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SUMMARY OF RECORDED BUILDING RESPONSES DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE WITH SOME IMPLICATIONS TO DESIGN MOTIONS

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ABSTRACT: During the Great East Japan earthquake, the BRI earthquake observation system retrieved numerous strong motion records from a variety of instrumented buildings and their surrounding ground in wide areas in Japan, including mainly-affected areas as well as highly urbanized areas such as Tokyo and Osaka. Although many buildings in these urban centers were far away from the epicenter, recorded responses from these buildings are very useful to infer their unique characteristics. This paper presents a summary of recorded motions of those instrumented buildings.

Key Words: Great East Japan earthquake, strong motion observation, building response, long-period motions, resonance, long duration

INTRODUCTION

The Building Research Institute (BRI) of Japan conducts strong motion observation of buildings in major cities across Japan [http://smo.kenken.go.jp/]. When the 2011 Off the Pacific coast of Tohoku earthquake (the Great East Japan earthquake, hereafter referred to as the Tohoku earthquake) occurred, 54 building monitoring stations among a total 79, placed in Hokkaido to Kansai triggered. [http://smo.kenken.go.jp/]. Locations of the triggered strong motion stations are shown in Fig.1. The recorded maximum accelerations as well as other pertinent information of each of the recording sites are listed in Table 1. Among them, about 30 buildings experienced shaking with seismic intensity 5 or larger in JMA scale.

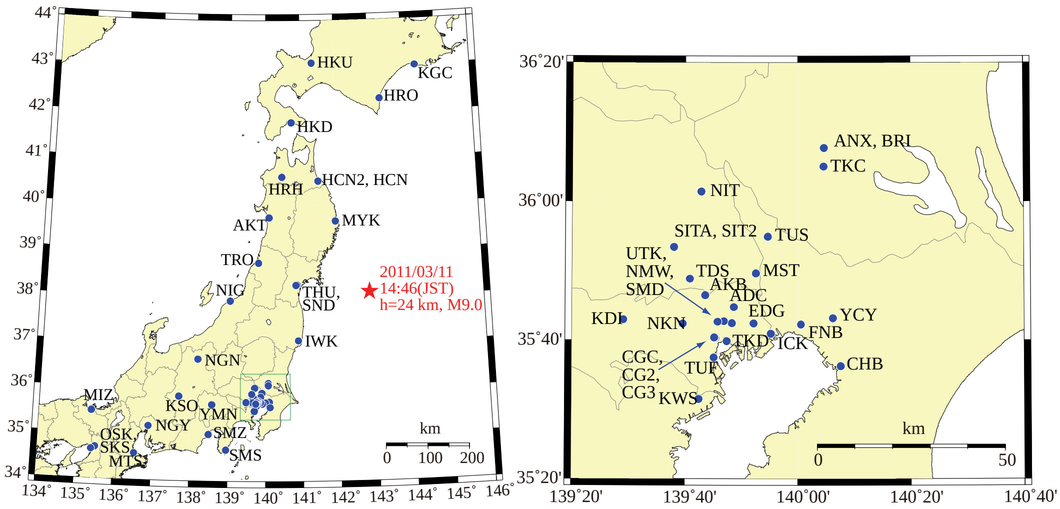

Fig. 1 BRI strong motion observation sites triggering the Tohoku earthquake
(Left: Nation-wide view, Right: Near Tokyo metropolitan area)

The instrumented buildings include variety of types of construction materials of steel or reinforced concrete, heights (low, mid-rise, tall and skyscrapers), design under older or current building standards or with new technology such as base-isolation or response control devices. At present, the inventory of buildings includes nine super high-rise buildings taller than 60 meters in height, and six base-isolated buildings. Studying responses of such types of instrumented buildings are equally important; however, due to limitations, we concentrate on detailed recorded motions from tall buildings and base-isolated buildings recorded during the Tohoku earthquake.

Before the Tohoku earthquake occurred, mega-earthquakes have been expected to occur in the very near future on the southern Pacific coast subduction zones of Japan. Nonetheless, the Tohoku earthquake demonstrated the shaking that is experienced in a very large area far from the epicenter of a such large earthquake.

EARTHQUAKE GROUND MOTIONS AS INPUT TO BUILDINGS

The earthquake motions subjected to buildings in Japan during the Tohoku earthquake are outlined depending upon the areas of the instrumented buildings. The earthquake motions of mainly-affected areas are investigated first. The affected area is wide because the earthquake source size was large causing the rupture to propagatefor a long time. When the recorded motions from K-NET and KiK-net are used, the 5% damped pseudo velocity response spectra with principal locations of the areas were shown in Fig. 2. These recordings are taken from ground surface. The locations of recorded stations in this figure are plotted in Fig. 3 together with the BRI stations explained previously with Fig. 1.

Figure 2 shows that some records exceed a level of 200 cm/s in 5% damped velocity response for periods shorter than approximately 2 second, that are more than double of the spectrum for the engineering bedrock (EB) assigned in the Building Standard Law of Japan. However, the amplitude will not exceed such high level for periods longer than 4 second.

The pseudo velocity response spectra with 5% damping for several records for the BRI stations (those recorded mostly in buildings) from the Tohoku (north-eastern side) area are shown in Fig. 4. The spectra with identical colors indicate a set of horizontal components. The spectra from the BRI stations, SND and IWK, located on the Pacific coastal side, show larger level, and slightly exceed the BSL (EB) spectrum for periods around 2 to 3 seconds. However, for periods longer than 4 second, the spectrum level is not so high, as was also seen from the K-NET station records shown in Fig. 2. The NIG (Niigata) station record shows instead rather larger level in spite of its longer distance from the hypocenter.

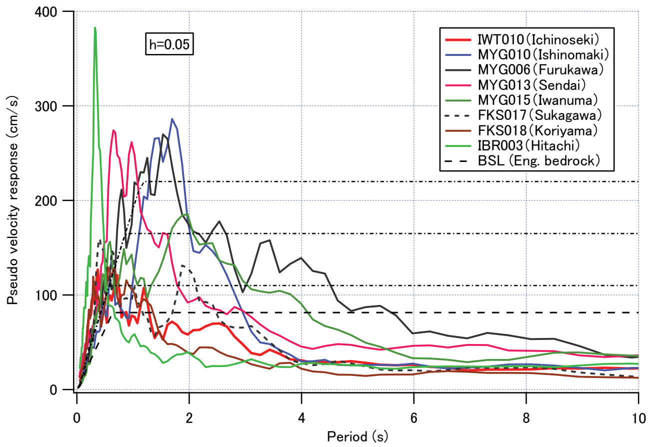

Fig. 2 Pseudo velocity response spectra with 5% damping for severely affected areas

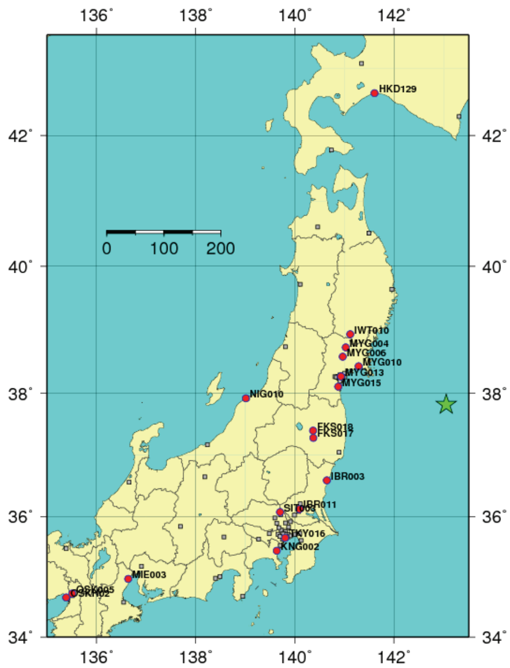

Fig. 3 Locations of the recording stations in Fg.2. Small rectangles are BRI stations

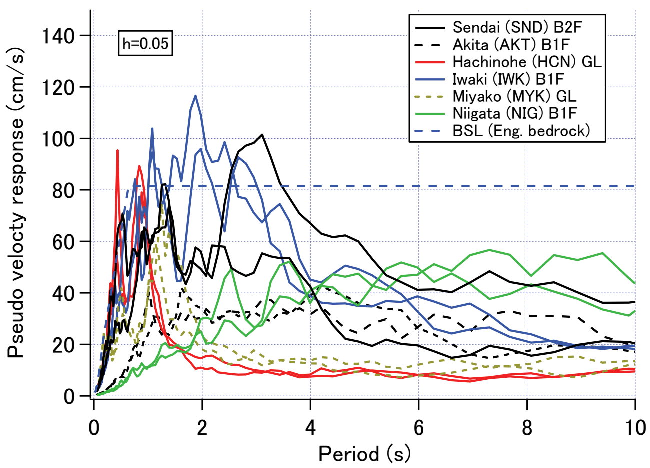

Fig. 4 Pseudo velocity response spectra with 5% damping for BRI stations in Tohoku area

From seismological view point, when the earthquake size is larger, the resultant ground motion contains significant long period components. However, the recorded motions obtained in the immediate affected area do not infer larger motions for periods longer than 4 seconds.

The response spectra shows maximum response indicating an instantaneous response index value. For seeing the property of ground motions such as cumulative plastic deformation, or influence of long duration to inelastic structural responses, the energy spectra with 10% damping are shown in Fig. 5 and compared. The dotted curves shown as BSL mean the averages energy spectra for 10 samples of simulated motions compatible with the BSL (EB) spectrum for 5% damping and the duration time of 120 second.

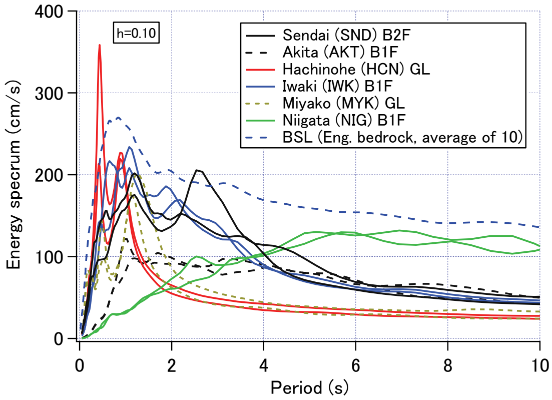

Fig. 5 Energy spectra with 10% damping for BRI stations in Tohoku area

Duration time

The long-period earthquake motion is often characterized as having long lasting later phase vibration with narrow band property. The recorded motions from the affected areas are featured as motions with very long duration time and those relatively close to the epicenter consist of groups of waves arriving with time lags corresponding to the main ruptures on the seismic source. The ground motions lasted extremely long and the durations time was exceptional compared from the large recorded motions in the past.

The difference in duration times is shown in Fig. 6 that compared the velocity histories. The Tohoku university station has records both for the 1978 Miyagiken-oki earthquake and the 2011 Tohoku earthquake. The Tomakomai (HKD129, K-NET) record from 2003 Tokachi-oki earthquake is one of the recorded motions including selective narrow band long-period motion. The difference in duration time between the THU and the near-source JMA-Kobe recorded motion from 1995 Hyogo-ken-Nambu earthquake is clearly seen.

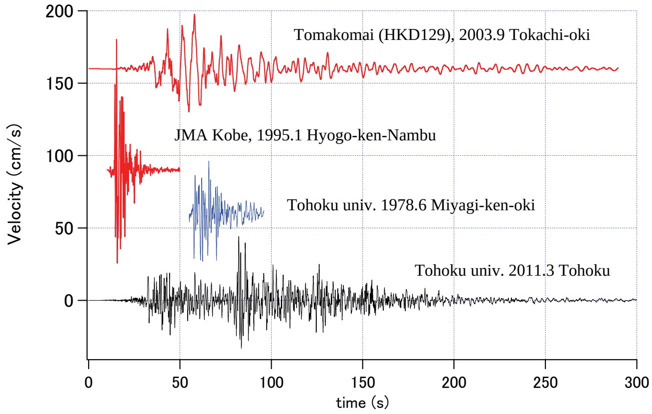

Fig. 6 Comparison of wave duration time

Recorded motions in Tokyo metropolitan area

There were great disruptions in telecommunications, traffic and other aspects of human life of the society in major metropolitan areas of Japan immediately after the Tohoku earthquake. Tall buildings were shaken for long periods of time (e.g. 5-15 minutes), and many elevators stopped trapping people inside.

The earthquake motions in Tokyo are shown in pseudo velocity response spectra and energy spectra in Fig. 7. These figures show spectra for the border area of Tokyo to Chiba with their bay area. It is seen that spectra levels are mostly within the assigned design level for the metropolitan coastal area.

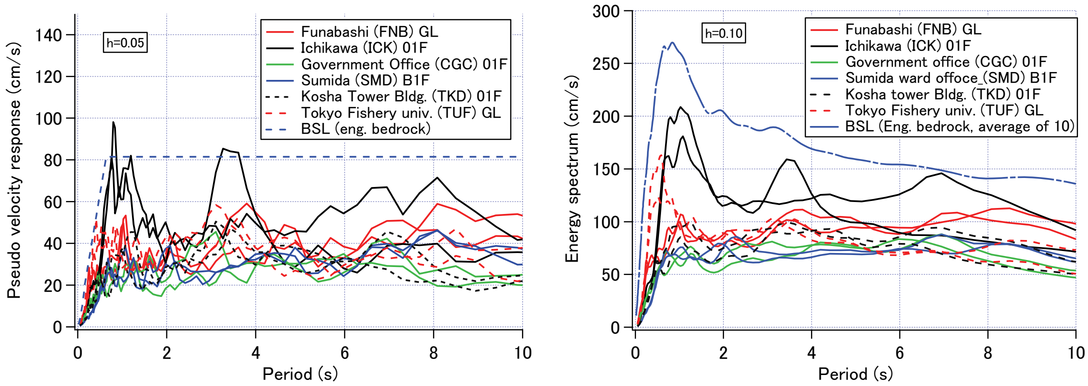

Fig. 7 Left: Pseudo velocity response (h=0.05), Right: Energy spectra (h=0.10) for recorded motions from buildings of Tokyo metropolitan coastal area

In addition, the recorded motions from the western part of Tokyo, i.e., Yamanote and Tama areas, show that the spectra levels are mostly around half of the assigned design level.

RECORDED RESPONSES OF TALL AND BASE-ISOLATED BUILDINGS

Recorded motions from two buildings, the 55 story office building (SKS) in Osaka, and the 7-story base-isolated office building (TKC) in Tsukuba, Ibaraki prefecture are presented as examples. .

The 55-story office building (SKS) in Osaka

This 55-story, steel SKS building was constructed in 1995 on the coast of the Osaka Bay and is the tallest in the western Japan at the time of the earthquake. It has 3 underground floors. The distance from the hypocenter is 770 kilometers. Five tri-axial accelerometers are installed at four levels (1F, 18F, 38F and 52F) as shown in Fig. 8. There is a tri-axial accelerometer on each of the two wings on the 52F floor. The recorded accelerations are shown in Fig. 9. The dominant period estimated from the spectral ratio between 1F and 52F are about 6.5 and 6.9 seconds in X and Y directions, respectively.

It took about 3 minutes for seismic wave to arrive at the area of the building from the epicentral area. It is estimated that the dominant period of the underlying ground above seismic bedrock coincides with the periods of the building. Therefore, a resonance occurred during the Tohoku earthquake, and the displacement at the top was estimated larger than 130 cm. The excess deformation of the building caused disorders such as an entangle of elevator wires, subsequent confinement of passengers and unexpected movement of fire-protection doors to cause breakage of sprinklers etc. and even making people feel sick with long time slow shaking.

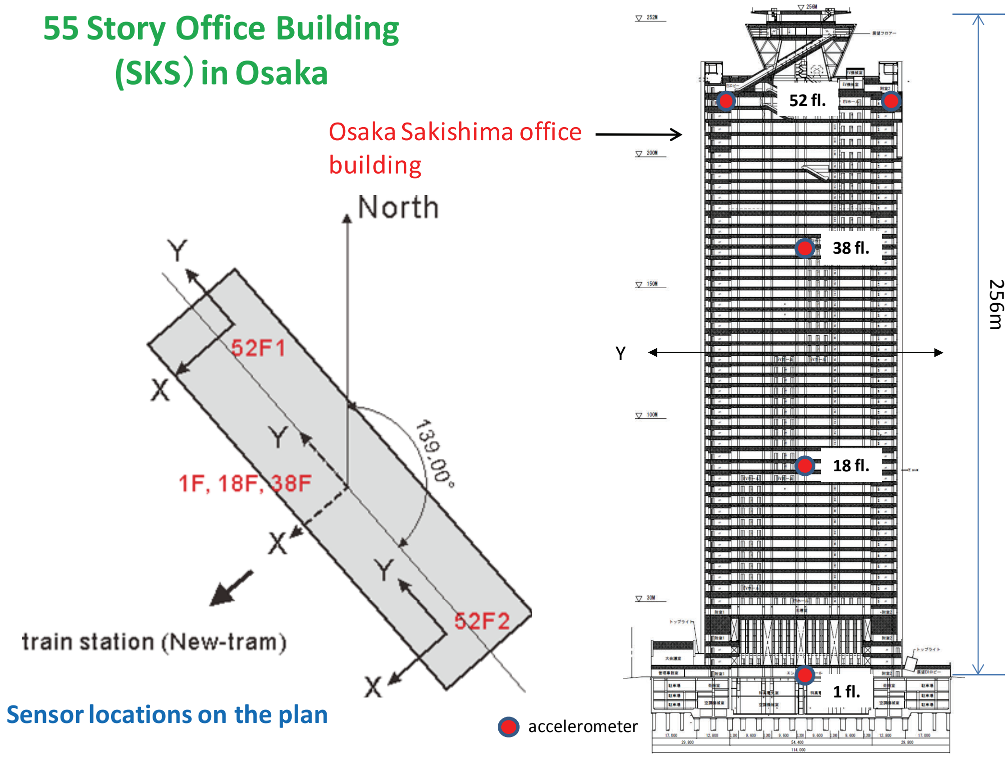

Fig.8 Sensor locations of the Osaka Sakishima (SKS) Office building

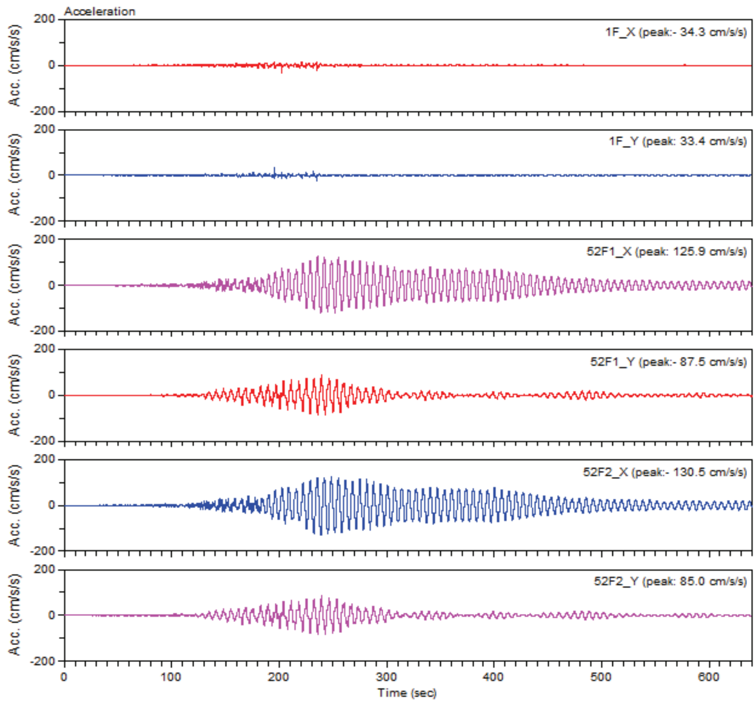

Fig.9 Recorded horizontal accelerations for 1F, 52F1 and 52F2 floors

The spectral ratios between 52F and 1F is computed and shown in Fig. 10. The natural periods for X and Y directions slightly differ. The pseudo velocity response spectra between 1F of Sakishima office and KiK-net Konohana (OSKH02) station is shown in Fig. 11 that displays the dominant periods of the site.

Thirty minutes after the main shock, a moment magnitude Mw 7.7 aftershock occurred off the Ibaraki prefecture. This building responded again to this earthquake and large vibration amplitudes were also recorded.

As was mentioned previously, the large response occurring at this site is explained as follows. The event of large magnitude caused strong long-period motion in the epicenter, propagated and attenuated less than the shorter-period motion. The motion was then amplified by the overlying thick sediment. The motion caused the structural response in resonance with the superstructure. More detailed study of this building is in progress (Çelebi and others, 2012).

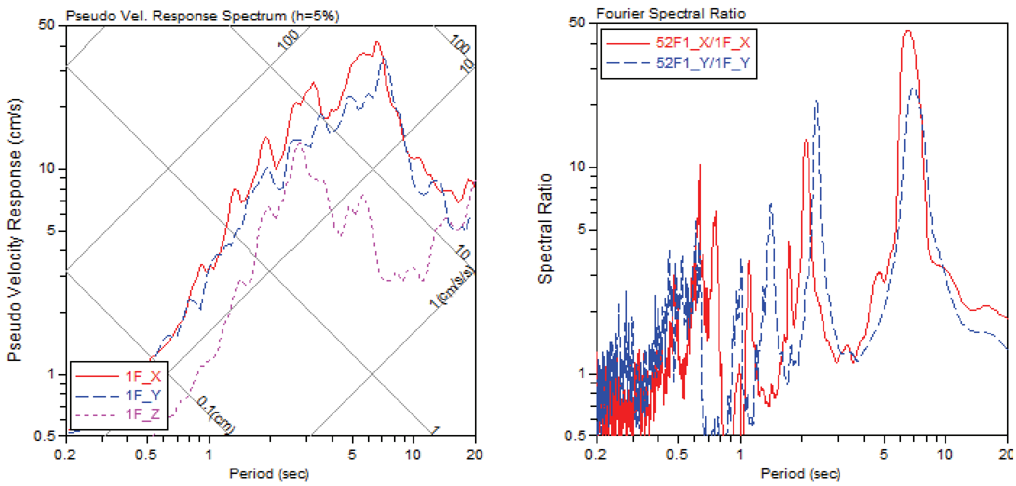

Fig. 10 Pseudo velocity response spectra of the 1F records and spectral ratio between 1F and 52F

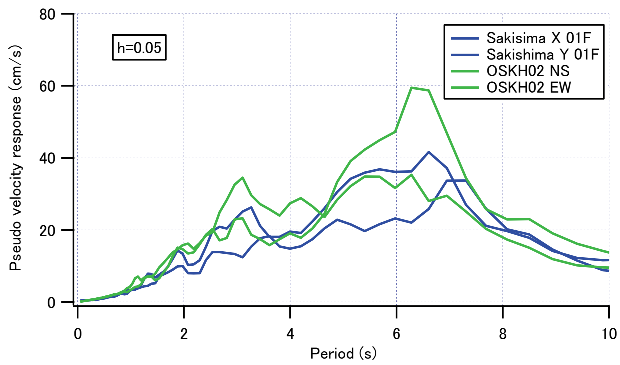

Fig. 11 Comparison of motions with pseudo velocity response spectra between1F of Sakishima office and KiK-net Konohana (OSKH02) station

The 7 story base-isolated office building (TKC) in Tsukuba, Ibaraki prefecture

The 7-story base-isolated precast and prestressed concrete Tsukuba city hall building was constructed in May, 2010. BRI installed tri-axial accelerometers at three locations in the building. The recorded motions recorded by this array during the Tohoku earthquake are shown in Fig. 12. The peak acceleration of motions below the isolator level was reduced by 2/3 on the first floor. The pseudo velocity response spectra for B1F records are shown in Fig. 13. It is noted that there are twodominant periods around 1 and 3.5 seconds. Although the input motion was sizeable wit peak acceleration of 0.33 g, the base-isolation system of this building was effective and the building performed well.

The orbit of displacement response of isolator is shown in Fig.14.

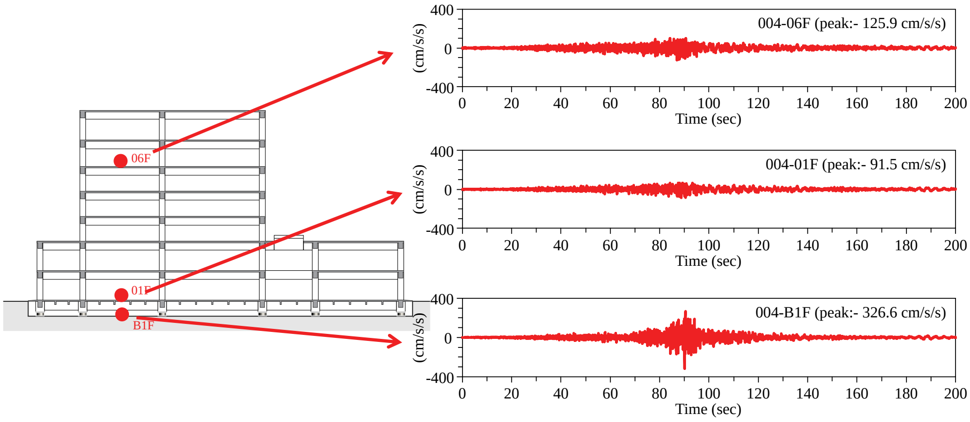

Fig.12 Recorded accelerations of B1F, 1F and 6F floor

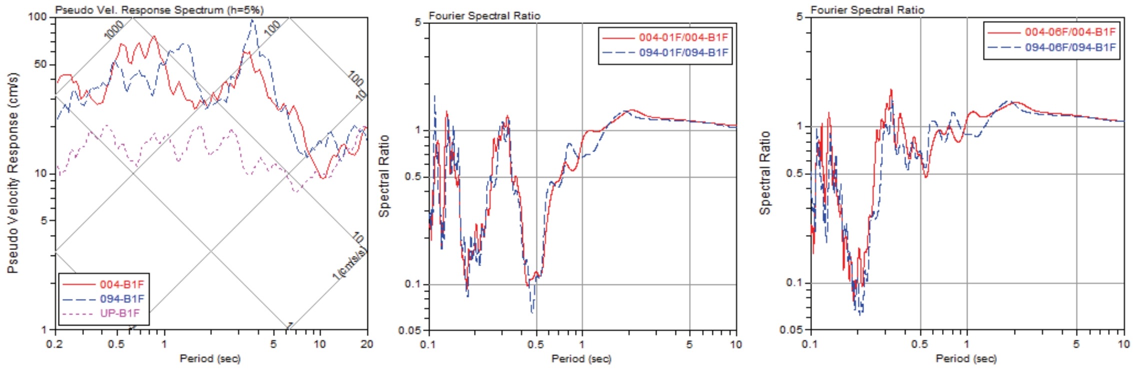

Fig.13 Pseudo velocity response spectrum, spectral ratio between 1F/B1F and 6F/B1F using records from the Tohoku earthquake

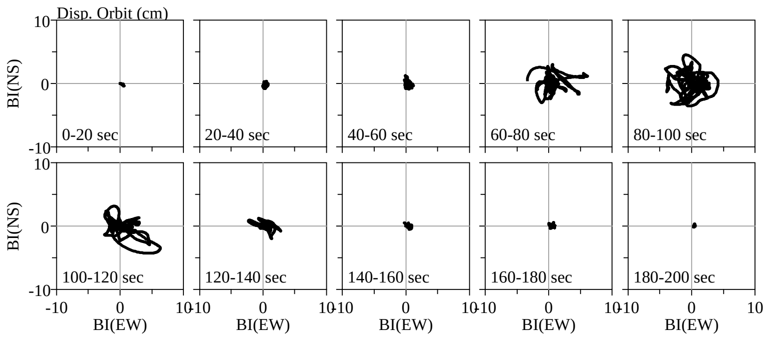

Fig.14 The orbital traces for displacement of isolator

CONCLUSIONS

During the Tohoku earthquake and subsequent aftershocks, many strong earthquake motions with long duration were recorded. The largest ground motion level was comparable with the recorded motions in the past. The duration of earthquake motion was very long due to its source size. The area of larger amplitudes was also wide. The long period motions drew much concern. However, the ground motion with period longer than 4 second was not so violent in affected area and the urbanized metropolitan area. The ground motion with period 2 to 3 second was found dominant in several recording stations. The resonance in high-rise building occurred and recorded with long epicentral distance site. Records from several structurally damaged buildings were also obtained.

Table 1 Strong motion records obtained by BRI strong motion network (1/4)

Code	Station name	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s^2) H1	H2	V
SND	Sendai Government Office Bldg. #2	175	5.2	074°	B2F*	163	259	147
					15F	361	346	543
THU	Tohoku University	177	5.6	192°	01F*	333	330	257
					09F	908	728	640
MYK	Miyako City Hall	188	4.8	167°	01F	138	122	277
					07F	246	197	359
					GL*	174	174	240
IWK	Iwaki City Hall	210	5.3	180°	B1F*	175	176	147
					09F	579	449	260
TRO	Tsuruoka Government Office Bldg.	275	3.9	182°	01F*	34	36	14
					04F	37	39	15
HCN2	Annex, Hachinohe City Hall	292	5.2	164°	GL*	286	210	61
					G30	86	89	49
					G105	36	46	32
					10F	120	123	206
					01F	91	122	73
					B1F	100	104	58
HCN	Main bldg., Hachinohe City Hall	292	4.6	164°	B1F*	97	110	55
					06F	348	335	78
AKT	Akita Prefectural Office	299	4.3	087°	08F	175	192	44
					B1F*	50	47	24
ANX	Building Research Institute	330	5.3	180°	A01*	279	227	248
					A89	142	153	102
					BFE	194	191	136
					8FE	597	506	344
					MBC	203	206	152
					M8C	682	585	311
BRI	Training Lab., BRI	330	5.4	180°	01F*	281	273	165
TKC	Tsukuba City Hall (Base-isolation)	334	5.2	004°	B1F*	327	233	122
					01F	92	76	198
					06F	126	91	243
NIG	Niigata City Hall	335	3.9	061°	B1F*	28	40	14
					07F	39	55	14
HRH	Hirosaki Legal Affairs Office	346	3.4	195°	01F*	28	25	15
TUS	Noda Campus, Tokyo Univ. Of Science	357	5.1	000°	01F*	269	263	151
YCY	Yachiyo City Hall	361	5.3	302°	B1F	140	135	92
					GL*	312	306	171
					07F	486	359	145
NIT	Nippon Institute of Technology	362	5.1	288°	GL*	230	197	79
					01F	150	119	63
					06F	283	322	131
MST	Misato City Hall	367	4.9	258°	01F	72	104	71
					GL*	130	127	73
					07F	219	190	106

Note) Δ: epicentral distance, I_{JMA} : JMA instrumental seismic intensity (using an asterisked sensor), Azimuth: clockwise direction from North, H1, H2, V : maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

Table 1 Strong motion records obtained by BRI strong motion network (2/4)

Code	Station name	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s²) H1	H2	V
FNB	Educational Center, Funabashi City	368	4.7	357°	01F	144	147	63
					GL*	133	145	105
					08F	359	339	141
CHB	Chiba Government Office Bldg. #2	369	4.9	346°	B1F	152	122	51
					08F	375	283	117
					GL*	168	175	100
ICK	Gyotoku Library, Ichikawa City	375	5.2	321°	01F*	164	163	71
					02F	178	186	80
					05F	240	300	104
EDG	Edogawa Ward Office	377	4.8	003°	01F*	112	112	69
					05F	256	299	77
ADC	Adachi Government Office Bldg.	377	4.8	012°	01F*	118	103	71
					04F	266	146	95
SIT2	Saitama Shintoshin Government Office Building #2	378	4.4	340°	B3F*	74	63	42
					10FS	119	138	62
					27FS	248	503	107
SITA	Arena, Saitama Shintoshin Government Office Building	378	4.5	313°	01F*	90	105	47
TDS	Toda City Hall	380	5.0	354°	GL*	203	206	53
					B1F	140	173	65
					08F	425	531	160
AKB	Akabane Hall, Kita Ward	380	4.6	354°	B1F*	85	139	59
					06F	180	250	86
SMD	Sumida Ward Office	380	4.3	000°	20F	385	290	81
					08F	263	197	46
					B1F*	69	66	34
NMW	National Museum of Western Art (Base-isolation)	382	4.8	218°	GL*	265	194	150
					B1FW	100	79	84
					01FW	76	89	87
					04F	100	77	90
UTK	Bldg. #11, University of Tokyo	383	4.7	348°	7FN	181	212	58
					7FS	201	360	160
					01F	73	151	49
					GL*	197	218	79
TKD	Kosha Tower Tsukuda	385	4.4	180°	01F*	87	98	41
					18F	118	141	64
					37F	162	198	108
CGC	Central Government Office Bldg. #6	386	4.4	208°	01F*	90	86	45
					20B	208	148	173
					19C	179	133	130
CG2	Central Government Office Bldg. #2	386	4.2	208°	B4F*	75	71	49
					13F	137	113	72
					21F	121	131	104
CG3	Central Government Office Bldg. #3 (Base-isolation)	386	4.5	208°	B2F*	104	91	58
					B1F	55	41	62
					12F	94	82	104

Note) Δ: epicentral distance, I_{JMA} : JMA instrumental seismic intensity (using an asterisked sensor), Azimuth: clockwise direction from North, H1, H2, V : maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

Table 1 Strong motion records obtained by BRI strong motion network (3/4)

Code	Station name	Δ (km)	I_{JMA}	Azimuth	Loc.	Max. Acc. (cm/s^2)		
						H1	H2	V
NDLA	Annex, National Diet Library	387	4.5	354°	B8F	61	88	53
					B4F	68	101	56
					01F*	76	104	84
					04F	125	192	94
NDLG	Ground, National Diet Library	387	5.0	354°	G35	72	71	51
					G24	95	116	54
					GL*	224	201	93
NDLM	Main Bldg., National Diet Library	387	4.5	354°	01S*	70	94	60
					17S	458	489	111
NKN	Nakano Branch, Tokyo Legal Affairs Bureau	390	4.8	359°	06F	172	375	56
					01F*	126	158	54
TUF	Tokyo University of Marine Science and Technology	390	5.0	000°	01F	174	169	60
					GL*	181	189	71
					07F	316	223	66
KDI	College of Land, Infrastructure and Transport	401	4.6	090°	03F	129	329	55
					01F	110	136	53
					GL*	167	143	50
KWS	Kawasaki-minami Office, Labour Standards Bureau	401	4.7	045°	01F*	107	77	30
					02F	133	123	49
					07F	366	304	76
NGN	Nagano Prefectural Office	444	2.7	157°	B1F*	8	7	8
					11F	35	27	9
HKD	Hakodate Development and Construction Department	447	3.5	180°	GL*	25	28	13
HRO	Hiroo Town Office	466	2.7	140°	01F*	17	20	8
YMN	Yamanashi Prefectural Office (Base-isolation	468	3.9	006°	B1F	47	39	18
					GL*	51	44	20
					01F	37	52	20
					08F	41	51	25
SMS	Shimoda Office, Shizuoka Prefecture	517	2.9	225°	GL*	12	19	10
SMZ	Shimizu Government Office Bldg.	520	4.2	165°	01F*	28	40	15
					11F	81	56	18
KSO	Kiso Office, Nagano Prefecture	524	2.6	292°	B1F*	9	10	8
					6F	32	31	10
KGC	Kushiro Government Office Bldg. (Base-isolation)	558	2.6	167°	GL*	12	14	6
					G10	10	10	4
					G34	5	5	3
					B1F	8	12	4
					01F	10	16	6
					09F	16	19	12
HKU	Hokkaido University	567	2.7	172°	GL*	10	9	5
NGY	Nagoya Government Office Bldg. #1	623	3.1#	174°	GL*	8	15	-
					B2F	9	14	7
					12F	25	46	7
MTS	Matsusaka Office, Mie Prefecture	688	2.3	216°	07F	16	8	4
					01F*	6	5	3

Note) Δ: epicentral distance, I_{JMA} : JMA instrumental seismic intensity (using an asterisked sensor), Azimuth: clockwise direction from North, H1, H2, V : maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

Table 1 Strong motion records obtained by BRI strong motion network (4/4)

Code	Station name	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s²)		
						H1	H2	V
MIZ	Maizuru City Hall	726	0.9	085°	01F	1	2	2
					05F*	1	1	2
OSK	Osaka Government Office Bldg. #3	759	2.9	189°	18F	65	38	7
					B3F*	11	9	5
SKS	Sakishima Office, Osaka Prefecture	770	3.0	229°	01F*	35	33	80
					18F	41	38	61
					38F	85	57	18
					52FN	127	88	13
					52FS	129	85	12

Note) Δ: epicentral distance, I_{JMA} : JMA instrumental seismic intensity (using an asterisked sensor), Azimuth: clockwise direction from North, H1, H2, V : maximum accelerations in horizontal #1 (Azimuth), horizontal #2 (Azimuth+90°) and vertical directions

Calculated from two horizontal accelerations because of trouble on the vertical sensor.

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The K-NET, KiK-net data were used. The program GMT (Wessel and Smith, 1998) was also used for making maps in Fig.1 and Fig.3.

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