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Summary of the Field Survey and Research on "The 2011 off the Pacific coast of Tohoku Earthquake" (the Great East Japan Earthquake)

National Institute for Land and Infrastructure Management (NILIM)
Ministry of Land, Infrastructure, Transport and Tourism, Japan

Building Research Institute (BRI)
Incorporated Administrative Agency, Japan

Preface

A magnitude 9.0 earthquake occurred off the coast of Sanriku, Japan at 14:46 JST on Friday, March 11, 2011 and triggered extremely destructive tsunami waves. The earthquake and tsunami destroyed, damaged, or washed away a number of buildings, houses and structures in Northeast Japan, including Iwate, Miyagi, Fukushima, Ibaraki, and Chiba prefectures. The highest Japanese seismic intensity scale of 7 was recorded at Kurihara city in the northern part of Miyagi prefecture. The earthquake was named the 2011 off the Pacific coast of Tohoku Earthquake (the Great East Japan Earthquake) by the Japanese government.

In order to learn lessons from the unprecedented disaster and contribute to the improvement of disaster mitigation measures, the National Institute for Land and Infrastructure Management (NILIM) and the Building Research Institute (BRI) has sent staff members to the affected regions and conducted extensive surveys on the damage to buildings and residential lands caused by the earthquake, tsunami and subsequent fires. The types and parts of buildings on which these surveys have been conducted include wood houses, reinforced concrete buildings, steel buildings, residential lands, non-structural components and seismically isolated buildings. In addition, NILIM and BRI have conducted scientific researches on the earthquake and tsunami and analyzed the recorded earthquake motions on various sites across Japan.

This report consists of the main results from these surveys and researches. We hope that this report will be informative in developing effective measures to mitigate damage from future earthquakes and tsunamis in Japan and other earthquake-prone countries in the world.

Finally, we would like to express our deepest condolences to those who lost their families and those who are suffering from the disaster. In addition, we would like to express our heartfelt appreciation to people from around the world for their warm support and cordial friendship.

September, 2011

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1. Introduction

An earthquake of moment magnitude (M_w) 9.0 occurred off Sanriku coast at 14:46 JST on March 11, 2011 and caused tremendous damage of collapse and washed-away of buildings, houses and other structures by ground motion and tsunami in the Pacific coast of eastern Japan, including prefectures of Iwate, Miyagi, Fukushima, Ibaraki and Chiba. The earthquake has recorded the seismic intensity 7, highest in the Japan Meteorological Agency (hereinafter referred to as JMA) scale, in north of Miyagi prefecture (Kurihara city). The JMA named the earthquake as “The 2011 off the Pacific coast of Tohoku Earthquake” (hereinafter referred to as ‘the 2011 Tohoku earthquake’) and the national government named the disaster “the Great East Japan Earthquake” based on a Cabinet decision. As of July 11, the JMA has confirmed six major aftershocks of magnitude 7 or larger. The Japanese National Police Agency has confirmed 15,550 deaths, 5,688 injuries and 5,344 people missing, as well as 224,798 housing units collapsed, 434,327 housing units partially damaged and 32,443 non-residential buildings damaged.

The seismic intensity 6 lower (6-) in JMA scale has been recorded for the first time in Tsukuba city, Ibaraki prefecture, where the National Institute for Land and Infrastructure Management (hereinafter referred to as NILIM) and the Building Research Institute (hereinafter referred to as BRI) are located. Both research institutes share the main building. Some office rooms suffered from falling of cabinets and bookshelves, even a staff has been locked indoors. Although cracks of wall and other structural damage occurred in the main building, fortunately there was no one injured. Immediately after confirmation of safety of staff members who were working in the buildings both institutes initiated to collect information on earthquake damage. Some staff members who were visiting Tokyo and other areas could not return to office in the next few days, since all the transportation systems stopped. As the e-mail system even within the institute had become unstable, it was difficult to collect overall information, except by using the micro-wave communication lines that are owned by the Headquarter of the Ministry of Land, Infrastructure, Transport and Tourism (hereinafter referred to as MLIT) in Kasumigaseki, Tokyo. Some NILIM staff members remained at office in order to maintain contacts with MLIT and to collect further information, while other staffs returned to their homes to continue collecting information and to prepare for operation in the next days in the daytime because electricity supply had been disrupted in both institutes and even traffic signals were out of order.

From the next day, Saturday March 12, both NILIM and BRI started activities including field survey and established the “NILIM / BRI Joint Survey Team on Building Damage Investigation (hereinafter referred to as Joint Survey Team; Note 1)” in order to prepare for the requests of support from the earthquake affected areas and for the future measures against earthquake and tsunami through learning of the damage situations to buildings. The Joint Survey Team has supported surveys on earthquake and the damage of buildings caused by the earthquake motions, mainly responding to the requests of MLIT for the first two weeks after the earthquake. In succession, NILIM and BRI jointly dispatched the team to the affected areas in Tohoku and Kanto regions in order to get an overall picture on damage by ground motion and also carried out surveys on damage of buildings in tsunami affected areas and so on, as joint surveys.

This report summarizes the research and studies that were mainly carried out during the six weeks after the earthquake until April 20 and that were published in Japanese as “Quick report of the Field Survey and Research on the 2011 off the Pacific coast of Tohoku earthquake (The Great East Japan Earthquake)”. However the research and studies conducted after the date are also partly included. The Joint Survey Team has held a lot of meetings and continues discussion on survey results and necessary additional surveys. This report does not cover all the disaster since the earthquake affected area was huge spreading from Tohoku region to Kanto region, as the name, ”the Great East Japan Earthquake” indicates.

Note 1: Members of the NILIM/BRI Joint Survey Team, as of April 20.
from NILIM, Kenji Takai, Tadashi Tonami, Isao Nishiyama, Atsuo Fukai, Tomoko Takagi, Ichiro Minato, Yoshiyuki Shibata, Katsuhiko Kusuda, Masanori Nishiyama, Haruhiko Watanabe, Hiroyuki Tanano, Yuji Kobayashi, Hiroshi Arai, Namihiko Inoue, Akiyoshi Mukai, Tatsuya Azuhata, Hitomitsu Kikitsu, Takahiro Tsuchimoto, Yoshihiro Iwata, Haruhiko Suwada, Tomohiro Naruse, Koji Kagiya, Tatsuya Iwami, Hideki Yoshioka, Ryo Ootake, Satoru Takahashi, Masashi Mori, Hiroshi Hasegawa, Kazuo Nishida, Satoshi Arikawa, Shuichi Takeya, Nozomi Kiuchi, Tomohiko Sakata, 33 staff members,
from BRI, Hiroshi Ito, Juntaro Tsuru, Takashi Nagasaki, Harunobu Murakami, Akira Iwasaki, Ryosuke Sasa, Shigeto Kawasaki, Masaaki Hasegawa, Shigenori Ootaka, Shuichi Go, Kazuhiko Karasawa, Hiroyuki Tasaki, Kunihiko Miyazawa, Zenichi Naito, Shoichi Ando, Takao Sawachi, Naoji Hasegawa, Nobuo Hurukawa, Izuru Okawa, Toshihide Kashima, Shin Koyama, Toshiaki Yokoi, Bunichiro Shibazaki, Tatsuhiko Hara, Tadashi Ishihara, Tsutomu Hirade, Masanori Iiba, Hiroshi Fukuyama, Hiroto Kato, Takashi Hasegawa, Yasuhiro Araki, Toshikazu Kabeyasawa, Mizuo Inukai, Koichi Morita, Masanori Tani, Nobuyoshi Yamaguchi, Shiro Nakajima, Takafumi Nakagawa, Yoshio Wakiyama, Taiki Saito, Tomohisa Mukai, Yasuo Okuda, Yuushiro Fujii, Ichiro Hagiwara, Yoshihiko Hayashi, Junichi Suzuki, Norimitsu Ishi, Wataru Gojo, 48 staff members

Note 2: Source of information (web-sites)

The web-sites for the 2011 Tohoku earthquake are established in NILIM (http://www.nilim.go.jp/) and BRI (http://www.kenken.go.jp/, http://iisee.kenken.go.jp/) showing original information of individual researches and surveys that are bases of this report.

Some data that are updated before the publication of this report were also added, when it is available.

2. Outline of Research and Field Survey

After the 2011 Tohoku earthquake, the Joint Survey Team started a series of research and field survey, and some of them were done in cooperation with other institutes. The outline of the research and field survey from March 11th to April 20th is as follows.

2.1 Outline of Research

The Joint Survey Team obtained information about the features of the 2011 Tohoku earthquake and tsunami based on observational data from research institutes in Japan and overseas including the Japan Meteorological Agency (JMA) and the National Research Institute for Earth Science and Disaster Prevention (NIED), strong motion seismogram of the BRI Strong Motion Observation Network, etc.

2.1.1 Mechanism of earthquake and tsunami

BRI confirmed the mechanism of the 2011 Tohoku earthquake through obtaining its precise hypocenters, identifying fault planes of major earthquakes and estimating magnitude based on duration of high frequency energy radiation. BRI also estimated the source of the tsunami using the tsunami waveform inversion based on data from tsunami sensors and tide gauges around Japan and simulated the tsunami based on the tsunami source model. Researchers involved are as follows.

Table 2.1-1 List of Researchers (1)

BRI	Nobuo Hurukawa, Dr.	Research Coordinator
	Tatsuhiko Hara, Dr.	Chief Research Scientist
	Yushiro Fujii, Dr.	Senior Research Scientist

2.1.2 Earthquake motion observation

NILIM and BRI showed the feature of the earthquake motion of the mainshock and its major aftershocks based on strong motion seismograms of the BRI Strong Motion Network, etc. Researchers involved are as follows.

Table2.1-2 List of Researchers (2)

NILIM	Tatsuya Azuhata, Dr.	Division Head
BRI	Shin Koyama, Dr.	Chief Research Engineer
	Toshihide Kashima, Dr.	Senior Research Engineer
	Tadashi Ishihara, Dr.	Senior Research Engineer

2.2 Outline of Field Survey

NILIM and BRI sent a total of 150 researchers to disaster areas in Iwate, Miyagi, Fukushima, Ibaraki, Tochigi and Chiba prefectures (Surveyed cities and towns are shown in Fig.2.2-1) from March 12th, the next day of the 2011 Tohoku earthquake, to April 16th, 2011 and surveyed damage situation on buildings categorized according to building structure, building use, cause of damage (earthquake motion, tsunami, fire), etc. Some surveys were done on the request of MLIT. Researchers involved in those field surveys are as follows.

Table 2.2-1 List of Researchers (3)

NILIM	Ichiro Minato	Senior Research Fellow
	Tatsuya Azuhata, Dr.	Division Head
	Atsuo Fukai	Division Head
	Takahiro Tsuchimoto, Dr.	Division Head
	Masashi Miyamura	Senior Researcher
	Namihiko Inoue	Senior Researcher
	Hiroshi Arai, Dr.	Senior Researcher
	Hitomitsu Kikitsu, Dr.	Senior Researcher
	Yoshihiro Iwata, Dr.	Senior Researcher
	Haruhiko Suwada, Dr.	Researcher
BRI	Masanori Iiba, Dr.	Director
	Naohito Kawai, Dr.	Chief Research Engineer (at present, Professor of Kogakuin University)
	Ichiro Hagiwara, Dr.	Chief Research Engineer
	Yasuo Okuda, Dr.	Chief Research Engineer
	Hiroshi Fukuyama, Dr.	Chief Research Engineer
	Taiki Saito, Dr.	Chief Research Engineer
	Shiro Nakajima, Dr.	Chief Research Engineer
	Koichi Morita, Dr.	Chief Research Engineer
	Nobuyoshi Yamaguchi, Dr.	Senior Research Engineer
	Hiroto Kato	Senior Research Engineer
	Tsutomu Hirade, Dr.	Senior Research Engineer
	Takashi Hasegawa, Dr.	Senior Research Engineer
	Yoshio Wakiyama, Dr.	Senior Research Engineer
	Takafumi Nakagawa, Dr.	Senior Research Engineer
	Tadashi Ishihara, Dr.	Senior Research Engineer
	Yasuhiro Araki, Dr.	Research Engineer
	Masanori Tani, Dr.	Research Engineer
	Toshikazu Kabeyasawa, Dr.	Research Engineer
	Hideki Matsumoto	Cooperative Researcher

Fig.2.2-1 Location of Surveyed Cities and Towns

3. Overview of Damage

The 2011 Tohoku earthquake was followed by tsunami and several aftershocks with largest seismic intensities greater than 5 in JMA scale and caused extensive damage in broad areas including the Pacific coast of Tohoku and Kanto region. With a sequence of aftershocks including the Off Miyagi Pref. Earthquake of April 7, the Earthquake in Hamadori, Fukushima Pref. of April 11 and 12, and the earthquake in northeastern part of Chiba prefecture of May 22, a large number of casualties and damage to buildings were reported in more than 20 prefectures. This chapter mainly presents the overview of damage to buildings based on the press releases by national agencies. Note that the data presented here is based on press releases on July 11, 2011 and earlier, and subject to change.

3.1 Distribution of JMA Seismic Intensity

Table3.1-1 summarizes municipalities where JMA seismic intensities 6 and 7 were recorded in the 2011 Tohoku earthquake. Fig. 3.1-1 illustrates distribution of JMA seismic intensity in the seismic affected prefectures.

Table 3.1-1 Largest JMA Seismic Intensity of municipalities in the 2011 Tohoku earthquake [3-1)]

JMA Seismic Intensity	Prefecture	Municipalities
7	Miyagi	Kurihara city
6 Upper	Miyagi	Sendai city Miyagino ward, Ishinomaki city, Shiogama city, Natori city, Tome city, Higashimatsushima city, Osaki city, Zao town, Kawasaki town, Yamamoto town, Ohira village, Wakuya town, Misato town
	Fukushima	Shirakawa city, Sukagawa city, Kunimi town, Kagamiishi town, Tenei village, Naraha town, Tomioka town, Okuma town, Futaba town, Namie town, Shinchi town
	Ibaraki	Hitachi city, Takahagi city, Kasama city, Hitachiomiya city, Naka city, Chikusei city, Hokota city, Omitama city
	Tochigi	Utsunomiya city, Moka city, Ohtawara city, Ichikai town, Takanezawa town
6 Lower	Iwate	Ofunato city, Hanamaki city, Ichinoseki city, Kamaishi city, Oshu city, Takizawa village, Yahaba town, Fujisawa town
	Miyagi	Sendai city Aoba ward, Sendai city Wakabayashi ward, Sendai city Izumi ward, Kesennuma city, Shiroishi city, Kakuda city, Iwanuma city, Ogawara town, Watari town, Matsushima town, Rifu town, Taiwa town, Osato town, Tomiya town, Minamisanriku town
	Fukushima	Fukushima city, Koriyama city, Iwaki city, Soma city, Nihonmatsu city, Tamura city, Minamisoma city, Date city, Motomiya city, Kori town, Kawamata town, Inawashiro town, Nishigo village, Nakajima village, Yabuki town, Tanagura town, Tamakawa village, Asakawa town, Ono town, Hirono town, Kawauchi village, Iitate village
	Ibaraki	Mito city, Tsuchiura city, Ishioka city, Joso city, Hitachiota city, Kitaibaraki city, Toride city, Tsukuba city, Hitachinaka city, Kashima city, Itako city, Bando city, Inashiki city, Kasumigaura city, Sakuragawa city, Namegata city, Tsukubamirai city, Ibaraki town, Shirosato town, Tokai village, Miho village
	Tochigi	Nasushiobara city, Nasukarasuyama city, Haga town, Nasu town, Nakagawa town
	Gunma	Kiryu city
	Saitama	Miyashiro town
	Chiba	Narita city, Inzai city

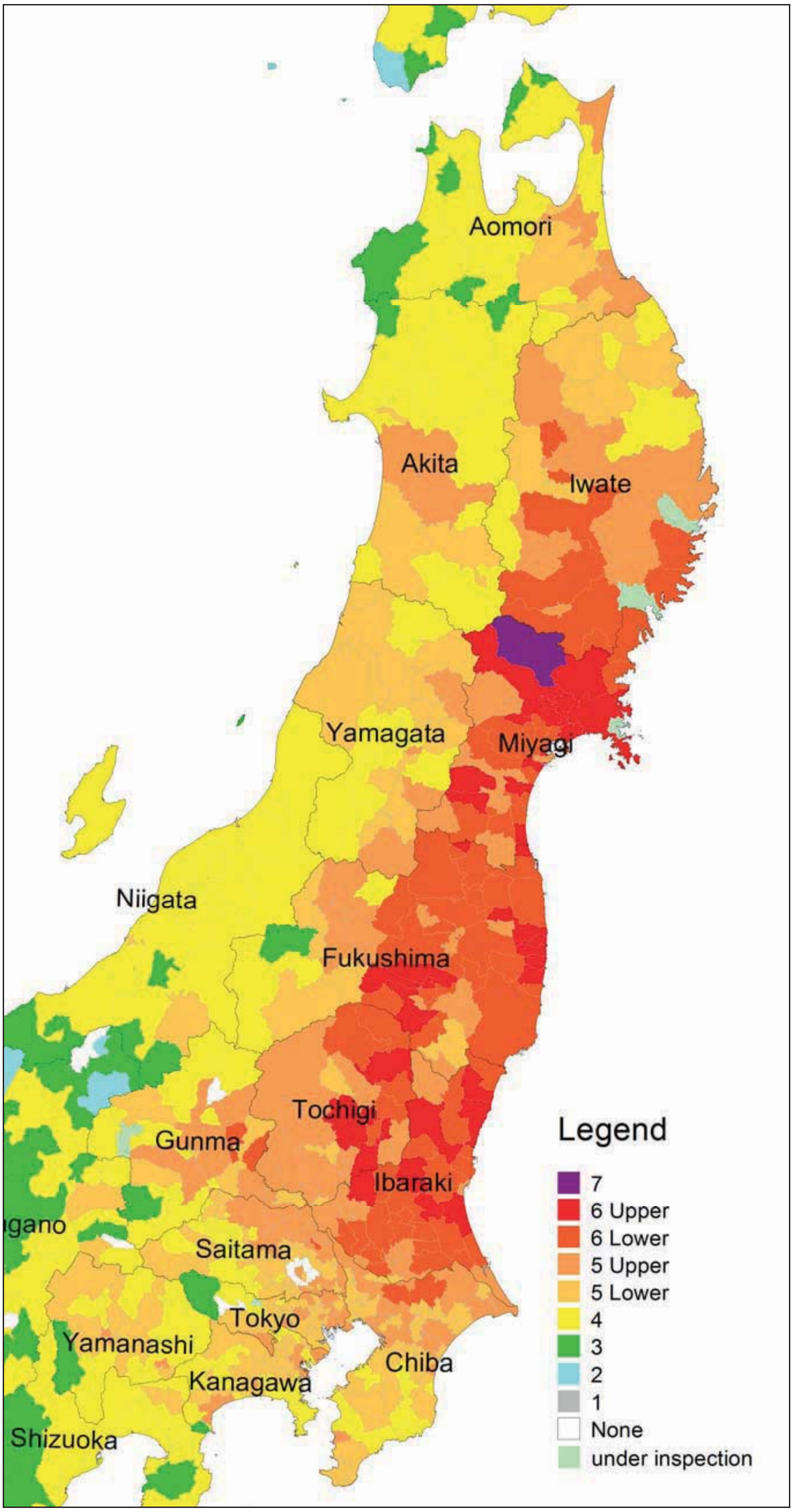

Fig. 3.1-1 Distribution of JMA seismic intensity in the 2011 Tohoku earthquake[3-1]

3.2 Casualties and Damage to Buildings and Utilities

3.2.1 Casualties

Table 3.2-1 shows the numbers of deaths, injuries and people missing due to a series of earthquakes as of July 11, 2011[3-2]. It also shows the number of evacuees in shelters, hotels, and houses of their relatives and friends. The number of evacuees has significantly decreased since mid-March when it exceeded 450,000. However, it still amounted to 68,816 as of June 30[3-3].

Table 3.2-1 Casualties and Evacuees[3-2)~3)]

Prefecture	Casualties*1			Evacuees*1*2
	Deaths [person]	Missing [person]	Injuries [person]	[person]
Hokkaido	1		3	959
Aomori	3	1	61	848
Iwate	4,584	2,247	186	9,339
Miyagi	9,300	2,807	3,777	15,871
Akita			12	1,240
Yamagata	2		29	2,300
Fukushima	1,600	286	236	19,484
Ibaraki	24	1	694	844
Tochigi	4		131	1,404
Gunma	1		38	1,073
Saitama			42	1,075
Chiba	20	2	248	3,432
Tokyo	7		90	2,216
Kanagawa	4		129	83
Niigata			3	3,967
Yamanashi			2	289
Nagano			1	349
Shizuoka			4	684
Others			2	3,359
Total	15,550	5,344	5,688	68,816

Notes: *1 Casualties and Evacuees include those caused by the Off Miyagi Pref. Earthquake of April 7, the Earthquake in Hamadori, Fukushima Pref. of April 11 and 12, and the Earthquake in northeastern part of Chiba Pref. of May 22.

Notes: *2 Evacuees also include those who relocated due to the 2011 Accident at Fukushima Nuclear Power Stations.

3.2.2 Damage to buildings

Table 3.2-2 shows the number of residential and non-residential buildings damaged by the disaster[3-2] and the number of earthquake-related fires[3-4].

Table 3.2-2 Number of Buildings Damaged[3-2) and 3-4)]

Prefecture	Residential Buildings					Non-Residential Buildings	Number of Fires*1
	Total Collapse*1*2 [housing unit]	Half Collapse*1 [housing unit]	Total burn down*1 [housing unit]	Partial burn down*1 [housing unit]	Partially Damaged*1 [housing unit]	Damaged*1 [building]	[case]
Hokkaido					5	470	
Aomori	307	854			96	1,193	5
Iwate	21,004	3,313	15		2,668	1,538	26
Miyagi	66,929	54,006	114		87,607	17,900	163
Akita					3	3	1
Yamagata	37	80					
Fukushima	16,198	32,458	77	3	100,881	1,015	11
Ibaraki	2,265	15,890	37		138,497	9,056	37
Tochigi	257	2,079			57,627	295	
Gunma		6			16,150	195	2
Saitama		5	1	1	1,800	33	13
Chiba	782	8,310	12		28,440	708	13
Tokyo		11	3		257	20	33
Kanagawa		7			279	1	6
Others					17	16	1
Total	107,779	117,019	263		434,327	32,445	311

Notes: *1 Damage and fires include those caused by the Off Miyagi Pref. Earthquake of April 7, 2011, the Earthquake in Hamadori, Fukushima Pref. of April 11 and 12, and the Earthquake in northeastern part of Chiba Pref. of May 22. Due to the inability to collect information in some areas affected by the tsunami and the 2011 Accident at Fukushima Nuclear Power Stations, the numbers presented in this table may not show the full extent of the damage.
*2 Total Collapse includes housing units washed away by the tsunami.

3.2.3 Damage to utilities

Table 3.2-3 shows the maximum damage to electricity supply, city gas supply, water supply and communication.

Table 3.2-3 Maximum Damage to Utilities

	Number of Damaged Units	Date	Source
Electricity supply (Power Failure)	8,450,000	March 11	Press release by Tohoku Electric Power Company and Tokyo Electric Power Company
City gas supply (Suspension)	458,495	March 23*1	Press release by the Japan Gas Association
Water supply (Suspension)	1,700,000	March 15	Press release by Ministry of Health, Labour and Welfare
Communication (Fixed phone Suspension)	879,500	March 12	Press release by Nippon Telegraph and Telephone (NTT) East Corporation

Note: *1 The number of damaged units of Gas supply (Suspension) as of March 23 reflects some correction later on.

3.3 Regions Affected by Tsunami

3.3.1 Tsunami affected area

The Geospatial Information Authority of Japan (GSI) estimated tsunami affected area and the total area in 6 prefectures (Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba) is about 561km^2. Table3.3-1 shows tsunami affected area classified by municipalities[3-5].

Table 3.3-1 Tsunami affected area(classified by municipalities)[3-5]

Prefecture/ Municipality	Tsunami affected area(km^2)[*1]	Municipality area (km^2)
Aomori Prefecture	24	844
Hachinohe city	9	305
Misawa city	6	120
Rokkasho village	5	253
Oirase town	3	72
Hashikami town	0.5	94
Iwate Prefecture	58	4,946
Miyako city	10	1,260
Ofunato city	8	323
Kuji city	4	623
Rikuzentakata city	13	232
Kamaishi city	7	441
Otsuchi town	4	201
Yamada town	5	263
Iwaizumi town	1	993
Tanohata village	1	156
Fudai village	1	70
Noda village	2	81
Hirono town	1	303
Miyagi Prefecture	327	2,003
Sendai city; Miyagino ward	20	58
Sendai city; Wakabayashi ward	29	48
Sendai city; Taihaku ward	3	228
Ishinomaki city	73	556
Shiogama city	6	18
Kesennuma city	18	333
Natori city	27	100
Tagajo city	6	20
Iwanuma city	29	61
Higashimatsushima city	37	102
Watari town	35	73
Yamamoto town	24	64
Matsushima town	2	54
Shichigahama town	5	13
Rifu town	0.5	45
Onagawa town	3	66
Minamisanriku town	10	164
Fukushima Prefecture	112	2,456
Iwaki city	15	1,231
Soma city	29	198
Minamisoma city	39	399
Hirono town	2	58
Naraha town	3	103
Tomioka town	1	68
Okuma town	2	79
Futaba town	3	51
Namie town	6	223
Shinchi town	11	46
Ibaraki Prefecture	23	1,444
Mito city	1	217
Hitachi city	4	226
Takahagi city	1	194
Kitaibaraki city	3	187
Hitachinaka city	3	99
Kashima city	3	106
Kamisu city	3	147
Hokota city	2	208
Oarai town	2	23
Tokai village	3	37
Chiba Prefecture	17	689
Choshi city	1	84
Asahi city	3	130
Sosa city	1	102
Sammu city	6	146
Oamishirasato town	0.5	58
Kujukuri town	2	24
Yokoshibahikari town	1	67
Ichinomiya town	1	23
Chosei village	1	28
Shirako town	1	27
Total	561	12,382

Note: *1 When the tsunami affected area is less than 0.5km^2, it makes 0.5. When it is 0.5km^2 and more, it has rounded at the 1km^2 unit.

3.3.2 Population affected by tsunami

NILIM and BRI estimated tsunami affected population and households. The way of estimation is as follows: firstly calculate the ratio of tsunami affected area on each basic unit blocks of national census, and then multiply that ratio by the number of population and households on each basic unit blocks, finally sum up those numbers on each prefecture. In that estimation, following two data were used: i) Tsunami boundary data made by GSI and ii) Preliminary counts of 2010 population census made by Ministry of Internal Affairs and Communications of Japan . The result is shown in Table 3.3-2.

Table 3.3-2 Estimated tsunami affected population and households

Prefecture/ Municipalities		Estimated tsunami affected population and households (a)		Population and households of tsunami affected municipalities (b)*2		Percentage of tsunami affected(%) (a)／(b)×100	
		Population*1	Households*1	Population	Households	Population*1	Households*1
Aomori		4,794	1,625	335,968	129,666	1.4	1.3
	Hachinohe city	1,995	706	237,473	91,925	0.8	0.8
	Misawa city	542	166	41,260	16,246	1.3	1.0
	Rokkasho village	837	301	11,092	4,751	7.5	6.3
	Oirase town	1,023	320	24,188	8,329	4.2	3.8
	Higashidori village	43	15	7,253	2,710	0.6	0.6
	Hashikami town	355	117	14,702	5,705	2.4	2.1
Iwate		54,025	21,274	274,114	101,900	19.7	20.9
	Miyako city	11,581	4,799	59,442	22,504	19.5	21.3
	Ofunato city	8,325	3,324	40,738	14,814	20.4	22.4
	Kuji city	2,488	960	36,875	14,015	6.7	6.8
	Rikuzentakata city	8,379	3,014	23,302	7,794	36.0	38.7
	Kamaishi city	5,896	2,520	39,578	16,095	14.9	15.7
	Otsuchi town	8,214	3,244	15,277	5,674	53.8	57.2
	Yamada town	6,834	2,594	18,625	6,605	36.7	39.3
	Iwaizumi town	262	100	10,804	4,355	2.4	2.3
	Tanohata village	219	77	3,843	1,309	5.7	5.9
	Fudai village	46	17	3,088	1,042	1.5	1.7
	Noda village	1,353	477	4,632	1,576	29.2	30.3
	Hirono town	427	148	17,910	6,117	2.4	2.4
Miyagi		242,573	87,056	1,205,851	466,356	20.1	18.7
	Sendai city; Miyagino ward	14,932	5,537	190,485	85,790	7.8	6.5
	Sendai city; Wakabayashi ward	7,313	2,092	132,191	58,891	5.5	3.6
	Sendai city; Taihaku ward	1,246	427	220,715	91,585	0.6	0.5
	Ishinomaki city	90,854	34,750	160,704	57,812	56.5	60.1
	Shiogama city	11,898	4,490	56,490	20,314	21.1	22.1
	Kesennuma city	19,985	7,376	73,494	25,464	27.2	29.0
	Natori city	11,186	3,654	73,140	25,150	15.3	14.5
	Tagajo city	15,172	6,038	62,979	24,047	24.1	25.1
	Iwanuma city	7,275	2,049	44,198	15,530	16.5	13.2
	Higashimatsushima city	28,638	9,615	42,908	13,995	66.7	68.7
	Watari town	11,201	3,315	34,846	10,899	32.1	30.4
	Yamamoto town	7,818	2,513	16,711	5,233	46.8	48.0
	Matsushima town	1,812	668	15,089	5,149	12.0	13.0
	Shichigahama town	4,491	1,363	20,419	6,415	22.0	21.2
	Rifu town	61	22	34,000	10,819	0.2	0.2
	Onagawa town	3,323	1,341	10,051	3,968	33.1	33.8
	Minamisanriku town	5,369	1,805	17,431	5,295	30.8	34.1
Fukushima		32,996	10,369	527,573	191,906	6.3	5.4
	Iwaki city	14,413	5,118	342,198	128,516	4.2	4.0

	Soma city	5,738	1,572	37,796	13,240	15.2	11.9
	Minamisoma city	6,334	1,681	70,895	23,643	8.9	7.1
	Hirono town	407	132	5,418	1,810	7.5	7.3
	Naraha town	498	143	7,701	2,576	6.5	5.6
	Tomioka town	467	187	15,996	6,141	2.9	3.0
	Okuma town	155	49	11,511	3,955	1.3	1.2
	Futaba town	416	123	6,932	2,393	6.0	5.1
	Namie town	2,131	610	20,908	7,171	10.2	8.5
	Shinchi town	2,437	753	8,218	2,461	29.7	30.6
Ibaraki		13,181	4,783	963,774	377,878	1.4	1.3
	Mito city	256	87	268,818	111,992	0.1	0.1
	Hitachi city	2,901	1,074	193,129	77,932	1.5	1.4
	Takahagi city	403	160	31,014	11,656	1.3	1.4
	Kitaibaraki city	3,370	1,257	47,026	16,965	7.2	7.4
	Hitachinaka city	2,329	869	157,012	60,276	1.5	1.4
	Kashima city	824	242	66,030	25,222	1.2	1.0
	Kamisu city	573	179	94,823	35,760	0.6	0.5
	Hokota city	414	130	50,161	16,946	0.8	0.8
	Oarai town	1,724	651	18,331	7,020	9.4	9.3
	Tokai village	386	134	37,430	14,109	1.0	1.0
Chiba		9,958	3,509	366,965	128,986	2.7	2.7
	Choshi city	277	128	70,225	26,948	0.4	0.5
	Asahi city	3,686	1,288	69,074	23,121	5.3	5.6
	Sosa city	658	210	39,826	12,869	1.7	1.6
	Sammu city	2,515	830	56,086	19,297	4.5	4.3
	Oamishirasato town	150	57	50,122	18,117	0.3	0.3
	Kujukuri town	1,475	556	18,009	6,617	8.2	8.4
	Yokoshibahikari town	363	124	24,679	8,278	1.5	1.5
	Ichinomiya town	306	123	12,042	4,452	2.5	2.8
	Chosei village	20	7	14,751	5,030	0.1	0.1
	Shirako town	509	185	12,151	4,257	4.2	4.3
Total		357,526	128,616	3,674,245	1,396,692	9.7	9.2

Notes: *1 This result does not mean real damage situation, number of victim, and number of refugees.
*2 Population and households of tsunami unaffected municipalities are not included.

3.4 Inspection of Damaged Buildings and Residential Lands

3.4.1 Post-earthquake quick inspection of damaged buildings

The post-earthquake quick inspection of damaged buildings aims to quickly identify the damage level of a building according to the observed damage status and to categorize each damage level into one of three different groups related to potential hazards which would be caused by aftershocks and so on[3-6]. As of June 2, 2011, 95,227 judgments were conducted in 10 prefectures (149 municipalities) and 11,587 of them were judged UNSAFE (RED). The inspection required a total of 8,515 man-days. Table 3.4-1 shows the interim result of the inspection[3-7].

Table 3.4-1 Result of Post-earthquake Quick Inspection of Damaged Buildings[3-7]

Prefecture	UNSAFE（RED）	LIMITED ENTRY（YELLOW）	INSPECTED（GREEN）	Total
Iwate	168	445	459	1,072
Miyagi	5,088	7,511	37,968	50,567
Fukushima	3,314	6,718	5,775	15,807
Ibaraki	1,561	4,684	9,618	15,863
Tochigi	676	1,845	2,658	5,179
Gunma	30	61	19	110
Saitama	0	42	83	125
Chiba	677	1,625	3,213	5,515
Tokyo	59	137	252	448
Kanagawa	14	81	446	541
Total	11,587	23,149	60,491	95,227

Note: It should be noted that: 1) inspection was hardly executed in the tsunami affected areas, 2) the comprehensive inspection was not carried out because there were a lot of damaged buildings in extensive areas, and 3) the result also includes the number of damage to non-structural elements.

3.4.2 Post-earthquake quick inspection of damaged residential lands

Similar to the case of damaged buildings, post-earthquake quick inspection was conducted for damaged residential lands. The post-earthquake quick inspection of damaged residential lands aims to quickly identify the damage level of a residential land according to the observed damage status and to categorize each damage level into one of three different groups related to potential hazards which would be caused by aftershocks and so on. Until July 10, 2011, 6,313 judgments were conducted in 9 prefectures (52 municipalities) and 1,449 of them were judged UNSAFE (RED). Table 3.4-2 shows the interim result of the inspection[3-8].

Table 3.4-2 Result of Post-earthquake Quick Inspection of Damaged Residential Lands[3-8]

Prefecture	UNSAFE（RED）	LIMITED ENTRY（YELLOW）	INSPECTED（GREEN）	Total
Iwate	114	103	162	379
Miyagi	886	1,470	1,640	3,996
Fukushima	269	258	484	1,011
Ibaraki	30	64	41	135
Tochigi	101	244	133	478
Gunma	24	9	7	40
Saitama	0	27	104	131
Chiba	10	18	9	37
Niigata	15	12	79	106
Total	1,449	2,205	2,659	6,313

3.5 Temporary Housing

In order to provide disaster victims with decent and stable living environments, local governments have been constructing temporary houses in the affected regions and providing the evacuees with information on available rental housing units across Japan.

3.5.1 Construction of temporary housing

According to the Disaster Relief Act, prefectural governments are in charge of providing temporary housing for individuals and families who have been displaced by a disaster and the central government provide financial assistance to these prefectural governments. Table 3.5-1 shows the progress of temporary housing construction[3-9)].

Table 3.5-1 The Progress of Temporary Housing Construction[3-9)]

Prefecture	Total Number of Housing Units Estimated to be Necessary	In the Planning Stage		Under Construction		Completed
		Number of Sites	Number of housing units	Number of Sites	Number of housing units	Number of Sites
Iwate	13,833	—	—	312	13,833	11,527
Miyagi	22,435	15	1,844	358	19,918	15,985
Fukushima	14,000	—	—	152	13,487	10,135
Ibaraki	10	—	—	2	10	10
Tochigi	20	—	—	1	20	20
Chiba	230	—	—	3	230	230
Nagano	55	—	—	2	55	55
Total	50,583	15	1,844	830	47,553	37,962

3.5.2 Information Provision Related to Available Rental Housing Units

Local and central governments have provided information on available public and private rental housing. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) set up the Center for Information on Public Houses for the Affected on March 22. Through the center and in cooperation with relevant ministries and private rental housing and real estate associations, MLIT has provided the displaced individuals and families with information on available public and private rental housing across Japan, including national public officers' housing, employment promotion housing, the Urban Renaissance (UR) Agency's housing and private rental housing.

Table 3.5-2 shows the approximate number of available housing units and those that were already allocated to displaced people in early July[3-10)]. It is notable that the Japanese government decided to reimburse the prefectures' costs of renting private housing for those who had been displaced by the disaster. As a result, more than 40,000 private rental housing units were allocated to the displaced. Including newly constructed ones, approximately 85,000 housing units were already allocated or at least ready for the allocation.

Table 3.5-2 Housing Units Available for the Displaced[3-10)]

	Total	Tohoku-region	Already Allocated
Public Housing[*1]	23,000	1,800	6,200
UR's Rental Housing	5,100	130	810
Private Rental Housing	—	—	42,300
Total	—	—	49,310

Note: *1 Public housing includes national public officers' housing, UR Agency's housing and employment promotion housing.

3.6 Building Restrictions

3.6.1 Building Restrictions based on the Building Standard Law of Japan

In order to prevent uncoordinated construction of buildings in the affected areas, Miyagi Prefecture and Ishinomaki city designated the building restricted areas on April 8 and restricted building construction works within these areas, pursuant to Article 84 of the Building Standard Law of Japan. Based on this law, Ishinomaki city has the authority over building regulations under an agreement with Miyagi prefecture. On April 12, the deadline of building restrictions was extended to May 11. Those designated areas include Ishinomaki city, Kesennuma city, Natori city, Higashi-matsushima city, Onagawa town, and Minami-Sanriku town in Miyagi prefecture.

3.6.2 Enactment of New Law concerning Building Restrictions

"Law on Special Provisions of building restrictions in the urban areas severely damaged by the Great East Japan Earthquake" was established on April 28, which took effect as issued on April 29. This law made it possible to implement building restrictions up to eight months from the date of the disaster in the affected areas. Based on this law, on May 11, Miyagi Prefecture and Ishinomaki city extended the period of building restrictions in these designated areas until September 11.

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3-1) Japan Meteorological Agency (JMA). (June 23, 2011). JMA seismic intensity in the 2011 off the Pacific coast of Tohoku Earthquake (3rd report).

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3-3) Cabinet Office, Government of Japan. (July 6, 2011). The Number of Evacuees across Japan.

3-4) Fire and Disaster Management Agency. (July 7, 2011). The 131th Daily Report on the 2011 off the Pacific coast of Tohoku Earthquake.

3-5) Geospatial Information Authority of Japan (GSI). (Apr 18, 2011). Tsunami affected area (5th report).

3-6) The Japan Building Disaster Prevention Association. Postearthquake Quick Inspection of Damaged Buildings. Retrieved August 12, 2011, from http://www.kenchiku-bosai.or.jp/english/file/epanfall.PDF

3-7) Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (June 2, 2011). Quick Inspections of Damaged Buildings.

3-8) Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (July 11, 2011). The Great East Japan Earthquake (the 81st report).

3-9) Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (July 11, 2011). The Progress of Temporary Housing Construction.

3-10) Ministry of Land, Infrastructure, Transport and Tourism (MLIT). (July 11, 2011). The Progress of Policy Measures taken by the Housing Bureau.

4. Outline of Earthquake and Tsunami

A M_w 9.0 (M_w by JMA) earthquake occurred off the Pacific Coast of Tohoku at 14:46 JST (5:46 UTC) on March 11, 2011 and generated gigantic tsunami in the Tohoku and Kanto regions of the northeastern part of Japan. This was a thrust earthquake occurring at the boundary between the North American and Pacific plates. A M_w 7.5 foreshock preceded the mainshock on March 9 and many large aftershocks including two M_w 7-class aftershocks followed the mainshock.

4.1 Earthquake Mechanism

Many researchers are studying source process of the 2011 Tohoku earthquake using different kinds of data, such as seismic waves, aftershocks' locations, GPS, tsunami, etc. Here shows as an example the first result for the source process from regional strong motion data by Yoshida *et al*. (2011)[4-1]. The main features are as follows. (a) The main rupture is located to the east of the initial break point (the shallower side of the hypocenter), and maximum slip amounts were more than 25 m. (b) The size of the main fault was about 450 km in length and 200 km in width; the duration of rupture was more than 150 s; and M_w was 9.0. (c) The initial rupture gradually expanded near the hypocenter (0–40 s) and subsequently propagated both southward and northward.

Other analyses show more or less very similar results to this result shown in Fig. 4.1-1. A result by tsunami inversion is shown in the section 4.4.2.

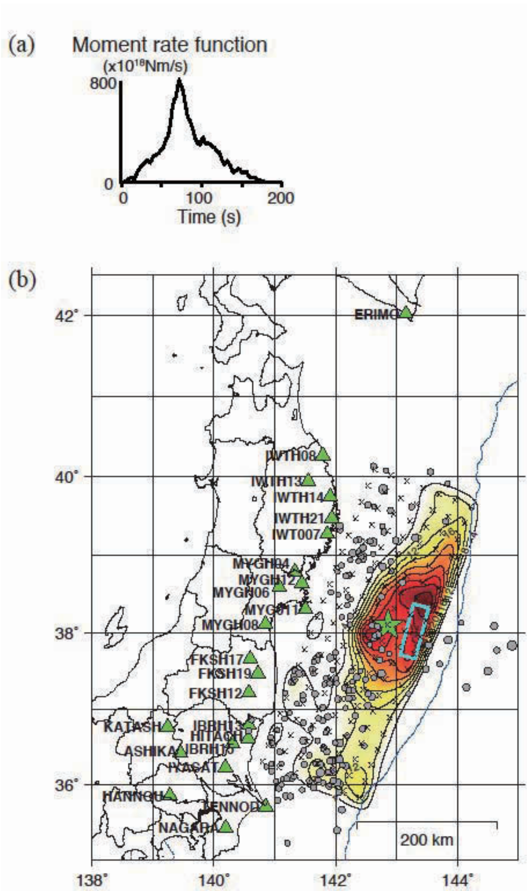

Fig. 4.1-1 Finite-source model from inversion of strong motion waves[4-1]: (a) Moment rate function. (b) Slip distribution on the fault. Large green star represents the epicenter of the mainshock, and gray circles represent aftershocks ($M \geq 5.0$) within 24 h of the mainshock. Triangles denote seismic stations used in this analysis. Contour interval in slip distribution is 4 m. The light blue rectangle shows the estimated peak of the highly uplifted area obtained from tsunami arrival times.

4.2 Relocation of Earthquakes

Foreshocks, mainshock, and aftershocks of the 2011 Tohoku earthquake (M_w 9.1 by global CMT) were relocated using the modified joint hypocenter determination (MJHD) method[4-2] in order to obtain their precise hypocenters and to identify fault planes of larger earthquakes. *P*-wave arrival times at stations worldwide reported by the U. S. Geological Survey (USGS) were used. It was confirmed by relocated hypocenters that the mainshock and aftershocks had occurred along the plate boundary between the North American and Pacific plates (Fig. 4.2-1). It was also confirmed that the M_w 7.5 foreshock, which occurred two days before the mainshock, and the largest aftershock (M_w 7.9), which occurred half an hour after the mainshock, were thrust earthquakes along the plate boundary. The second largest aftershock (M_w 7.6), which was a normal-faulting earthquake and was a bending-stress intra-plate event caused by the strain reduction on the subduction thrust, occurred at the outer rise of the Japan Trench and was well relocated with its aftershocks. It was found that its fault plane dipped westward and it bounded the aftershock distribution on the seaward side. This implies that the western side of the fault plane had subsided, corresponding with the westward plate subduction. The size of the one-day aftershock area was ~450 km x ~150 km if the outer rise area is excluded. If the outer rise area is included, the size was ~450 km in the northerly direction and ~400 km in the easterly direction. The details of these analyses are given by Hurukawa (2011)[4-3].

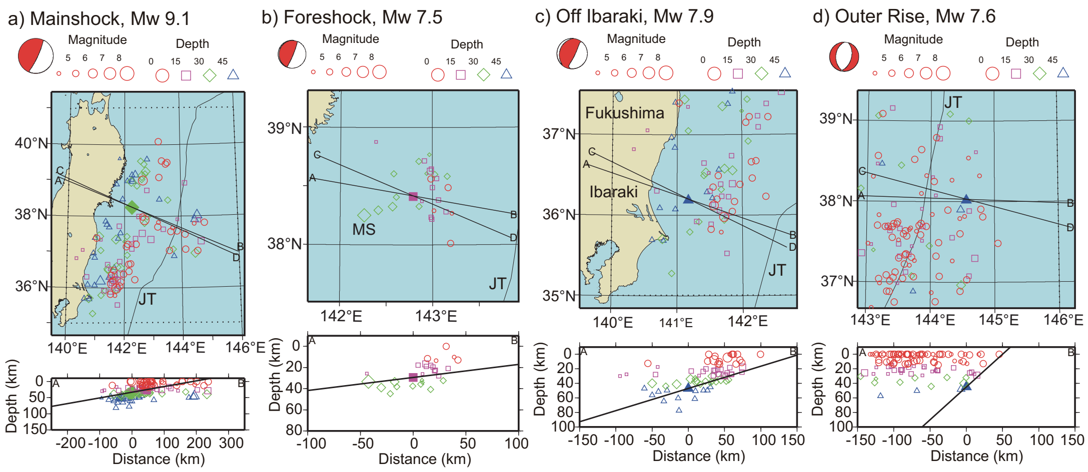

Fig. 4.2-1 Relocated hypocenters by the MJHD method[4-3]: Epicentral distribution and a vertical cross section along A-B line, which is perpendicular to strike of the nodal plane of the global CMT solution, are shown. This nodal plane corresponds with the fault plane. a) The mainshock (2011/03/11 5:46 UTC) and immediate aftershocks within 24 hours. b) The largest foreshock (2011/03/09 2:45 UTC) and its aftershocks. MS indicate the mainshock. c) The largest M_w 7.9 aftershock off Ibaraki (2011/03/11 6:15 UTC) and aftershocks within 24 hours after the mainshock. d) The M_w 7.6 aftershock at the outer rise (2011/03/11 6:25 UTC) and aftershocks. JT: Japan Trench.

4.3 High Frequency Energy Radiation Duration and its Corresponding Magnitude

Durations of high frequency energy radiation (HFER) measured from tele-seismic P waves well correlate with source times, and can be used as their guesses. HFER durations of the 2011 Tohoku earthquake were measured using broadband waveforms recorded at the Global Seismograph Network stations; we retrieved data from the data management center of the IRIS (Incorporated Research Institutions for Seismology). Figure 4.3-1 shows the measured HFER durations as a function of station azimuths. Their mean was 170.5 s. This suggests that the source time of this event was around 3 minutes. The azimuthal dependence shown in Fig. 4.3-1 suggests that the rupture which generated strong HFERs propagated in the southwest direction.

The magnitude of this event was calculated using the following formula of Hara (2007) [4-4]:

$$M = 0.79\log A + 0.83\log\Delta + 0.69\log t + 6.47 \qquad \text{(Eq.4.3-1)}$$

where M is an earthquake magnitude, A is the maximum displacement (m) during the estimated duration of HFER from the arrival time of a P-wave, Δ is the epicentral distance (km), t is the estimated duration (s) of HFER. The mean of the calculated magnitudes for all the stations was 8.96. Figure 4.3-2 shows the contribution of the first and second terms (i.e., maximum displacement with distance correction) and that of the third term (i.e., HFER duration) for this event and other large ($M_w \geqq 8$) shallow earthquakes that occurred since 1994. Compared to the December 26, 2004 Sumatra earthquake (M_w 9.0-9.3), the HFER duration of this event was shorter, while the maximum displacement was larger. The details of these analyses are given by Hara (2011)[4-5].

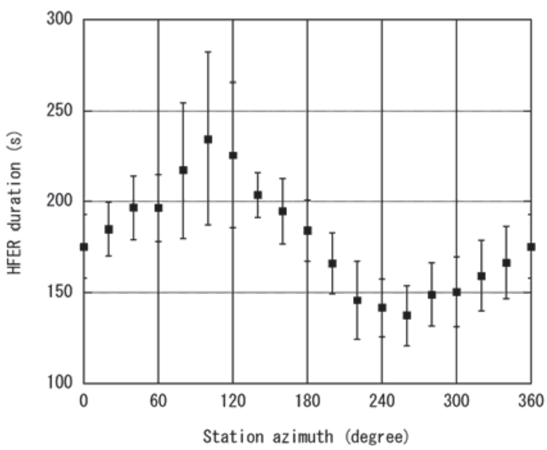

Fig. 4.3-1 The measured HFER durations as a function of station azimuths. The moving window (±30 degree) averages are shown.

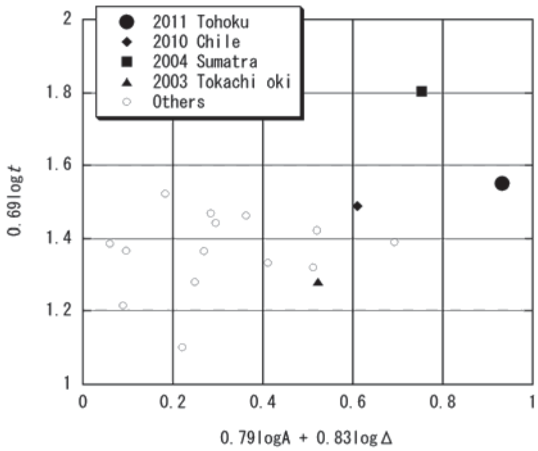

Fig. 4.3-2 Contributions to magnitudes from maximum displacement amplitudes and epicentral distances (the horizontal axis) and those from HFER durations (the vertical axis)

4.4 Tsunami

4.4.1 Observed tsunami heights

The 2011 Tohoku tsunami was recorded instrumentally at four types of gauges. They are ocean bottom tsunami sensor (OBTS), GPS gauge, wave gauge (WG) and tide gauge (TG), which are installed in deep to shallow sea. Japan Meteorological Agency (JMA) reported the tsunami heights observed at coastal tide gauges (Fig. 4.4-1). According to JMA (2011) [4-6], the tsunami heights were less than 3 m along the coasts of Hokkaido to Aomori prefectures, and more than 4 m along the coasts of Iwate, Miyagi and Fukushima prefectures. Many coastal tide gauges on the Pacific coast of the Tohoku region stopped recording after the first tsunami arrival, because of power failure or the stations were damaged by the tsunami. Later JMA retrieved the tide gauge records on site and announced that the observed tsunami heights were more than 8.5 m at Miyako, more than 8.0 m at Ofunato, more than 7.6 m at Ayukawa (Ishinomaki), and more than 9.3 m at Soma.

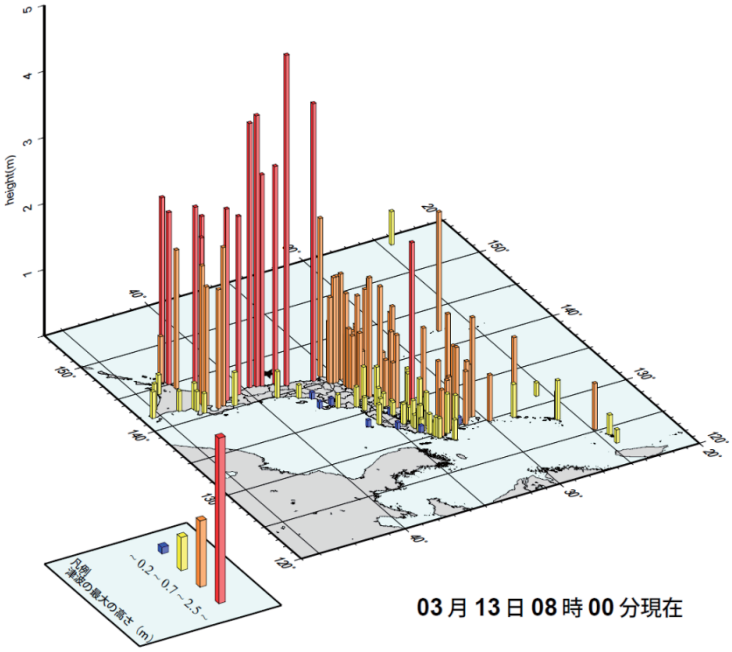

Fig. 4.4-1 Observed tsunami heights at tide gauge stations as of March 13th 8 AM[4-6]

Tsunami heights in the coastal areas of Japan were measured and reported by the 2011 Tohoku Earthquake Tsunami Joint Survey Group which consists of coastal engineers, seismologists, tsunami researchers from universities or research institutes, and other tsunami-related officials. The field surveys were mainly conducted along the Pacific coasts from Hokkaido to Okinawa. The survey results all end up on the internet site and are being updated appropriately[4-7]. According to the preliminary survey results, inundation or runup heights were about 5 m in the Pacific coasts of Hokkaido, up to 10 m in Aomori and Chiba prefectures, more than 30 m in some locations along the Sanriku coasts of Iwate, up to 20 m in Miyagi prefecture (Fig. 4.4-2, as of 5 July 2011).

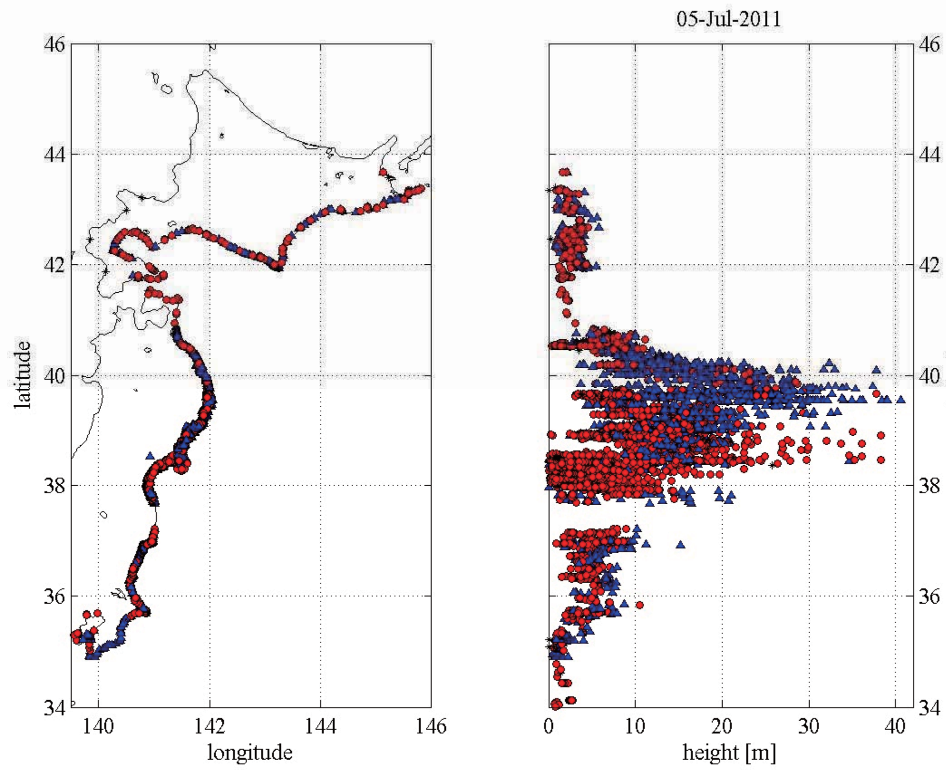

Fig. 4.4-2 Distribution of measured tsunami heights by the field surveys[4-7]: Red circles and blue triangles indicate inundation heights and runup heights, respectively.

4.4.2 Tsunami source model and simulated maximum tsunami heights

A tsunami waveform inversion was performed to estimate the tsunami source of the 2011 Tohoku earthquake[4-8]. The tsunami waveforms were recorded at various types of sensors such as OBTSs of Deep-ocean Assessment and Reporting of Tsunamis (DART) by National Oceanic and Atmospheric Administration (NOAA), cabled OBTSs by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Earthquake Research Institute (ERI), The University of Tokyo, GPS wave gauges, tide and wave gauges by Japan's Nationwide Ocean Wave information network for Ports and Harbours (NOWPHAS) and tide gauges of JMA and Japan Coast Guard (JCG). The stations used for the tsunami waveform inversion are shown in Fig. 4.4-3.

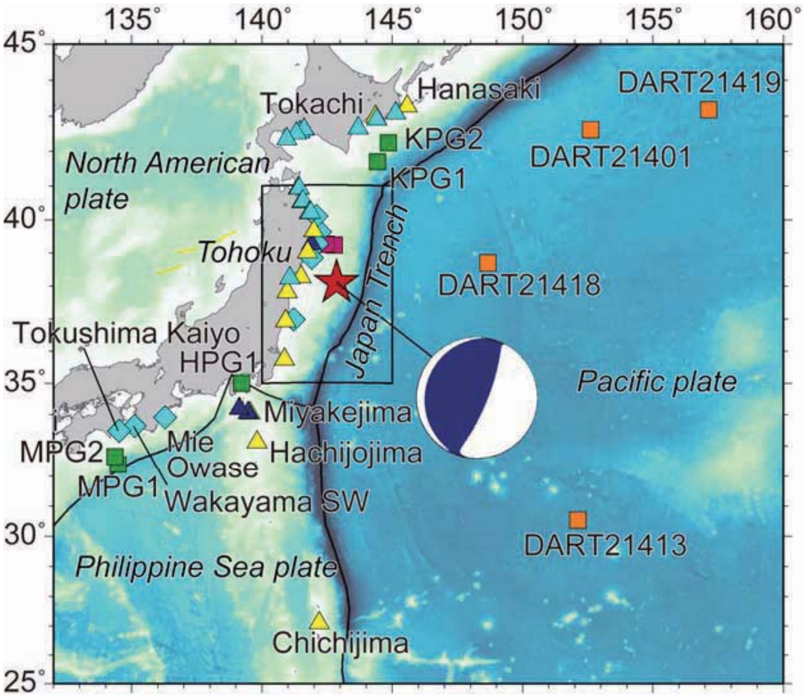

Fig. 4.4-3 Epicenter of the 2011 Tohoku earthquake (red star), W phase MT solution by USGS, and stations that recorded the tsunami[4-8]. Triangles, diamonds and squares indicate the locations of coastal (tide or wave) gauges, offshore GPS wave gauges and OBTSs or DART systems, respectively. Colors indicate operating agencies (yellow: JMA, blue: JCG, green: JAMSTEC, orange: NOAA, light blue: NOWPHAS, and purple: ERI). Square indicates the region shown in Fig.4.4-4.

Forty subfaults are located within the aftershock area (see Fig. 4.4-4). The length and width are 50 km × 50 km for each subfault. The focal mechanisms of the all subfaults are strike: 193º, dip:14º and slip:81º from the USGS's W-phase moment tensor solution. The top depths of the subfaults were assumed to 0 km, 12.1 km, 24.2 km and 36.3 km for near-trench, shallow, middle and deep subfaults, respectively. An instantaneous rupture was assumed on the fault.

In order to calculate the Green's functions from source to stations, static deformations of the seafloor, the initial conditions for tsunami, were calculated for a rectangular fault model[4-9] for each subfault. The used bathymetry data are 30 arc-second grid from JTOPO30 for tide gauges in Japan and 2 arc-minute grid for off shore (Pacific Ocean), resampled from GEBCO_08 30 arc-second grid data. To calculate tsunami propagation, the linear shallow-water, or long-wave, equations were numerically solved by using a finite-difference method[4-10].

The inversion result (Fig. 4.4-4) shows a tsunami source length (with more than 2 m slip) of about 350 km, extending from over southern Sanriku-oki, Miyagi-oki, Fukushima-oki as well as near the trench axis. The largest slips with more than 40 m are estimated along the Japan trench axis off southern Sanriku. Around the epicenter, in southern Sanriku region, the estimated slip was about 28 – 34 m. On the deeper subfault in Miyagi-oki region, the slip was 9 – 23 m. To the north of the epicenter, 5 – 11 m slip was estimated in a part of central Sanriku region. To the south, the slip was about 10 m in Fukushima-oki region, and less than 3 m in Ibaraki-oki region. The total seismic moment was calculated from these slip distributions as 3.8×10^{21} Nm (M_w 9.0) which is consistent with other studies based on seismic data analyses. The comparison of tsunami waveforms are shown in Fig. 4.4-5.

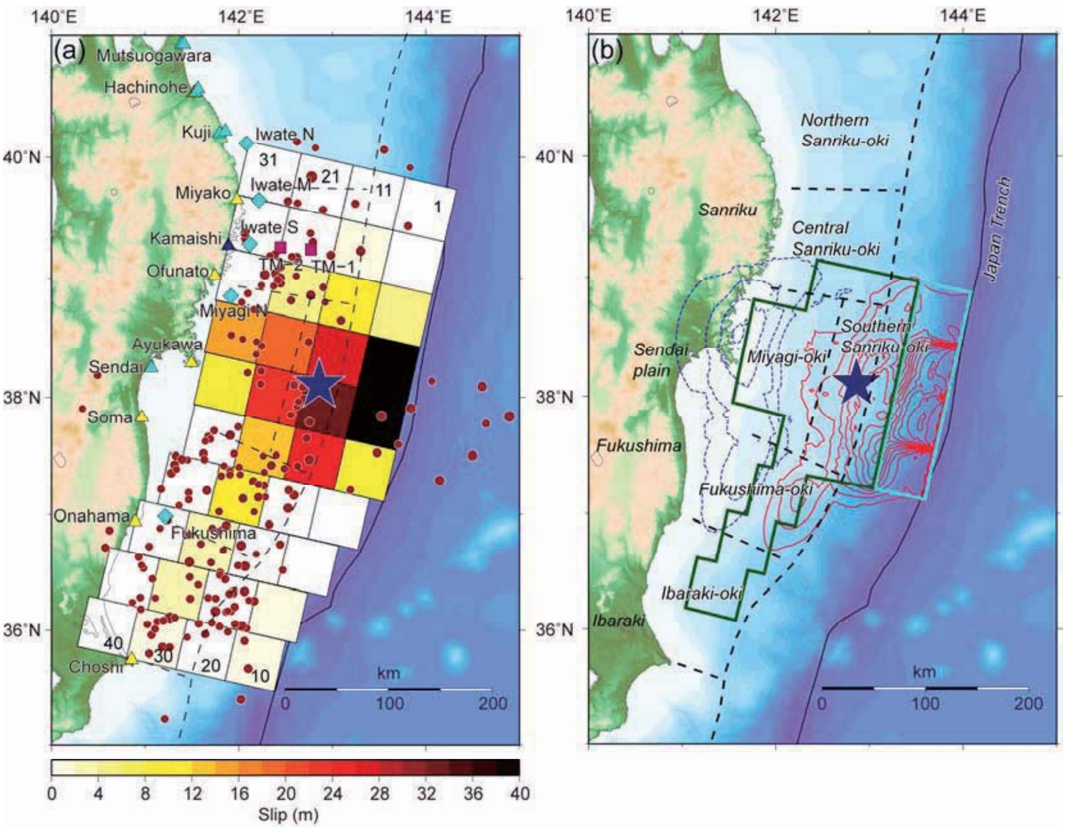

Fig. 4.4-4 (a) Slip distribution estimated by tsunami waveform inversion[4-8]. The subfault numbers are shown in the northernmost and southernmost subfaults. Star shows the mainshock epicenter. Circles indicate aftershocks within one day after the mainshock (JMA data). Dashed lines indicate regions where the probabilities and size of future subduction-zone earthquakes were estimated by Earthquake Research Committee (2009) [4-11]. Coastal and offshore stations (the same symbol as Fig. 4.4-3) are also shown. (b) Seafloor deformation computed from the estimated slip distribution. The red solid contours indicate uplift with the contour interval of 1.0 m, whereas the blue dashed contours indicate subsidence, with the contour interval of 0.5 m. The light blue and dark green frames show the subfaults with more than 2 m slips located near the trench axis and in deep interplate, respectively.

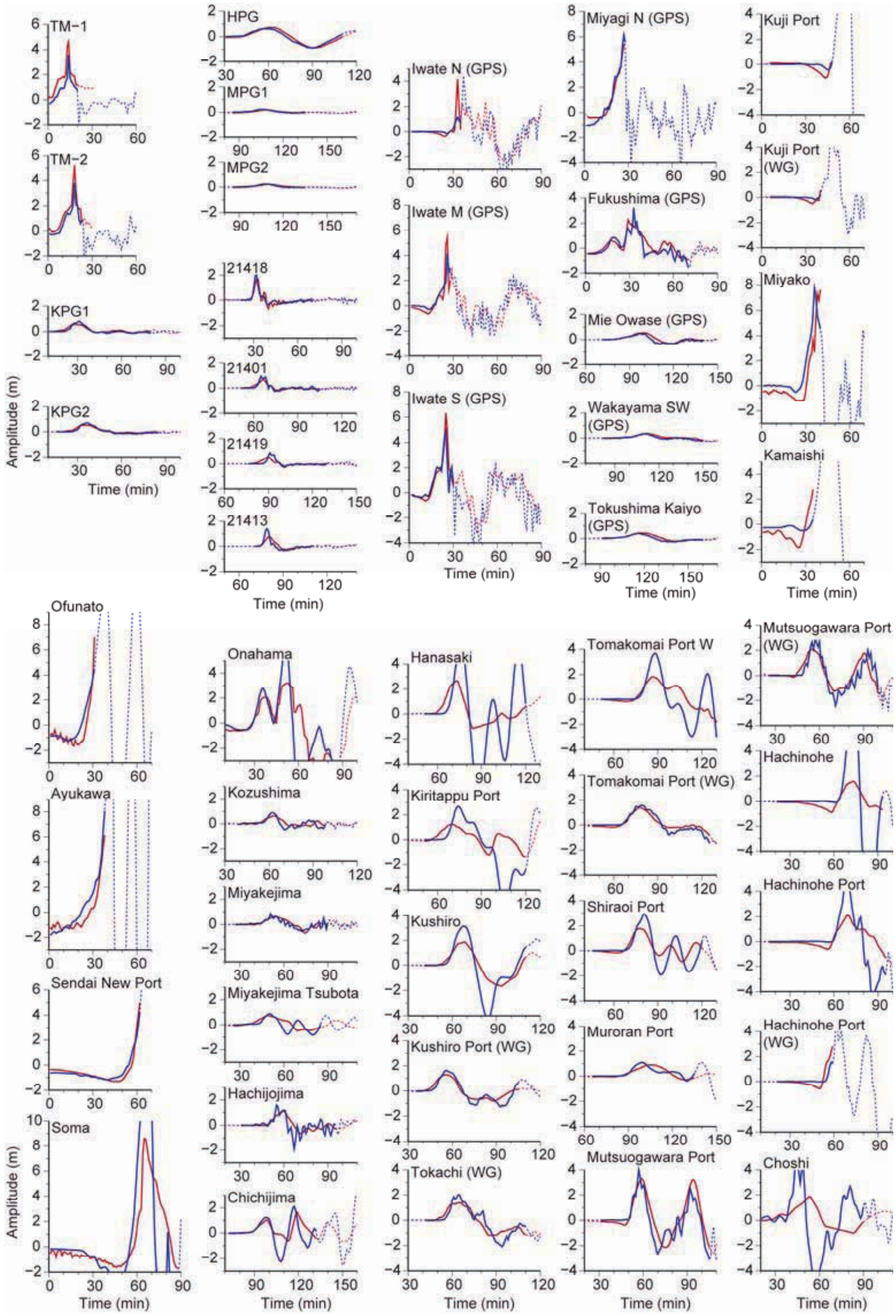

Fig. 4.4-5 Comparisons of the observed (red curves) and synthetic (blue curves) tsunami waveforms computed from the estimated slip distribution[4-8]. Time ranges shown by solid curves are used for the inversions; the dashed parts are not used for the inversions, but shown for comparison. Note the same vertical scales for bottom pressure gauges (the upper left two columns), GPS wave gauges (upper central two columns) and coastal tide and wave gauges (upper right one column and bottom columns). See Figs.4.4-3 and 4.4-4(a) for the station locations.

The tsunami heights were simulated along the Japanese coasts adopting the tsunami source model described above. The non-linear shallow-water equations were numerically solved by using a finite-difference method[4-10]. The used bathymetry grid is the 30 arc-second uniform grid from JTOPO30 data. The reproduced tsunami heights were about 5 – 10 m along the coasts from southern part of Iwate to Fukushima and more than 10 m in some locations such as a tip of peninsula or a back of bay (Fig. 4.4-6).

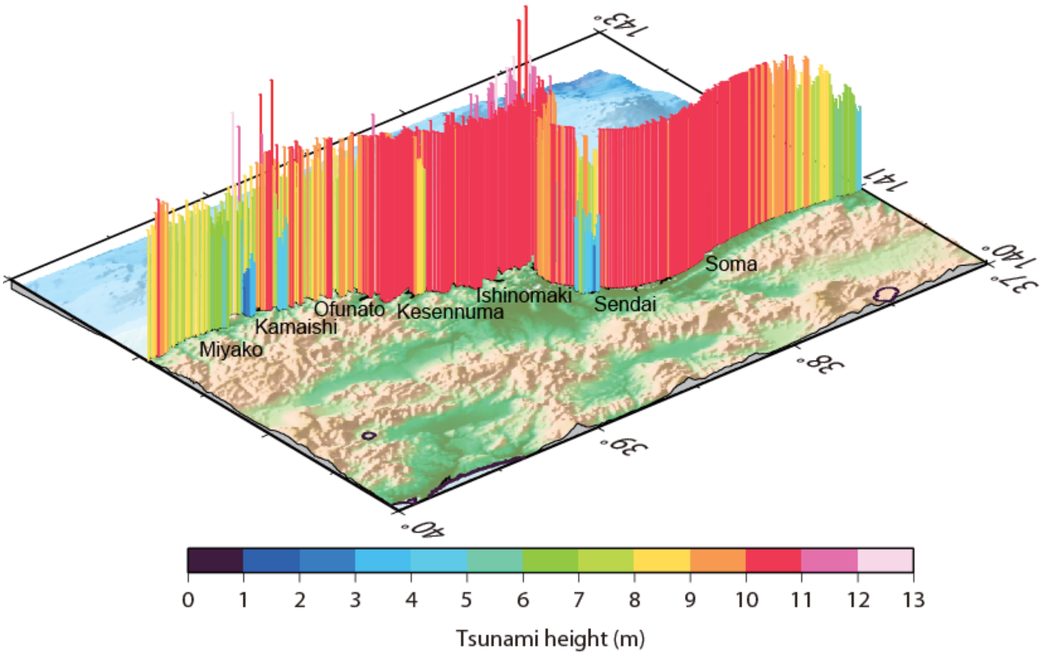

Fig. 4.4-6 Simulated tsunami heights along the coasts from southern part of Iwate to Fukushima prefectures. The used tsunami source model is based on Fujii *et al*. (2011) [4-8].

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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.

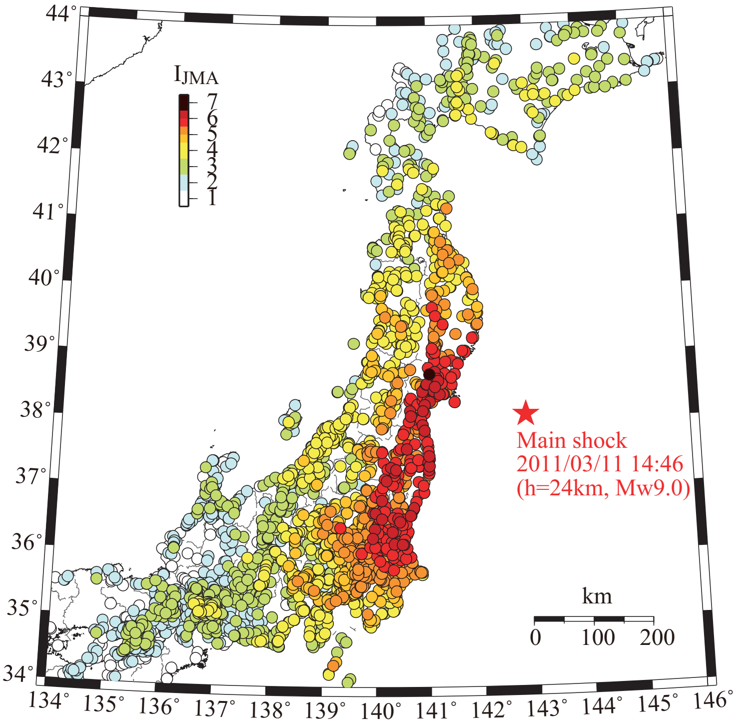

Fig. 5.1-1 Distribution of JMA seismic intensity

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.

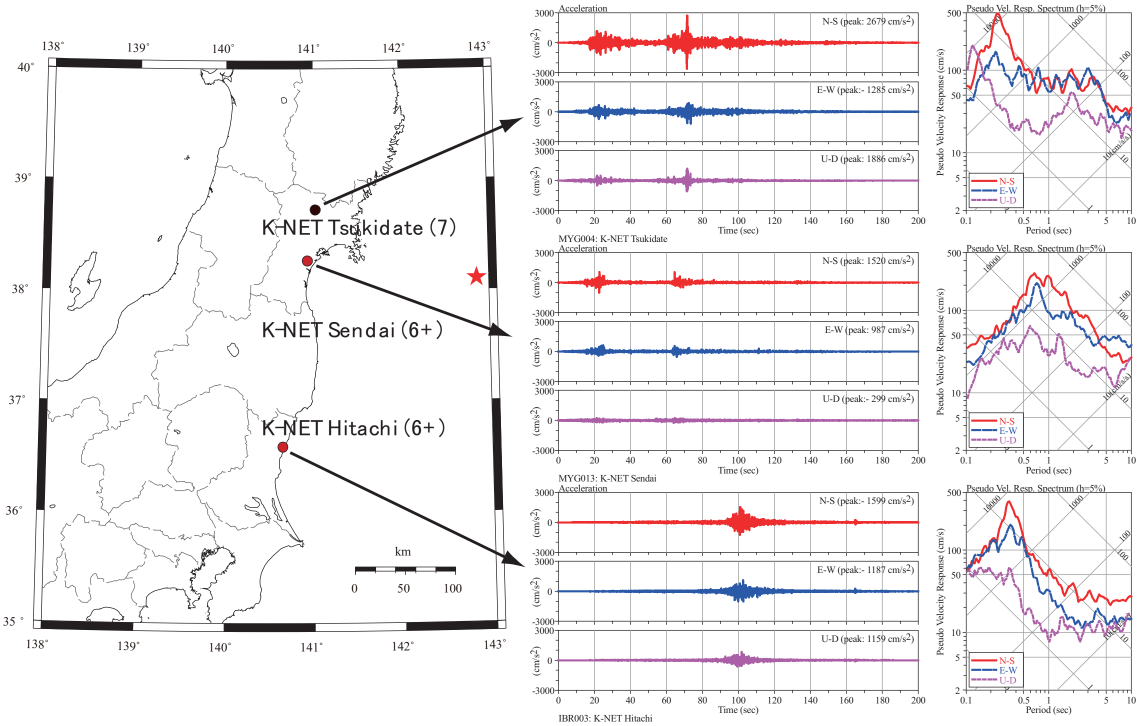

Fig. 5.2-1 Acceleration waveforms and pseudo velocity response spectra recorded at K-NET stations

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/s²)		
						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

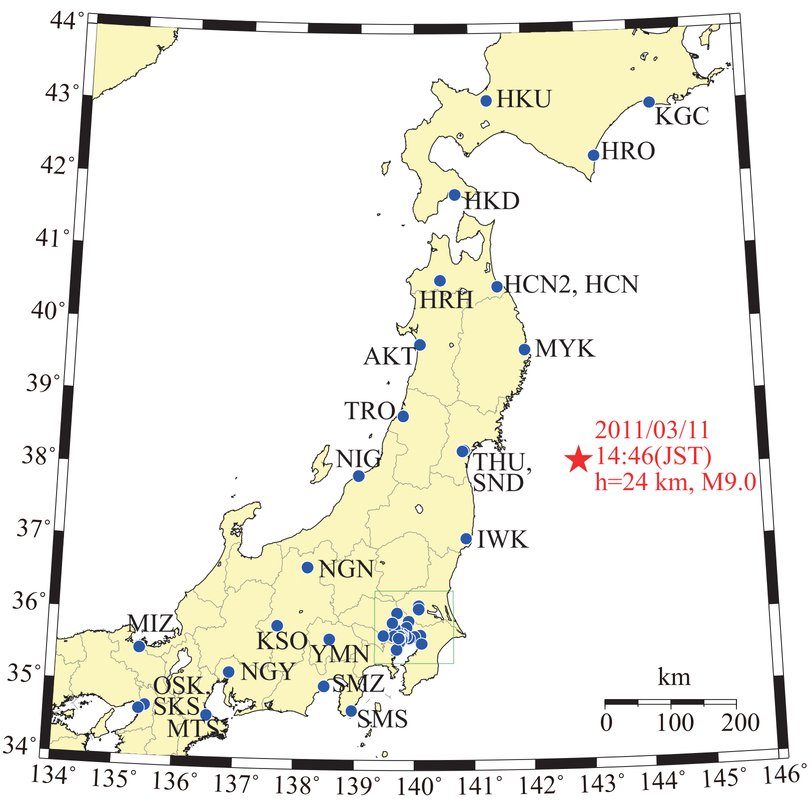

Fig. 5.3-1   Locations of epicenter (★) and BRI strong motion stations (●)

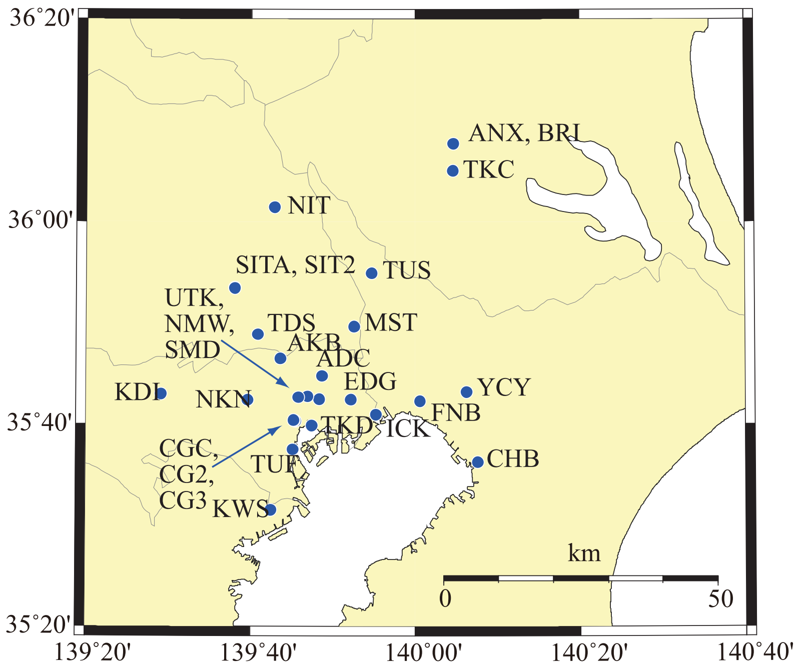

Fig. 5.3-2 BRI strong motion stations in Kanto area (corresponding to the green rectangle in Fig. 5.3-1)

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

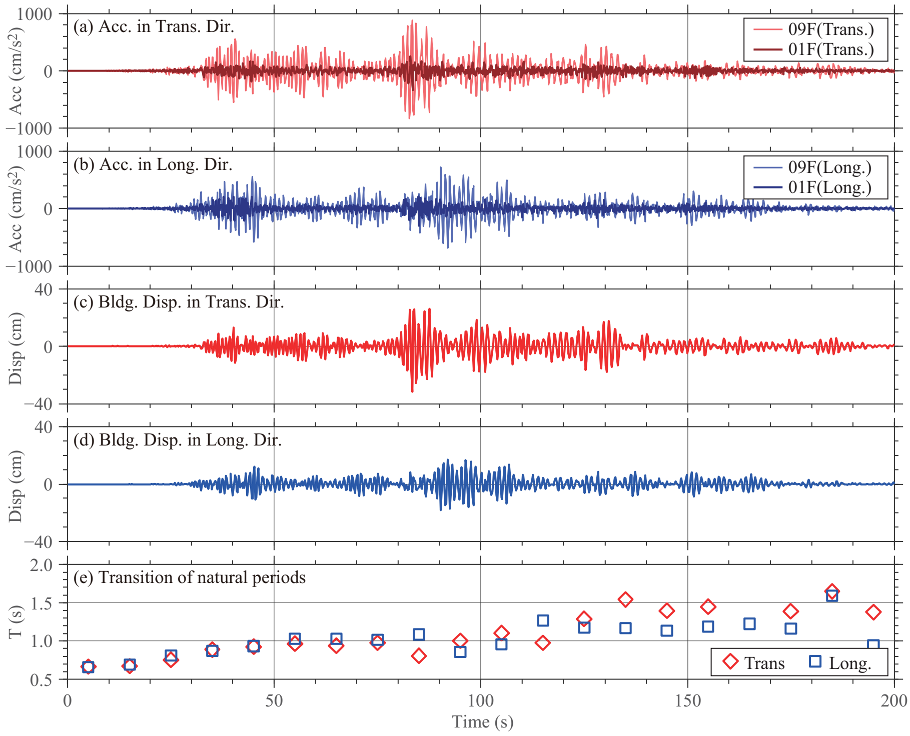

Fig. 5.3-3 Strong motion records of the research building of Tohoku University and transition of natural periods with time. (a) acceleration waveforms in the transverse direction, (b) acceleration waveforms in the longitudinal direction, (c) building displacement in the transverse direction (relative 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.

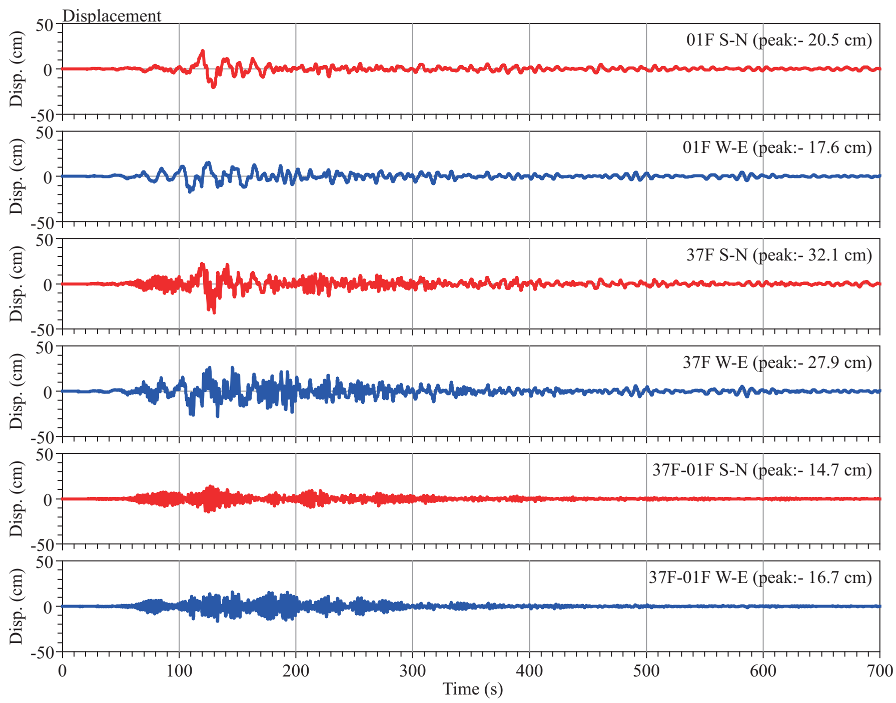

Fig. 5.3-4 Displacement waveforms observed at a 37-story residential building in

Tokyo Bay area

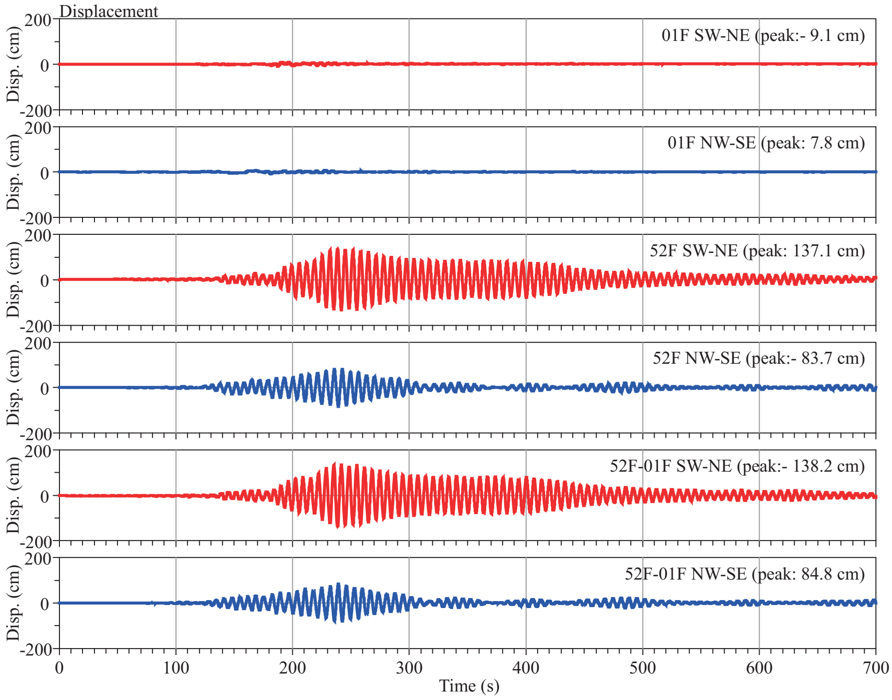

Fig. 5.3-5　Displacement waveforms observed at a 55-story office building in Osaka Bay area: From the top to the bottom; absolute displacements in the SW-NE and in the NW-SE on the 1st floor, absolute displacements in both of the directions on the 52nd floor, and building displacements (relative displacements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

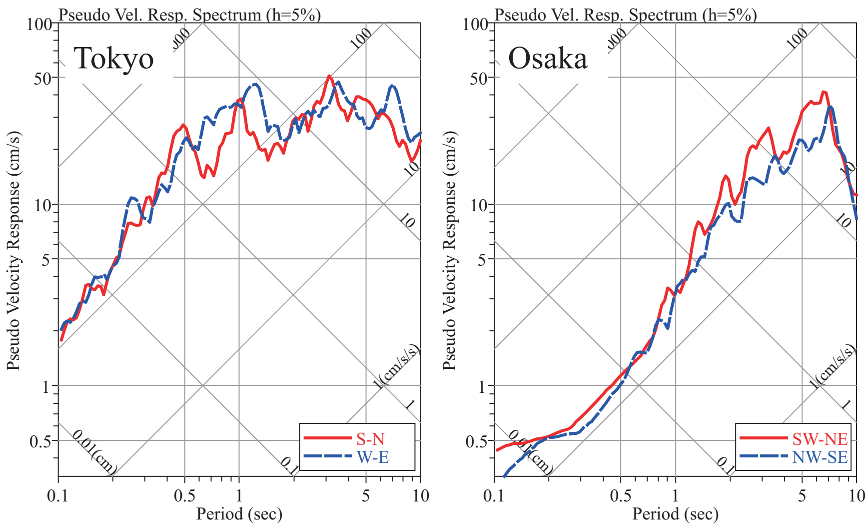

Fig. 5.3-6　Pseudo response spectra with damping ratio of 5% of records in Tokyo Bay area (left) and Osaka Bay area (right)

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