vertical component.

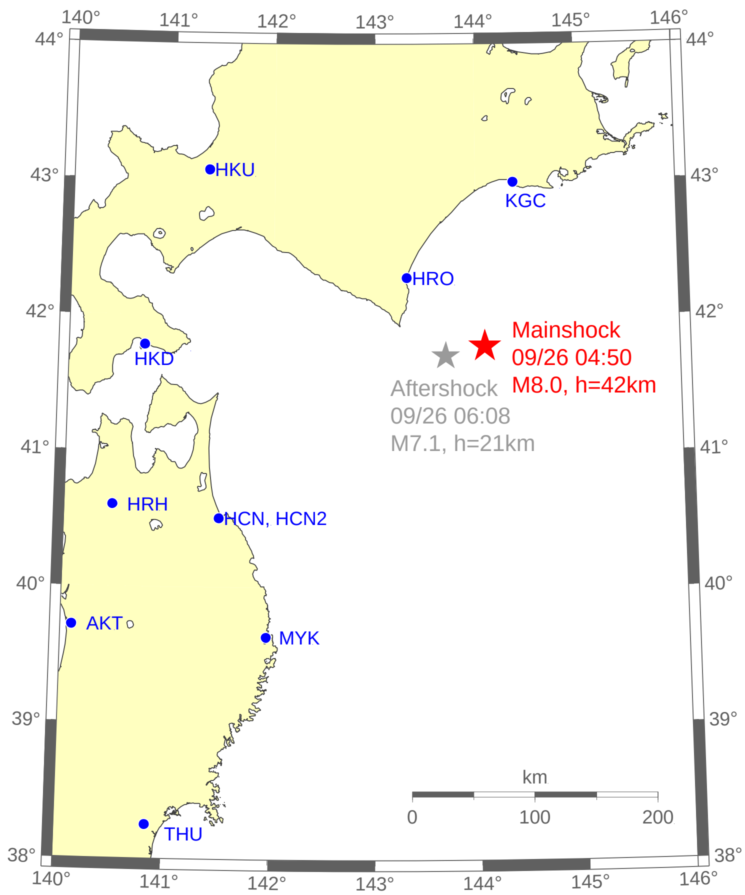
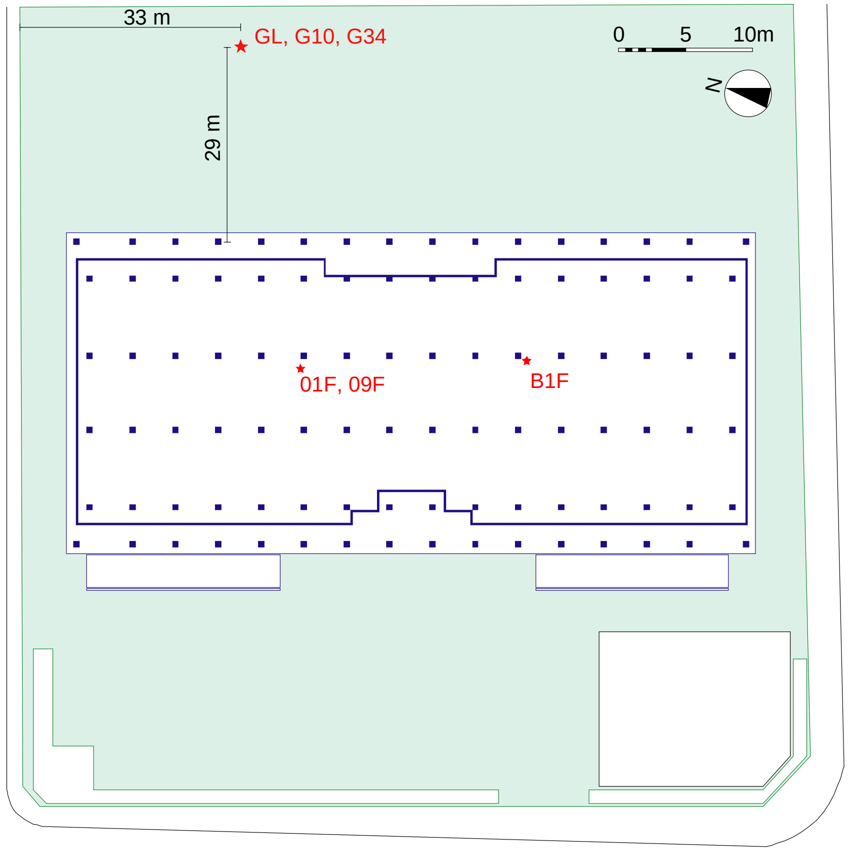


Figure 2. Epicenters of the mainshock and the major aftershock of the 2003 Off Tokachi Earthquake and strong motion stations of BRI

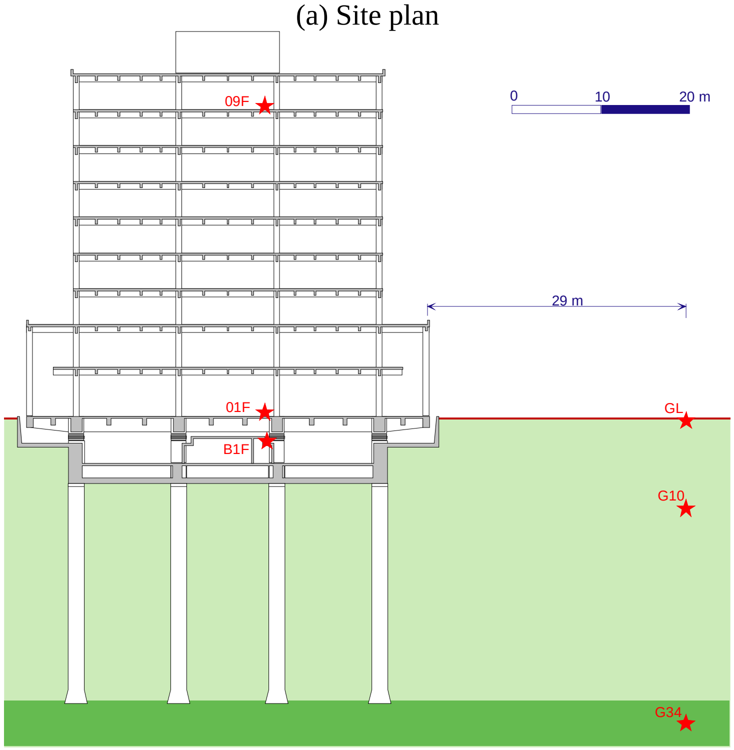
SENSOR CONFIGURATION AT THE KUSHIRO GOVERNMENT OFFICE BUILDING

The Kushiro Government Office Building is a base-isolated building completed in 1998. The building has nine stories above ground and one below. The building height is 43.7 meters and the amount of floor space is 24,612 m^2. The base isolation system consists of 64 laminated rubber bearings, 56 lead dampers and 32 hysteretic steel dampers, and is equipped between the first floor and the basement floor. The upper structure is the steel reinforced concrete frame system with steel braces. The building foundation has reinforced concrete piles that are supported by the sandstone layer 31 meters underground.

Six acceleration sensors are configured in the building and in the ground as shown in Figure 3. Three borehole sensors are buried in the ground in order to investigate amplification effects of the surface geology. Other three sensors are placed in the building so as to grasp dynamic behavior of the base-isolated building.



(a) Site plan



(b) Section

Figure 3. Sensor configuration at the Kushiro Government Office Building.

GENERAL FEATURE OF THE STRONG MOTION RECORD

The instrument in the Kushiro Government Office Building acquired precious strong motion records during the 2003 Off Tokachi Earthquake. Peak accelerations and peak velocities of all sensors are listed in Table 2. Figure 4 presents distribution of horizontal peak accelerations along the height and Figure 5 shows acceleration records at all sensor locations in the N257°E (longitudinal) direction. The earthquake motion was magnified twice by the surface soil layers of 30 meters in thickness. The peak accelerations were reduced by two thirds as the input to the building. The base isolation system decreased accelerations by half from the basement floor (B1F) to the first floor (01F).

Table 1. Peak accelerations and peak velocities by the 2003 Off Tokachi Earthquake

	Loc.	Peak Acceleration (cm/s^2)			Peak Velocity (cm/s)		
		N167°E	N257°E	UD	N167°E	N257°E	UD
Building	09F	93.8	120.6	183.6	30.80	29.59	7.78
	01F	70.3	80.6	85.1	23.23	23.72	6.69
	B1F	154.1	192.4	76.4	24.82	29.67	6.76
Ground	GL	210.2	259.8	106.3	28.09	30.84	8.32
	G10	173.3	214.4	71.9	23.73	31.03	7.40
	G34	137.6	134.5	61.5	18.65	24.25	5.67

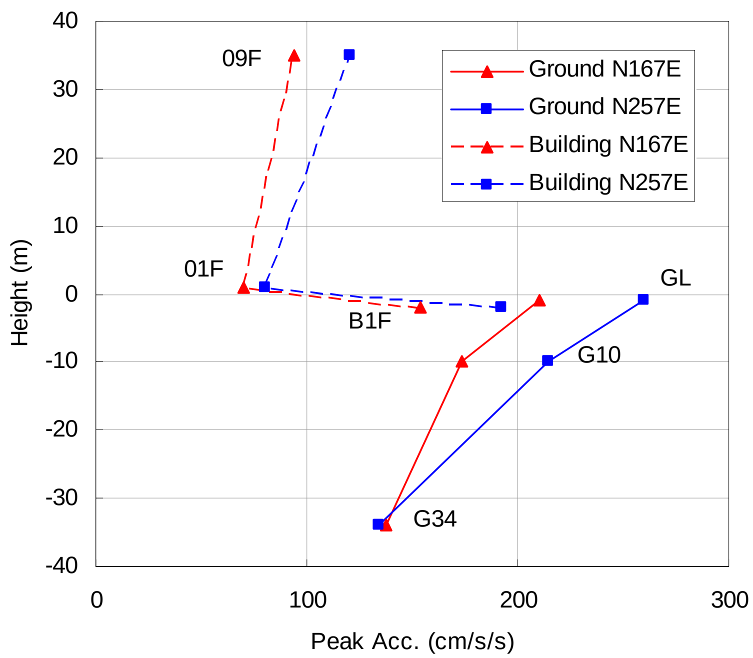


Figure 4. Distribution of peak accelerations in the horizontal directions along the height.

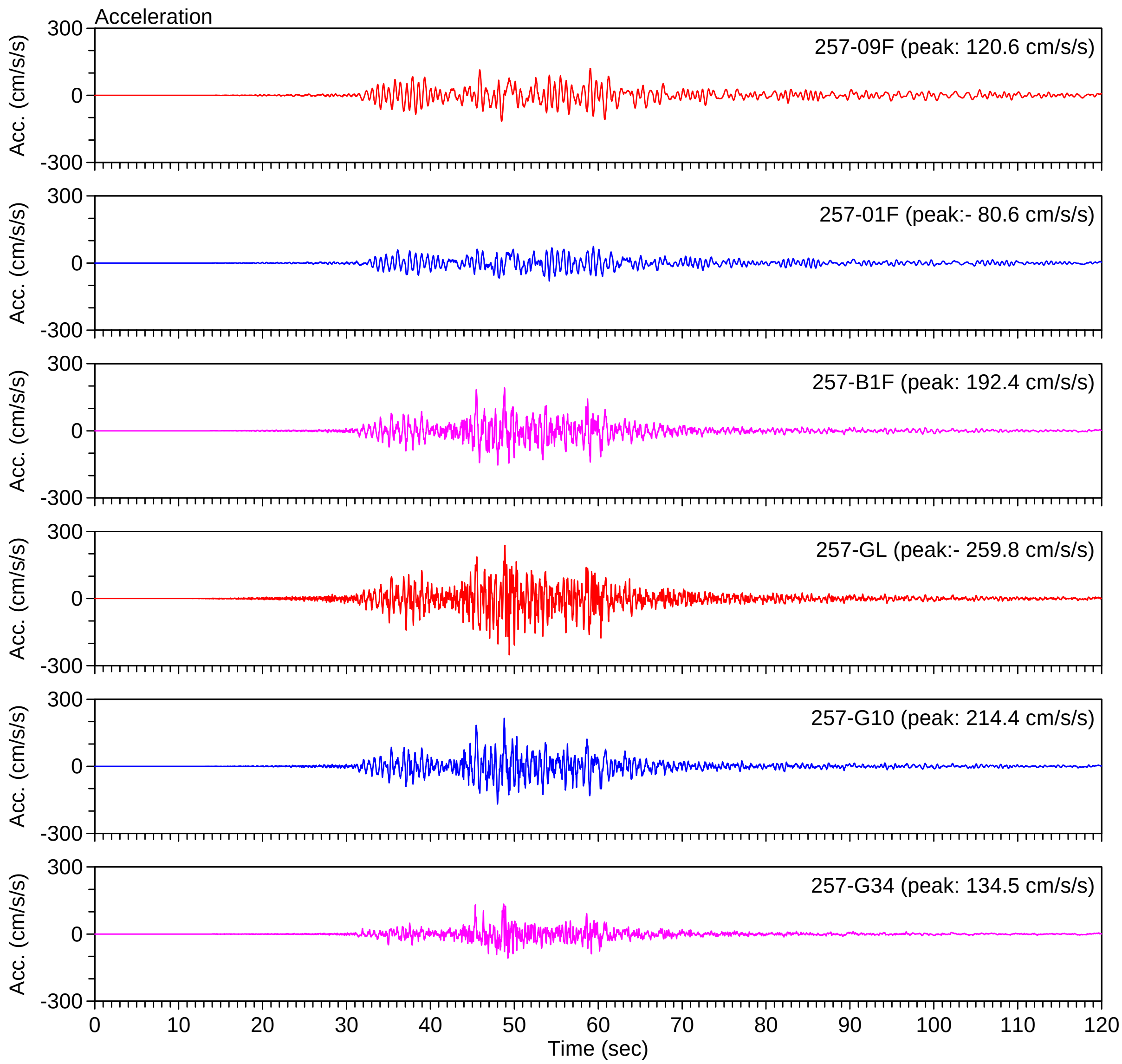


Figure 5. Acceleration records in the N257°E direction. Sensors are placed at ninth floor (09F), first floor (01F), basement floor (B1F), ground surface (GL), 10 meters deep (G10) and 34 meters deep (G34) from top to bottom.

Fourier amplitude spectra of the acceleration records on the ground surface (GL) are plotted in Figure 6. Remarkable amplitudes in the frequencies 0.5 to 3 Hz can be recognized on the spectra in the horizontal directions. This range of frequency has a great influence on behavior of building structures. For example, the natural frequency of the upper structure of the Kushiro Government Office Building is around 1 Hz as mentioned later. This sort of strong motion can be severe input to the building if it doesn't have the base isolation system. Incidentally, amplitudes in the vertical component are relatively small.

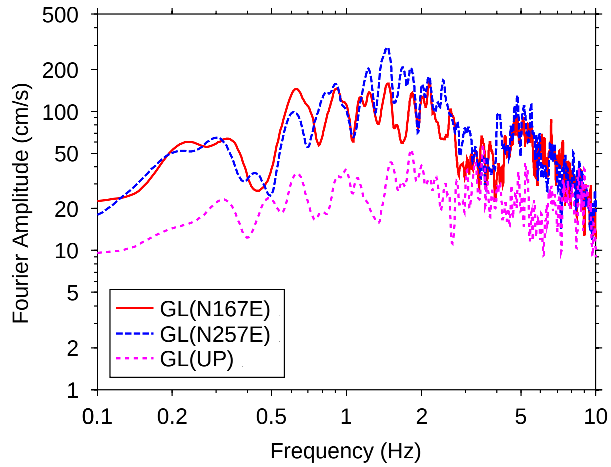


Figure 6. Fourier amplitude spectra of the acceleration records on the ground surface (GL).

AMPLIFICATION BY SURFACE GEOLOGY

Figure 7 shows Fourier spectrum ratios of records on ground surface to the ones 34 meters below the ground (GL/G34). A dotted line represents the theoretical result using measured share wave velocities (Kashima et al. 2001). Although the peak frequency of the theoretical ratio is around 2 Hz, spectrum ratios of observed records have the first peak at 1.5 Hz. Non-linearity of soil layers may cause such decrease of the peak frequency.

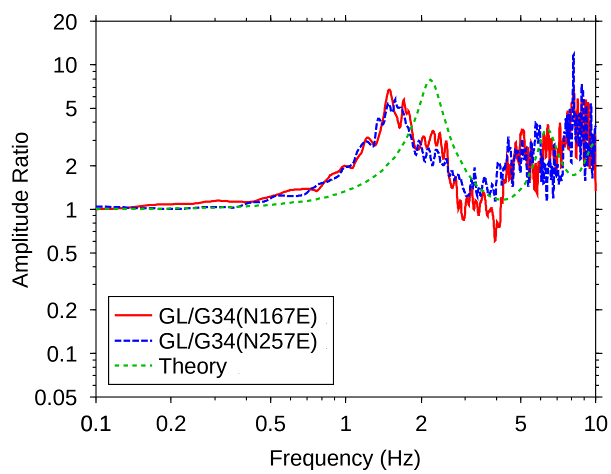


Figure 7. Fourier spectrum ratios GL/G34 in the horizontal directions and the theoretical transfer function.

Non-stationary Fourier spectrum ratio of GL/G34 in the N257°E direction is shown in Figure 8. First peak of spectrum ratio appears at approximately 2 Hz in the beginning portion. The frequency of the peak lessens in the main part from 40 seconds to 60 seconds, and becomes about 2 Hz again in the subsequent coda part. The phenomena can be regarded as the result of non-linear response of the soil layers.

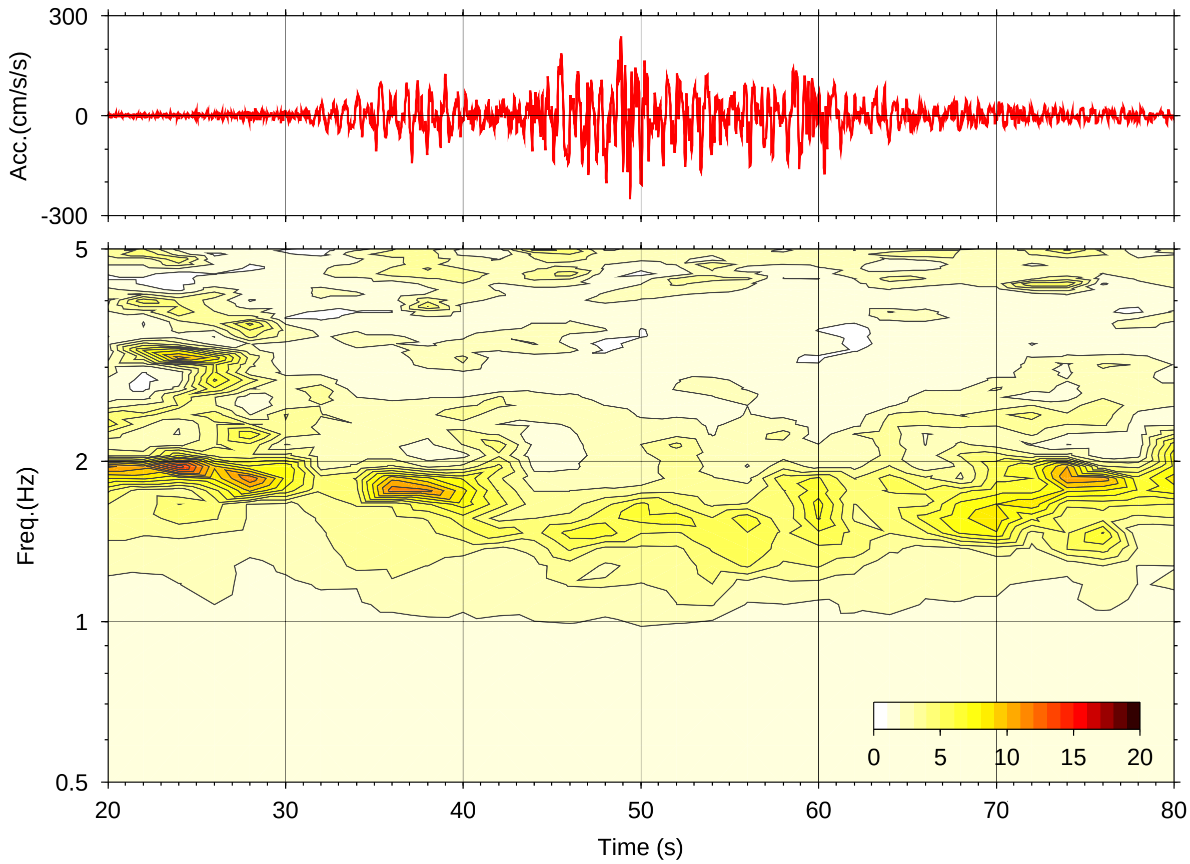


Figure 8. Non-stationary spectrum ratio of GL/G34 in the N257E direction.

DYNAMIC BEHAVIOR OF THE BASE ISOLATED BUILDING

Dynamic behavior of the base-isolated building is discussed in this chapter. Figure 9 (a) shows Fourier spectrum ratios of B1F/GL. This represents the input loss of the earthquake motion in terms of the soil-structure interaction effect. The spectrum ratios in the horizontal directions are gently decreasing from 1 Hz to the higher frequencies. The loss of the input motion is not so large in general. Figure 9 (b) presents the spectral ratio of 1F/B1F. The spectrum ratios have peaks at 0.4 to 0.5 Hz and billows in the higher frequency range. Spectrum ratios of 9F/1F are plotted in Figure 9 (c). This indicates characteristics of the upper structure. The first and second natural frequencies clearly appear in the both horizontal directions. The first natural frequencies, 1 Hz in the both horizontal directions, are very close to the values that were assumed in the design process. Spectral ratios 9F/GL in Figure 9 (d) shows overall dynamic properties of the building system including the base isolation system and the soil-structure interaction effect. The first natural frequencies can be recognized at 0.4 to 0.5 Hz in terms of the total system. In the frequency range higher than 1.5 Hz, response of the building system drastically decreases. On the other hand amplitudes in the vertical component are magnified in the high frequency range. Further discussion is necessary on characteristics of vertical motions.

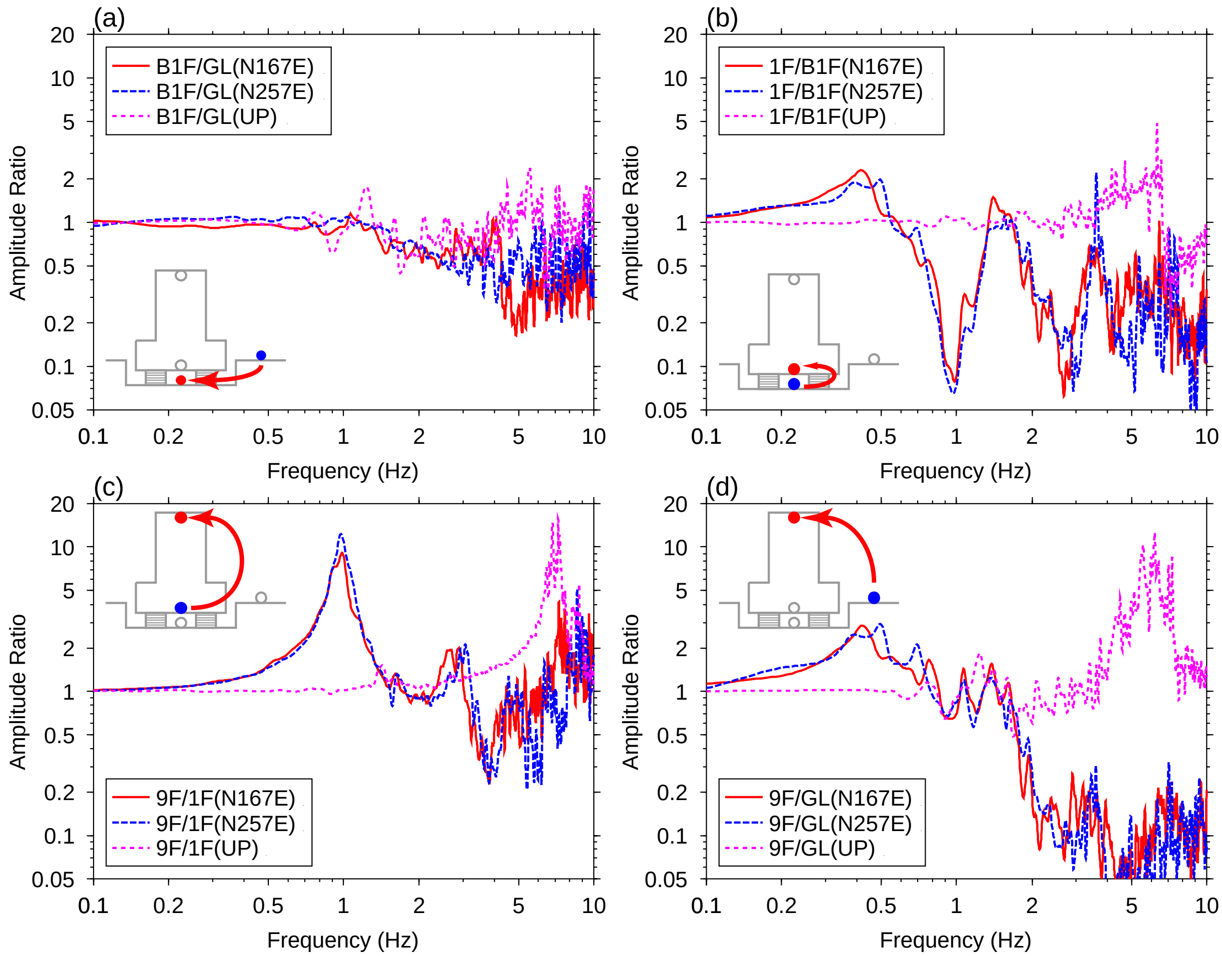


Figure 9. Fourier spectrum ratios of (a) B1F/GL, (b) 1F/B1F, (c) 9F/1F and (d) 9F/GL.

Figure 10 shows story displacement of the basement floor that has the base isolation devices. The maximum displacement of the base isolation devices reached more than 10 centimeters. This result shows good agreement with traces of movement left around the building.

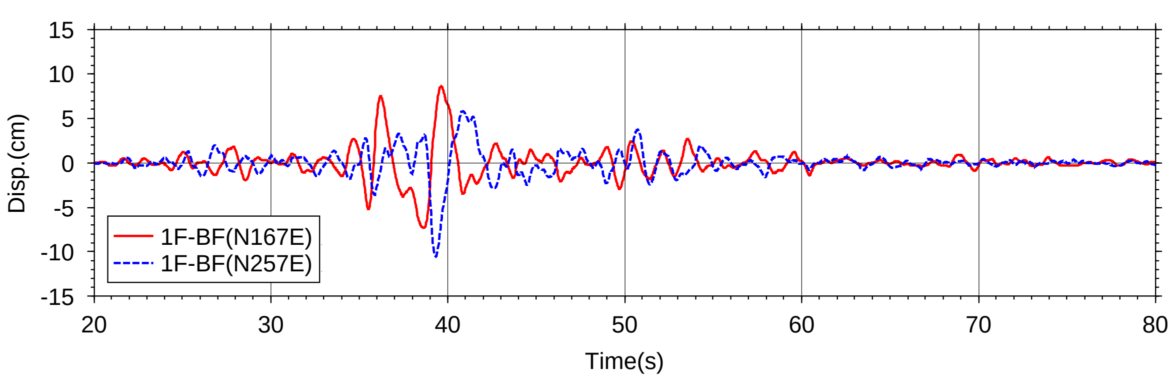


Figure 10. Relative displacement of the base-isolated story (B1F).

I tried to simulate non-linear response of the base-isolated building using the lumped mass system. The laminated rubber bearing is assumed to be a linear spring. The force-displacement relations of the lead damper and the steel damper are imitated by the tri-linear and bi-linear models respectively. The simulated displacements of the base-isolated story are shown in Figures 11 and 12 with the observed ones. Although the general transition can be simulated well, the second big cycle has some differences. More discussion on the simulation technique may be necessary.

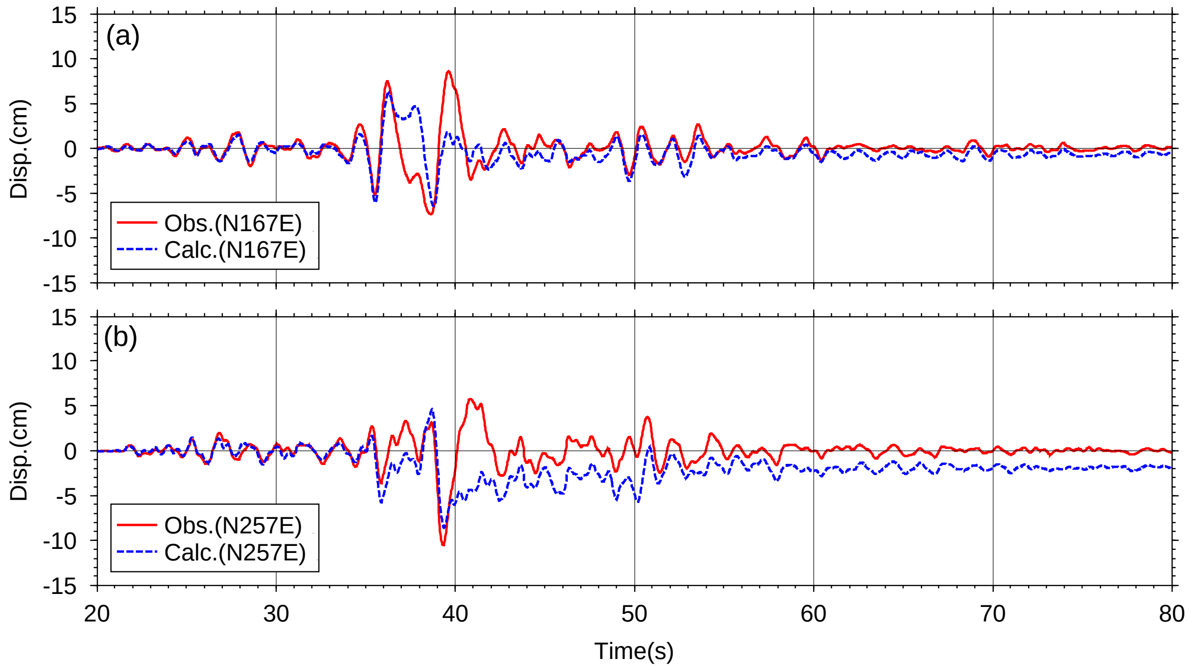


Figure 11. Comparison between observed story displacement at B1F and calculated one. (a) is in the N167E component and (b) is in the N257E component.

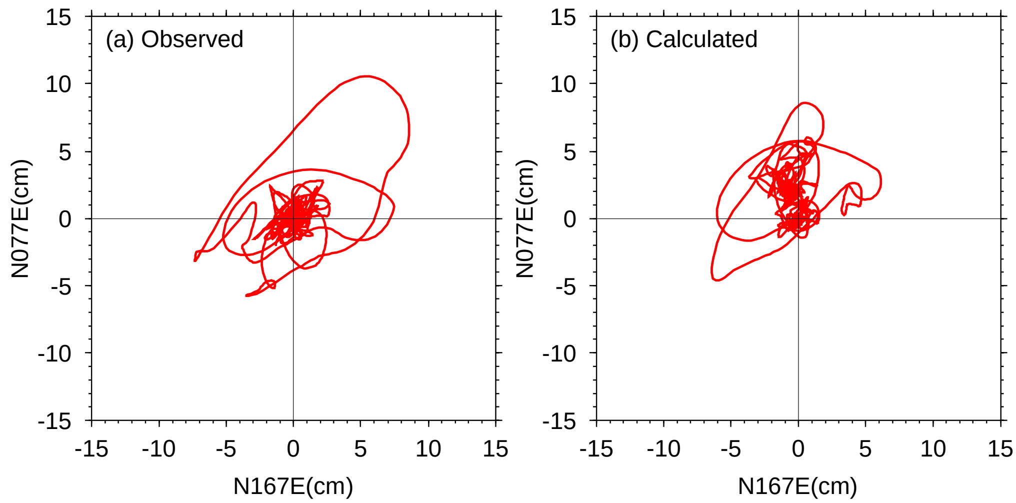


Figure 12. Displacement orbits of the base-isolated story in the horizontal plane. (a) is the observed data and (b) is the calculated result.

CONCLUSIONS

The strong motion network of Building Research Institute has obtained precious records from the 2003 Off Tokachi Earthquake. The Kushiro Government Office Building underwent the severe earthquake motion. The strong motion instrument at this station precisely recorded seismic response of the building with non-linear behavior of the base isolation devices. The borehole record of the surface soil layers under the strong earthquake motion is also one of the valuable results. We will continue the discussion on the strong motion records at the Kushiro Government Office Building.

REFERENCES

Kashima, T., Okawa, I., and Koyama, S., 2001. Characteristics of Earthquake Ground Motions at Old and New Kushiro JMA Observatories, *Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan*, Volume B-2, pp.67-68. (Japanese)

Kashima, T., Ito, A. and Fujita, H., 2004. Strong motion records observed at the Kushiro Government Office Building for the 2003 Tokachi-oki Earthquake, *MENSHIN*, Japan Society of Seismic Isolation, No. 43, 36–38. (Japanese)