Strong Motion Records in Buildings from the 2011 Great East Japan Earthquake

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SUMMARY:
Building Research Institute (BRI) of Japan is operating a nationwide strong motion network for building structures. The 2011 East Japan Earthquake has triggered 60 stations out of 79 stations of the BRI network. Most of the stations experienced the strongest shaking ever. Among buildings in the BRI network, at least four buildings suffered some damage due to the severe earthquake motions. Through the analyses of strong motion data recorded in those buildings, obvious change of the natural periods during intense shaking were identified. Long-period earthquake motions generated by the gigantic earthquake were observed in Tokyo, Osaka and other large cities that are away from its hypocentre. The stations of the BRI network include nine super high-rise buildings and nine base-isolated buildings suffered by severe long-period motions.

Keywords: 2011 East Japan Earthquake, strong motion network, building damage, long-period ground motion

1. 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 and houses is one of the most important research targets of BRI. BRI operates a nationwide strong motion network as one of its research activities. Most of the targets of instrumentation are building structures. Currently, we run nearly 80 strong motion stations deployed in major cities throughout Japan.

Sixty instruments of the BRI strong motion network have been triggered by the East Japan Earthquake of March 11, 2011. Some instrumented buildings suffered damage that was identified by the analysis of the strong motion data. The instruments located in large urban areas, such as Tokyo and Osaka, successfully captured remarkable long-period ground motions and responses of super high-rise buildings. The paper reports notable strong motion data recorded during the East Japan Earthquake.

2. OUTLINE OF BRI STRONG MOTION NETWORK

To enhance the seismic safety of building structures, it is necessary to understand the characteristics of earthquake ground motions and the behaviours of buildings during an earthquake. BRI is performing strong motion observation to reveal the actual dynamic behaviours of buildings and is conducting research projects to clarify these motions.

BRI has installed strong motion instruments in major cities throughout Japan. Nearly 80 observation stations are now in operation. One third of these stations are located in Tokyo and its outskirts. Other stations are distributed at intervals of about 200 kilometres in order to cover all over Japan. All of the stations are equipped with digital instruments and most of them are connected to BRI via public telephone lines or the Internet so that these instruments may be appropriately maintained and strong motion data may be collected immediately after an earthquake.

3. STRONG MOTION DATA OF THE 2011 EAST JAPAN EARTHQUAKE

On March 11, 2011, a gigantic earthquake with a moment magnitude (Mw) 9.0 occurred off the Pacific coast of the north-eastern Japan. The earthquake, hereinafter referred to as the East Japan Earthquake, brought about monstrous tsunami and enormous damage to the eastern Japan.

Sixty stations out of 79 stations of the BRI strong motion network have been triggered by the East Japan Earthquake (Kashima et al., 2012). The locations of the triggered strong motion stations and the epicentre are plotted in Fig. 1. Circles that indicate the stations in Fig. 1 are coloured according to the JMA (Japan Meteorological Agency) seismic intensity scales. The JMA seismic intensity scales were calculated using strong motion data recorded on the ground or on the closest floor to the ground surface. The JMA scale classifies the intensity of ground shaking into ten levels, i.e. 0, 1, 2, 3, 4, 5-, 5+, 6-, 6+ and 7. Some damage may be expected in case of the JMA scale 5+ and higher. In the BRI network, the JMA scale 6- (six lower) was recorded in one station, 5+ (five upper) in 17 stations, and 5- (five lower) in 17 stations.

In the sixty stations that were triggered, fifty buildings were equipped with two or more acceleration sensors. Those included nine super high-rise buildings whose heights were over 60 meters and six base-isolated buildings. The distinctive strong motion data obtained in the BRI network are introduced hereinafter.

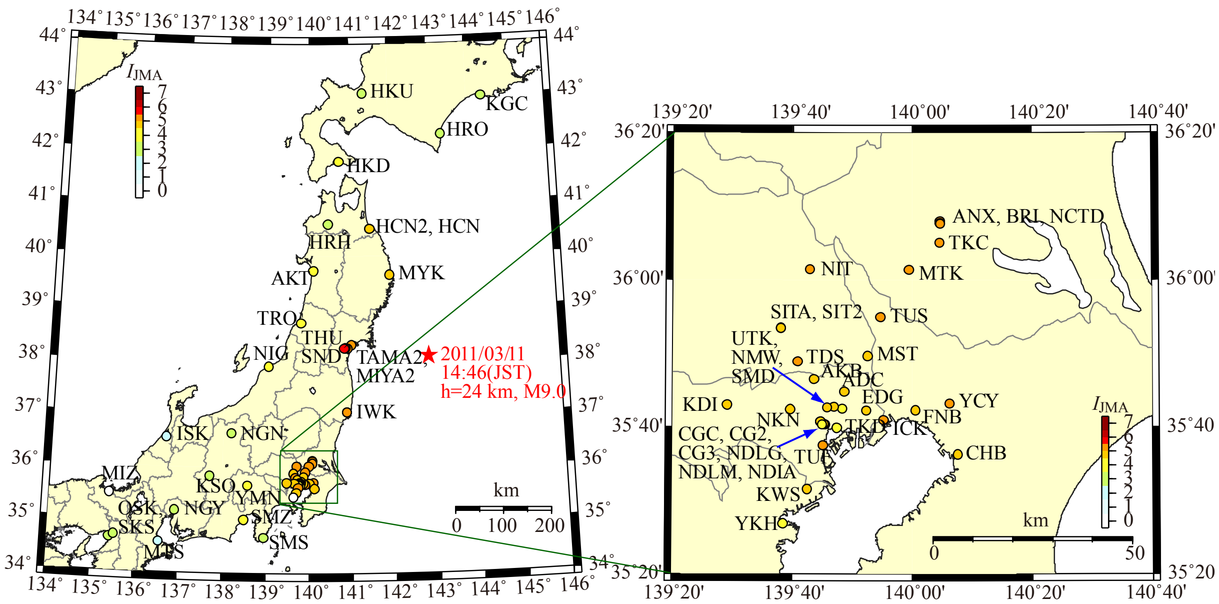


Figure 1. Triggered stations in the BRI strong motion network by the 2011 East Japan Earthquake and the epicentre (★)

4. STRONG MOTION DATA RECORDED IN DAMAGED BUILDINGS

Some buildings in the BRI strong motion network were damaged by severe earthquake motion during the East Japan Earthquake. Strong motion data recorded in four buildings that suffered damage are listed in Table 1. “Azimuth” in Table 1 indicates the sensor installation direction that accords with the building axis as a clockwise angle from the north. For example, two horizontal directions (H1 and H2 in Table 1) of the sensor in the THU station correspond to N192°E and N282°E, respectively. The damaged buildings were steel-framed reinforced concrete buildings of seven to nine storeys. This chapter describes a seriously damaged building of the THU station in detail.

Table 1. Strong Motion Data recorded in Damaged Buildings

Code	Location Structure/Floors	Δ (km)	I_{JMA}	Azi-muth	Sensor Place	Max. Acc. (cm/s^2)			Remarks
						H1	H2	V	
THU	Sendai City SRC/9F	177	6-	192°	01F*	333	330	257	
					09F	908	728	640	
IWK	Iwaki City SRC/8F+B1F	210	5+	180°	B1F*	175	176	147	
					09F	579	449	260	
ANXA	Tsukuba City SRC/8F+B1F	330	5+	180°	BFE*	194	191	136	B1F East
					8FE	597	506	344	8F East
ANXM	Tsukuba City SRC/7F+B1F	330	5+	180°	MBC*	203	206	152	B1F Centre
					M8C	682	585	311	8F Centre

Note) Δ: Epicentral distance, I_{JMA}: JMA seismic intensity scale (calculated using acceleration data of an asterisked sensor), Azimuth: Clockwise direction from North, H1, H2 and V: Maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

The THU building is a school building of a university located in Sendai City at the epicentral distance of 177 kilometres. Multi-storey share walls of the building suffered bending fracture at the third floor level and the outer columns were severely crushed as shown in Photo 1 (Tsoggerel and Motosaka, 2011).

Figure 2 indicates acceleration records, building displacements (relative displacements of the ninth floor to the first floor), natural periods and damping ratios of the THU building. The natural periods and damping ratios represent those of the first vibration mode identified in every 10 second by the method of searching optimal parameters of a single-degree-of-freedom system using the strong motion data (Kashima et al., 2006).

In Fig. 2 (a) and (b), thick lines and thin lines indicate acceleration waveforms on the first floor (01F) and ninth floor (09F), respectively. Two notable wave groups at the times of 40 seconds and 80 or 90 seconds can be recognised on the waveforms. Earthquake motions and building responses of the second wave group seem to be more severe than those of the first wave group. The natural periods were 0.65 seconds in the initial stage, and then increased to 1 second at the time of 50 seconds after the first wave group arrival. When the second wave group arrived around 80 seconds, the natural periods in the both of horizontal directions were extended to over 1 second. Especially in the N282°E direction (corresponding to the transverse direction of the building), the increase of the natural period was notable. During the time of 130 second to 180 seconds, the natural periods in the N282°E direction were twice as long as the initial natural period.

Photo 1. THU building and its damage

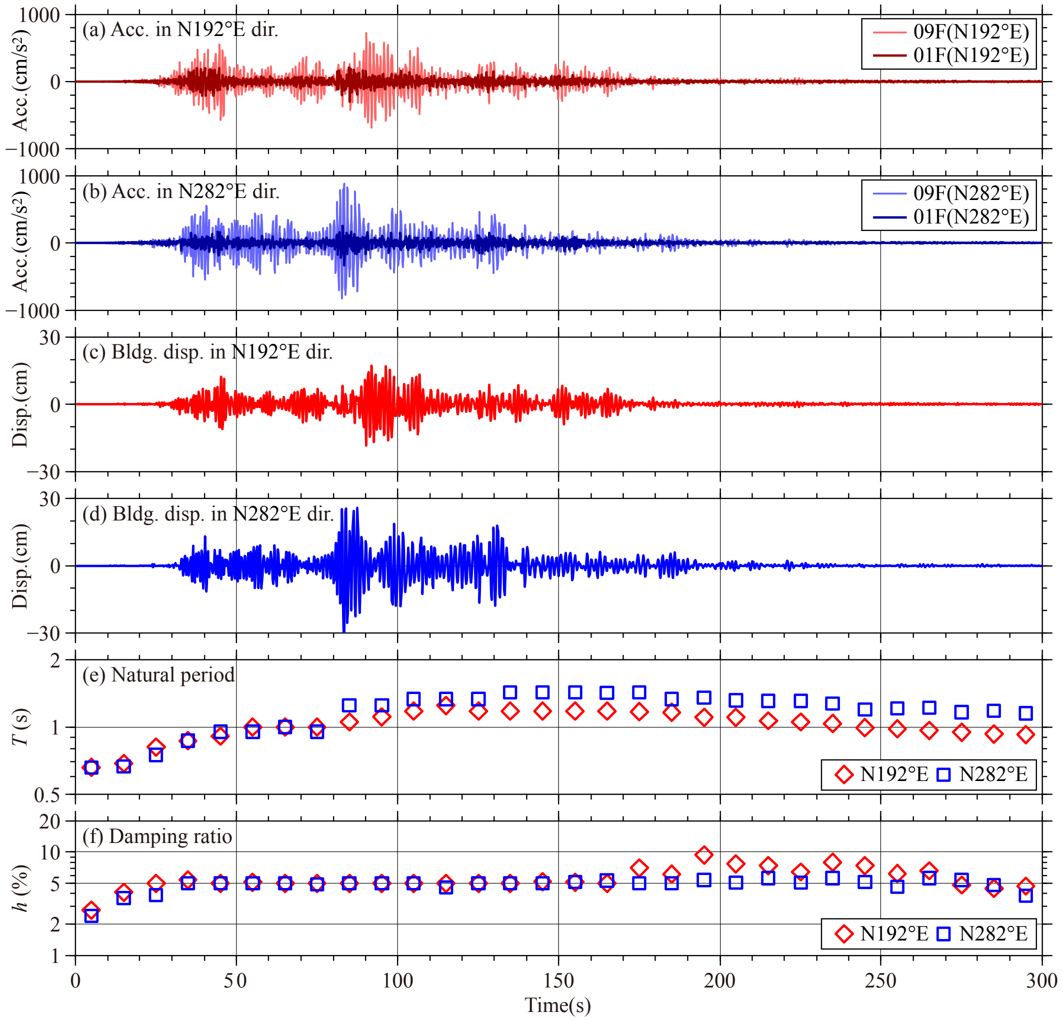


Figure 2. Accelerations, building displacements, natural periods and damping ratios of the THU building

5. STRONG MOTION DATA RECORDED IN SUPER HIGH-RISE BUILDINGS

There are nine super high-rise buildings that are higher than 60 meters in the BRI strong motion network. Strong motion data of the East Japan Earthquake were obtained in all of the super high-rise building as listed in Table 2. One building is located in Sendai, six buildings are in Tokyo and its outskirts, and two buildings are in Osaka.

The building in the station SND is located in Sendai City, Miyagi Prefecture, at an epicentral distance of 175 kilometres. This was the closest building to the epicentre in the BRI network and the JMA seismic intensity scale calculated from the records on the second basement floor (B2F) was 5+. The maximum acceleration on the 15th floor (15F) is 361 cm/s^2 in the N074°E direction and was 2.2 times as large as that on the second basement floor (B2F).

Stations SIT2, TKD, CGC, CG2 and YKH are situated in the metropolitan area around Tokyo. The epicentral distances of those stations were 378 to 412 kilometres and the JMA seismic intensity scales were 4. In those buildings, maximum accelerations in the horizontal directions on the basement floors were less than 100 cm/s^2. On the other hand, the maximum accelerations on the top floors widely varied from 112 cm/s^2 to 503 cm/s^2.

Table 2. Strong Motion Data recorded in Super High-rise Buildings

Code	Location Structure/Floors	Δ (km)	I_{JMA}	Azi-muth	Sensor Place	Max. Acc. (cm/s^2)			Remarks
						H1	H2	V	
SND	Sendai City S/15F+B2F	175	5+	074°	B2F*	163	259	147	
					15F	361	346	543	
SIT2	SaitamaCity S/26F+B3F	378	4	340°	B3F*	74	63	42	
					10FS	119	138	62	10F South
					27FS	248	503	107	27F South
SMD	Sumida Ward, Tokyo S/19F+B2F	380	4	000°	B1F*	69	66	34	
					08F	263	197	46	
					20F	385	290	81	
TKD	Chuo Ward, Tokyo RC/37F+B1F	385	4	180°	01F*	87	98	41	
					18F	118	141	64	
					37F	162	198	108	
CGC	Chiyoda Ward, Tokyo S/20F+B3F	386	4	208°	01F*	90	86	45	
					20B	208	148	173	B Bldg. 20F
					19C	179	133	130	C Bldg. 19F
CG2	Chiyoda Ward, Tokyo S/21F+B4F	386	4	208°	B4F*	75	71	49	
					13F	137	113	72	
					21F	121	131	104	
YKH	Yokohama City S/22F+B3F	412	4[*1]	213°	B2F*	60	-	30	
					23F	162	-	72	
OSK	Osaka City S/15F+B3F	759	3	189°	B3F*	11	9	5	
					18F	65	38	7	
SKS	Osaka City S/52F+B3F	770	3	229°	01F*	34	33	80	
					18F	41	39	61	
					38F	86	56	19	
					52FN	126	88	13	52F North
					52FS	130	85	12	52F South

Note) Δ: Epicentral distance, I_{JMA}: JMA seismic intensity scale (calculated using acceleration data of an asterisked sensor), Azimuth: Clockwise direction from North, H1, H2 and V: Maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

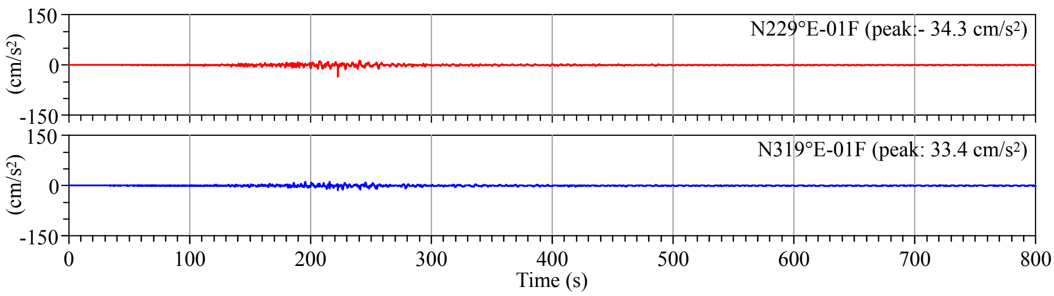
[*1] Calculated using H1 and V components because of abnormality of H2 component.

Remarkable strong motion data were recorded in the SKS station. The building of the SKS station is a 52-storey steel-framed building located in the Osaka Bay area. The building (Photo 2) is 256 meters in height and is the third tallest in Japan. The strong motion instrument of the SKS station has five acceleration sensors on the first floor (01F), 18th floor (18F), 38th floor (38F), and 52nd floor (52FN and 52FS). Two sensors (52FN and 52FS) are placed in the north and south on the 52nd floor to investigate torsional movement.

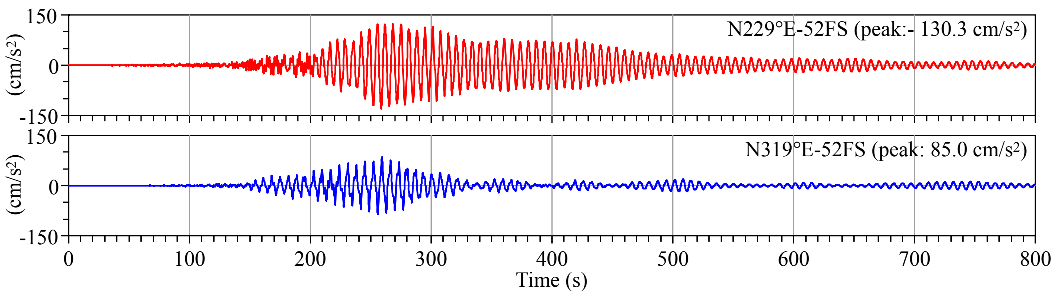
Although the building was 770 kilometres away from the epicentre, it suffered severe shaking. Acceleration waveforms in the horizontal directions on the first floor (01F) and 52nd floor (52FS) are shown in Fig. 3. The acceleration records on the first floor (01F) were affected by the collision of lift cables, so the maximum accelerations by the earthquake motion might be smaller than the values in Table 2 and Fig. 3. In contrast, the maximum acceleration in the N229°E direction on the 52nd floor was extremely large exceeding 130 cm/s^2.

Pseudo velocity response spectra with the 5% damping ratio of the horizontal records on the first floor (01F) are shown in Fig. 4. The response spectra have obvious peaks at the natural periods of about 7 seconds. The predominant periods matched the natural periods of the SKS building, consequently the resonance and the low damping ratios of the building enormously magnified building response. Figure 5 shows Lissajous curves of the displacements on the 52nd floor (52FS) in the horizontal plane at every 20 seconds. The floor was intensely shaken in oval shape from 200 seconds to 300 seconds. Subsequently, the shaking continued for more than 400 seconds mainly in the N229°E direction.

Photo 2. SKS building



(a) First floor (01F)



(b) 52nd floor (52FS)

Figure 3. Acceleration waveforms on the first floor (01F) and 52nd floor (52FS) at SKS

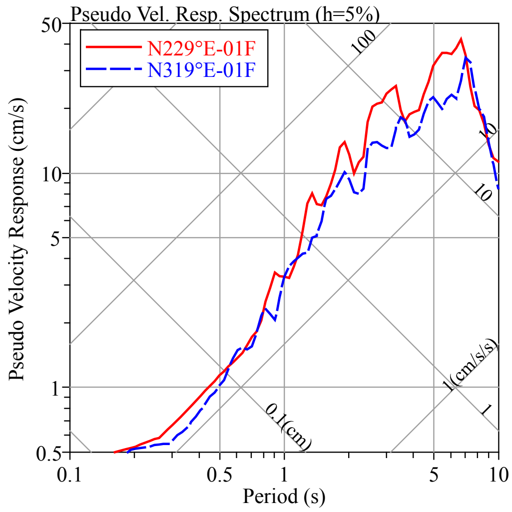


Figure 4. Pseudo velocity response spectra of the records on the first floor (01F) of the SKS building

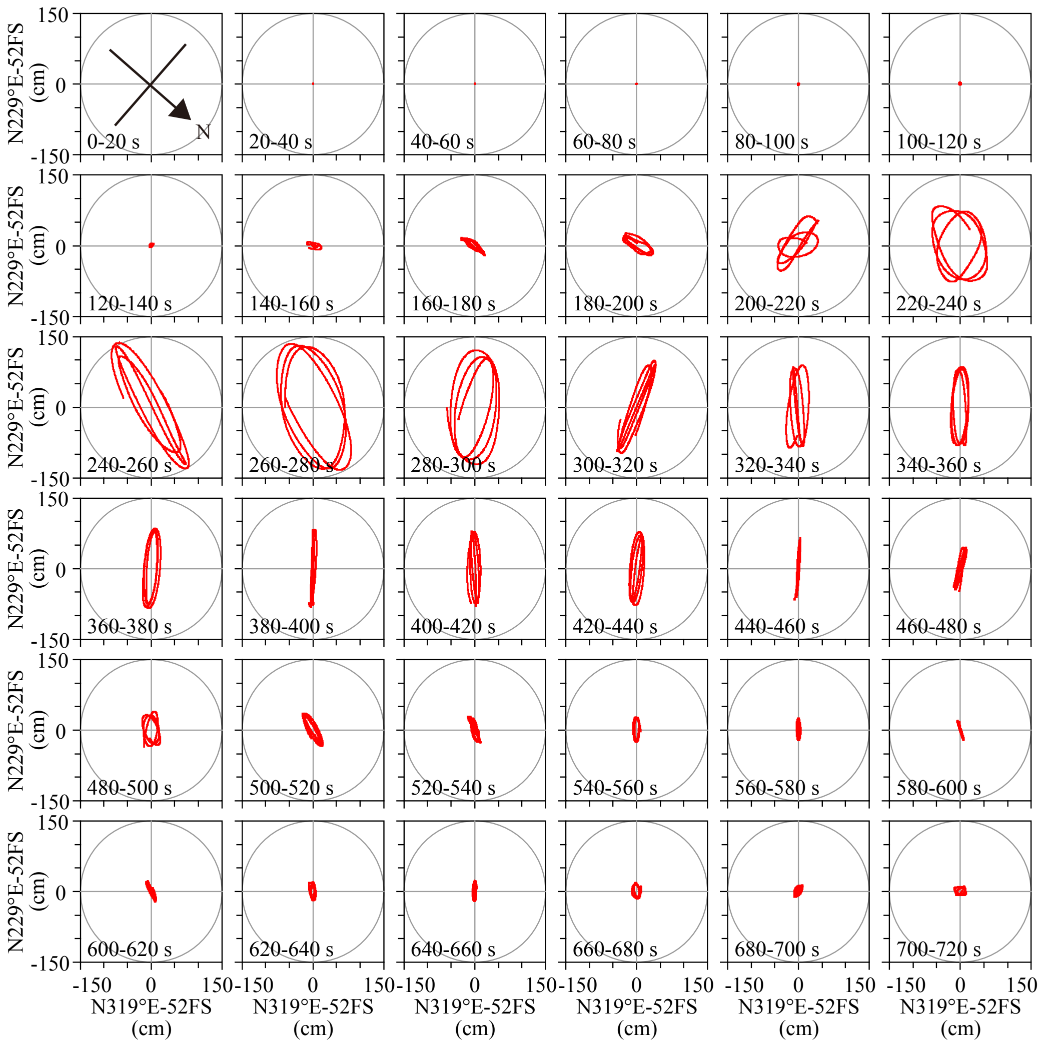


Figure 5. Lissajous curves of displacements on the 52nd floor (52FS) of the SKS building

6. STRONG MOTION DATA RECORDED IN BASE-ISOLATED BUILDINGS

Six base-isolated buildings are instrumented in the BRI strong motion network. All instruments in the base-isolated building have been triggered by the East Japan Earthquake. Maximum accelerations of the strong motion data recorded in the base-isolated buildings are listed in Table 3. The stations are widely distributed from northern Japan to central Japan. In each station, at least three sensors are placed on the floors below the base-isolation devices, above the devices and of building top. In addition, supplementary sensors are set up on and in the ground in some stations.

Table 3. Strong Motion Data recorded in Base-isolated Buildings

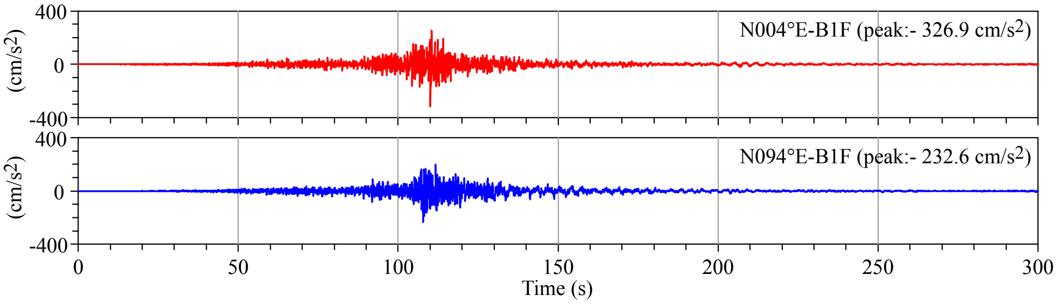
Code	Location Structure/Floors	Δ (km)	I_{JMA}	Azi-muth	Sensor Place	Max. Acc. (cm/s^2) H1	H2	V	Remarks
HCN2	Hachinohe City SRC/10F+B1F	292	5+	164°	GL*	286	210	61	
					G30	86	89	49	GL-30 m
					G105	36	46	32	GL-105 m
					B1F	100	104	58	Below B.D.
					01F	91	122	73	Above B.D.
					10F	120	123	206	
TKC	Tsukuba City Precast Concrete/7F	334	5+	004°	B1F*	327	233	122	Below B.D.
					01F	92	76	198	Above B.D.
					06F	126	91	243	
NMW	Taito Ward, Tokyo RC/3F+B1F	382	5-	218°	GL*	265	194	150	
					B1FW	100	79	84	Below B.D.
					01FW	76	89	87	Above B.D.
					04F	100	77	90	
CG3	Chiyoda Ward, Tokyo SRC/11F+B2F	386	5-	208°	B2F*	104	91	58	Below B.D.
					B1F	55	41	62	Above B.D.
					12F	94	82	104	
YMN	Kofu City RC/8F+B1F	468	4	006°	GL*	51	44	20	
					B1F	47	39	18	Below B.D.
					01F	37	52	20	Above B.D.
					08F	41	51	25	
KGC	Kushiro City SRC/9F+B1F	558	3	167°	GL*	12	14	6	
					G10	10	10	4	GL-10 m
					G34	5	5	3	GL-34 m
					B1F	8	12	4	Below B.D.
					01F	10	16	6	Above B.D.
					09F	16	19	12	

Note) Δ: Epicentral distance, I_{JMA}: JMA seismic intensity scale (calculated using acceleration data of an asterisked sensor), Azimuth: Clockwise direction from North, H1, H2 and V: Maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

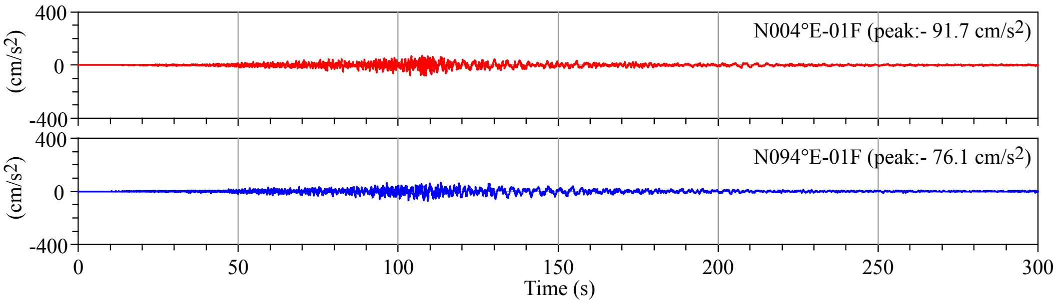
The maximum acceleration on the basement floor (B1F) at the station TKC was 327 cm/s^2 and was the largest value among the base-isolated buildings. The TKC building is a seven-storey precast concrete building located in Tsukuba City as shown in Photo 3. The building is equipped with 11 natural rubber bearings, 45 lead rubber bearings and 9 steel damper rubber bearings between the first floor (01F) and the building foundation (B1F). Acceleration waveforms recorded in the TKC building are shown in Fig. 6. The maximum accelerations in the horizontal directions on the first floor (01F) were reduced to about 30% compared with those on the foundation (B1F) in consequence of the function of the base-isolation devices.

Figure 7 indicates the relationship between the share force (Q) and the displacement of the base-isolation devices in the both of the horizontal directions. The share force was calculated from acceleration records on the first floor (01F) and sixth floor (06F), and the building mass. The device displacement was estimated as the relative displacement of the first floor (01F) to the building foundation (B1F). Each displacement was calculated by the integration using the Fast Fourier Transform (FFT) from the acceleration record. A dotted line represents the skeleton curve of the design hysteresis model of the base-isolation devices. The actual hysteresis generally agrees with the design model and the maximum displacement of the base-isolation devices reached nearly six centimetres. It seems that the base-isolation devices were working properly.

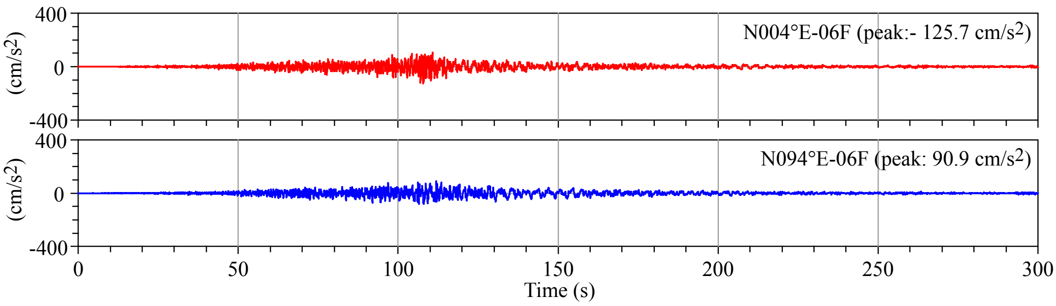
Photo 3. TKC building



(a) Basement floor (B1F, below the base-isolation devices)



(b) First floor (01F, above the base-isolation devices)



(c) Sixth floor (06F)

Figure 6. Acceleration waveforms recorded in the TKC building

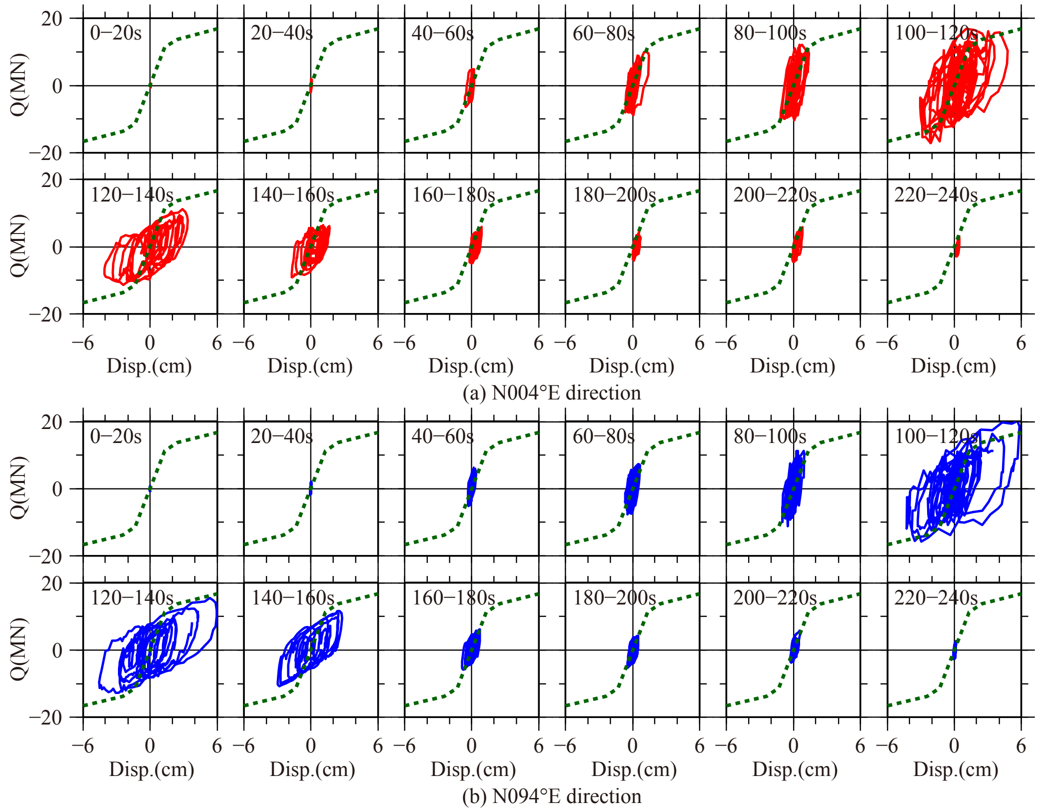


Figure 7. Relationship between share force (Q) and displacement of the base-isolation devices

7. CONCLUSIONS

The BRI network obtained valuable strong motion data in many buildings during the 2011 East Japan Earthquake. Strong motion data in the THU building were able to identify serious damage to the building. Strong motion data in the SKS building captured tremendous vibration caused by the resonance with the predominant long-period earthquake motions at the site 770 kilometres distant from the epicentre. In the TKC station, good performance of the base-isolated building was grasped through the analysis of the strong motion data. We intend to continue the study using a great number of strong motion data brought by the East Japan Earthquake and its aftershocks.

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