5. Earthquake Motions and Strong Motion Observation in Buildings

5.1 Distribution of Seismic Intensities

Figure 5.1-1 shows the distribution of JMA seismic intensities recorded during the 2011 Tohoku earthquake. An asterisk represents the location of the epicenter. Intensity 7 was recorded in Kurihara city, Miyagi prefecture, and JMA intensity 6 upper (6+) was recorded in wide area of Miyagi, Fukushima, Ibaraki, and Tochigi prefectures. Area of JMA intensity 6 lower (6-) extends to Iwate, Gunma, Saitama, and Chiba prefectures in addition to Miyagi, Fukushima, Ibaraki, and Tochigi prefectures.

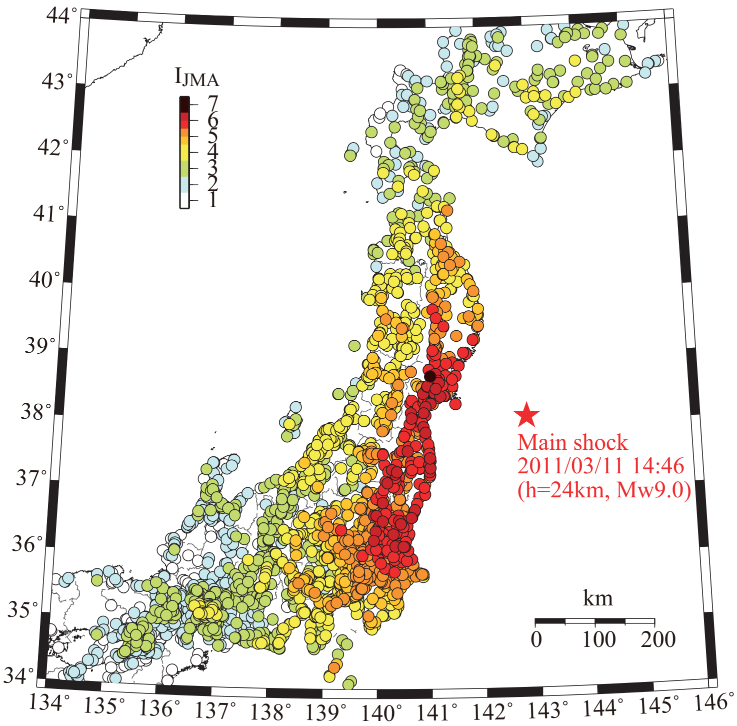

Fig. 5.1-1 Distribution of JMA seismic intensity

5.2 Characteristics of Earthquake Motions

When the 2011 Tohoku earthquake occurred, severe ground shakings were observed in wide area, and massive amount of strong motion records were accumulated. This section describes the characteristics of the strong motion records at observation stations that suffered high seismic intensities, based on the strong motion network K-NET of the National Research Institute for Earth Science and Disaster Prevention (NIED)[5-1]. Fig. 5.2-1 shows acceleration waveforms and pseudo velocity response spectra with damping ratio of 5% of strong motion records at K-NET Tsukidade station that recorded Intensity 7, and K-NET Sendai and K-NET Hitachi stations among Intensity 6+ stations, with the locations of the stations.

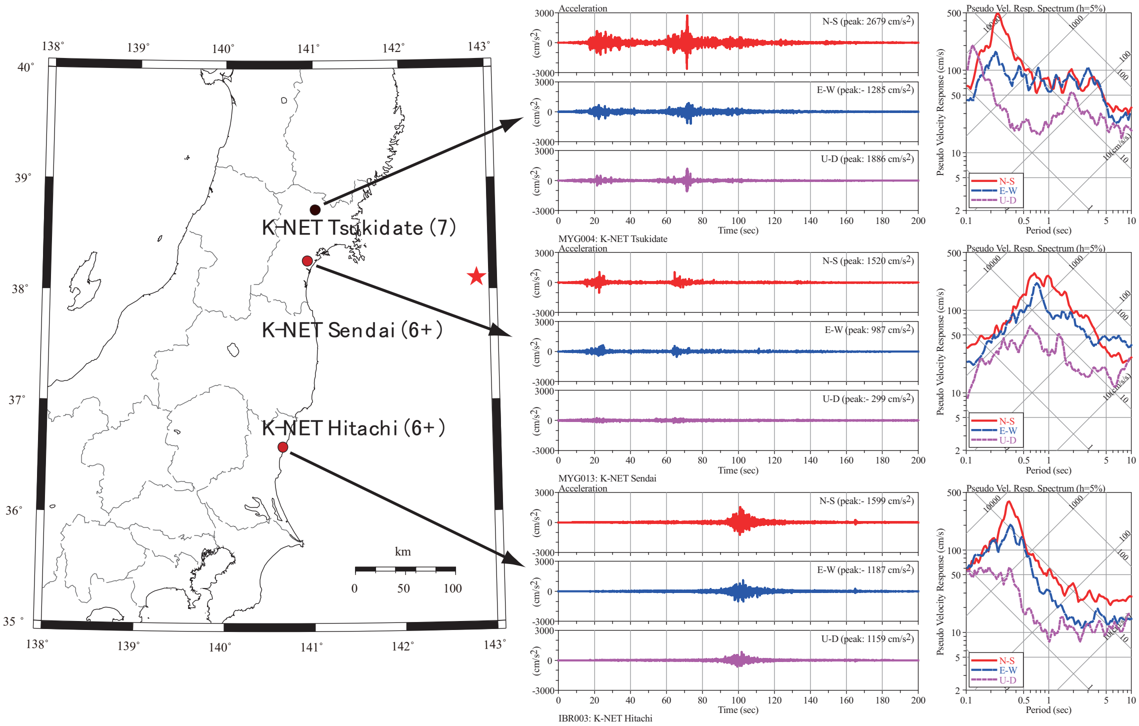

Fig. 5.2-1 Acceleration waveforms and pseudo velocity response spectra recorded at K-NET stations

K-NET Tsukidade, which is located in Kurihara city, Miyagi prefecture, was the only station that recorded Intensity 7 during the main shock of the 2011 Tohoku earthquake. From the acceleration records in the upper-row in Fig. 5.2-1, a maximum acceleration in the N-S direction reached almost 3,700 cm/s^2, representing that the mainshock caused excessively severe earthquake motions. As seen from the pseudo velocity responses on the right diagram, a response in the N-S direction with a period of about 0.2 s becomes particularly large. This indicates earthquake ground motions that were dominated by short periods.

K-NET Sendai, which is located about 4 km east from the JR Sendai Station, recorded Intensity 6+ during the mainshock. A maximum acceleration in strong motion records (mid-row in Fig. 5.2-1) obtained from the network exceeds 1,500 cm/s^2 in the N-S direction, indicating a higher level of the main shock. In contrast to K-NET Tsukidate, earthquake motions that were recorded in K-NET Sendai were dominated by a period range of 0.5 to about 1 s, and a maximum response velocity exceeds 200 cm/s. This result seems to reflect the ground condition around K-NET Sendai station that is covered with thick alluvium.

The lower-row in Fig. 5.2-1 shows strong motion records that were obtained from K-NET Hitachi in Hitachi city, Ibaraki prefecture. The seismic intensity with the mainshock was 6+. The maximum acceleration in the N-S direction reached a higher level, or about 1600 cm/s^2, while the pseudo velocity response spectra had a peak at about 0.3 s. On the other hand, the response was sharply reduced at a period longer than 0.5 s. This indicates that the earthquake motions were dominated in short period range.

Both records of K-NET Tsukidate and K-NET Sendai show two wave groups at about 20 and 70 seconds on the time axis, but the strong motion record obtained at much southern station such as K-NET Hitachi, Ibaraki prefecture in Kanto area shows one large wave group. This phenomenon may have occurred associated with the focal rupture process and the wave propagation to recording stations.

5.3 Results of BRI Strong Motion Observation Network

BRI conducts strong motion observation that covers buildings in major cities across Japan[5-2)]. When the 2011 Tohoku earthquake occurred, 58 strong motion instruments placed in Hokkaido to Kansai started up[5-2)]. Peak accelerations of the strong motion records are listed in Table 5.3-1. Locations of the strong motion stations are plotted in Fig. 5.3-1 and Fig. 5.3-2. Among them, about 30 buildings suffered a shaking with JMA intensity 5- or higher. This section presents some characteristics of strong motion records.

The detailed data on the recorded motions from the BRI strong motion observation network can be seen through the Internet at http://smo.kenken.go.jp/

Table 5.3-1 Strong motion records obtained by BRI observation network (1/4)

Code	Station name [prefecture]	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s^2)		
						H1	H2	V
SND	Sendai Government Office Bldg. No.2 [Miyagi]	175	5.2	074°	B2F*	163	259	147
					15F	361	346	543
THU	Tohoku University [Miyagi]	177	5.6	192°	01F*	333	330	257
					09F	908	728	640
MYK	Miyako City Hall [Iwate]	188	4.8	167°	01F	138	122	277
					07F	246	197	359
					GL*	174	174	240
IWK	Iwaki City Hall [Fukushima]	210	5.3	180°	B1F*	175	176	147
					09F	579	449	260
TRO	Tsuruoka Government Office Bldg. [Yamagata]	275	3.9	182°	01F*	34	36	14
					04F	37	39	15
HCN2	Annex, Hachinohe City Hall [Aomori]	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 [Aomori]	292	4.6	164°	B1F*	97	110	55
					06F	348	335	78
AKT	Akita Prefectural Office [Akita]	299	4.3	087°	08F	175	192	44
					B1F*	50	47	24
ANX	Building Research Institute [Ibaraki]	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 [Ibaraki]	330	5.4	180°	01F*	281	273	165
TKC	Tsukuba City Hall (Base-isolation) [Ibaraki]	334	5.2	004°	B1F*	327	233	122
					01F	92	76	198
					06F	126	91	243
NIG	Niigata City Hall [Niigata]	335	3.9	061°	B1F*	28	40	14
					07F	39	55	14
HRH	Hirosaki Legal Affairs Office [Aomori]	346	3.4	195°	01F*	28	25	15
TUS	Noda Campus, Tokyo Univ. of Science [Saitama]	357	5.1	000°	01F*	269	263	151
YCY	Yachiyo City Hall [Chiba]	361	5.3	302°	B1F	140	135	92
					GL*	312	306	171
					07F	486	359	145
NIT	Nippon Institute of Technology [Saitama]	362	5.1	288°	GL*	230	197	79
					01F	150	119	63
					06F	283	322	131
MST	Misato City Hall [Saitama]	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

Table5.3-1 Strong motion records obtained by BRI observation network (2/4)

Code	Station name [prefecture]	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s^2)		
						H1	H2	V
FNB	Educational Center, Funabashi City [Chiba]	368	4.7	357°	01F	144	147	63
					GL*	133	145	105
					08F	359	339	141
CHB	Chiba Government Office Bldg. No.2 [Chiba]	369	4.9	346°	B1F	152	122	51
					08F	375	283	117
					GL*	168	175	100
ICK	Gyotoku Library, Ichikawa City [Chiba]	375	5.2	321°	01F*	164	163	71
					02F	178	186	80
					05F	240	300	104
EDG	Edogawa Ward Office [Tokyo]	377	4.8	003°	01F*	112	112	69
					05F	256	299	77
ADC	Adachi Government Office Bldg. [Tokyo]	377	4.8	012°	01F*	118	103	71
					04F	266	146	95
SIT2	Saitama Shintoshin Government Office Building No.2 [Saitama]	378	4.4	340°	B3F*	74	63	42
					10FS	119	138	62
					27FS	248	503	107
SITA	Arena, Saitama Shintoshin Government Office Building [Saitama]	378	4.5	313°	01F*	90	105	47
TDS	Toda City Hall [Saitama]	380	5.0	354°	GL*	203	206	53
					B1F	140	173	65
					08F	425	531	160
AKB	Akabane Hall, Kita Ward [Tokyo]	380	4.6	354°	B1F*	85	139	59
					06F	180	250	86
SMD	Sumida Ward Office [Tokyo]	380	4.3	000°	20F	385	290	81
					08F	263	197	46
					B1F*	69	66	34
NMW	National Museum of Western Art (Base-isolation) [Tokyo]	382	4.8	218°	GL*	265	194	150
					B1FW	100	79	84
					01FW	76	89	87
					04F	100	77	90
UTK	Bldg. No.11, The University of Tokyo [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 [Tokyo]	385	4.4	180°	01F*	87	98	41
					18F	118	141	64
					37F	162	198	108
CGC	Central Government Office Bldg. No.6 [Tokyo]	386	4.4	208°	01F*	90	86	45
					20B	208	148	173
					19C	179	133	130
CG2	Central Government Office Bldg. No.2 [Tokyo]	386	4.2	208°	B4F*	75	71	49
					13F	137	113	72
					21F	121	131	104
CG3	Central Government Office Bldg. No.3 (Base-isolation) [Tokyo]	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 5.3-1 Strong motion records obtained by BRI observation network (3/4)

Code	Station name [prefecture]	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s^2)		
						H1	H2	V
NDLA	Annex, National Diet Library [Tokyo]	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 [Tokyo]	387	5.0	354°	G35	72	71	51
					G24	95	116	54
					GL*	224	201	93
NDLM	Main Bldg., National Diet Library [Tokyo]	387	4.5	354°	01S*	70	94	60
					17S	458	489	111
NKN	Nakano Branch, Tokyo Legal Affairs Bureau [Tokyo]	390	4.8	359°	06F	172	375	56
					01F*	126	158	54
TUF	Tokyo University of Marine Science and Technology [Tokyo]	390	5.0	000°	01F	174	169	60
					GL*	181	189	71
					07F	316	223	66
KDI	College of Land, Infrastructure and Transport [Tokyo]	401	4.6	090°	03F	129	329	55
					01F	110	136	53
					GL*	167	143	50
KWS	Kawasaki-minami Office, Labour Standards Bureau [Kanagawa]	401	4.7	045°	01F*	107	77	30
					02F	133	123	49
					07F	366	304	76
NGN	Nagano Prefectural Office [Nagano]	444	2.7	157°	B1F*	8	7	8
					11F	35	27	9
HKD	Hakodate Development and Construction Department [Hokkaido]	447	3.5	180°	GL*	25	28	13
HRO	Hiroo Town Office [Hokkaido]	466	2.7	140°	01F*	17	20	8
YMN	Yamanashi Prefectural Office (Base-isolation) [Yamanashi]	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 [Shizuoka]	517	2.9	225°	GL*	12	19	10
SMZ	Shimizu Government Office Bldg. [Shizuoka]	520	4.2	165°	01F*	28	40	15
					11F	81	56	18
KSO	Kiso Office, Nagano Prefecture [Nagano]	524	2.6	292°	B1F*	9	10	8
					6F	32	31	10
KGC	Kushiro Government Office Bldg. (Base-isolation) [Hokkaido]	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 [Hokkaido]	567	2.7	172°	GL*	10	9	5
NGY	Nagoya Government Office Bldg. No.1 [Aichi]	623	3.1#	174°	GL*	8	15	-
					B2F	9	14	7
					12F	25	46	7

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.

Table 5.3-1 Strong motion records obtained by BRI observation network (4/4)

Code	Station name [prefecture]	Δ (km)	I_{JMA}	Azi-muth	Loc.	Max. Acc. (cm/s^2)		
						H1	H2	V
MTS	Matsusaka Office, Mie Prefecture [Mie]	688	2.3	216°	07F	16	8	4
					01F*	6	5	3
MIZ	Maizuru City Hall [Kyoto]	726	0.9	085°	01F	1	2	2
					05F*	1	1	2
OSK	Osaka Government Office Bldg. No.3 [Osaka]	759	2.9	189°	18F	65	38	7
					B3F*	11	9	5
SKS	Sakishima Office, Osaka Prefecture [Osaka]	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

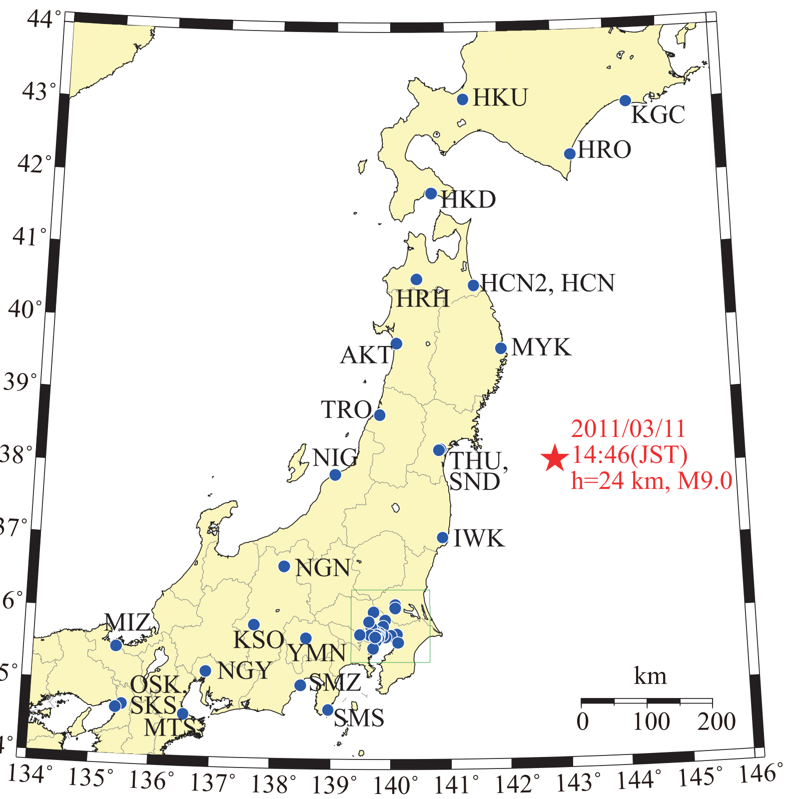

Fig. 5.3-1 Locations of epicenter (★) and BRI strong motion stations (●)

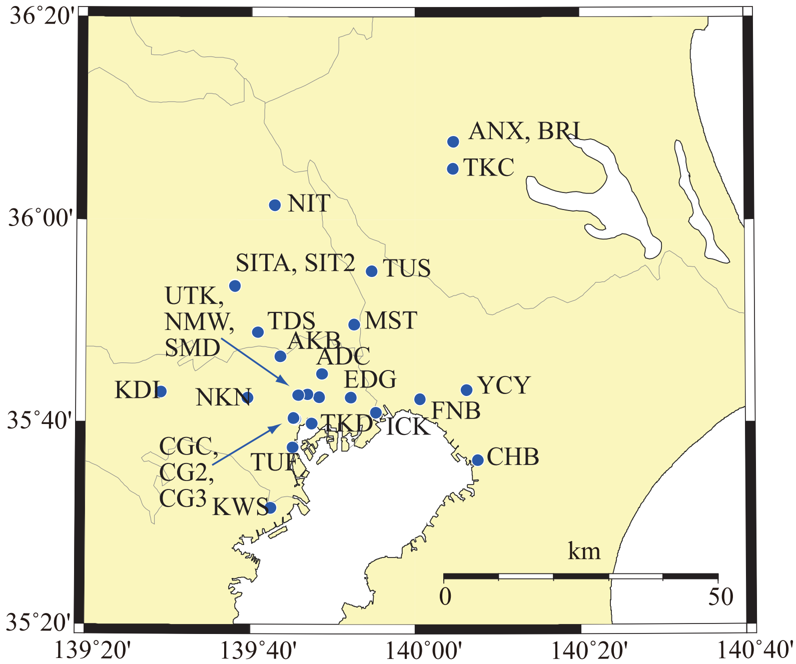

Fig. 5.3-2 BRI strong motion stations in Kanto area (corresponding to the green rectangle in Fig. 5.3-1)

5.3.1 Strong motion records of damaged buildings

Among buildings in the BRI strong motion network, at least 4 buildings suffered severe earthquake motions and then some damage. One example of the damaged buildings is the research building of Civil Engineering and Architecture, Tohoku University (Photo 5.3-1). This is the 9-story reinforced concrete with embedded steel frames (SRC) school building that is located in the Aobayama Campus of Tohoku University. This building has a long history of strong motion observation. Among them, strong motion records on the ninth floor of the building that had been obtained in the 1978 Miyagi-ken-oki earthquake are well known to have represented a maximum acceleration of more than 1,000 cm/s^2.

During the Tohoku earthquake, multi-story shear walls suffered flexural failure and other damage. Strong motion records were obtained during the mainshock as shown in Fig. 5.3-3. Maximum accelerations on the first floor exceeded 330 cm/s^2 in both of the directions. A maximum acceleration on the ninth floor was twice to three times larger than that on the first floor, and exceeded 900 cm/s^2 in the transverse direction. The fundamental natural periods in Fig. 5.3-3 (e) represented about 0.7 s at the initial time of the earthquake motion in both of the directions, but increased to about 1 s in the first wave group at the time of 40 to 50 s, and increased from 1.2 s to about 1.5 s in the second wave group at the time of 80 to 100 s. Due to the seismic damage, the fundamental natural period finally became twice longer than the natural period at the initial stage. The stiffness of the building was reduced to 1/4.

Photo 5.3-1 The research building of Tohoku University

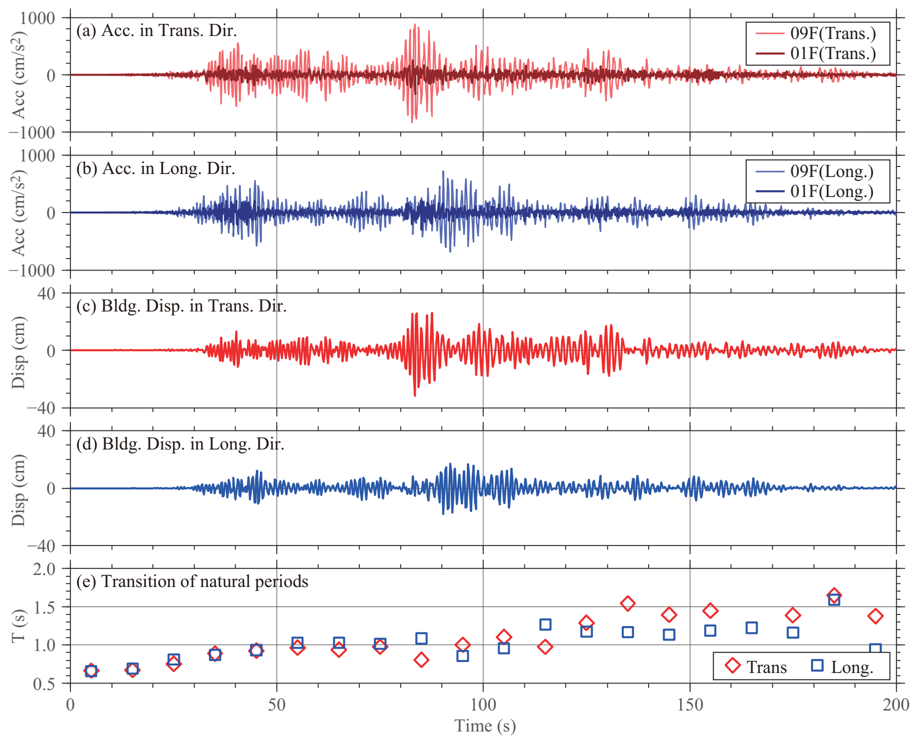

Fig. 5.3-3 Strong motion records of the research building of Tohoku University and transition of natural periods with time. (a) acceleration waveforms in the transverse direction, (b) acceleration waveforms in the longitudinal direction, (c) building displacement in the transverse direction (relative displacement to first floor of the 9-story building), (d) building displacement in the longitudinal direction, and (e) fundamental natural periods of the building that were calculated every 10 s[5-3)]. Thick and thin lines in Fig. 5.3-3 (a) and (b) represent acceleration waveforms on the first and ninth floors, respectively.

5.3.2 Long-period earthquake motions in Tokyo and Osaka

In Japan, long-period earthquake motions and responses of super high-rise buildings that are shaken under the motions have been socially concerned in recent years. When the 2011 Tohoku earthquake occurred, long-period earthquake motions were observed in Tokyo, Osaka and other large cities that were away from its hypocenter. This section presents two cases in Tokyo and Osaka from the BRI observation network.

Firstly, a 37-story reinforced concrete (RC) super high-rise building on the coast of Tokyo Bay is introduced. Fig. 5.3-4 shows waveforms of displacement (in two horizontal directions of S-N and W-E) that were calculated from the integration of acceleration records on the 1st and 37th floors in this building, and building displacements that were calculated by subtracting the displacements on the 1st floor from those on the 37th in the two horizontal directions. A maximum value of ground motion displacement was about 20 cm. It is understood that the ground itself was greatly shaken. A displacement of the building caused by its deformation reached 15 to 17 cm.

Secondly, Figure 5.3-5 shows strong motion records that were obtained from the 55-story steel office building on the coast of Osaka Bay that is 770 km away from the hypocenter. The figure represents absolute displacements in the SW-NE and in the NW-SE on the 1st floor, absolute displacements in both of the directions on the 52nd floor, and building displacements (relative displacements of 52th floor to 1st floor) in both of the directions. A ground motion displacement was not large, or less than 10 cm, but the 52nd floor in the building suffered a large motion with a zero-to-peak amplitude of more than 130 cm (displacement).

In order to examine the properties of earthquake motions on both of the coasts of Tokyo Bay and Osaka Bay, pseudo velocity response spectra with a dumping ratio of 5% of strong motion records that were obtained from the 1st floors in the buildings at the two locations are shown in Fig. 5.3-6. The response spectrum (left) in the records on the coast of Tokyo Bay had peaks at a period of 1 to 1.2 s, at 3 s and at 7 s, but a relatively flat shape in general.

On the other hand, the response spectrum (right) in the records on the coast of Osaka Bay had a large peak at 7 s, and amplitude of the response was not much different from on the coast of Tokyo Bay. The coincidence of the fundamental natural period (6.5 to 7 s) in the office building with a predominant period of the earthquake motion is considered to have caused a resonance phenomenon and then large building motions.

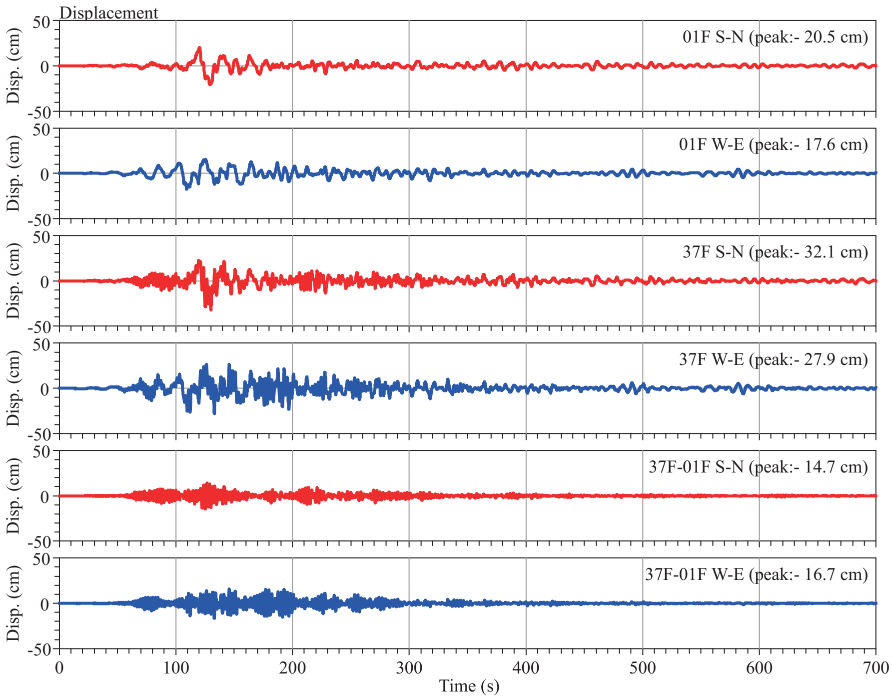

Fig. 5.3-4 Displacement waveforms observed at a 37-story residential building in

Tokyo Bay area

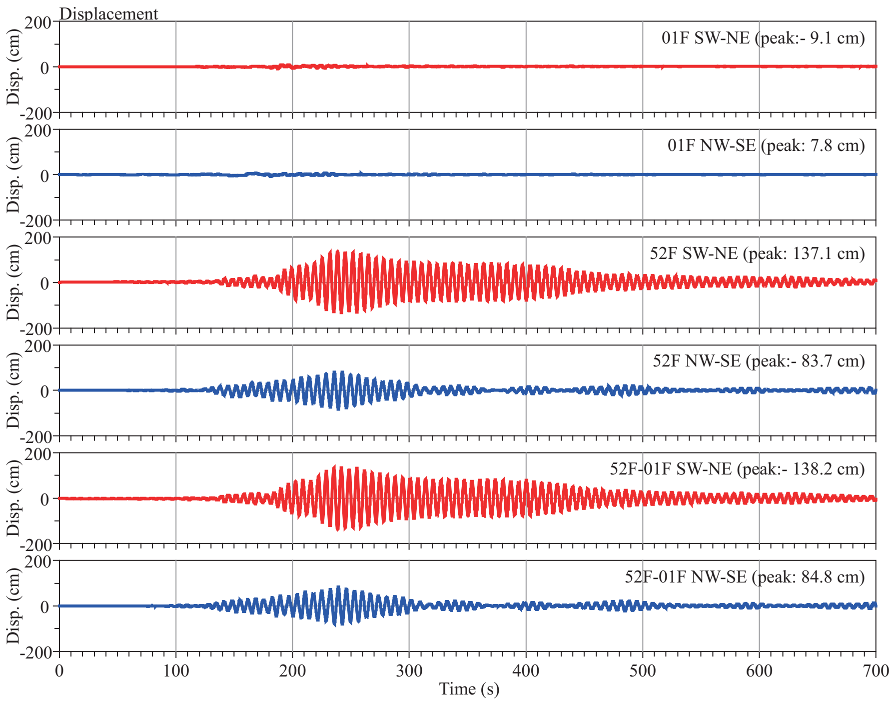

Fig. 5.3-5　Displacement waveforms observed at a 55-story office building in Osaka Bay area: From the top to the bottom; absolute displacements in the SW-NE and in the NW-SE on the 1st floor, absolute displacements in both of the directions on the 52nd floor, and building displacements (relative displacements of 52th floor to 1st floor) in both of the directions.

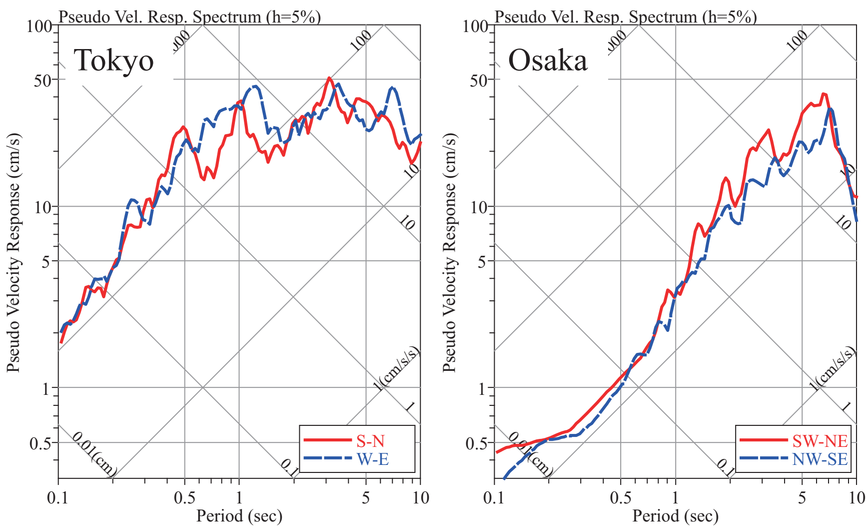

Fig. 5.3-6　Pseudo response spectra with damping ratio of 5% of records in Tokyo Bay area (left) and Osaka Bay area (right)

References

5-1) National Research Institute for Earth Science and Disaster Prevention K-NET, http://www.k-net.bosai.go.jp/

5-2) BRI Strong Motion Observation Network Website: http://smo.kenken.go.jp/

5-3) T. Kashima and Y. Kitagawa: Dynamic Characteristics of Buildings Estimated from Strong Motion Records, Proceedings of the 8th U.S. National Conference on Earthquake Engineering, Paper No. 1136, December 2005