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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

Juntaro Tsuru
Deputy Director-General
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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

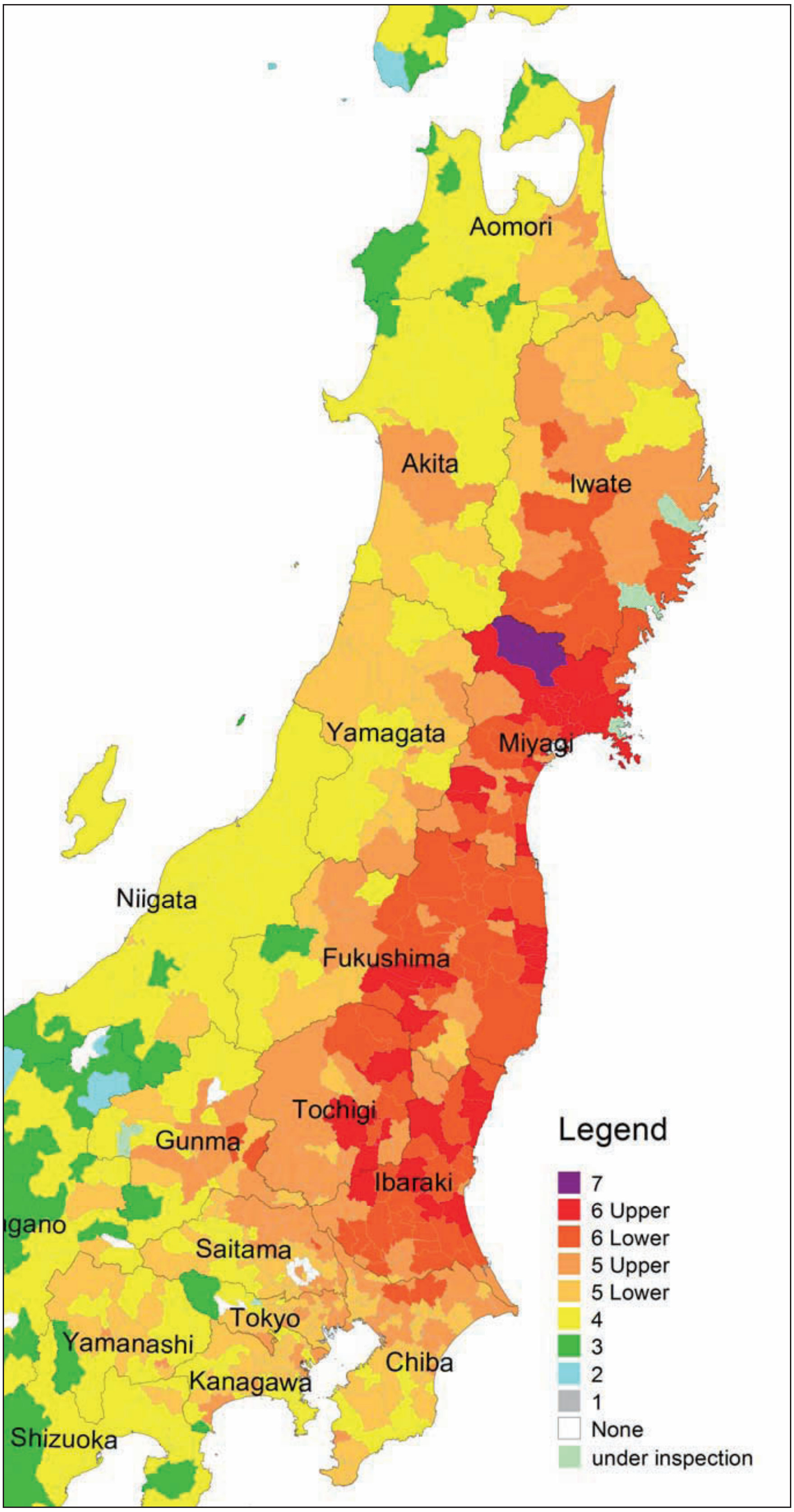

Fig. 3.1-1 Distribution of JMA seismic intensity in the 2011 Tohoku earthquake[3-1)]

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)]

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

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

Prefecture/ Municipality	Tsunami affected area(km^2)*1	Municipality area (km^2)
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).

3-2) National Police Agency of Japan. (July 11, 2011). Damage Situation and Police Countermeasures associated with 2011 Tohoku district - off the Pacific Ocean Earthquake.

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.

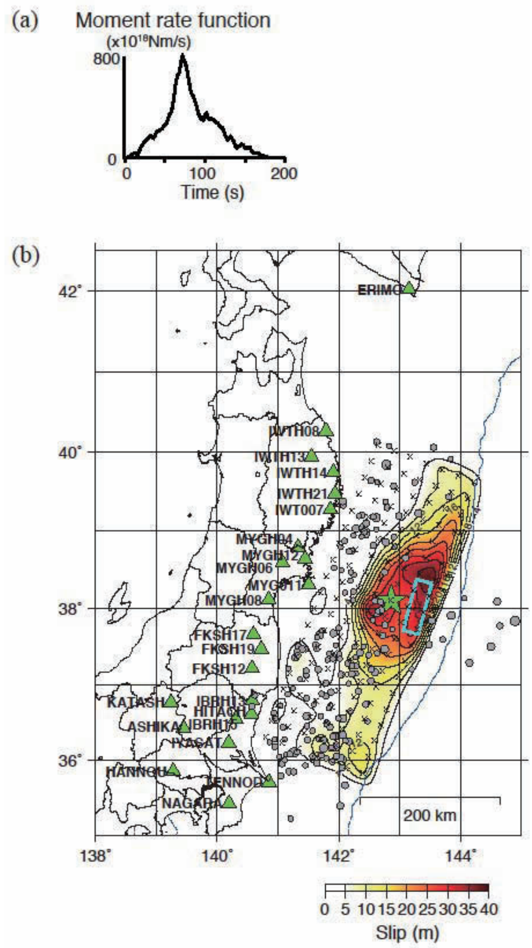

Fig. 4.1-1 Finite-source model from inversion of strong motion waves[4-1]: (a) Moment rate function. (b) Slip distribution on the fault. Large green star represents the epicenter of the mainshock, and gray circles represent aftershocks ($M \geq 5.0$) within 24 h of the mainshock. Triangles denote seismic 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].

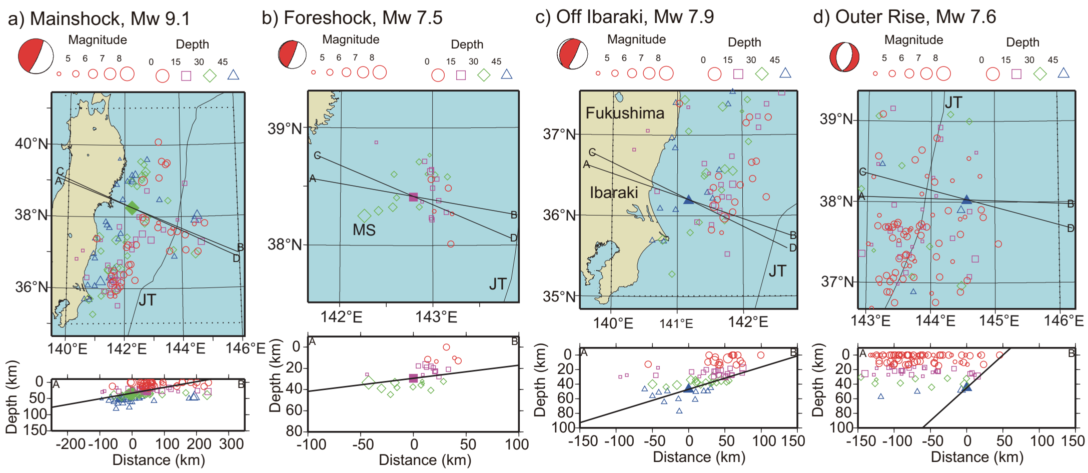

Fig. 4.2-1 Relocated hypocenters by the MJHD method[4-3]: Epicentral distribution and a vertical cross section along A-B line, which is perpendicular to strike of the nodal plane of the global CMT solution, are shown. This nodal plane corresponds with the fault plane. a) The mainshock (2011/03/11 5:46 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]:

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

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].

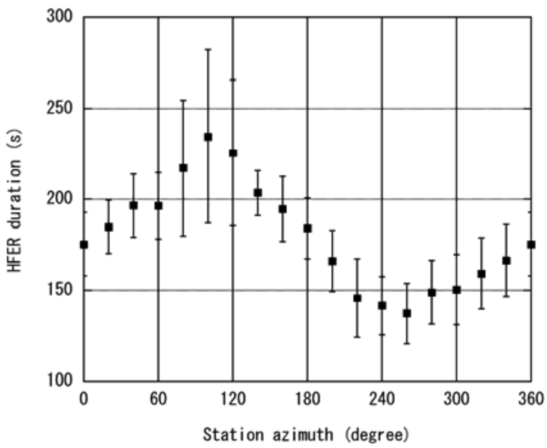

Fig. 4.3-1 The measured HFER durations as a function of station azimuths. The moving window (±30 degree) averages are shown.

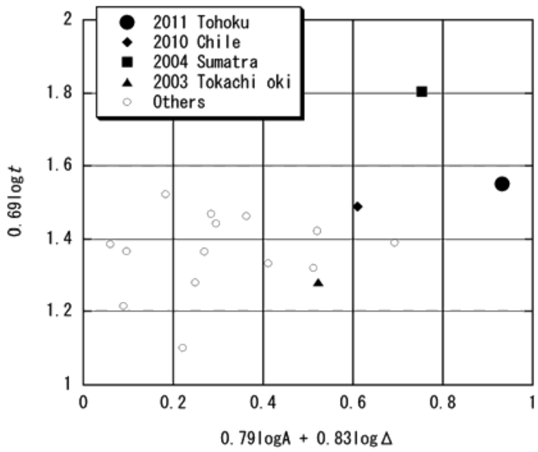

Fig. 4.3-2 Contributions to magnitudes from maximum displacement amplitudes and epicentral distances (the horizontal axis) and those from HFER durations (the vertical axis)

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.

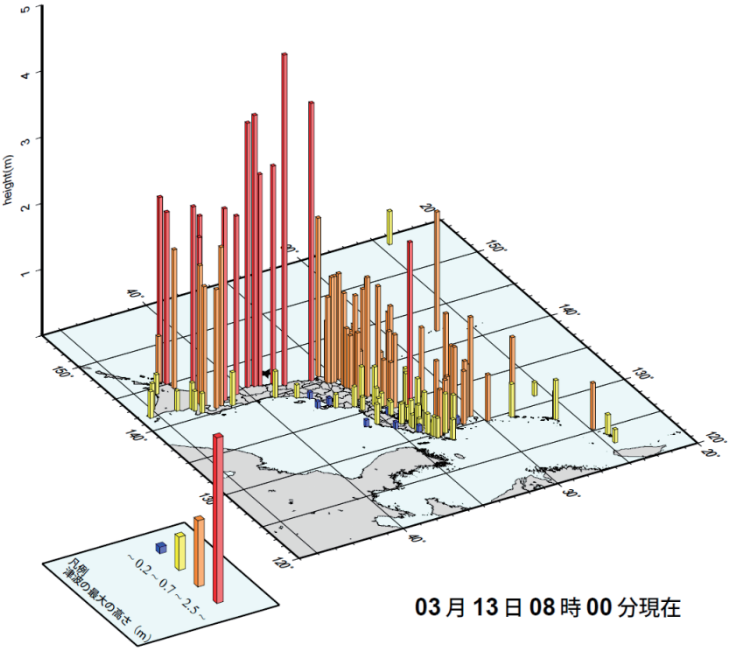

Fig. 4.4-1 Observed tsunami heights at tide gauge stations as of March 13th 8 AM[4-6]

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).

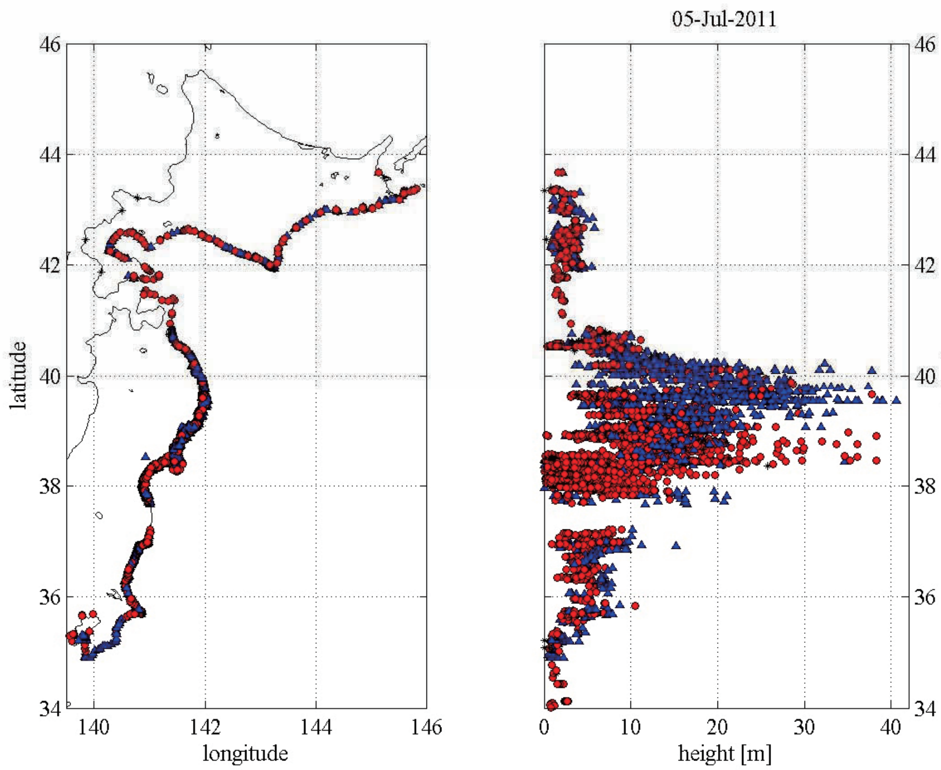

Fig. 4.4-2 Distribution of measured tsunami heights by the field surveys[4-7]: Red circles and blue triangles indicate inundation heights and runup heights, respectively.

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.

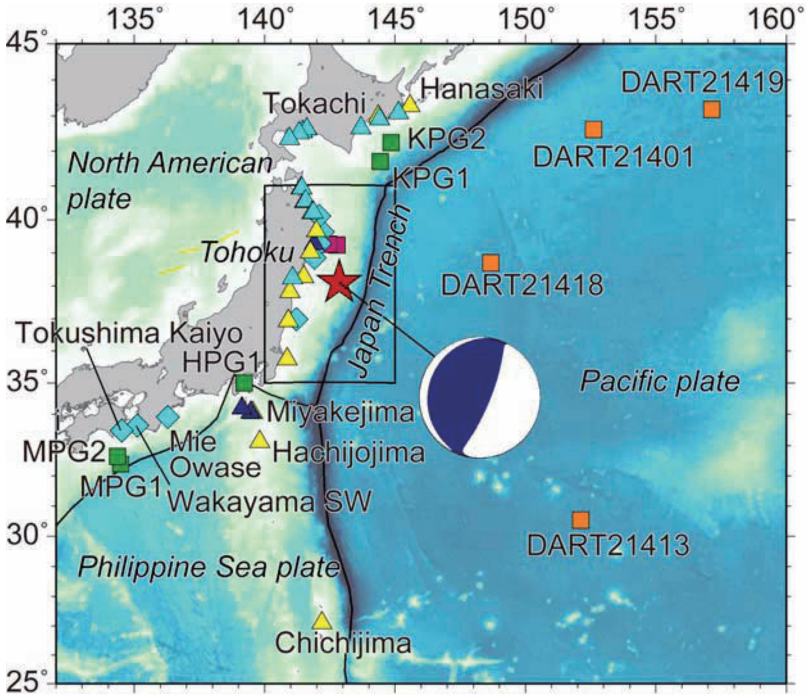

Fig. 4.4-3 Epicenter of the 2011 Tohoku earthquake (red star), W phase MT solution by USGS, and stations that recorded the tsunami[4-8]. Triangles, diamonds and squares indicate the locations of coastal (tide or wave) gauges, offshore GPS wave gauges and OBTSs or DART systems, respectively. Colors indicate 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.

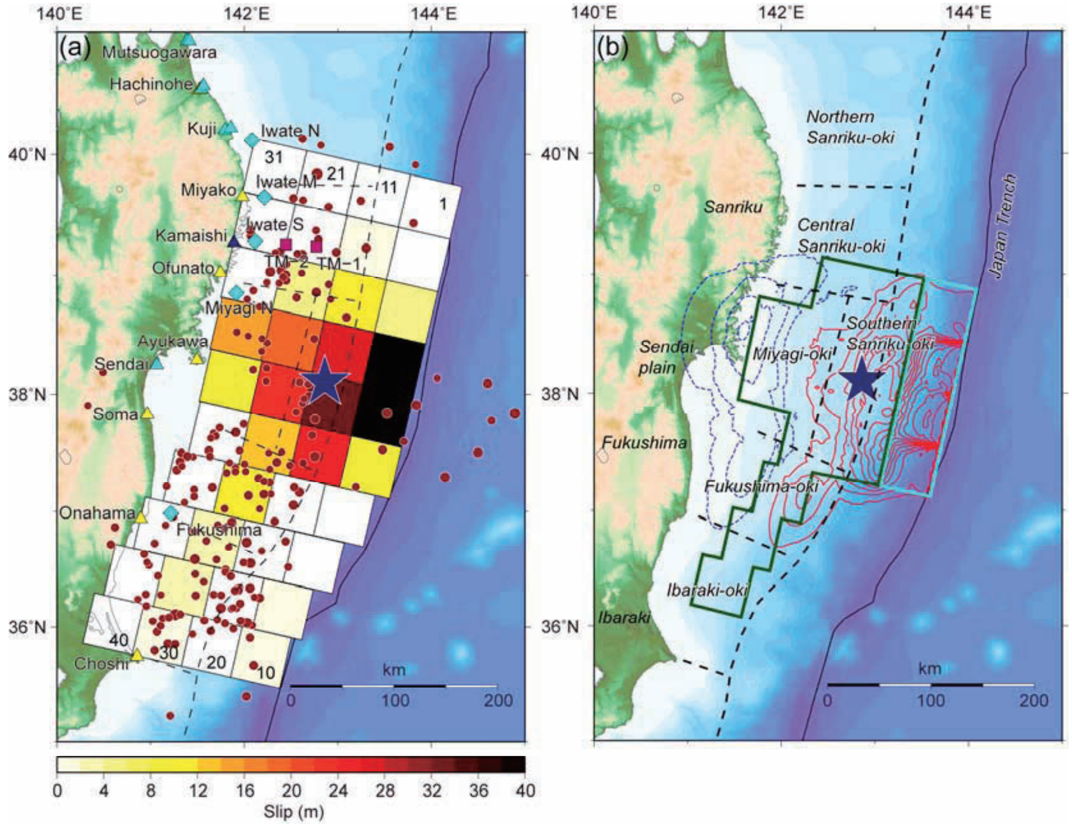

Fig. 4.4-4 (a) Slip distribution estimated by tsunami waveform inversion[4-8)]. The subfault numbers are shown in the northernmost and southernmost subfaults. Star shows the mainshock epicenter. Circles indicate aftershocks within one day after the mainshock (JMA data). Dashed lines indicate regions 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.

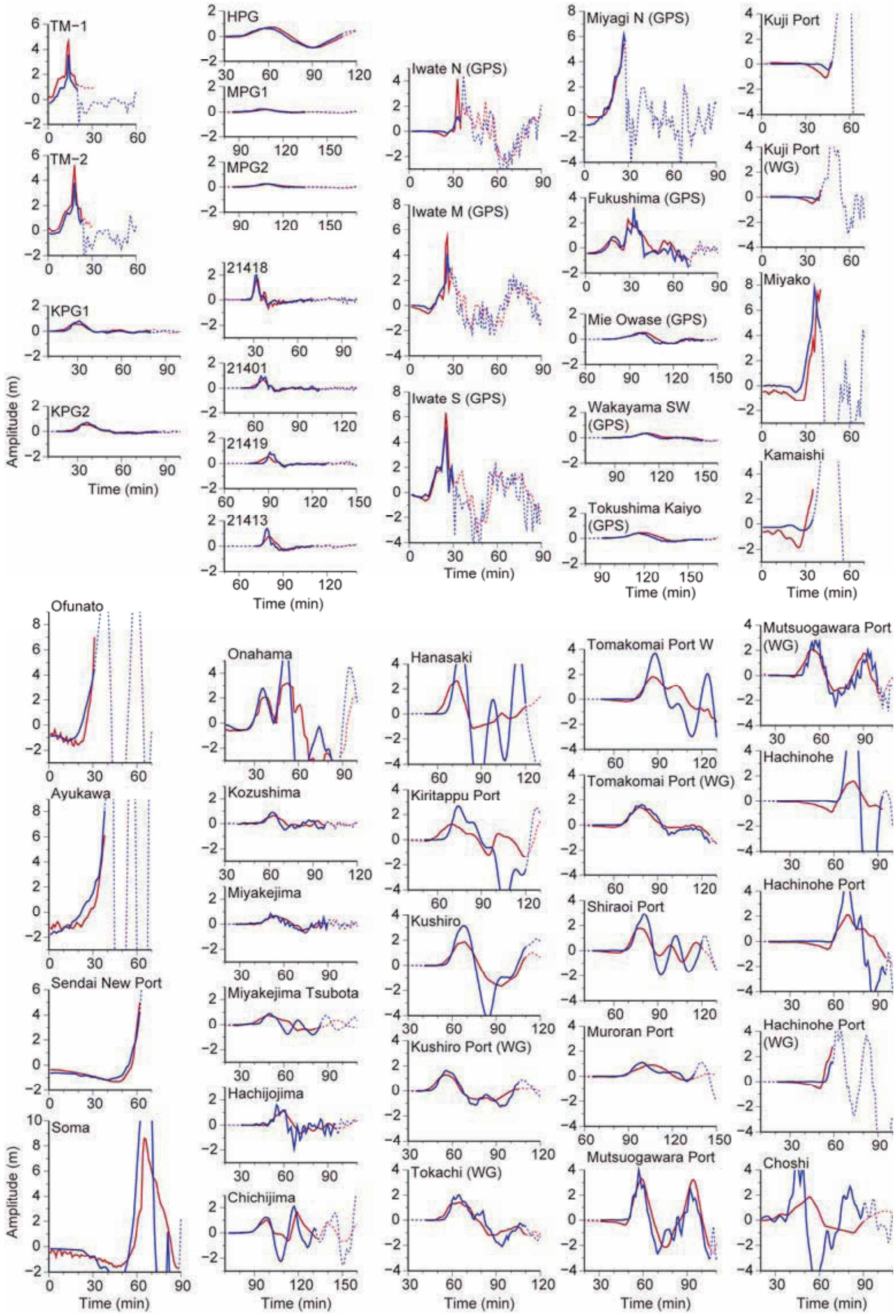

Fig. 4.4-5 Comparisons of the observed (red curves) and synthetic (blue curves) tsunami waveforms computed from the estimated slip distribution[4-8]. Time ranges shown by solid curves are used for the inversions; the dashed parts are not used for the inversions, but shown for comparison. Note the same 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).

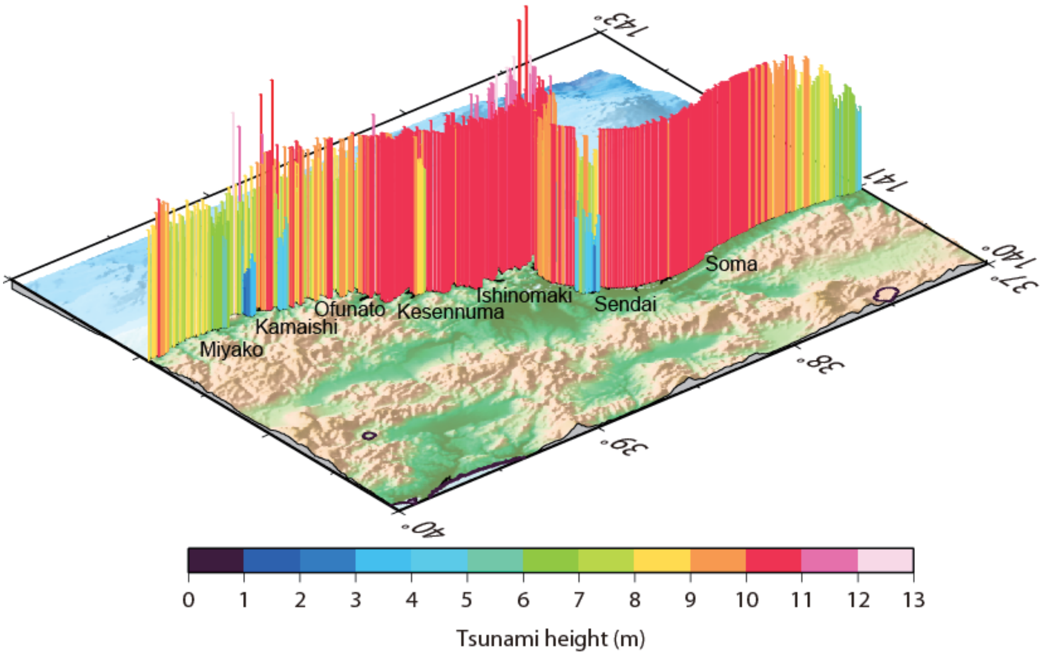

Fig. 4.4-6 Simulated tsunami heights along the coasts from southern part of Iwate to Fukushima prefectures. The used tsunami source model is based on Fujii *et al*. (2011)[4-8].

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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.

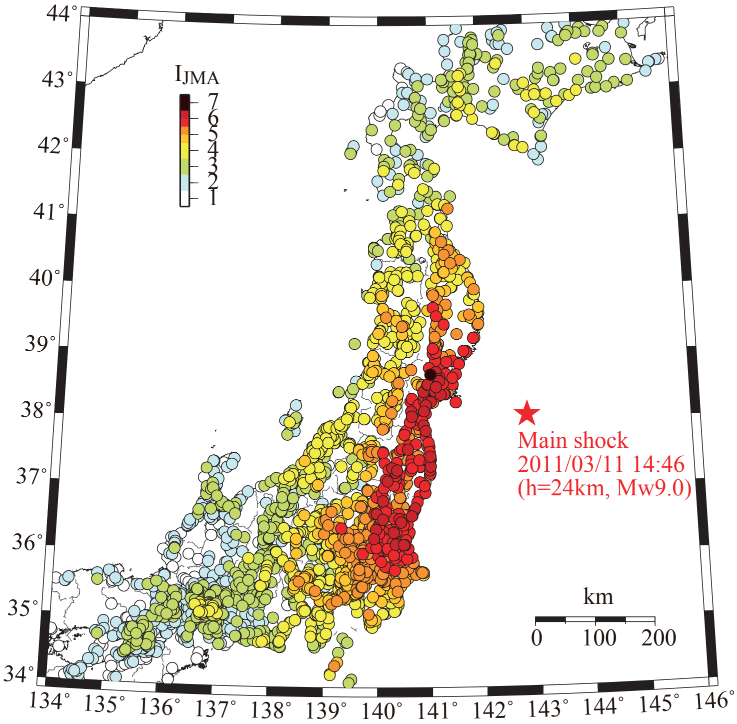


Fig. 5.1-1 Distribution of JMA seismic intensity

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.

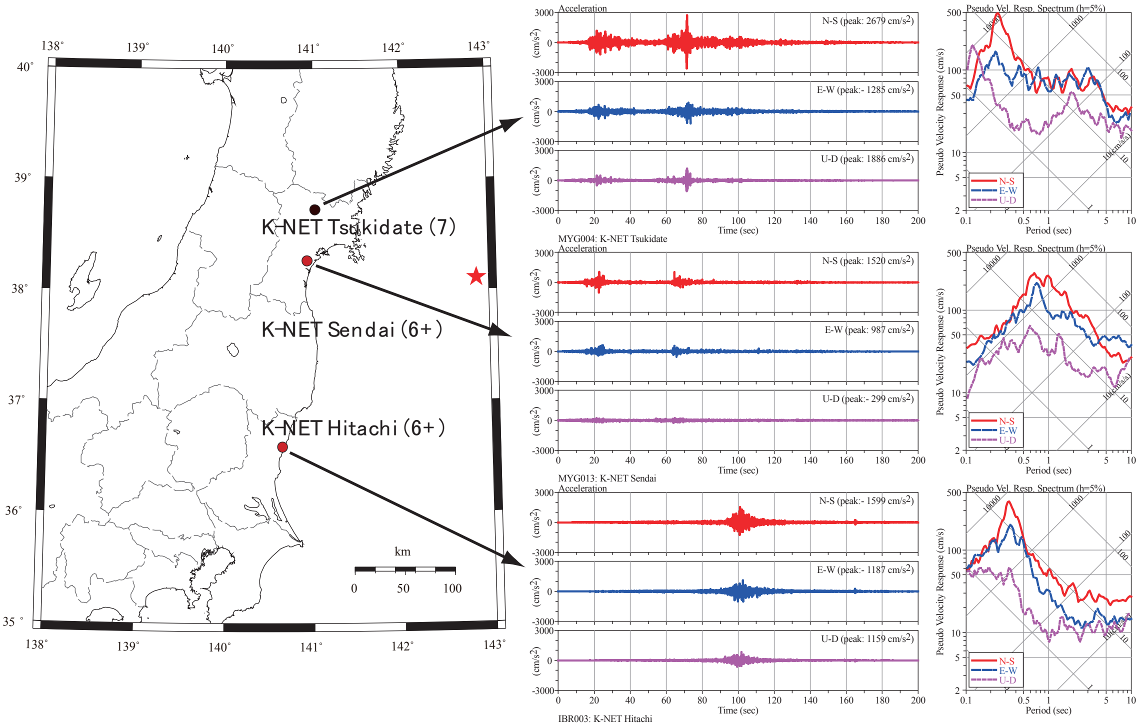


Fig. 5.2-1 Acceleration waveforms and pseudo velocity response spectra recorded at K-NET stations

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/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

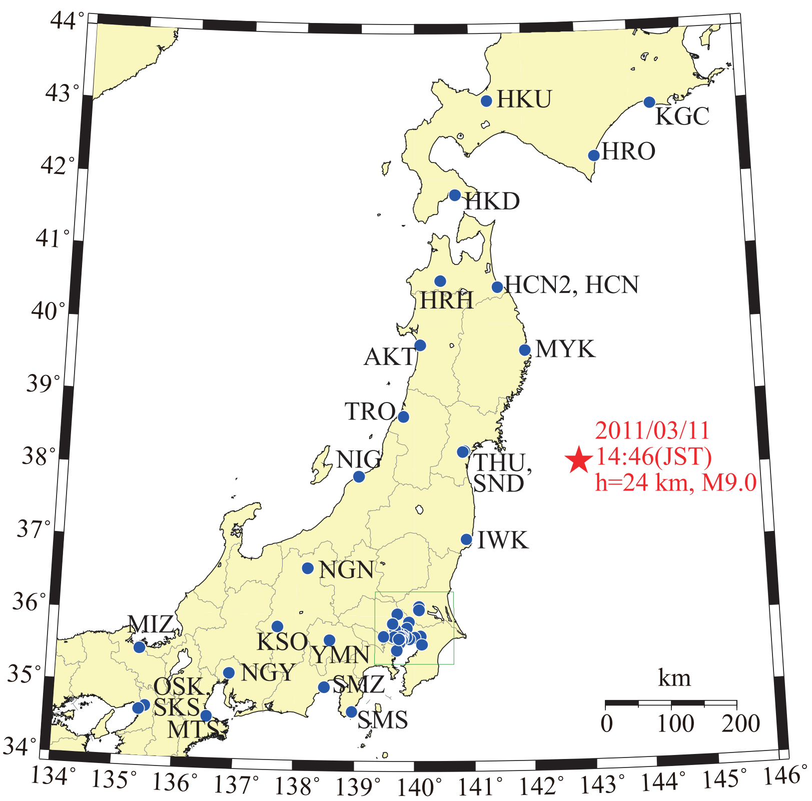


Fig. 5.3-1 Locations of epicenter (★) and BRI strong motion stations (●)

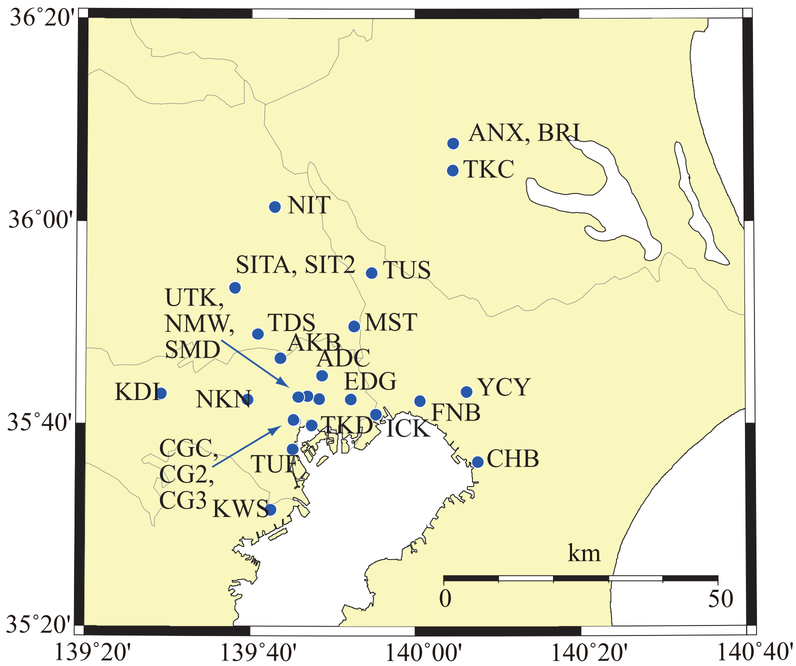


Fig. 5.3-2 BRI strong motion stations in Kanto area (corresponding to the green rectangle in Fig. 5.3-1)

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

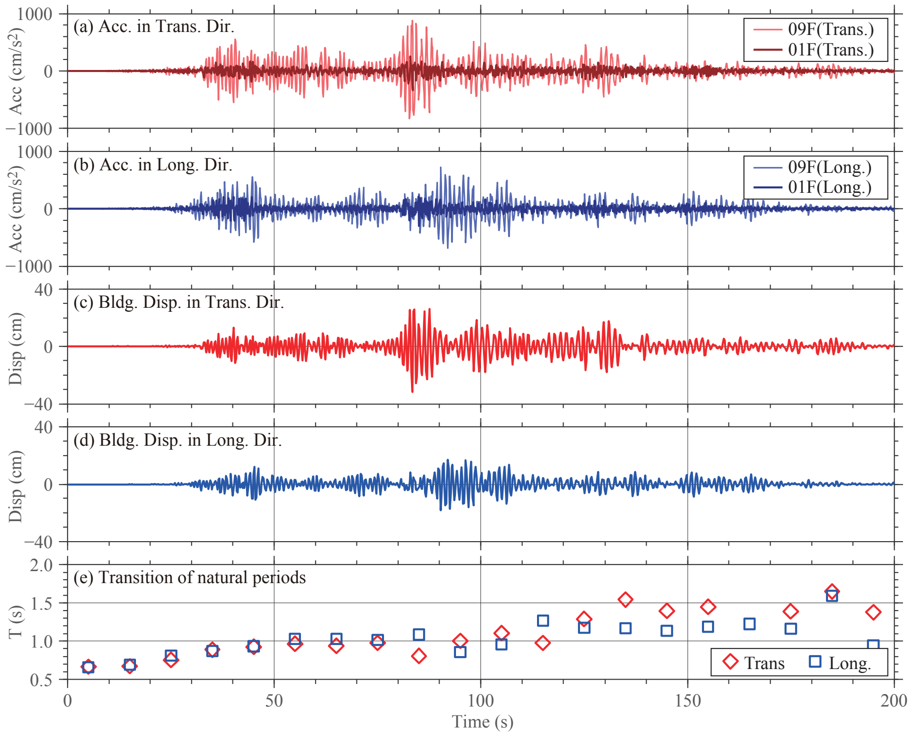


Fig. 5.3-3 Strong motion records of the research building of Tohoku University and transition of natural periods with time. (a) acceleration waveforms in the transverse direction, (b) acceleration waveforms in the longitudinal direction, (c) building displacement in the transverse direction (relative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

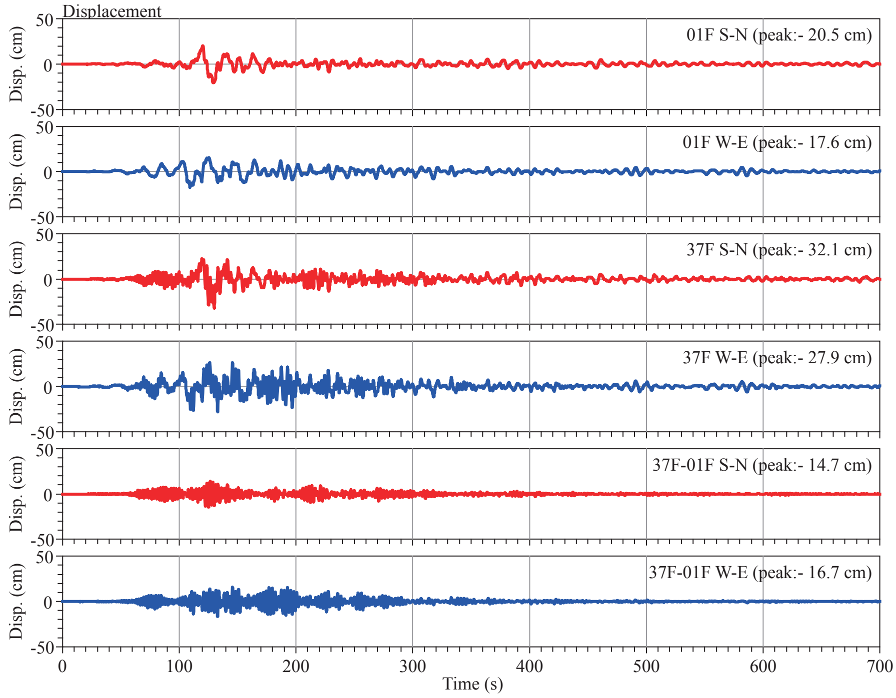


Fig. 5.3-4 Displacement waveforms observed at a 37-story residential building in

Tokyo Bay area

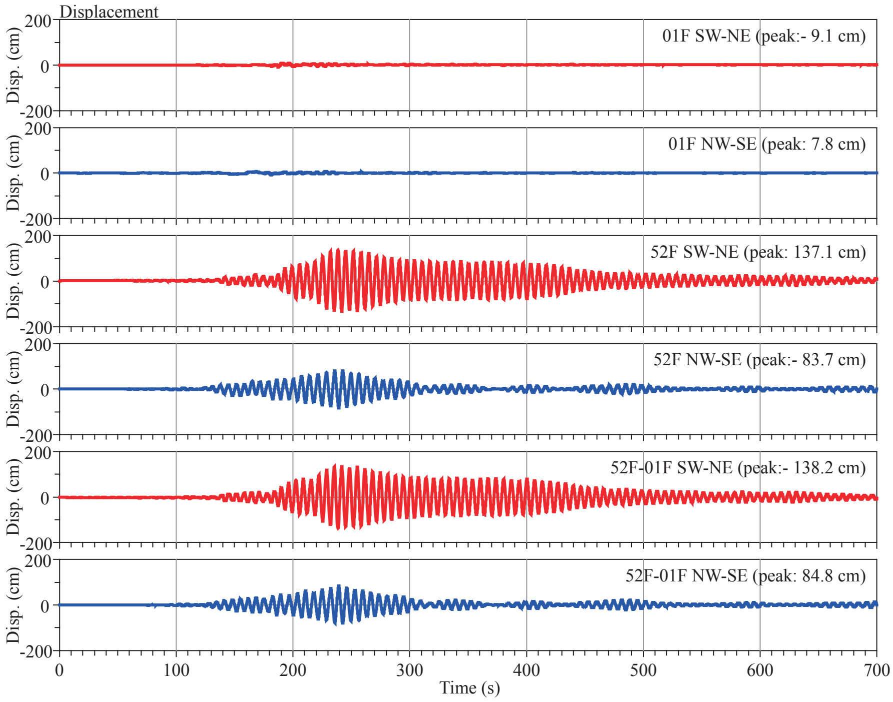


Fig. 5.3-5 Displacement waveforms observed at a 55-story office building in Osaka Bay area: From the top to the bottom; absolute displacements in the SW-NE and in the NW-SE on the 1st floor, absolute displacements in both of the directions on the 52nd floor, and building displacements (relative displacements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

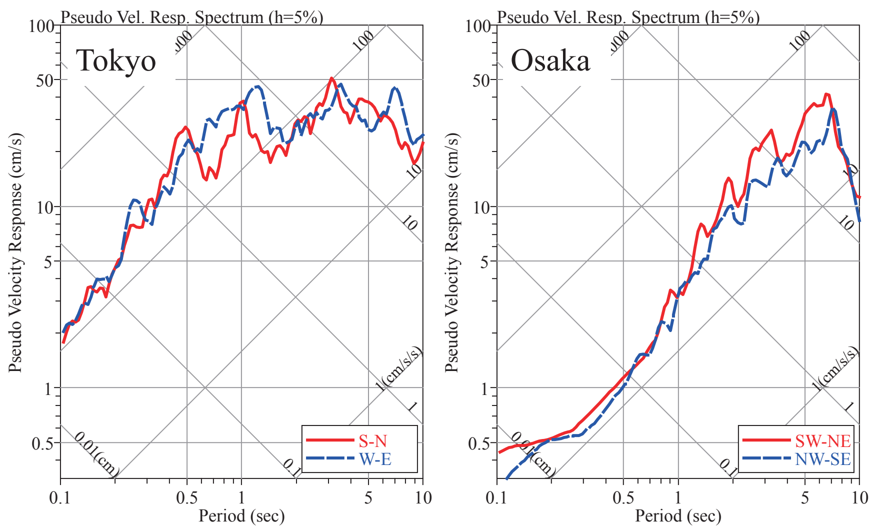


Fig. 5.3-6 Pseudo response spectra with damping ratio of 5% of records in Tokyo Bay area (left) and Osaka Bay area (right)

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

6. Damage to Buildings by Earthquake Motions

6.1 Policy on Earthquake Damage Investigation for Buildings

The 2011 Tohoku earthquake brought about building damage in a wide area of various prefectures on the Pacific coast in eastern Japan such as Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures.

The epicentral area of this earthquake has a length of about 450 km and a width of about 150 km, almost in parallel with the Pacific coast in eastern Japan. Distance from the fault plane of the earthquake to the above prefectures is almost same. As indicated in Chapter 5, observed earthquake motions in Sendai City close to the epicenter are not much different from those in cities far away from Sendai, for instance, Tsukuba City.

Based on these circumstances, NILIM and BRI decided to widely survey damaged wooden buildings as a primary damage investigation in the northern part of Miyagi (Kurihara City) where JMA Seismic Intensity 7 was observed, and in a wide area of Miyagi to Ibaraki including inland Tochigi prefecture that suffered larger damage than coastal prefectures. In addition, as a secondary investigation, it was planned to select affected areas from those subject to the primary investigation to conduct a more detailed survey on buildings collecting building plans and wood-shear-wall layout.

In order to conduct a damage investigation of steel buildings, it was decided that mainly a primary visual inspection would be done in Sendai City since a large stock of steel buildings is accumulated, and also in Fukushima and Ibaraki prefectures. As mentioned later, severer damage to structural elements seemed to be limited, while there were so many types of damage to nonstructural elements such as falling of exterior cladding. Consequently, focusing not on private buildings that are difficult to investigate in detail but on school gymnasiums in Ibaraki prefecture where many damage cases were reported that enabled interior investigations, it was decided to continue the primary investigation. For reference, the school gymnasiums can be seen to be similar to factories and warehouses. If the structural damage in interior building is clarified in future, more detailed secondary investigation on buildings other than the gymnasiums will be considered.

Concerning damage investigation for reinforced concrete buildings, in addition to an investigation of reportedly collapsed buildings, a primary investigation was conducted on city halls and other public buildings that are located in a wide area of the north to the south as done in the damage investigation for wooden buildings, and damage patterns whether they are similar or different from previously grasped patterns are examined. If there are characteristic damage patterns that should be incorporated into technical standards, the secondary investigation will be considered.

A primary investigation for damage of building lands and foundations was conducted in Itako City, Ibaraki, and in Urayasu City, Chiba and its peripheral areas that were subject to severe liquefaction in the region of Kanto. The areas that had been affected by the 1978 Miyagi-Ken-Oki Earthquake were damaged again. In these areas, also a primary damage investigation that focuses on developed housing lands was conducted in some areas of Miyagi, Fukushima and Tochigi prefectures.

In order to survey the damage of nonstructural elements, a primary investigation was performed, altogether with damage investigation for steel and reinforced concrete buildings including a requested investigation of ceiling falls in the Ibaraki Airport Building as an administrative support.

6.2 Damage to Wood Houses

6.2.1 Objectives of damage survey

A lot of wood buildings were damaged by the 2011 Tohoku earthquake. NILIM and BRI surveyed the damage of wood building starting from March 14, three days after the earthquake occurrence for the purpose of grasping the general image of the damage. Because the disaster by the earthquake occurred in wide areas, we carried out the first survey for multiple times, but cannot grasp the whole aspect of the damage. In this chapter, results of these multiple survey were summarized as basic documents to devise a survey plan in afterward to consider about the damage cause.

6.2.2 The selection of the survey area and the outline of the survey

The survey area and the reasons of the selection are as follows;
Kurihara city in Miyagi pref. : The seismic intensity 7 was recorded,
Osaki city in Miyagi pref. : As a result of damage survey[6.2-1), heavy damage was reported,
Sukagawa city in Fukushima pref.: RC buildings were heavily damaged,
Nasu and Yaita cities in Tochigi pref., and Hitachiota and Naka cities in Ibaraki pref. : As a result of damage survey[6.2-1) by others, damage information has not been reported, at the time of our survey,
Ishinomaki city in Miyagi pref. : Although it was almost included in the inundation area, the selected area of the city was not inundated by the tsunami, and,
Joso and Ryugasaki cities in Ibaraki pref. : There was damage information and they are located close to NILIM and BRI.

The locations of the surveyed cities and towns are shown in Fig. 6.2-1, and the schedules of the survey are shown in table 6.2-1.

Table 6.2-1 Schedules of survey.

Month/Day	Surveyed area
3/14～16	Kurihara and Sendai in Miyagi prefecture
3/23	Joso and Ryugasaki in Ibaraki prefecture
3/24～25	Sukagawa in Fukushima prefecture and Nasu and Yaita in Tochigi prefecture
3/25	Hitachiota, Naka, and Mito in Ibaraki prefecture
4/21	Hitachiota and Naka in Ibaraki prefecture
4/27～29	Osaki, Misato, and Ishinomaki in Miyagi prefecture

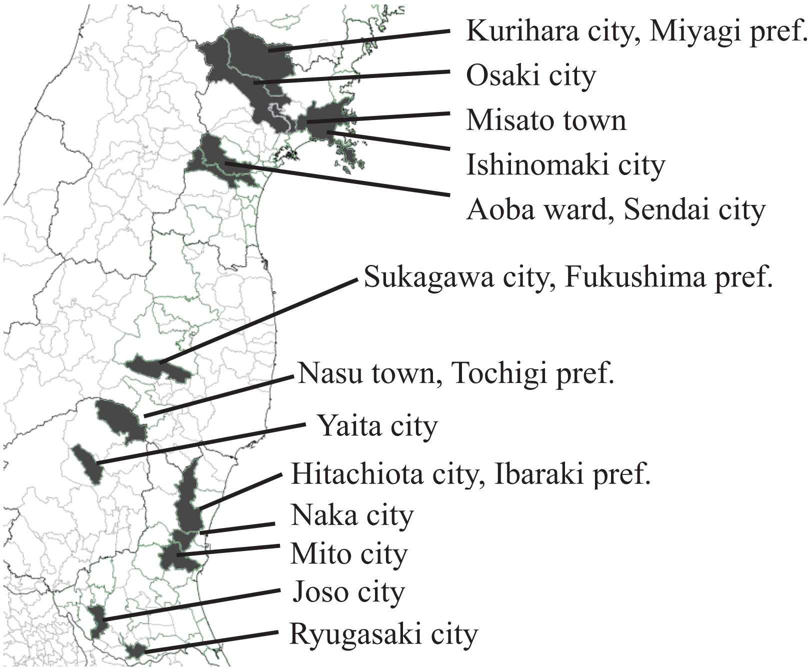


Fig. 6.2-1 Locations of surveyed cities and towns.

6.2.3 Results of the survey

(1) Kurihara city, Miyagi prefecture

According to the Kurihara city office, Miyagi where seismic intensity 7 was recorded, post-earthquake quick inspection of damaged buildings was conducted for 590 wood houses (excluding warehouses) in greatly damaged areas: Wakayanagi-Kawakita (139), Wakayanagi-Kawaminami (246), Wakayanagi-Fukuoka (80), Semine (187), Kurikoma-Sakurada (70), as of March 15. Location of these places is shown in Fig. 6.2-2. Unsafe wood houses in danger, wood houses with limited entry and inspected (safe) wood houses accounted for 18%, 29% and 54% of the total, respectively. The number of collapsed houses was only one, and the number of completely

Fig.6.2-2 Surveyed areas in Kurihara city

destroyed houses and almost-destroyed houses were 42. The ground conditions in Wakayanagi and KurikomaSakurada are poor, and most of the houses in the north and south side of Wakayanagi, KurikomaSakurada and Semine had age of about 30 to 40 years. On the other hand, since the ground conditions are good near the city office, structural damage was not observed in the city office.

K-NET Kurihara Tsukidate (MYG004 : Instrumental seismic intensity 6.6) is set up on the hillock 3m higher (by eye measurement) than south of parking lot of Kurihara lyceum. There was a possibility of the amplification of earthquake motions (Photo 6.2-1). In Wakayanagi district, the ground was bad and sand boil due to liquefaction was observed (Photo 6.2-2). Damage to houses caused by ground transformation (Photo 6.2-3) and damage to houses with store were also observed (Photo 6.2-4).

A large residual deformation was observed in the longitudinal direction in the large-scale wood building used as a movie theatre then renovated to a factory (Photos 6.2-5, 6.2-6)

According to the observation of overturning of tombstones in three places in Wakayanagi district, the ratio of overturning was from 10% to 40%, and it seemed that there were a lot of overturnings in north to south direction (Photo 6.2-7).

In Kurikomasakurada district, collapse of work hut, drop of the mud plasters of Nagaya-mon gates (Photo 6.2-8), damage of plastered storehouses were observed, but any heavy damage in house was not observed.

The Seismograph of Kurikoma (JMA seismic intensity 6-) is set up on the parking lot in the west of “Michinoku-Densokan（Photo 6.2-9）”. From the exterior damage investigation, damage was not observed in “Michinoku-Densokan” and Kurikoma Branch office (Glulam frame structure: Photo 6.2-10).

Photo 6.2-1 K-NET KuriharaTsukidate

Photo 6.2-2 Sand boil due to liquefaction

Photo 6.2-3 Damage of houses caused by ground transformation

Photo 6.2-4 Damage of houses with store

Photo 6.2-5 Large-scale wood building renovated to a factory

Photo 6.2-6 Inside of the building shown in Photo 6.2-5

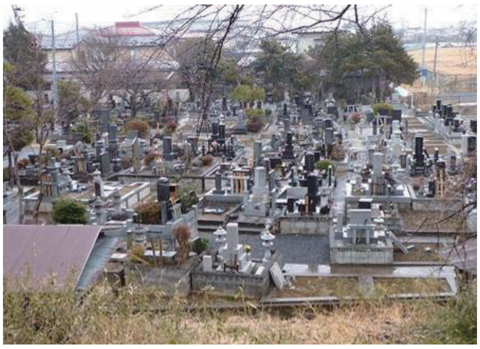


Photo 6.2-7 Overturning of tombstones

Photo 6.2-8 Drop of mud plasters of Nagaya-mon gate (Kurikomasakurada)

Photo 6.2-9 Seismograph of Kurikoma

Photo 6.2-10 Kurikoma Branch office (Glulam frame structure)

(2) Osaki city, Miyagi prefecture

According to the Osaki city office, it was informed that the damage concentrated in the neighbourhood of the city office and the northwest of JR Freight Company Furukawa Station, as shown in Fig. 6.2-3. In the other areas, it was informed that there was damage on building along the old main road in Furukawa-Araya, but damage on buildings in the mountain region including Naruko district and so on, had not been reported.

Heavy damage including the collapse of houses was confirmed on the way to the northwest of JR Freight Company Furukawa Station from the Osaki city office. Besides the damage reported by the other institutions[6.2-2)], a largely deformed house, a damaged house with store, a partially collapsed house, and so on were observed.

For example, warehouse with the mud walls renovated as store or gallery (Photo 6.2-11) was damaged heavily or slightly. There was the one whose roof system with roof tiles collapsed and fell down, as shown in Photo 6.2-12. In the area of these warehouses, there was a Japanese traditional post and beam construction house with large deformation (Photo 6.2-13) which was renovated as a store. On the opposite side of this house, there was the house with store (Photo 6.2-14) with story shear deformation whose exterior mortar came off and wood lath under the mortar near the opening of the ventilation fan was deteriorated and attacked by termites, as shown in Photo 6.2-15. Such damage was confirmed in the other buildings. Most of these damage occurred along a small river, except for a few case, and it was considered that the soft ground near the river might amplify the earthquake ground motion.

Seismograph at JMA Furukawa (Photo 6.2-16) which recorded seismic intensity 6+ was located in the northeast corner of the Mikkamachi park. There were the former school buildings around it. One of them was not almost damaged (Photo 6.2-17), while the other was damaged on roof tiles and exterior mortar without story drift. In addition to them, a rare damage example (Photo 6.2-18) that only the 2nd story collapsed was observed. On the other hand, a wood school building (Photo 6.2-19) in the west of the Osaki city office seemed not to be damaged in the appearance. Besides these, the house with store with large story drift in 1st story (Photo 6.2-20), those with large story drift in 2nd story (Photo 6.2-21), and 1-story wood house with large story drift caused by the land liquefaction were observed.

In the northwest of JR Freight Company Furukawa Station, a collapsed steel frame building, an RC structure apartment house with rocking drift caused by the land deformation, and a temple building (Photo 6.2-22) with large story deformation were observed.

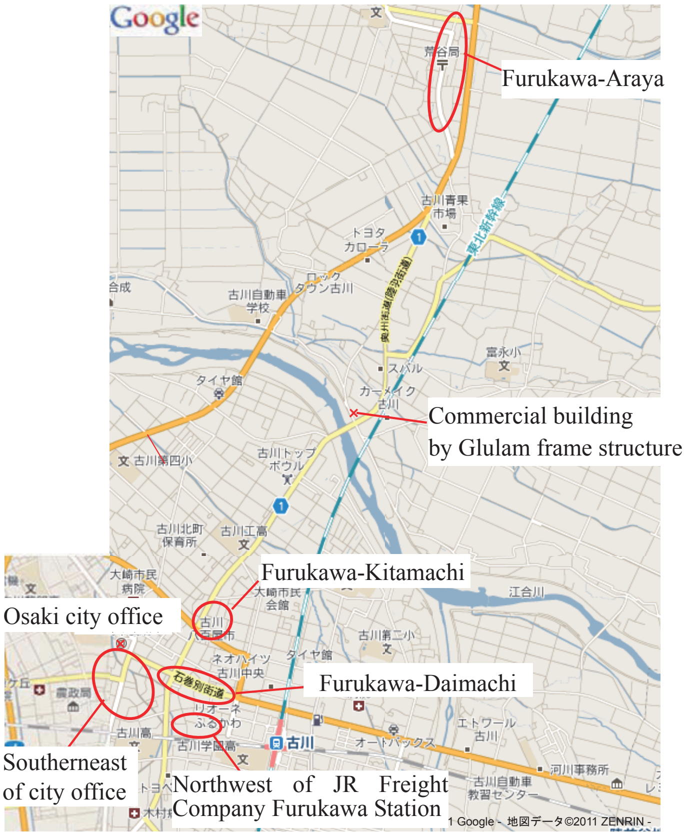


Fig. 6.2-3 Surveyed areas in Osaki city

Photo 6.2-11 Warehouse with mud walls damaged heavily or slightly

Photo 6.2-12 Warehouse with mud walls whose roof system with roof tiles fell down

Photo 6.2-13 Damaged Japanese traditional house with large story deformation

Photo 6.2-14 House with store with large story deformation

Photo 6.2-15 Deterioration in building of Photo 6.2-14

Photo 6.2-16 JMA seismic station at Furukawa (Seismic Intensity 6+)

Photo 6.2-17 School building suffering damage on roof tiles and exterior walls

Photo 6.2-18 School building whose 2nd story collapsed

Photo 6.2-19 Seemingly slightly damaged School building

Photo 6.2-20 House with store with large story deformation

Photo 6.2-21 House with store with 2nd story drift more than that of 1st story

Photo 6.2-22 Heavily damaged temple building

(3) Misato town, Miyagi

According to the Misato town office, the number of damaged structure was shown in table 6.2-2. There were a lot of damaged structures in Nakazone and Hirabari of Kogota area in this town.

Table 6.2-2 Number of damaged structures in Misato town as of April 28

Damage		Kogota area	Nango area	Total
Residential	Fully destroyed	60	17	77
	Half destroyed	243	70	313
	Partially destroyed	1,577	307	1,884
Non-residential		1,193	232	1,425

In Hirabari of Kogota area, there were a lot of wood houses which tilted largely in the east-west direction along the Eaigawa river (Photo 6.2-23). Photo 6.2-24 shows the wood house which leans to the fence. Most of the tombstones in this area fell toward in the east-west direction (Photo 6.2-25). Photo 6.2-26 shows the tilted wood house of which two-story might have been extended. In the southern side of Eaigawa river, there were log house without damage (Photo 6.2-27), wood house which tilted largely at first story (Photo 6.2-28) and tilted shrine building (Photo 6.2-29).

In Nango area, ground deformation was observed in the branch town office (Photo 6.2-30), but there were few damaged houses. Photo 6.2-31 shows the tilted wood house in Nango area. The structures in this area were damaged in a certain level during the 2003 northern Miyagi prefecture earthquake. There is a possibility that damaged buildings were retrofitted or rebuilt after the 2003 earthquake, because structures in this area seemed to be new.

Photo 6.2-23 Largely tilted house

Photo 6.2-24 Collapsed wood house

Photo 6.2-25 Tombstones in Hirabari

Photo 6.2-26 Tilted two-story house

Photo 6.2-27 Log house without damage

Photo 6.2-28 Largely tilted wood house

Photo 6.2-29 Damaged shrine

Photo 6.2-30 Ground deformation in Nango branch town office

Photo 6.2-31 Heavily damaged house

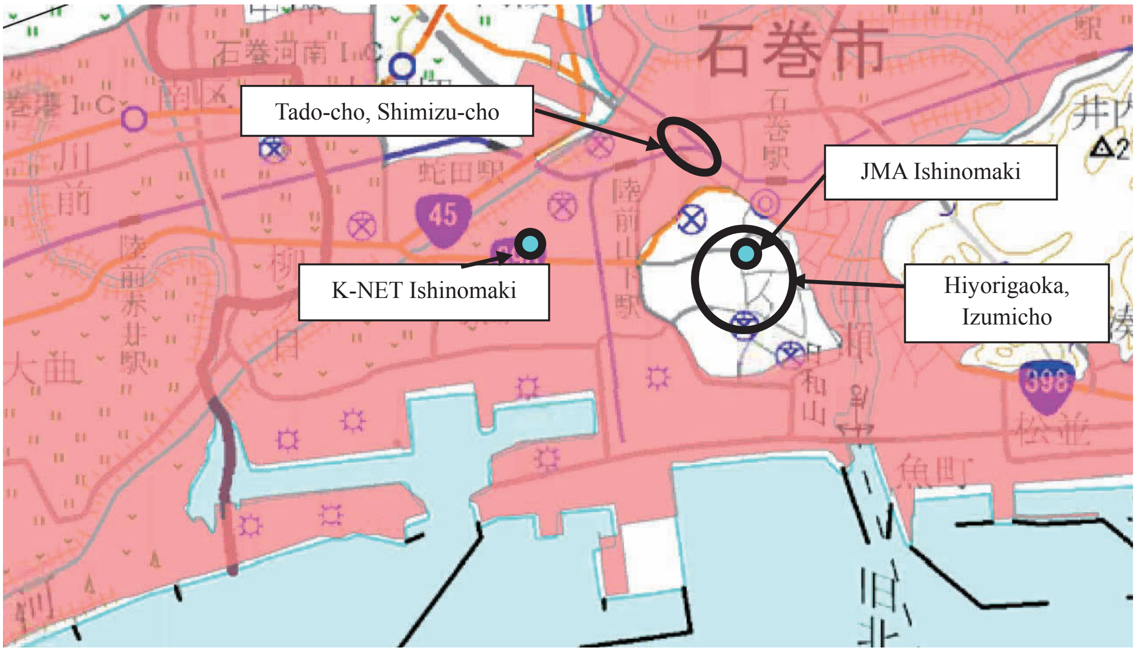
Photo 6.2-32 Inside of the house in Photo 6.2-31

(4) Ishinomaki city, Miyagi prefecture

Hiyorigaoka and Izumi-cho in Ishinomaki city are located on a hill (max. Altitude, 56.4m) at the western side of Kyu-kitakami river, almost all of the buildings are residence without public facilities (Photo 6.2-33). There were not heavily damaged wood houses and a few wood houses of which roof tile damaged (Photo 6.2-34).

Tado-cho and Shimizu-cho are located at the northern side of Hiyorigaoka hill and the area inundated by the tsunami according to the information[6.2-5)] of GSI (Fig. 6.2-4). There are a lot of low-rise wood houses with store which have big opening along the street between Ishinomaki-kaido and Ishinomaki-betsukaido street. The inundation depth estimated by the trace was 80-150cm. The inhabitant said that the fluid velocity of the tsunami was very slow and the inundation depth increased like flood. So it was estimated that the damage of the buildings was caused by the earthquake motion.

On the both sides of the street, there were collapsed wood house by earthquake (Photo 6.2-35) and tilted wood house with store (Photo 6.2-36). It was estimated that the wood houses with store which have less seismic elements at the first story were heavily damaged.



Colored area: inundated area

Fig. 6.2-4 GSI Inundation area map of Ishinomaki city [6.2-5)]

Photo 6.2-33 Appearance of Izumicho

Photo 6.2-34 Damaged roof tile in Hiyorigaoka

Photo 6.2-35 Collapsed wood house

Photo 6.2-36 Tilted wood house with store

(5) Sendai city in Miyagi prefecture

According to the Tohoku Regional Bureau, Ministry of Land, Infrastructure Transport and Tourism and Aoba ward office, Sendai city, the regions, where post-earthquake quick inspection of damaged buildings was conducted, were Asahigaoka 1, 2, 3, 4 chome(2, 250), Oritate 4, 5, 6 chome (470), Kaigamori 1 chome (400), Seikaen 1, 2chome (540) in Aoba ward, and Higashikuromatsu, Kuromatsu 1 chome and 3 chome in Izumi ward and so on. Location of those places was shown in Fig.6.2-5.

From the results of investigations on Oritate and Seikaen where the damage of the houses were serious, it was found that almost all of the damage of house were caused by ground transformation. Moreover, ground transformation caused retaining wall collapse (Photo 6.2-37, 6.2-38), landslide and damage of houses (Photo 6.2-39). On the other hand, there were some sloping lands in Kaigamori and Asahigaoka where the number of damage of retaining wall was minor, and damage of roof tile, collapse of concrete block wall and outer wall were observed. In Komatsujima, Aoba ward, drop off the mortar wall and damage of columns and biodeterioration by termites were observed in the house with store (Photo 6.2-40). Moreover, the house with large residual deformation on the 1st floor was observed (Photo 6.2-41). In Mukaiyama, Taihaku ward, collapse of a Japanese-style hotel was observed because of the sudden fall of stone of hillback (Photo

6.2-42, 6.2-43).

Fig. 6.2-5 Observation points in Sendai city
(◯:observation completed, ◌: not completed)

Photo 6.2-37 Damage of retaining wall and houses（Oritate, Aoba ward）

Photo 6.2-38 Damage of house in Photo 6.2-37

Photo 6.2-39 Damage of house caused by the ground transformation (Oritate)

Photo 6.2-40 Drop off the mortar wall (Komatsujima)

Photo 6.2-41 House with large residual deformation (Komatsujima)

Photo 6.2-42 Collapse of Japanese-style hotel (Mukaiyama)

Photo 6.2-43 Hillback of the hotel

(6) Sukagawa city, Fukushima prefecture

According to the Sukagawa city office, it was said that the damage of buildings was concentrated on around the city office at Hachiman-machi, Kaji-machi and Minami-machi. The post-earthquake quick inspection of damaged buildings (Table 6.2-3) was conducted only around the city office and finished by March 24.

There was a little damage on the upper timber construction of wood houses, and the damage of several residential lands was reported in the east part of the city. A lot of Japanese traditional warehouse with wood structural members and mud walls were built and left at present because Sukagawa city prospered as a merchant town. A lot of warehouses with mud wall and stone built about 30 years ago suffered heavy damage.

A lot of damaged wood houses were observed around the collapsed RC structure building. Examples are as follows: the failed exterior mortar wall of the 2nd floor in a house with store (Photo 6.2-44), deterioration and damage by Reticulitermes on a part of structural member and wood lath of exterior mortar wall (Photo 6.2-45), a wood house whose stair hall was removed and collapsed (Photo 6.2-46), and so on.

The wood warehouses with mud wall were heavily damaged near the hotel with the window glass broken. For example, the warehouses which deformed much (Photo 6.2-47) and whose roof system collapsed (Photo 6.2-48) were observed. A few wood houses with roof tiles damaged (*e.g.* Photo 6.2-49) were found. On the other hand, roof tiles of temple gate (called as "*Sanmon*") were damaged, while the main hall of the temple was not so damaged (Photo 6.2-50 and 51). The sand eruptions caused by the soil liquefaction and the damage on the roof tiles were seen here and there in Minami-machi, Sukagawa city. In addition, on the web site of the city, the collapsed house was reported (Photo 6.2-52, From the city website).

Another collapsed building with uncertain structural type was found (Photo 6.2-53). According to the damage overview seen from the east of Minami-machi (Photo 6.2-54), it was observed that the wood houses with roof covered temporarily with blue vinyl sheet which was guessed to be damaged to roof tiles were relatively many.

Table 6.2-3 Results of Post-earthquake quick inspection of damaged buildings in Sukagawa city as of March 24

Structural type	Checked number	Unsafe	Limited Entry	Inspected
Timber	1,023	245	315	463
Steel	188	51	44	93
Reinforced concrete	73	25	16	32
Total	1,284	321	375	588
Ratio	100 %	25.0 %	29.2 %	45.8 %

Photo 6.2-44 Fallen mortar of wall (Wood house with store)

Photo 6.2-45 Deterioration and damage due to termite on column and wood lath of exterior mortar

Photo 6.2-46 Collapsed stair hall

Photo 6.2-47 Failed warehouse with mud wall

Photo 6.2-48 Fallen roof of warehouse with mud wall

Photo 6.2-49 Damage of roof tile

Photo 6.2-50 Minor damage of temple gate

Photo 6.2-51 No damage on main hall of temple

Photo 6.2-52 Collapsed wood house at Minami-machi (From Sukagawa city website)

Photo 6.2-53 Collapsed building (Unknown structure type)

Photo 6.2-54 Damage overview from the east of Minami-machi (Many roofs covered with blue vinyl sheet)

(7) Nasu town, Tochigi prefecture

According to the Nasu town office, the post-earthquake quick inspection of damaged buildings had not been carried out. The primary damage survey was conducted only by the town officials. With the survey, 32 wood houses were found totally collapsed.

It was said that the damage on buildings was concentrated in the area of Nishi-Ohkubo near the town office, although there was no collapsed wood house. It was reported that there was little damage in Nasu-kogen highland area in the west of national road route 4. On the other hand, it was said that damage on many wood houses were found in Toyohara-Otsu area where many cottages built on slope lands.

The damaged houses were in the area of Shio-akutsu, Chausu, Hoshibata, Akiyamasawa, Nigashimuro, Yanome, Higashi-Iwasaki, Numanoi, Hongo, Nishizaka, Ishizumi, Muronoi etc. and most of them were developed as residential lands. The locations of surveyed areas are shown in Fig. 6.2-6.

The stone-built warehouse was heavily damaged near the town office (Photo 6.2-55). The exterior stonewall of the former post office was failed (Photo 6.2-56).

Toyohara-Otsu area is in the north of Nasu town, and cottages are built along the path on slightly elevated hills. The movement and collapse of the wood deck (Photo 6.2-57) and collapse of the stone exterior were often observed. Several damages on wood houses caused by the slope land or the embankment were observed. The damage on the wood house due to large ground deformation caused by the earthquake motion was also found (Photo 6.2-58). It was confirmed that the metal fasteners were installed in the column end joint and the brace end joint of this house. (Photo 6.2-59). Besides the story drift, crack of concrete foundation (Photo 6.2-60), crack and loss of the exterior siding board, broken window glass, and failed ceiling of eaves (Photo 6.2-61) were observed.

In Nishi-Ohkubo area, several wood houses whose exterior mortar wall in the 1^{st} floor was almost failed were found (Photo 6.2-62). And, the wood house with large story drift (Photo 6.2-63) and the other one damaged due to deformation of the residential land (Photo 6.2-64) were found.

Photo 6.2-55 Damage of stone-built warehouses

Photo 6.2-56 Damage of an old post office

Fig. 6.2-6 Surveyed area in Nasu town

Photo 6.2-57 Damage of wood deck in Toyohara-Otsu, Nasu town

Photo 6.2-58 Heavily damaged wood house

Photo 6.2-59 Metal fastener at the end of column and brace

Photo 6.2-60 Crack of foundation

Photo 6.2-61 Failed ceiling of eave

Photo 6.2-62 Damage of exterior mortar wall

Photo 6.2-63 Wood house with large story drift

Photo 6.2-64 Damaged house due to deformation of residential land

(8) Yaita city, Tochigi

According to the Yaita city office, the post-earthquake quick inspection of damaged buildings was limited to the houses at the request of residents and all houses in evacuation zone due to deformation of the residential land. By March 23, 108 buildings (including 3 buildings, such as stone warehouse, which couldn't be evaluated) were surveyed by the post-earthquake quick inspection of damaged buildings. The numbers of "Unsafe", "Limited Entry" and "Inspected" were 40, 42 and 23, respectively.

Evacuation was announced officially to the east of Lobin-city due to the deformation of the residential land. It was said that many damage were observed in the northeast area of Narita-Happy-Highland, Arai, Hariu, and Koshiwata where development was made by sharpening slope lands and filling up swamps. The locations of the above areas are shown in Fig. 6.2-7.

In Lobin-city (Photo 6.2-65), cracks of fence and retaining wall, caving of road bed, ups and downs of the residential land (Photo 6.2-66) and cracks of the foundation concrete (Photo 6.2-67) were often observed. In addition, damage on the roof tile, especially top of the roof, and collapsed concrete block fences were observed.

Narita-Happy-Highland located at the north of Lobin-city was a developed residential land. Most of the damage on buildings was due to the deformation of the residential land. A wood house with 1/10 radian shear deformation (Photo 6.2-68) was found.

Fig. 6.2-7 Research area in Yaita city

Photo 6.2-65 No damaged houses at Lobin-city area

Photo 6.2-66 Ups and downs of residential land

Photo 6.2-67 Crack of foundation

Photo 6.2-68 Wood house with large shear deformation

(9) Hitachiohta city, Ibaraki prefecture

According to the post-earthquake quick inspection of damaged buildings, the number of “Unsafe” was 199, “Limited Entry” was 549 and “Inspected” was 574 in the city. The number of “Unsafe” was 87, “Limited entry” was 235 and “Inspected” was 97 in the Matsuzaka-cho. There were a lot of damaged buildings at the Kanasago area (Matsuzaka-cho and Nakano) in the Kujigawa river basin. Hitachiohta city office had made the hazard map that considers the subduction-zone earthquake. The seismic intensity was from 5+ to 6- at the Kujigawa river basin area.

There were a lot of damaged fence made by the Ohyaishi stone. A collapsed farm type house was observed (Photo 6.2-69, 6.2-70). The mortar plastered wall finish of the wood house at the land filled paddy field fell down (Photo 6.2-71).

Photo 6.2-69 Collapsed wood house

Photo 6.2-70 Breakage of entrance part.

Photo 6.2-71 Falling down of mortar plastered wall

(10) Naka city, Ibaraki prefecture

Naka city is surrounded by the Nakagawa river and the Kujigawa river and the center of the city is located on the plateau. A lot of damaged buildings were located at the Kujigawa river basin. The number of totally collapsed houses was 4 at Kadobe-shimogawara, 1 at Motoyonezaki as of March 25. By the post-earthquake quick inspection of damaged buildings, the number of "Unsafe" was 88. The damage information was reported at Kadobeakutsu and Urizura.

At Kadobe-shimogawara in Naka city, there were a lot of collapsed barns (Photo 6.2-72) and heavily damaged nagayamon gates (Photo 6.2-73). A damaged house with store was observed (Photo 6.2-74). A lot of collapsed barns were observed at Kadobe-akutsu.

A two story wood house with mortar finish collapsed at the urban area of Urizura in Naka city (Photo 6.2-75).

At the wood gymnasium (Photo 6.2-76, Photo 6.2-77) with curved glue laminated timber built in 1985-1989 in Urizura, buckling and tensile failure of the steel braces, the breakages of the foundation concrete at the brace joint were observed (Photo 6.2-78). At the wood school building (Photo 6.2-79), the slip of wood braces (Photo 6.2-80), the deformation of steel roof plate, wood flooring and interior material due to the contact with the stairway made by reinforced concrete were observed.

Photo 6.2-72 Collapsed nagayamon gate (Kadobe)

Photo 6.2-73 Tilted nagayamon gate (Kadobe)

Photo 6.2-74 Damaged house with store (Kadobe)

Photo 6.2-75 Collapsed house (Urizura)


Photo 6.2-76 Wood gymnasium


Photo 6.2-77 Inside of the gymnasium


Photo 6.2-78 Breakage of the foundation concrete


Photo 6.2-79 Wood school building


Photo 6.2-80 Slip of the wood brace

(11) Mito city, Ibaraki prefecture

According to the Mito city office, the number of totally collapsed building was 34 (residential 2, non-residential 32), half destroyed building, 66 (residential 34, non-residential 32) as of March 25.

The damaged buildings were mainly located around the city hall and in Motomachi, Yoshinuma-cho, Aoyagi-cho, Yanagawa-cho, Kamikochi-cho, Taya-cho, Joto and Sannomaru. The number of the collapsed residential house was two at Motomachi.

In the southern part of the Mito railway station, the ground settlement occurred and the gap between the high-rise building and ground was observed. This area had been a part of the Senbako lake and was developed as residential land in 1965-1974. The ground settlement was also observed at the city hall and the entry to the building was restricted.

There was a heavily damaged Nagayamon gate at Yoshinuma-cho (Photo 6.2-81). The damaged barns were observed at Aoyagi-cho, Yanagawa-cho, Taya-cho (Photo 6.2-82).

Photo 6.2-81 Heavily damaged Nagayamon gate (Yoshinuma-cho)

Photo 6.2-82 Damaged barn (Aoyagi-cho)

(12) Joso city, Ibaraki prefecture

According to the Joso city office, Ibaraki prefecture, structural damage was not observed for houses. An announcement of collapsed house immediately after the earthquake, was the damage to a wood hut in a resting place. The house built in the side of Lake of crescent was inclined because of the soil liquefaction (Photo 6.2-83, 6.2-84). Although there were several inclined houses because of the soil liquefaction, a lot of damage to the roof tile were observed, and it seemed that the ratio of the damage of the roof tile was comparatively high.

Photo 6.2-83 Damage of resting place (Joja-machi, offered by Joso city office)

Photo 6.2-84 Damage of ground near the resting place（offered by Joso city office）

(13) Ryugasaki city, Ibaraki prefecture

According to the Ryugasaki city office, Ibaraki prefecture, structural damage was not observed in houses, and information about collapsed house immediately after the earthquake, was the damage of barn in the Takasu-cho. The post-earthquake quick inspection of damaged buildings was conducted for 58 wood houses based on the request from the citizens. According to the department, unsafe wood houses in danger and wood houses with limited entry accounted for 12, and 29 respectively. Most of the damage of houses was damage of roof tile and outside wall. There was no damage due to inclination of structural building frame. Though 6 houses and 1 barn were judged as partial collapse, the sites of those buildings were not located in concentrated specific region. The surrounding of the city office and JR Sanuki station are old urban areas, grounds of those areas are low and weak, and have a lot of damage of the roadbed. On the other hand, two new towns in the east and the west areas in the city are located on the hill, the ground is sound, and the damage of houses was not reported. Sand eruption by soil liquefaction was partly observed in the Takasu-cho area.

6.2.4 Conclusions

From the damage survey on the wood houses due to ground motion in Kurihara city, Osaki city, Misato town, Ishinomaki city, Sendai city in Miyagi prefecture, Sukagawa city in Fukushima, Nasu town, Yaita city in Tochigi prefecture, and Hitachiota city, Naka city, Mito city, Joso city, Ryugasaki city in Ibaraki prefectue, the followings were summarized.

1) The damage on many wood houses due to ground motion was confirmed in Osaki city in Miyagi prefecture, Sukagawa city in Fukushima prefecture, Nasu town in Tochigi prefecture, and Hitachiota city and Naka city in Ibaraki prefecture.
2) Although the seismic intensity 7 was recorded in Kurihara city, Miyagi prefecture, it was observed that the damage on wood houses was minor.
3) The heavy damage on wood houses caused by the failures of residential land was confirmed in Sendai city, Miyagi prefecture, and Yaita city, Tochigi prefecture. The number of wood houses suffering such damage was quite large.
4) The damage of the roof tile in Fukushima and Ibaraki prefectures seemed much larger than that in Miyagi prefecture where large earthquakes occurred frequently.
5) The possibility that the ground motion was amplified on the land filled up from swampland or rice field, even if the residential land did not fail, was suggested in Kurihara city, Osaki city in Miyagi prefecture, Nasu town in Tochigi prefecture, Hitachiota city, Naka city, Joso city, Ryugasaki city in Ibaraki prefecture, and so on.
6) In Osaki city, several rare damage examples that residual story deformation of 2nd floor was larger than that of 1st floor were confirmed.

The selected houses will be surveyed in detail and each damage cause will be discussed in future, based on the results of the damage summary of the above-mentioned wood houses.

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6.3 Damage to Reinforced Concrete Buildings

6.3.1 Introduction

The 2011 Tohoku earthquake caused a lot of damage to buildings in a wide area of Tohoku and Kanto regions of Japan. The Joint Survey Team investigated the damage to reinforced concrete (RC) buildings and reinforced concrete buildings with embedded steel frames (referred to as steel reinforced concrete, or SRC) in the affected areas where seismic intensities were classified as 6 lower (6-) and over by the Japan Meteorological Agency (JMA) in Iwate, Miyagi, Fukushima and Ibaraki. The objective of the field investigation was to see the picture of the overall damage to the buildings and to classify their damage patterns. The surveys were conducted several times from March 14 to the middle of May in the districts as shown in Fig. 6.3-1. This report presents the outline of the field investigation.

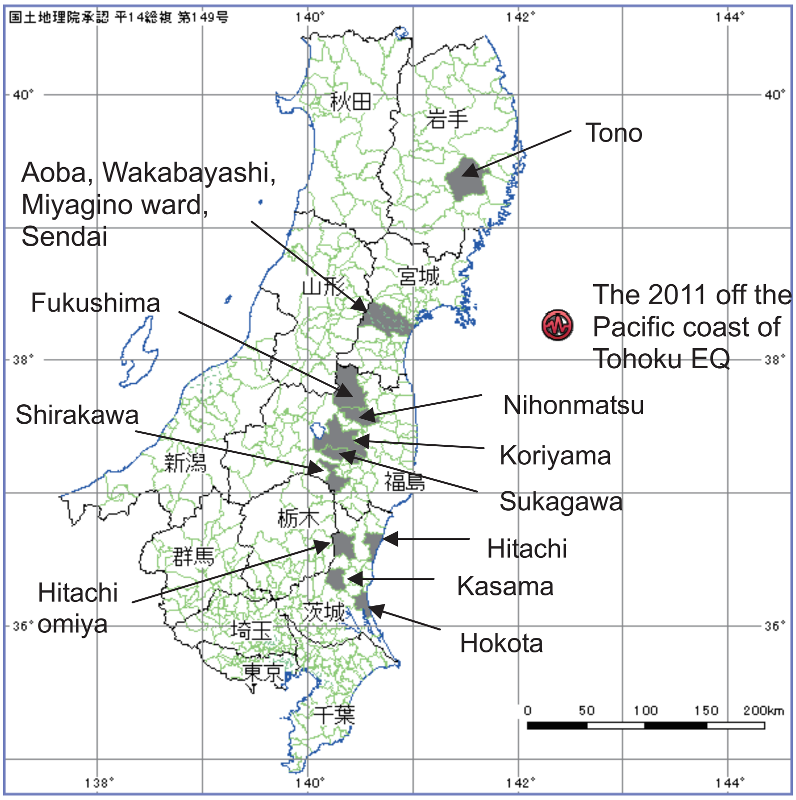

Fig. 6.3-1 Investigated Area (free mapping program, ‘KenMap’ was used)

6.3.2 Characteristics of damage on RC buildings

In the 2011 Tohoku earthquake, strong earthquake motions were recorded in various locations of Tohoku and Kanto regions and caused various patterns of damage in a wide area. At the same time, the damage concentrated on a specific area was not seen generally. As a rule, it would appear that structural damage to buildings was not particularly heavy in comparison with the measured JMA seismic intensities. Consequently, there was not a significant difference in damage situations among the locations. However, the damage to structural members was somewhat concentrated on limited areas, such as Wakabayashi ward in Sendai city and Sukagawa city. It is known that these areas were formed on paddy fields or moats. Therefore, it can be well estimated that ground conditions in the areas possibly contributed to the damage.

The patterns of structural damage on RC buildings identified by the field surveys were almost the same with those that had been observed in past earthquake damage investigations. Some serious types of damage were observed, such as story collapse of low-rise buildings, collapse of soft-first story (pilotis), and the loss of vertical load carrying capacity of columns due to shear failure. Most of severely damaged buildings were designed with the previous seismic design code that was enforced before June 1981. Some SRC buildings designed under the current seismic design code enforced after June 1981, caused damage of buckling of their longitudinal reinforcements near base plates at the bottom of column. The same damage is known to have occurred also in the Hyogoken Nambu Earthquake in 1995 (Kobe Earthquake). In addition, buildings designed under the current seismic design code were confirmed to have no collapse but some damage like shear cracks at their beam-column joints or horizontal cracks at their concrete placing joints. The patterns of the damage of RC and SRC buildings that were observed through the site investigation are classified into those for structural and nonstructural elements in the following.

A) Damage of structural elements

- A-1) Collapse of first story
- A-2) Mid-story collapse
- A-3) Shear failure of columns
- A-4) Flexural failure at the bottom of column and base of boundary columns on multi-story shear walls
- A-5) Pullout of anchor bolts and buckling of longitudinal reinforcements at exposed column base of steel reinforced concrete (SRC) buildings
- A-6) Shear failure or bond splitting failure of link beam of multi-story coupled shear walls
- A-7) Building tilting
- A-8) Destruction, failure or tilting of penthouses
- A-9) Damage of seismic retrofitted buildings

B) Damage of nonstructural elements

- B-1) Flexural failure at the bottom of column with wing wall
- B-2) Damage of nonstructural wall in residential building
- B-3) Damage and falling of cladding

B-4) Tilting or dropout of components projecting on the roof

B-5) Collapse of concrete block wall and stone masonry wall

6.3.3 Damage of Structural Elements

A-1) Collapse of first story

The first story in a two-story RC office building shown in Photo 6.3-1 was completely collapsed in Wakabayashi ward, Sendai city. In addition, the shear failure and the axial deformation of the columns on the second floor of this building caused the buckling of the longitudinal reinforcements and the fracture of the hoops of columns in the first story.

Photo 6.3-1 First-story collapsed building (Wakabayashi ward, Sendai city)

The soft-first story collapse occurred on a four-story RC residential building with a shop in the first floor in Koriyama city, and was attributed to the shear failure of the columns on the first story and the torsional deformation (Photos 6.3-2 and 6.3-3). The RC shear wall on the first story was collapsed out-of-plane with buckling of reinforcing bars.

Photo 6.3-2 First-story collapsed building (Koriyama city)

Photo 6.3-3 Close-up view of the fallen story

A three-story RC building shown in Photo 6.3-4 was severely damaged on the first story, which was located at the intersection in Sukagawa city, had a few walls on the facade on the first story and many walls on the back of the first story and the second story and higher. The corner columns faced to the intersection were significantly destroyed as shown in Photo 6.3-5. The loss of axial load carrying capacity of the first-story columns caused the drop of the second and higher stories.

Photo 6.3-4 First-story collapsed building (Sukagawa city)

Photo 6.3-5 Close-up view of the fallen story

A-2) Mid-story collapse

A three-story office building shown in Photo 6.3-6 in Wakabayashi ward, Sendai city partially collapsed on the second story and the building tilted. Only the second story has openings on the wall at the gable side, as shown in the left of Photo 6.3-6. For this reason, it was assumed that the openings were intensively deformed and resulted in shear failure of the short columns formed by the hanging and spandrel walls. The shear failure of the long columns on the third story was observed possibly due to the effect of the collapse of the second story. The damage to the columns and beams on the first story was not seen, while shear cracks were observed on the nonstructural walls.

Photo 6.3-6 Mid-story collapsed building (Wakabayashi ward, Sendai city)

Photo 6.3-7 shows a three-story RC school building, which was constructed in

1966 and has a Y-letter shape plan in Fukushima city. The mid-story collapse occurred on the second story, and the part of the third story was heavily damaged. In addition, the shear failure also occurred on the columns in the first story, as shown in Photo 6.3-8. Visual damage was not seen in other school buildings and the gymnasium on the same site. The seismic indices of the structure, I_S on the first and second stories of the building were below the seismic demand index of structure, I_{S0} by the seismic evaluation method [6.3-1], therefore the seismic retrofit of the building had been planned.

Photo 6.3-7 Mid-story collapsed building (Fukushima city)

Photo 6.3-8 Shear failure of the first-story column

A-3) Shear failure of columns

A three-story RC building constructed in 1963 was suffered from the shear failures of columns in Tono city of Iwate prefecture, where the JMA seismic intensity was 5 upper (5+) (Photo 6.3-9). Two extremely short columns on the first-story, four columns on the northern plane of structure and an interior shear wall were failed in shear as shown in Photo 6.3-10, and short columns with spandrel wall, some long columns on the southern plane of structure had shear cracks. The post-earthquake damage evaluation [6.3-2] was conducted for the building in the longitudinal direction. In the result, the building was determined to represent heavy damage (residual seismic performance ratio, R=57.8%). The building had been damaged in the South Sanriku Earthquake in 2003 (JMA seismic intensity 6 lower). For this reason, cover concrete was then recast on the shear-cracked columns, and the existing columns were temporary strengthened with H-shaped steel, as shown in Photo 6.3-11. However, the 2011 Tohoku earthquake affected these columns again.

Photo 6.3-9 Appearance of the damaged building (Tono city)

Photo 6.3-10 Shear crack on shear wall

Photo 6.3-11 Column strengthened with H-shaped steel

The next case is that the shear failure occurred on the first-story columns in a two-story RC building in Aoba ward, Sendai city (Photos 6.3-12 and 6.3-13). Some columns of the building were intact after the mainshock on March 11, but aftershocks caused shear failure to some of them, as shown on the right of Photo 6.3-13. It was confirmed that the aftershocks accelerated the damage level of this building.

Photo 6.3-12 Appearance of the damaged building (Aoba ward, Sendai city)

Photo 6.3-13 Shear cracks of first-story columns

Photo 6.3-14 shows the four-story RC building that was constructed in 1970 in Sukagawa city. The columns with the spandrel wall on the first story were heavily damaged in shear and shorten in the axial direction as shown in Photo 6.3-15. The same damage was observed on the second-story exterior columns. Some of the reinforcing bars of the damaged columns that were raised from the foundation were anchored with a 180-degree hook near the mid height of story. It is considered that the shear failure began at this point. Two shear walls were severely damaged, which were arranged in the center core of the building to resist mainly horizontal forces. In particular, the second-story core wall was failed in shear in both of the span and longitudinal directions, and the longitudinal reinforcements in the boundary column of shear wall were heavily buckled as shown in Photo 6.3-16.

Photo 6.3-14 Appearance of damaged building (Sukagawa city)

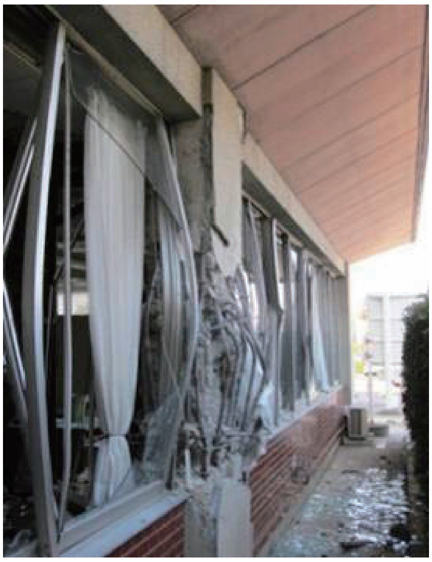

Photo 6.3-15 Shear failure of short column

Photo 6.3-16 Failure of shear wall

A three-story RC building constructed in 1964 on a hill in Kasama city of Ibaraki prefecture shown in Photo 6.3-17 also suffered damage. Cracks in the ground were observed around the building. As seen in the photo, the RC structure on the first story was severely damaged. Shear failure occurred on many exterior columns, which were made shorter in clear height by the hanging and spandrel walls without structural slit, as shown in Photo 6.3-18. In addition, the failure of the shear wall with opening was observed (Photo 6.3-19).

Photo 6.3-17 Appearance of damaged building (Kasama city)

Photo 6.3-18 Shear failure of column

Photo 6.3-19 Shear failure of wall with opening

A-4) Flexural failure at the bottom of column and base of boundary columns on multi-story shear walls

A building that consists of nine-story SRC and two-story RC structures in Aoba ward, Sendai city suffered from the earthquake (Photo 6.3-20). In the high-rise building, the multi-story shear wall of the gable side was subject to flexural failure at the third floor. Crushing of concrete and buckling of the longitudinal reinforcements was observed at the bottom of the boundary column of shear wall, as shown in Photo 6.3-21. This building was also damaged by the Miyagiken-oki Earthquake in 1978 and had been retrofitted.

Photo 6.3-20 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-21 Crushing at the bottom of column of the multi-story shear wall

A-5) Pullout of anchor bolts and buckling of longitudinal reinforcements at exposed column base of steel reinforced concrete (SRC) buildings

Photo 6.3-22 shows the appearance of a damaged building, which is the nine-story SRC residential building constructed in 1991 in Koriyama city of Fukushima prefecture. Pullout of anchor bolts, buckling of reinforcing bars and compressive failure of concrete occurred at the corner column and the bottom of multi-story shear wall in the first story, as shown in Photo 6.3-23, and shear cracks and bond splitting cracks were observed on the first story columns.

Photo 6.3-22 Appearance of damaged building (Koriyama city)

Photo 6.3-23 Damage at the bottom of SRC column

The damage at the bottom of SRC column and shear wall was also observed on a building in Shirakawa city shown in Photos 6.3-24 and 6.3-25, which was composed of RC and SRC structures. Pullout of anchor bolts of the exposed-type column base occurred. In consequence, the reinforcing bars were forced to stretch large and the buckling of them occurred around the base plate, as shown in Photo 6.3-26.

Photo 6.3-24 Appearance of damaged building (Shirakawa city, Fukushima pref.)

Photo 6.3-25 Damage of the bottom of SRC column and shear wall

Photo 6.3-26 Close-up view of the bottom of SRC column

This type of damage was observed not only in buildings designed under the previous seismic design code but also in some buildings constructed under the current seismic design code.

A-6) Shear failure or bond splitting failure of link beam of multi-story coupled shear walls

The shear failure or bond splitting failure occurred on the link beam connecting coupled shear walls from low-rise to high-rise stories on a eight-story RC building in Aoba ward, Sendai city, as shown in Photo 6.3-27. The link beams have two openings at the center of them, and were damaged around these parts (Photo 6.3-28).

Photo 6.3-27 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-28 Damage of boundary beam with opening

A-7) Building tilting

A fourteen-story RC building shown in Photo 6.3-29 was settled down and was tilted about 1/70 radian. The building is one of two residential buildings located in L-shape with expansion joint in Miyagino ward, Sendai city. The shear cracks on the nonstructural walls over every story and some parts of mullions occurred in both buildings as shown in Photos 6.3-30 and 6.3-31, which damage was classified as B-2). Though the other building without inclination had same shear cracks on the nonstructural walls from first to sixth story in the Miyagiken-oki Earthquake in 1978 and had been repaired with concrete replacement, almost same damage was happened on the similar part.

Photo 6.3-29 Appearance of tilted building (Miyagino ward, Sendai city)

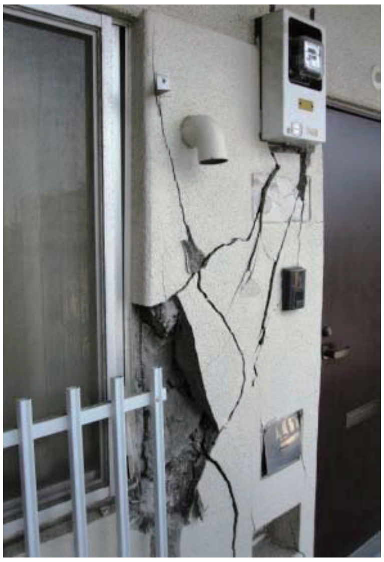

Photo 6.3-30 Shear cracks on nonstructural wall

Photo 6.3-31 Shear cracks on mullion

Photo 6.3-32 shows a residential building that sank and leaned in the longitudinal direction in Shirakawa city. The balcony, of which height above ground level was about 77cm, went down to ground surface in the gable side, as shown in Photo 6.3-33.

Significant settling was also observed on a sidewalk in surrounding area.

Photo 6.3-32 Appearance of sunken and leaned building (Shirakawa city)

Photo 6.3-33 Sunken balcony

A-8) Destruction, failure or tilting of penthouses

The damage on penthouses was observed everywhere, like tilting of it in Aoba ward, Sendai city, as shown in Photo 6.3-34. The clock tower attached to a five-story RC building constructed in 1954 was destroyed at the bottom of it, despite the building was heavily damaged in Fukushima city (Photos 6.3-35 and 6.3-36).

Photo 6.3-34 Damaged penthouse (Aoba ward, Sendai city)

Photo 6.3-35 Damaged clock tower (Fukushima city)

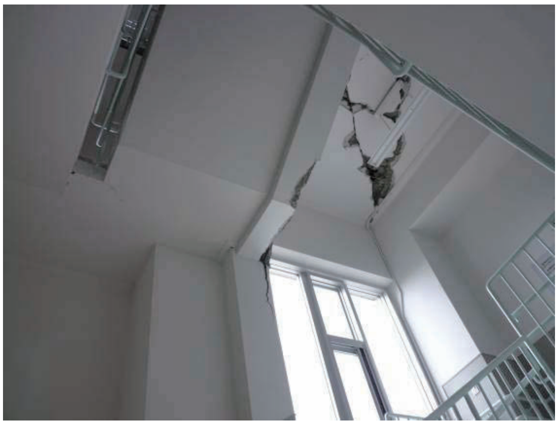

Photo 6.3-36 Bottom of the tower

A-9) Damage of seismic retrofitted buildings

Photo 6.3-37 shows a two-story RC office building constructed in 1969 in Hitachiomiya city of Ibaraki prefecture. The building had been retrofitted with framed steel braces in the longitudinal direction in 2003, because the seismic index of structure, I_S on the first story of the building was below the seismic demand index of structure, I_{S0} by the seismic evaluation method [6.3-1)]. Meanwhile, the building in the span direction was not retrofitted, as a consequence the seismic index of structure in the direction satisfied the seismic demand index of structure. The steel braces had been eccentrically installed to the center axis of the beams and columns.

Shear cracks occurred on the columns with the framed steel braces at the 2011 Tohoku earthquake as shown in Photo 6.3-38, although the remarkable damage such as yield of steel was not seen on the braces. Flexural cracks at the beam ends of the second-story in the span direction and shear cracks at the beam ends of the third-story were observed, respectively. A maximum deflection of 128mm was happened at the center in the span direction with a span of 12m. It would appear that the deflection was increased due to the damage occurred on the beam end by the earthquake, thought the under-surface of the beam has been strengthened. Because the beam had cracks caused by the past earthquake, it had been reinforced with steel plates in the range of quarter beam length from the column.

Photo 6.3-37 Appearance of damaged building (Hitachiomiya city)

Photo 6.3-38 Shear crack on column with framed steel braces

There were many seismic retrofitted buildings including school buildings in the affected areas where the strong earthquake motions were observed. Based on the results of the investigation, these retrofitted buildings were heavily damaged or slightly harmed, it means that the seismic strengthening of existing buildings act effectively against the earthquake.

6.3.4 Damage to nonstructural elements

B-1) Flexural failure at the bottom of column with wing wall

The separation of cover concrete at the bottom of wing wall was observed on a five-story RC building constructed in 2007 in Sukagawa city of Fukushima prefecture, as shown in Photos 6.3-39 and 6.3-40. In this report, that case is classified as the damage of nonstructural elements, because the wing wall is generally designed as the nonstructural element, which is not expected to resist the external force.

Photo 6.3-39 Appearance of damaged building (Sukagawa city)

Photo 6.3-40 Separation of concrete of wing wall

B-2) Damage of nonstructural wall in residential building

The nonstructural walls around the front doors from lower to top floors were subject to shear failure, while the doors were deformed on a ten-story SRC residential building constructed in Aoba ward, Sendai city in 1996, as shown in Photos 6.3-41 and 6.3-42. In addition, shear cracks were observed on the mullion walls on balconies in some of the lower floors.

Photo 6.3-41 Appearance of damaged building (Aoba ward, Sendai city)

Photo 6.3-42 Shear failure of nonstructural wall

In a nine-story SRC residential building shown in Photo 6.3-22 in Koriyama city, damage of the nonstructural elements was seen (Photo 6.3-43). In addition, large shear cracks occurred on the nonstructural wall in the longitudinal direction. For this reason, the front door was deformed out-of-plane as shown in Photo 6.3-44, and could not be opened and closed. The shear cracks on the mullion walls also occurred in a eight-story RC hotel building in Sukagawa city (Photos 6.3-45 and 6.3-46).

The cases where shear cracks occurred on the nonstructural walls around the front door or on the mullion wall of the balcony were relatively often observed in urban residential buildings, regardless of application of the seismic design codes.

Photo 6.3-43 Damage of nonstructural wall in same building shown in Photo 6.3-22 (Koriyama city, Fukushima pref.)

Photo 6.3-44 Damage of nonstructural wall and deformed door in same building shown in Photo 6.3-22

Photo 6.3-45 Appearance of damaged building (Sukagawa city)

Photo 6.3-46 Shear crack on nonstructural wall

B-3) Damage and falling of cladding

Photos 6.3-47 and 6.3-48 show the case where the AAC (Autoclaved lightweight Aerated Concrete, the abbreviated term ‘ALC’ is commonly used in Japan.) panel on the upper floor in a eight-story building fell down, and Photo 6.3-49 is the case where the tile on exterior wall was dropped, in Aoba ward, Sendai city.

These kinds of damage relatively often occurred in buildings without structural damage, not limited to specific areas. Despite of the construction period and the seismic design codes application, these damage were often observed in many buildings.

Photo 6.3-47 Damaged building with AAC panels (Aoba ward, Sendai city)

Photo 6.3-48 Dropped AAC panels

Photo 6.3-49 Damage of tile on exterior wall

B-5) Collapse of concrete block wall and stone masonry wall

The collapse of concrete block wall and stone masonry wall are well known as earthquake damage caused by strong seismic motion. The damage of that type was often observed in the field investigation, as shown from Photo 6.3-50 to Photo 6.3-53.

Photo 6.3-50 Collapse of concrete block wall (Koriyama city)

Photo 6.3-51 Collapse of concrete block wall (Sukagawa city)

Photo 6.3-52 Collapse of stone masonry wall (Fukushima city)

Photo 6.3-53 Collapse of stone masonry wall (Shirakawa city)

6.3.5 Concluding Remarks

In this report, the patterns of damage of reinforced concrete (RC) and steel reinforced concrete (SRC) buildings caused by earthquake motions under the 2011 Tohoku earthquake were classified as the damage on structural and nonstructural elements and the examples of them were described. As previously stated, almost all of the patterns of damage were observed in past destructive earthquakes such as the Hyogoken Nambu Earthquake (Kobe Earthquake) in 1995 and the Mid Niigata Prefecture Earthquake in 2004. However, the following patterns of structural damage that had been observed in the Hyogoken Nambu Earthquake have not been confirmed within the scope of the investigation conducted so far.

- Story collapse of soft-first story building designed under the current seismic design code
- Mid-story collapse in mid-rise and high-rise buildings
- Overturning of buildings

- Failure of beam-column joint in building designed under the current seismic design code
- Fracture of pressure welding of reinforcements
- Falling of pre-cast roof in gymnasium

In general, there were only a few cases of serious structural damage that were caused by the earthquake motions. On the contrary, it was the remarkable cases caused by the earthquake that public buildings like city hall under the past seismic design code suffered from severer damage and could not be continuously used. The main cause of the damage on these buildings was the loss of the vertical load carrying capacity due to shear failure of short columns. The fact makes us reconfirm that seismic retrofit of these public buildings is particularly important, which must be operated as the disaster management facilities.

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6.4 Damage to Steel Gymnasiums

6.4.1 Introduction

The damage to steel buildings such as offices and shops caused by the 2011 Tohoku earthquake in the areas of Ibaraki, Fukushima and Miyagi prefectures with JMA seismic intensity around 6 was investigated for two weeks after the earthquake. Structures of steel buildings are generally covered with exterior cladding and interior finishing. For this reason, the real situations of the damage to columns, beams and braces may not be correctly determined under the visual damage observation. Therefore, the damage investigation on steel gymnasiums whose structural members are generally exposed was considered and conducted. The damage investigation for such steel gymnasiums was carried out in the areas of Ibaraki prefecture with JMA seismic intensity around 6. This section describes the outline of the damage investigation of the steel gymnasiums.

6.4.2 Outline of damage investigation of steel gymnasiums

(1) Outline of damage investigation of high school gymnasiums in Ibaraki prefecture

Gymnasiums designed under the seismic code before June 1981 (hereinafter referred to as previous seismic code) were heavily damaged in the Mid Niigata Prefecture Earthquake in 2004, but most of gymnasiums designed under the current seismic code were not damaged[6.4-1)~6.4-3)]. Consequently, as the subject of the damage investigation, steel gymnasiums constructed under the previous seismic code were mainly chosen. The investigation covered a wide range of areas in Ibaraki prefecture where JMA seismic intensities 5 (+) to 6 (+) were recorded (Ooarai town, Shirosato town, Hitachi city, Mito city, Naka city, Hitachinaka city, Chikusei city, Kasama city, Hokota city, Tsuchiura city, Bando city, Koga city, Shimotsuma city and Joso city). The main purpose of the investigation is to determine what damage pattern was often observed in these areas and in which area the pattern was often distributed. A total of 44 gymnasiums in high schools were chosen and investigated.

(2) Outline of damage investigation of elementary and junior high school gymnasiums in Mito city

In general, building size (total floor area) of high school gymnasiums seems to be larger than the size of elementary and junior high school gymnasiums. In order to know an effect of building size on earthquake damage situation, damage investigation of elementary and junior high school gymnasiums was considered and conducted. The result of the damage investigation for the high school gymnasiums in Ibaraki prefecture showed that the areas around Mito city suffered relatively larger structural damage than other areas. Then, Mito city was chosen as the survey area of the damage investigation for gymnasiums in elementary and junior high school. A total of 22 gymnasiums in elementary and junior high schools constructed under the previous seismic code in Mito city were investigated.

6.4.3 Results of damage investigation of steel gymnasiums

(1) Results of high school gymnasiums in Ibaraki prefecture

1) Outline of structure of investigated gymnasiums

A total of 44 gymnasiums were investigated in Ibaraki prefecture. The number of gymnasiums constructed under the previous seismic code is 41. There are 4 two-story gymnasiums, and 40 one-story gymnasiums. The number and percentage of structural types of the investigated gymnasiums are shown in Table 6.4-1. In general, the structural types of gymnasiums are classified into 3 classes as shown in Table 6.4-1, but the percentages of the types seem to strongly depend on the regions. For example, in the damage investigation[6.4-1)~3)] of the Mid Niigata Prefecture Earthquake in 2004, the percentage of the mixed structure consists of lower RC frame and upper steel frame was 75%, and the percentage of steel moment-resisting frames was 6%. From table 6.4-1, it is found that the percentage of the mixed structure in Ibaraki prefecture is smaller than Niigata prefecture, and the percentage of steel moment-resisting frames is larger.

Table 6.4-1 Structural types of investigated high school gymnasiums

Mixed structure consist of lower RC frame and upper steel frame		Steel frame structure		RC frame structure having steel roof frame	Unidentified
20(45%)		15(34%)			
Steel brace frame	Steel moment-resisting frame	Steel brace frame	Steel moment-resisting frame		
15(34%)	5(11%)	7(16%)	8(18%)	6(14%)	3(7%)

2) Structural damage

The types of observed structural damage in this investigation include a) buckling and fracture of brace member and fracture of its joint, b) buckling of diagonal member of latticed column, c) damage of connection (bearing support part) between RC column and steel roof, d) deflection, buckling and fracture of roof horizontal brace, and e) cracking of column base concrete. The a) and b) damage types are included as the type of severe structural damage based on the damage evaluation standard of earthquake damaged buildings[6.4-4)]. However, the number of these severe damaged gymnasiums is 2 and 1 corresponding to the damage type a) and b), respectively. Buckling of diagonal member of latticed column is damage to the column in span direction frames, and was not observed under the damage investigation of the Mid Niigata Prefecture Earthquake in 2004[6.4-1)~6.4-3)].

From the results of this investigation, it seemed that structural damage in Mito city, Hokota city and Naka city was relatively larger than in other areas.

3) Nonstructural damage

The types of nonstructural damage observed in this investigation include dropping of ceilings and exterior walls and breakage of windows, etc. In four of the investigated gymnasiums, ceiling materials were extensively dropped, which is classified into the severe damage category based on the damage evaluation standard[6.4-4]. In five gymnasiums, breakage of many windows was observed.

4) Damage situations of seismic retrofitted buildings

Seismic retrofitting was performed in five of the investigated gymnasiums. One of the five retrofitted gymnasiums was constructed in the area where relatively severe damage was observed. Structural and nonstructural damage of this gymnasium were not observed.

(2) Results of elementary and junior high school gymnasiums in Mito city

1) Outline of structure of investigated gymnasiums

A total of 22 gymnasiums were investigated. 20 of the gymnasiums were constructed under the previous seismic code. All of the investigated gymnasiums are one-story. The structural types of the gymnasiums are shown in Table 6.4-2, as the case of the high school gymnasiums. The percentage of the mixed structure that consists of lower RC frame and upper steel frame is 19%, and the percentage of RC frame structure having steel roof frame is 41%.

Table 6.4-2 Structural types of investigated elementary and junior high school gymnasiums

Mixed structure consist of lower RC frame and upper steel frame		Steel frame structure		RC frame structure having steel roof frame	Unidentified
4(19%)		7(32%)			
Steel brace frame	Steel moment-resisting frame	Steel brace frame	Steel moment-resisting frame		
3(14%)	1(5%)	1(5%)	6(27%)	9(41%)	2(10%)

2) Structural damage

Five types of the structural damage, shown in the result of the investigation of high-school gymnasiums, were also observed in the elementary and junior high school gymnasiums. However, the degree of structural damage in the elementary and junior high school gymnasiums seems to be smaller than in the case of high school gymnasiums.

3) Nonstructural damage

Severe nonstructural damage in which ceiling members were widely dropped, as observed in the investigation for the high school gymnasiums, was not observed in the elementary and junior high school gymnasiums. However, 20 of the gymnasiums suffered some sort of nonstructural damage. The degree of nonstructural damage in the elementary and junior high school gymnasiums seems to be smaller than in the case of high school gymnasiums.

6.4.4 Classification and characteristics of damage to steel gymnasiums

During this earthquake damage investigation, a total of 66 gymnasiums in the high schools within Ibaraki prefecture and in the elementary and junior high schools within Mito city were surveyed. The damage to the gymnasiums was classified into the types of (1) to (7). The types of (1) to (6) and the type of (7) represent structural damage and nonstructural one, respectively.

(1) Buckling and fracture of brace member and fracture of its joint
(2) Buckling of diagonal member of latticed column
(3) Damage of connection (bearing support part) between RC column and steel roof frame
(4) Deflection, buckling and fracture of roof horizontal brace
(5) Cracking of column base concrete
(6) Other (Overturning of floor strut, etc.)
(7) Nonstructural damage such as dropping of ceilings and exterior walls and breakage of windows

Each damage photograph shows each damage type in the following pages.

(1) Buckling and fracture of brace member and fracture of its joint

Buckling of brace member (Photo 6.4-1) and fracture of brace joint (Photos 6.4-2 ~ 6.4-4) were observed. Angle section was often used for many brace members, but circular hollow section steel (Photo 6.4-3) was also used for brace members. Fractured sections include steel plate inserted into steel pipe, end of bracing member and section loss part by bolt hole. These types of the damage are classified into the severe damage category based on the damage evaluation standard[6.4-4]. The number of the gymnasiums of this type is 3. The gymnasiums constructed under the previous seismic code that had been severely damaged by the Mid Niigata Prefecture Earthquake in 2004 had accounted for about 30% of the total[6.4-1)~6.4-3]. It is impressed that a rate of the gymnasiums severely damaged by the 2011 Tohoku earthquake was lower than by the Mid Niigata Prefecture Earthquake in 2004.

Photo 6.4-1 Buckling of brace

Photo 6.4-2 Net section fracture at bolt hole

(a) Fracture at column top (b) Fracture at brace crossing

Photo 6.4-3 Fracture of brace welded connection

Photo 6.4-4 Fracture of bolts

(2) Buckling of diagonal member of latticed column

In one of the investigated gymnasiums, buckling of diagonal members in some latticed columns was observed (Photo 6.4-5). Damage of column buckling caused in steel frames for span direction had not been observed under the damage investigations of the Mid Niigata Prefecture Earthquake in 2004[6.4-1)~6.4-3)].

(a) Latticed column (b) Buckling of diagonal member

Photo 6.4-5 Buckling of diagonal member of latticed column

(3) Damage of connection (bearing support part) between RC column and steel roof frame

In the investigated gymnasiums, exposure of anchor bolts due to spalling of the concrete at connection (bearing support part) between the RC column and steel roof frame (Photos 6.4-6 and 6.4-7), spalling of finish mortars on the RC column at the roof bearing support part, and pullout of hole-in anchors (Photo 6.4-8) were often observed.

Photo 6.4-6 Spalling of concrete

Photo 6.4-7 Spalling of concrete

Photo 6.4-8 Pullout of hole-in anchors

(4) Deflection, buckling and fracture of roof horizontal brace

Roof horizontal braces were damaged in two high school gymnasiums and five elementary and junior high school gymnasiums. Such damage mainly occurred at horizontal braces with turnbuckles; obvious deflection of the horizontal brace (Photo 6.4-9) and fracture at thread and fracture of bolt connections were observed (Photo 6.4-10).

Photo 6.4-9 Deflection of horizontal braces

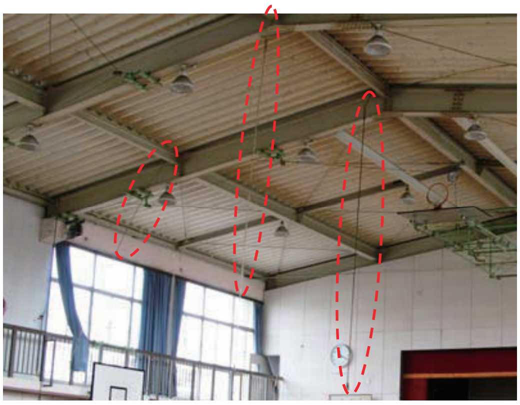

Photo 6.4-10 Fracture of horizontal braces

(5) Cracking of column base concrete

Damage of cracking of the column base concrete and mortar in the gallery of some gymnasiums was observed (Photo 6.4-11). Concrete and mortar of steel column base at a ground level was also cracked (Photo 6.4-12). However, almost all of these cracking are classified into minor or slight damage.

Photo 6.4-11 Cracking of column base concrete

Photo 6.4-12 Cracking of column base concrete

(6) Other (Overturning of floor strut, etc.)

As the other types of the structural damage, the following damage was observed; (a) overturning of floor strut (Photo 6.4-13), (b) tilting of concrete block self-standing wall and (c) peeling of paint of beam members which was observed near the top of the V-shaped roof beams or arch beams (Photos 6.4-14 and 6.4-15). In terms of the peeling of paint, it was uncertain whether yielding of the beams occurred or not.

Photo 6.4-13 Overturning of floor strut

Photo 6.4-14 Peeling of paint of beams

Photo 6.4-15 Peeling of paint of beams

(7) Nonstructural damage such as dropping of ceilings and exterior walls and breakage of windows

The types of nonstructural damage of gymnasiums included dropping of ceilings and lighting equipment (Photos 6.4-16 ~ 6.4-18), breakage of windows (Photo 6.4-19), dropping of exterior walls (Photo 6.4-20), dropping of interior walls and eave soffit (Photo 6.4-21). In particular, the severe damage such as dropping of extensive ceiling in the high school gymnasiums was observed more than in the elementary and junior high school gymnasiums.

Photo 6.4-16 Dropping of extensive ceiling components

Photo 6.4-17 Dropping of extensive ceiling components

Photo 6.4-18 Dropping of extensive ceiling components

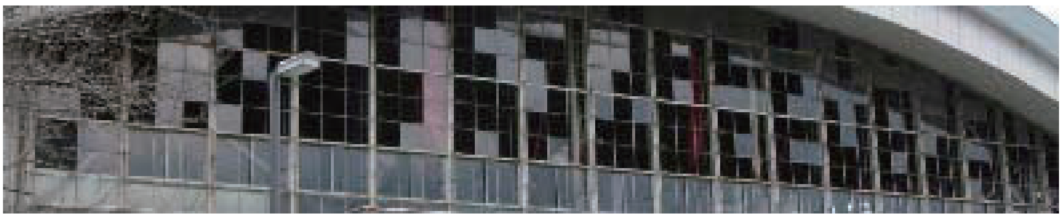

Photo 6.4-19 Breakage of windows

Photo 6.4-20 Falling of exterior finish components

Photo 6.4-21 Falling of eave soffit

6.4.5 Conclusions

The damage to the steel gymnasiums constructed under the previous seismic code in the areas with JMA seismic intensity around 6 in Ibaraki prefecture was investigated, and the outline of the investigation was described in this section. The results of the damage investigation of the steel gymnasiums are summarized as follows.

a) Structural damage to the steel gymnasiums

1) The types of observed structural damage to the gymnasiums are classified into the following six categories. (1) Buckling and fracture of brace member and fracture of its joint, (2) Buckling of diagonal member of latticed column, (3) Damage of connection (bearing support part) between RC column and steel roof frame, (4) Deflection, buckling and fracture of roof horizontal brace, (5) Cracking of column base concrete, and (6) Other (overturning of floor strut, etc.).
2) In three among the 66 investigated gymnasiums, severe structural damage such as "fracture of brace member and joint" occurred. This rate of the damage seems to be smaller than that in the Mid Niigata Prefecture Earthquake in 2004.
3) Severe structural damage was observed in Mito city, Hokota city and Naka city than in other areas.

b) Nonstructural damage to the steel gymnasiums

1) The types of observed nonstructural damage include dropping of ceilings, dropping of exterior and interior walls, falling of eave soffit and breakage of windows.
2) In four of the investigated gymnasiums, ceiling materials were extensively dropped, which is classified into the severe damage category. In some of the gymnasiums, many windows were broken.
3) Severe nonstructural damage was observed in Mito city, Hokota city and Hitachi city than in other areas.

4) Severe structural and nonstructural damage seemed to have occurred in the high school gymnasiums rather than in the elementary and junior high school gymnasiums.

References

6.4-1) NILIM, MILT, Japan and BRI, Japan: Report on the Damage Investigation of Buildings Due to the Mid Niigata Prefecture Earthquake in 2004, pp.305-353, October, 2006 (in Japanese)

6.4-2) Takashi Hasegawa, Akiyoshi Mukai, Kazuo Nishida and Tadashi Ishihara: Damage Investigation of Steel Gymnasiums Due to the Niigataken-chuetsu Earthquake (Part1 Study on structural damage), Summaries of Technical Papers of Annual Meeting, AIJ, B-2, pp.569-570, September, 2005 (in Japanese)

6.4-3) Kazuo Nishida, Akiyoshi Mukai, Takashi Hasegawa and Tadashi Ishihara: Damage Investigation of Steel Gymnasiums Due to the Niigataken-chuetsu Earthquake (Part2 Study on nonstructural damage), Summaries of Technical Papers of Annual Meeting, AIJ, B-2, pp.571-572, September, 2005 (in Japanese)

6.4-4) The Japan Building Disaster Prevention Association: Damage evaluation standard and repair technology guidelines of earthquake damaged buildings, August, 2002 (in Japanese)

6.5 Damage to Residential Land

6.5.1 Introduction

The outline of damage situations associated with liquefaction in the alluvial plain area along the Tone River on the border between Ibaraki and Chiba prefectures and in Urayasu city, Chiba prefecture is reported. Furthermore the outline of damage situations of developed housing areas in Miyagi and Fukushima prefectures is also reported.

6.5.2 Damage due to Liquefaction in alluvial plain area along Tone River

Damage associated with liquefaction has occurred in the same areas as in the areas where liquefaction had been reported in the past earthquakes, such as abandoned river channel, back marsh and reclaimed paddy field. This section describes the damage situations in Nishishiro, Inashiki city, Hinode, Itako city and Kamisu city in Ibaraki prefecture. Liquefaction damage in Nishishiro, Inashiki city and Hinode, Itako city had been reported in the 1987 East Off Chiba Prefecture earthquake.

(1) Nishishiro, Inashiki city, Ibaraki prefecture

Large-scale and extensive damage occurred within the area of 500 m by 500 m that route 51 of national highway and the Yokotone River on the east of the road enclose. Route 11 of prefectural road was closed to vehicles, and sand boiling, large-scale road upheaval or severe fissure that was associated with liquefaction were seen mainly along the road. As a ground deformation, the ground subsided up to about 40 cm, and lateral displacement was up to about 1 m. An automobile was buried in boiled sand to the extent of a half of height of their tires.

Finishes of the sidewalks around a large-scale commercial establishment along Route 11 were scattered. The subsidence of the surrounding ground was about 40 cm, and the settlement of the facility itself was slight. The commercial building was tilted about 0.7/100 in the longitudinal direction. The pile foundation of the building was observed from an opening between surrounding fissures (Photo 6.5-1).

Photo 6.5-1 Situations around the commercial building and state of pile head

A boiled sand was seen everywhere on the roads or sites also in surrounding residential area. A house constructed on an embankment was tilted to an adjacent warehouse with sand boiling. An angle of tilting was 5.0/100 (Photo 6.5-2).

(2) Hinode, Itako city, Ibaraki prefecture

In Hinode, large-scale damage occurred in the area of about 200 m by 200 m along the Hitachi-tone River. Boiled sand, uplift of buried structures, and subsidence or tilting of utility poles, which were caused by liquefaction, were seen everywhere on the site. Many houses facing to the road subsided 20 to 30 cm from the front sidewalk (Photo 6.5-3). Foundation cracks or gaps were not observed.

Photo 6.5-2 House tilted 5.0/100

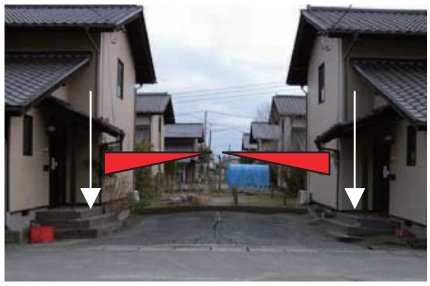

Photo 6.5-3 Subsidence of two houses enclosing vacant land

(3) Kamisu city, Ibaraki prefecture

This section describes the damage situations around Yokose Elementary School, and in Tsutsui, Horiwari and Fukashiba areas.

1) Around Yokose Elementary School

Yokose Elementary School is located about 3 km southeast from the Kamisu city office. The boiled sand by liquefaction was seen on the ground near the school. The ground subsidence was caused about 15 cm of difference in level on the rim of the building, and about 40 cm of difference in level at the outer slope (Photo 6.5-4). The building is supported by pile foundation. The outer slope and stairs were spread foundations, and the differential settlement was caused in this building.

2) Tsutsui area

The types of damage, such as sand boiling, uplift of buried structures, road gaps and subsidence or tilting of utility poles which were caused by liquefaction, occurred in the area of about 300 m by 300 m near Sotonasakaura in the area of Tsutsui that is located in the western part of Kamisu city. Due to damage to residential land, a severe fissure was generated, a house subsided approximately 15 cm from the surrounding ground and caused about 30 cm of difference in level from the ground (Photo 6.5-5). Cracking or crack fissures on the foundations were not visually observed.

3) Horiwari area

The uplift and the gap caused by site ground subsidence were occurred in the area of about 500 m by 500 m along Route 124 of national highway in Horiwari area that is located in the western part of Kamisu city. Along a street in the center of the area, uplift of the sidewalk or subsidence of the housing site caused a 25 to 30 cm of difference in level, and a side ditch around the house was damaged (Photo 6.5-6). A case where the ground around a house subsided about 15 cm without settlement of the house was observed. It is considered that the lower part of the sidewalk was damaged by the uplift of culverts.

4) Fukashiba area

Fukashiba is located in the western part of Kamisu city and on the opposite side of Horiwai along Route 124. In this area, many houses were damaged due to ground deformation and embankment deformation. Most of the damage patterns of the houses seem to have included their movement, subsidence and tilting without structural damage on their upper structures and foundations (Photo 6.5-7).

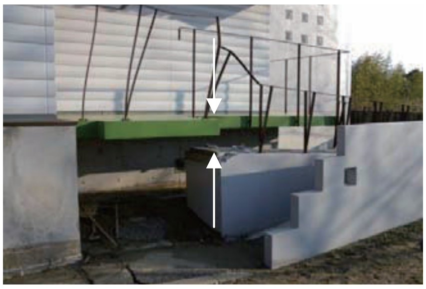

Photo 6.5-4 Slope difference in level

Photo 6.5-5 Crack in the site

Photo 6.5-6 Damage to side ditch

Photo 6.5-7 Damage situations by liquefaction

6.5.3 Damage due to Liquefaction in Urayasu city, Chiba prefecture

Area of reclaimed ground accounts for 3/4 of a total area in Urayasu city at present. The southern part of the city is the area that was developed under a reclamation project using sea sand. In the result, the area consists of soft layers up to GL-40 m. For reference, liquefaction damage was also reported in the 1987 East Off Chiba Prefecture earthquake. The damage situations are given below.

(1) Mihama area

In Mihama, subsidence and tilting were observed in houses that have a dry area in the basement (Photo 6.5-8). An angle of tilting of the house was about 3 degrees. It is considered that the basement was uplifted and another remaining parts of the house was subsided. Around the house, in-site of house was totally covered with boiled sand by liquefaction, and a foundation of fence at site boundary was deformed. In addition, carport in a house was ruptured and moved (Photo 6.5-9). The carport and the house was separated and moved about 50 cm due to the movement of the ground associated with liquefaction.

(2) Benten area

Significant tilting and subsidence of houses were observed at a zone in Benten (Photo 6.5-10). In another zone, the ground subsided by liquefaction, damage to the road that was waved and a 10 cm of difference in level was generated between a side ditch and the road. These types of damage were concentrated on an extension line of the boundary between the sites of tilted houses. Inhabitants told us that there was an old river on a straight line where the damage was concentrated.

Photo 6.5-8 Tilted house

Photo 6.5-9 Moved carport

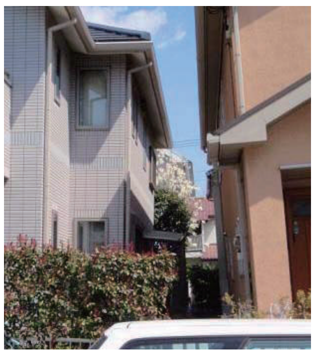

Photo 6.5-10 Settled and tilted house

(3) Irifune area

In Irifune, a difference in settlement between adjacent buildings on spread and pile foundations was observed. The building on spread foundation settled about 35 cm from the front sidewalk, while the case of building on pile foundation was about 30 cm of difference in level from the front sidewalk (Photo 6.5-11).

(4) Hinode area

In Hinode, the ground subsidence was observed (Photo 6.5-12). This building is considered to have a pile foundation. A relative gap between the building and ground was about 50 cm. Building lifeline was damaged due to ground subsidence and displacement.

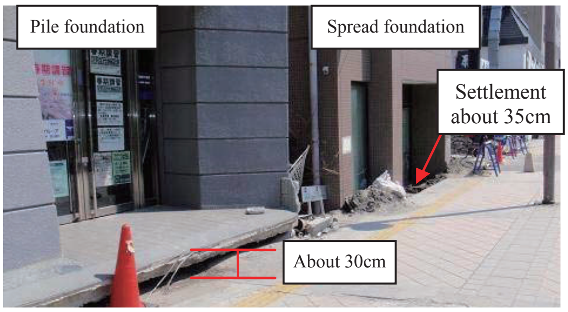

Photo 6.5-11 Difference in damage due to support mechanisms

Photo 6.5-12 Building with subsidence of surrounding ground

6.5.4 Damage to Developed Housing Area

The damage investigation for developed housing area was conducted in several areas of Miyagi, Fukushima and Tochigi prefectures, while only the damage in Miyagi and Fukushima prefectures is reported in this section.

(1) 5-chome, Oritate, Aoba-ku, Sendai city, Miyagi prefecture

In one corner of a large-scale housing area, where a slope in the N-NE direction had been developed, ground deformation due to sliding of the reclaimed area by banking to the slope direction, and damage to the retaining walls due to ground deformation were often observed (Photo 6.5-13). Houses on the site were recognized to have different damage patters, such as movement, subsidence and tilting without structural damage, severe structural deformation and fractured foundation.

(2) 2-chome, Aoyama and 4-chome, Midorigaoka, Taihaku-ku, Sendai city, Miyagi prefecture

This area is located at one corner of the large-scale housing area where a hill was developed. Ground deformation due to sliding of the reclaimed area by banking to the slope direction, and damage to the retaining walls due to ground deformation, were often observed. The damaged area in 4-chome, Midorigaoka during the 2011 Tohoku earthquake was almost same as that during the 1978 Miyagi-oki earthquake. The land in 2-chome, Aoyama is wavier than in 4-chome, Midorigaoka. Near the zone of 2-chome, Aoyama, large-scale sliding of the embankment occurred (Photo 6.5-14). In this zone, large deformation and damage were seen on both of upper structures and foundations of houses in the housing area. In other places with embankment sliding, deformation and damage to upper structures of houses were observed, but it seemed that there was limited significant damage to foundations. In 2-chome, Aoyama, a retaining wall for the housing area with a height of over 5 m was damaged.

Photo 6.5-13 Damage to retaining wall and house due to sliding and ground deformation

Photo 6.5-14 Group of houses damaged due to sliding and ground deformation

(3) 1-chome, Futabagaoka, Aoba-ku, Sendai city, Miyagi prefecture

This area is located at one corner of a large-scale housing area where a slope in the eastern direction was developed. The area suffered ground deformation due to sliding of the reclaimed area by banking to the slope direction. Large structural deformation (Photo 6.5-15) was relatively often seen in houses in the area, but houses without structural damage were sporadically observed. In addition, a gap between the house foundation and surrounding ground that was caused by ground subsidence and transformation, and damage to the lifeline, were observed. Damage to a retaining wall in the area was hardly seen, while traces of flaking and falling of block fences on the upper part of the wall were sporadically observed.

(4) 1 to 2-chome, Midorigaoka, Shiroishi city, Miyagi prefecture

This is a housing area where a hill was developed. Fissures on the slope of the hill and near the top of the hill, and damage to housing foundations and retaining walls due to deformation of the reclaimed area by banking, were observed in the area. The slope in 1-chome, Midorigaoka had been significantly collapsed under the 1978 Miyagi-oki earthquake. A level of ground deformation on the slope under the 2011 Tohoku earthquake was lower than that during the 1978 earthquake. Near the top of the hill, ground deformation of the reclaimed area by banking caused fracture of the embankment retaining wall, damage to house foundations (Photo 6.5-16) and push-out of the retaining wall on embankment.

Photo 6.5-15 Damage to houses due to sliding and ground deformation

Photo 6.5-16 Houses damaged near the top of hill

(5) Shimomiyamae, Asohara, Yamamoto Town, Watari-gun, Miyagi perfectere

This is a housing area where a hill was developed. Land sliding of the slope at the end of the hill, and ground deformation that seemed to be related with the sliding were observed. This ground deformation caused serious damage to houses. In the result, some houses were in a state of sliding on the slope of the hill (Photo 6.5-17). On the other hand, there was no ground deformation in a house located in the flat part of the hill, while paper sliding doors on the first-story of the house were only broken during the earthquake.

(6) Numanoue, Fushiogami, Fukushima city, Fukushima prefecture

This area is located at one corner of a large-scale housing area where a hill was developed. The result of investigation was revealed ground deformation due to land sliding on the slope of the hill. This ground deformation caused serious damage to houses. In the result, several houses were in a state of sliding on the slope of the hill (Photo 6.5-18). On the other hand, houses near the top of the hill suffered only damage associated with slight deformation of the reclaimed area by banking.

Photo 6.5-17 Fracture of embankment retaining wall and houses tilting due to land sliding on the slope of hill end

Photo 6.5-18 Land sliding of slope on the southwest of hill and sliding houses

6.5.5 Conclusions

The outline of the damage situations in the investigate scope is as follows.

(1) Damage due to liquefaction:

In the alluvial plain area of the Tone River and the coastal area of Tokyo Bay, extensive damage such as sand boiling or ground deformation associated with liquefaction was confirmed. Heavily tilted houses were seen, while cracks or fissures on the foundations were not observed.

(2) Damage to developed housing area:

Severe damage with ground deformation such as slope sliding was observed mainly in the elevated and developed housing area (particularly marginal part of development). In several areas, ground deformation occurred again in the developed area that had been affected by the past earthquakes.

6.6 Damage to Nonstructural Components

6.6.1 Introduction

This section is based on the surveys by the Joint Survey Team after March 11th 2011. External surveys were conducted to various buildings in three prefectures of Miyagi, Fukushima and Ibaraki, and external and internal ones were also done in Ibaraki prefecture to gymnasiums and an airport passenger terminal building. This section describes the outline of the damage to exterior walls, openings, suspended ceilings, interior walls focusing on the buildings without severe structural damage patterns such as story collapse.

6.6.2 Damage to exterior walls

Many damaged exterior walls, including walls finished with ceramic wall tiles, cement mortar and metal lath wall and AAC (Autoclaved lightweight Aerated Concrete) panel walls, were observed.

Detachment of ceramic wall tiles was often observed at buildings of RC nonstructural exterior walls. Types of the detachment were classified according to existence or nonexistence of crack on the damaged RC wall.[6.6-1) 6.6-2)] In Photo 6.6-1, ceramic wall tile detached from RC exterior wall. Cracks were observed on the damaged RC wall. Photo 6.6-2 shows detachment of ceramic wall tiles installed on a cylindrical RC wall above the building entrance (within a circle). No crack was externally observed on the undersurface RC wall. A net was placed over the damaged area to catch falling tiles.

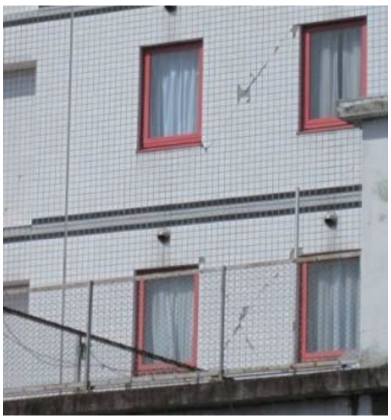

Photo 6.6-1 Detachment of ceramic wall tiles from damaged RC exterior wall

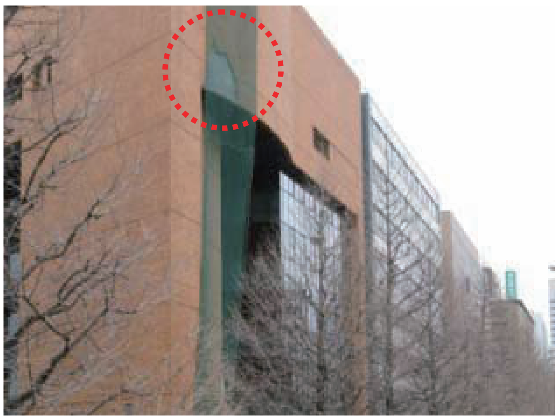

Photo 6.6-2 Detachment of ceramic wall tiles from RC wall

Damage to cement mortar and metal lath exterior walls was often observed in steel buildings. Photo 6.6-3 shows detachment of cement mortar and metal lath exterior wall in a 3-story building. Damage to the window glass was not observed, but cement mortar and metal lath fell from the exterior wall (shown in Photo 6.6-3) and from the parapet on another side. Photo 6.6-4 shows a one-story steel building in which cement mortar and metal lath detached from an exterior wall and from an eaves soffit. Photo 6.6-5 shows a damaged gable end wall of a gymnasium. This wall consisted of two layers. The undersurface wall was cement mortar and metal lath exterior wall. The surface one was exterior boards nailed to furring installed on the undersurface wall. Both were damaged and fell by the earthquake.

Photo 6.6-3 Falling of cement mortar and metal lath wall

Photo 6.6-4 Falling of cement mortar and metal lath from eaves soffit

Photo 6.6-5 Damage to gymnasium gable end wall

Photo from 6.6-6 to 6.6-7 shows damage to AAC panel exterior walls. Photo 6.6-6 shows falling of finishing ceramic wall tiles on AAC panels and broken light-weight aerated concrete in a 3-story building. Ceramic wall tiles on all faces of the exterior walls detached and the corners of the AAC panels were chipped. AAC panel was broken and internal iron wires were exposed at the circular broken line in the photo. AAC panels fell from another side. The construction method of the AAC panel exterior wall was not observed in the external survey. Photo 6.6-7 shows falling of AAC panels from the top-floor of a 5-story building. The damaged AAC panels were observed to be installed to the support metal with cement mortar and steel bar. This AAC construction method appeared in 3rd edition of Japanese Architectural Specification Standard JASS 12 as one of standard construction methods for AAC panel exterior wall but not included in its 4th edition.[6.6-3)] [6.6-4)] AAC panels installed with this AAC construction method were frequently observed to be damaged.

Photo 6.6-6 Falling of ceramic wall tiles and breakage of AAC panels

Photo 6.6-7 Detachment of AAC panels

6.6.3 Damage to openings

Damage to openings was observed in window glasses and window frames.

Photo 6.6-8 shows broken window glasses in the upper area of a windbreak room on the ground level of a 5-story building. Exterior ceramic wall tiles fell from another side.

Photo 6.6-8 Broken window glass

Photo 6.6-9 shows damaged window glasses installed to the upper fixed window with hardening putty at a gymnasium gable end wall. Cracked wired window glasses were also observed at the lower double sliding window with hardening putty. Flaking of paints was observed on the center of an arch beam of the gymnasium. Photo 6.6-10 shows breakage of window glasses in a gymnasium. The window glasses were installed to fixed window frames with glazing bead and twelve window glasses were broken at three exterior surfaces. Flaking of concrete at the roof bearing support part, deformation of almost all roof horizontal braces and fracture of one roof horizontal brace in the gymnasium were observed.

Photo 6.6-9 Breakage of window glasses installed to fixed window frame with hardening putty

Photo 6.6-10 Breakage of window glasses installed to fixed window frame with glazing bead

Photo 6.6-11 shows broken window glasses on the longitudinal surface in a gymnasium. Twenty-six wired window glasses were broken, which were installed to double sliding window frames with glazing bead. On the windows of opposite side, there were no damage to the frosted window glasses and a detachment of a mullion cover of a window. No damage was observed in the structure.

Photo 6.6-11 Breakage of wired window glass installed to double sliding window frame with glazing bead

Photo 6.6-12 shows a damaged glass wall system at the 1st floor of a 6-story building. A glass mullion was broken in an area circled by a broken line (steel pipe adjacent to the broken glass were installed after the earthquake for the repair work).

Photo 6.6-13 shows damage to window frame in a gymnasium. The photo shows the window frames near the center of the longitudinal surface of the gymnasiums. The upper part of the window frame was dislocated and leaned to the outside. The same damage was observed also at the opposite side. Fracture or buckling was observed in most of the section loss parts by bolt holes on longitudinal direction frame braces. Braces were fractured in three of four frames.

Photo 6.6-12 Breakage of glass mullion of glass wall system

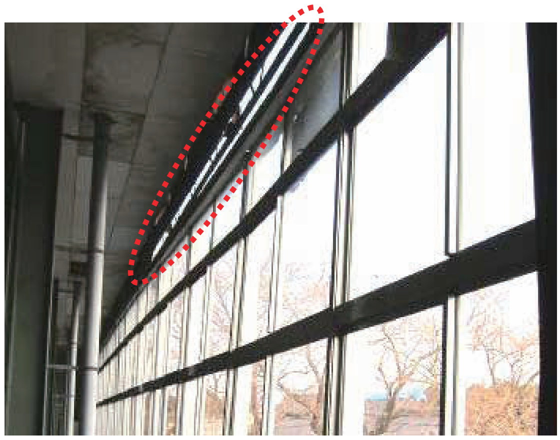

Photo 6.6-13 Dislocation of window frame

6.6.4 Damage to suspended ceilings

Many damaged suspended ceilings were observed in the damage investigation of gymnasiums and an airport passenger terminal building. The damaged suspended ceilings included wooden suspended ceilings faced with wooden boards, metal furring ones faced with plaster boards and absorption boards of rock wool, ones with exposed T system and glass wool boards and others.

Photo 6.6-14 shows a damaged wooden suspended ceiling in a gymnasium. The ceiling almost fell with light fittings except at perimeter. Partial falling of an eaves soffit, dislocation of a window frame and 33 broken window glasses were also observed.

Photo 6.6-14 Falling of wooden suspended ceiling

Photo 6.6-15 shows a metal furring suspended ceiling broken at the center of a pitched ceiling. Damage was also observed at interior walls above the stage. No damage was observed to the steel roof and supporting RC columns. Photo 6.6-16 shows damage to a high ceiling above the lobby of an airport passenger terminal building. There were five metal furring suspended ceilings of 3m x 11m. The metal-sheet clips hanging the metal furring channels were damaged by the earthquake and one of the ceilings fell. In the ceiling plenum, vertical diagonal members were unevenly installed and the members were complicatedly installed near the connection with the surrounding wall. No damage to the structure was observed.

Photo 6.6-15 Falling of metal furring suspended ceiling

Photo 6.6-16 Falling of metal furring suspended ceiling

Photo 6.6-17 shows damaged ceilings in a gymnasium. The horizontal ceiling marked with red dotted lines was composed of corrugated steel plates and steel members and the pitched ones were composed of metal furring channels and other steel members faced with gypsum board. Both ceilings fell. The broken window glasses and the leaned interior wall above the stage were also observed. Many roof horizontal braces were fractured.

In the gymnasium shown in Photo 6.6-18, many glass wool boards on exposed T system fell. Flaking of concrete was observed in the structure.

Photo 6.6-17 Falling of metal furring suspended ceiling and corrugated steel plates

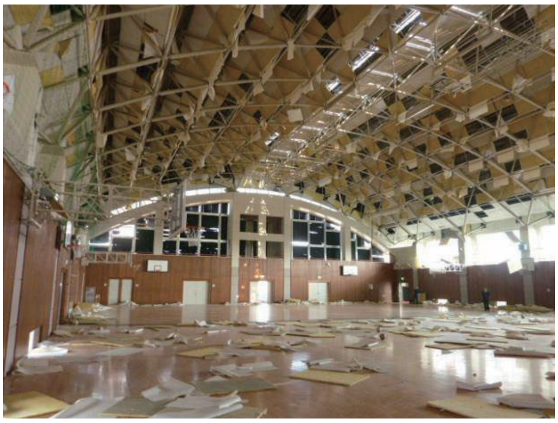

Photo 6.6-18 Falling of glass wool board of T system ceiling

Photo 6.6-19 shows a damaged metal furring suspended ceiling in a gymnasium. Significant visual damage was not observed, but the ceiling board sagged near the center of pitched ceiling marked with a red dotted oval line in the photo. This was possibly due to the displacement of ceiling members in the plenum. Cement mortar finish of interior wall above the stage was flaked as shown in Photo 6.6-23, and the exterior boards were broken at the gable end wall. No damage to the structure was observed.

Photo 6.6-20 shows damaged ceiling at the connection with surrounding wall in a gymnasium. Bending of the metal furring channels and detachment of ceiling boards were observed. In the corner of the ceiling, the sheet-metal clips were damaged and the ceiling sagged in several meters long. The gymnasium is composed of lower RC frame and upper steel frame.

Photo 6.6-19 Sagging of metal furring suspended ceiling

Photo 6.6-20 Damage to metal furring ceiling at the connection wall

Photo 6.6-21shows damaged ceiling boards at the connection with the structure of a gymnasium. It was reported that one window glass was broken. No damage to the structure was observed.

Photo 6.6-22 shows damaged ceilings at an office building. The ceiling was damaged at the connection with the partition. Bending of a metal furring channels and falling of ceiling boards were observed.

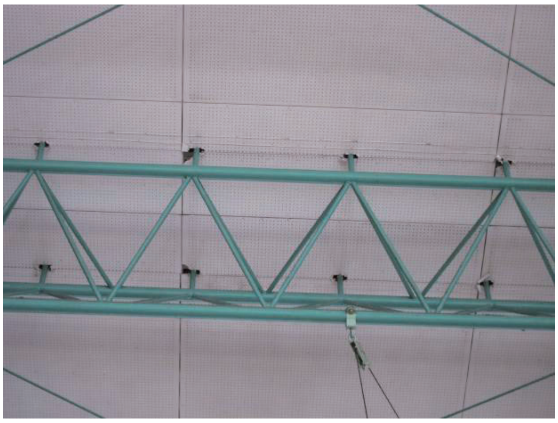

Photo 6.6-21 Damage to metal furring suspended ceiling at the connection

Photo 6.6-22 Damage to metal furring suspended ceiling at the connection

6.6.5 Damage to interior walls

Photo 6.6-23 shows damaged walls above the stage in the gymnasium shown in Photo 6.6-19. Cement mortar finishes on the studs were broken and fell. Damage to the walls above the stage was observed also in some gymnasiums such as shown in Photo 6.6-15 or Photo 6.6-17.

Photo 6.6-23 Falling of cement mortar finish above stage

Photo 6.6-24 shows a lift of the nail fixing interior wall boards to the studs in the arena of gymnasium.

Photo 6.6-25 shows damaged interior walls in a gymnasium. Interior walls around the supports leaned at two of three basketball hoops. The damaged hoops were temporarily supported with ropes.

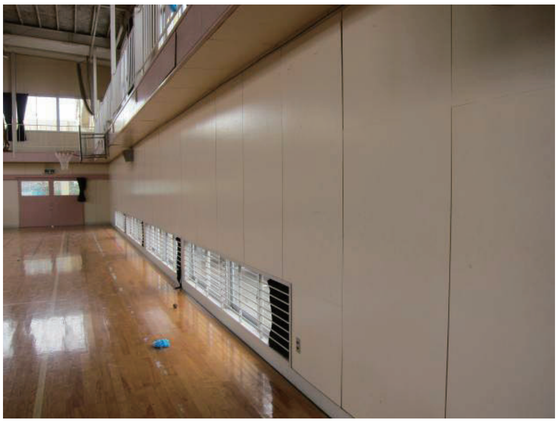

Photo 6.6-24 Loosen nails fixing board

Photo 6.6-25 Damaged interior wall

6.6.6 Conclusion

This section described the outline of damage to nonstructural components. Damage to nonstructural components constructed with relatively older building methods was often observed. Breakage and falling of nonstructural components placed on relatively higher parts were also observed.

The frequently observed damage to each nonstructural component is summarized as below:

Exterior wall

Ceramic wall tiles were detached from RC nonstructural walls. Cement mortar and metal lath were detached from steel buildings. AAC panels installed to support metal with cement mortar and steel bar were also detached from steel buildings.

Openings

Glasses of fixed window were broken, mostly installed with hardening putty.

Suspended ceiling

Various types of suspended ceilings were damaged. Breakage at connection with interior walls was frequently observed at gymnasiums.

Interior wall

Walls were broken and fell above the stage of gymnasiums.

References

6.6-1) Manual for Seismic Design of Exterior Walls – For Mid-rise Buildings -, 2nd edition, supervised by Building Guidance Division, Housing Bureau, Ministry of Construction and Japan Conference of Building Officials, published by Building Center of Japan, 1998

6.6-2) Akio BABA and Hiroshi ITO, Full Scale Experiment on the Seismic Safety of Exterior Finishing Material and Construction Method, Cement & Concrete No.376, published by the Cement Association of Japan, 1978

6.6-3) Japanese Architectural Standard Specification JASS 21 AAC Panel Work, 3rd edition, Architectural Institute of Japan, 1998

6.6-4) Japanese Architectural Standard Specification JASS 21 AAC Panel Work, 4th edition, Architectural Institute of Japan, 2005

7. Damage to Buildings in Inundation Areas Induced by Tsunami

7.1 Introduction

The purpose of this investigation is to understand an overview of buildings damaged by tsunami, in order to obtain basic data and information required to evaluate mechanisms for causing damage to the buildings and to contribute to tsunami load and tsunami-resistant designs for buildings such as tsunami evacuation buildings. The investigation was conducted by collecting building damage cases caused by tsunami, classifying the damage patterns for different structural categories, and making a comparison between the calculated tsunami force acting on buildings and the strength of the buildings.

The tsunami damage survey team* organized in the Joint Survey Team consists of 27 members, for voluntary investigation. The team collected national and international standards and codes concerning tsunami evacuation buildings and tsunami loads and surveyed about 100 buildings and structures in three site investigations.

7.2 Classification and Discussion of Damage Patterns

7.2.1 Reinforced concrete buildings

1) Collapse of first floor

A case that column capitals and bases on the first floor in a building were subject to bending failure and subsequently to story collapse was seen in a 2-story building (Photo 7.2-1).

The building had column-to-beam frames. The first floor had relatively small number of walls, but many concrete block walls were placed on the second floor. The first and second floors of the building in Photo 7.2-1 were used as shop and dwelling, respectively. The relevant building was estimated to have structural characteristics of low strength and stiffness on the first floor. As an opening on the second floor was not large, it is assumed that the second floor suffered a large tsunami wave pressure and the shear force acting on the first floor exceeded the lateral load-bearing capacity, resulting in the collapse of the building. Story collapse of the first floor has not been observed in 3-story or higher buildings in the investigations. In 3-story buildings, in general, reinforced concrete walls are often used in the first floor. Therefore, the strength of the first floor of 3-story buildings is considered to have been larger than that of 2-story buildings.

Photo 7.2-1 Story collapse of a 2-story reinforced concreted building

2) Overturning

Overturning was observed in 4-story or lower buildings. In all overturned buildings, the maximum inundation depth exceeded their height. Overturning types include buildings that fell sidelong (Photo 7.2-2) and buildings that turned upside down. Most of the overturned buildings were of mat foundation. In some overturned buildings on pile foundation, piles were pulled out.

Photo 7.2-2 Overturning of a 3-story reinforced concrete building

Overturning cases were often seen in 4-story or lower buildings with relatively small size of openings. However, there were many cases that 4-story or lower buildings with large size of openings were not overturned. Consequently, the size of opening on an exterior wall is considered to have greatly affected overturning.

In some cases, there were tsunami traces at the heights of the upper end of openings on the top floor inside the buildings whose heights were exceeded by maximum inundation depths. It is considered that air has accumulated in the space between the ceiling and the upper end of openings. Overturning is considered to occur when an overturning moment by tsunami wave force exceeds an overturning strength by a dead load of a building (considering the effect of buoyancy as required). A building, in which the distance from the upper end of an opening on each floor to a ceiling is long, may be overturned even by a slight horizontal tsunami force when buoyancy significantly acts on the building.

3) Movement and washout

Most of the overturned buildings were moved from their original positions. It is estimated that large buoyancy acted on the buildings. Moved and overturned buildings left no dragged traces on the ground. One of the buildings moved over a concrete block fence that had about 2m height on an adjoining land without destroying the fence (Photo 7.2-3). The building seems to have floated up by buoyancy. Some of the 2-story apartment houses with the same shape that were overturned were washed away and missing. A buoyancy and large horizontal force seem to have acted on these buildings.

Photo 7.2-3 A 2-story reinforced concrete building that moved over the fence and overturned

4) Tilting by scouring

When tsunami acted on a building, a strong stream was generated around the corner of the building, resulting in many large holes on the ground that were bored by scouring. In one case, a building on mat foundation fell into a hole bored by scouring (Photo 7.2-4).

Photo 7.2-4 A 2-story reinforced concrete building that was tilted by scouring

5) Fracture of wall (fracture of opening)

When tsunami acts on openings in a building and openings of the opposite side of the building are smaller than the affected openings, a stream flowing from the affected openings concentrates on the opposite small openings. In one observed case related to this event, a stream generated by tsunami provided a large pressure to a reinforced concrete non-structural wall around small opposite openings. The pressure enlarged the concrete wall to the outside and fractured the wall reinforcement. A tsunami wave force that acts on a building will be reduced if the size of opening affected by the force becomes larger. The same trend is considered to apply to an outlet surface of the stream.

Cases that such wall reinforcement was fractured were often seen in wall members with single layer bar arrangement. In one damaged building (Photo 7.2-5), a 300 mm-thick shear wall with double layer bar arrangement and a support span of more than 10 m and without the second and third floor slabs was bent inside by tsunami wave pressure. However, a shear wall in an area (Photo 7.2-5 Back of the building, right-hand side), where there was a floor on the second story and a support span was not long in the same building, was not bent.

Photo 7.2-5 Out-of-plane fracture of reinforced concrete shear wall without floor

6) Debris impact

Debris impact was seen in most of the non-structural members such as window and ceiling materials. The number of cases of clear damage to skeletons was not large, but in one observed case, a multi-story wall in an apartment house was probably bored by debris impact (Photo 7.2-6).

Photo 7.2-6 Wall opening probably generated by debris impact

7.2.2 Steel buildings

1) Movement and washout by fracture of exposed column base

A typical case of building movement and washout was that a building moved and flew due to the fracture of anchor bolts and/or base plates at steel exposed column bases and the fracture of a weld between the column and the base plate (Photo 7.2-7). In most cases, foundation and some column bases were left in the site, but the upper structure of the building was moved beyond the site or missing.

Photo 7.2-7 Steel building overturned by fracture of column base anchor bolts

2) Movement and washout by fracture of capital connection

In damage cases relatively often seen that a capital connection on the first or second floor in a building was fractured, then the building was moved and washed away. When a column base has a large strength like concrete encases type or embedded type, this type of fracture is considered to occur. In one case (Photo 7.2-8), foundation in a building, and several columns on the first floor (or up to the second floor) were left on the site, and the columns fell in the same direction.

In most cases, welds between diaphragms with lower flanges and the first-floor columns were fractured and the sections of the columns were exposed. In one building, flanges of the second-floor H-shaped beams were torn. Based on the deformation states near the column bases, it is estimated that a tensile force acted on the first-floor columns, and then the first-floor capital connections were fractured after the first floor was greatly tilted to the same extent as the inclination of the remaining columns.

Photo 7.2-8 First-floor columns falling in the same direction

3) Overturning

One case that a whole building including foundation was overturned, was confirmed. Most of the AAC panels of claddings were left (Photo 7.2-9).

Photo 7.2-9 Overturning of a 3-story steel building

4) Collapse

Skeleton collapse including story collapse of the first floor was seen in a 2-story steel building (Photo 7.2-10). Partial collapse of a warehouse was also seen on the coast.

Photo 7.2-10 Story collapse of first floor in a 2-story steel building

5) Large residual deformation

Slight tilting was often observed with remaining their skeletons in steel buildings. In one case (Photo 7.2-11), a gabled roof frame building did not collapsed despite large residual deformation.

Photo 7.2-11 Tilted gabled roof frame

6) Full fracture and washout of cladding and internal finishing materials

Cladding materials such as AAC panel were almost fully fractured and washed away, and then a steel frame as a skeleton was remaining. This case was often observed (Photo 7.2-12). It is considered that an external force that acted on the skeleton became small due to early washout of the cladding materials. In the remaining building, slight tilting of the skeleton, member deformation on the face affected by tsunami, and members locally damaged possibly by debris impact, were observed.

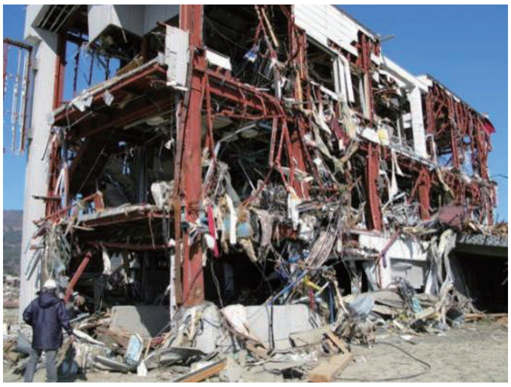

Photo 7.2-12 A remaining 3-story steel building

In another damage case, openings on the face affected by tsunami and on its opposite face, or transverse faces were severely damaged and fractured possibly due to stream runoff.

7.3 Database for Investigated Buildings

Outer dimensions of about 100 buildings and dimensions of their skeletons were measured in the site investigation. Maximum inundation depths were measured from tsunami traces on surveyed buildings and surrounding buildings. These measurement results were integrated into a database for investigated buildings. Building name, address, building use, construction year, designation as tsunami evacuation building, structure category, number of stories, outer dimension, distance from seacoast (river), GPS position, altitude, surrounding circumstances, damage situations, etc., were recorded in the database. In addition, photos of investigated buildings that were taken from four directions as possible were attached to the database. Based on the database, the joint survey team estimated strengths of the buildings and tsunami loads on them, and is evaluating whether the estimated values are consistent with the damage situations.

7.4 Damage to Wood Buildings

7.4.1 Objectives of damage survey

Many of wood buildings built in the Pacific coast of Tohoku region were washed away by the tsunami caused by the 2011 Tohoku Earthquake. However, there were not few wood houses that remained in tsunami affected areas. The field surveys were conducted to grasp the outline of the damage to the wood buildings due to tsunami and the characteristics or conditions of the building washed away and remained.

7.4.2 Outline of survey

The field surveys were carried out both in plain area and slope land. The surveyed area and survey schedule were shown in Fig. 7.4-1 and Table 7.4-1, respectively. However, in the surveyed city and town, we didn't survey all the area of the city and town exhaustively, and surveyed only a part of the inundated area selectively. Therefore, what are mentioned in the followings are the knowledge which was provided in the surveyed area at the surveyed time.

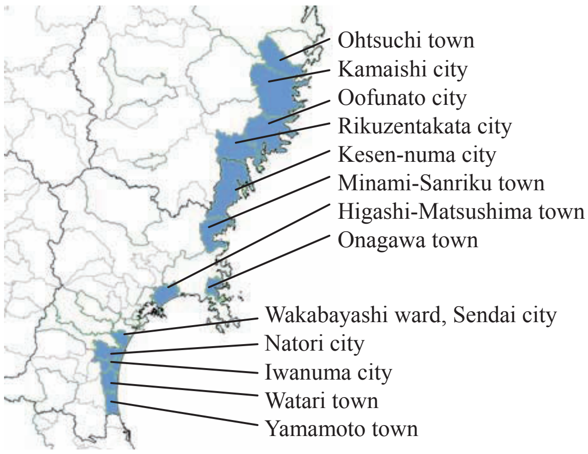

Fig. 7.4-1. Locations of surveyed area

Table 7.4-1. Survey schedule

Category	Surveyed cities and towns	Date of survey
Plain area	Wakabayashi ward in Sendai city, Natori city, Iwanuma city, Watari town, and Ymamoto town in Miyagi prefecture	April 6-8, 2011.
Slope land	Ohtsuchi town, Kamaishi city, Oofunato city, and Rikuzen-takata city in Iwate pref., Kesen-numa city, Minami-Sanriku town, Onagawa town, Higashi-Matsushima town in Miyagi pref.	May 25-27, 2011.

7.4.3 Damage in Plain Area

There were few things to block tsunami in plain area, a lot of wood buildings suffered crushing damage due to tsunami caused by the 2011 off the Pacific coast Thohoku Earthquake. The water depth in the surveyed area estimated by the water trace on the building wall was shown Table 7.4-2.

(1) Damage to wood houses

In the area with over 5 m water depth, most of the wood houses in the inundated area were washed away by the tsunami. How the houses were washed away; as for the case which the whole house including foundations was washed away (Photo 7.4-1), the case which only foundations were left (Photo 7.4-2), the case which sills and foundations were left (Photo 7.4-3), the case which sills, foundations and floor boards were left (Photo 7.4-4), and so on, were observed. There were several cases that the hold down fastener was failed, as shown in Photo 7.4-5. The foundations or wall of bath room made by concrete block often remained, as shown in Photo 7.4-2.

(2) Wood buildings remained in Arahama and Arahama-shin, Wakabayashi ward, Sendai city

Most of wood houses near the shore were washed away. However, not all the houses were washed away. For example, many houses which were located far from the shore remained, as shown in Photo 7.4-6. The houses in the downstream of RC building remained, as shown in Photo 7.4-7.

A line of wood houses remained were confirmed in Arahama-shin, Wakabayashi ward, Sendai city, as shown in Photo 7.4-8. The front survived house of the line was non-wooden. The water depth in this area was estimated at the level about 4-5 m. On the other hand, some wood houses which didn't have survived buildings in the direction where the tsunami came remained, but suffered heavy damage, as shown in Photo 7.4-9. Several such houses were confirmed in each surveyed area, and they were built by the construction methods with many metal fasteners.

Table 7.4-2. Estimated water depth

Surveyed area	Estimated water depth (m)
Arahama, Wakabayashi ward, Sendai city	6-8
Arahama-shin, Wakabayashi ward, Sendai city	5-6
Yuriage, Natori	5-6
North of Arahama port, Watari town	6
West of Arahama port, Watari town	4

Photo.7.4-1. Foundations washed away.

Photo.7.4-2. Only foundation remained.

Photo.7.4-3. Foundation and sills remsined.

Photo.7.4-4. Sills, foundation and floor boards remained.

Photo.7.4-5. Failed hold down fastener.

Photo.7.4-6. Many wood houses remained.

Photo.7.4-7. Wood house remained in the downstream of RC building in Arahama, Wakabayashi ward, Sendai city.

Photo 7.4-8. A line of wood houses remained
in Arahama-shin, Wakabayashi ward, Sendai city.

Photo 7.4-9. Remained house which didn't have survived buildings
in the direction where the tsunami came in Arahama-shin, Wakabayashi ward, Sendai city.

(3) Remained wood buildings in Yuriage, Natori city

Wood buildings also suffered crushing damage due to tsunami, as shown in Fig. 7.4-2. The parts of buildings remained, for example foundation, sill, and so on, were as same as mentioned in (1). Figures in rectangles in Fig. 7.4-2 show the locations of buildings mentioned in the followings. The wood house (Photo 7.4-10:1) united with the foundation and carried away. In the original position of it, steel tube piles remained as shown in Photo 7.4-11(2). Because a temple building (Photo 7.4-12:3) and a steel-frame house (4) were damaged heavily and remained, tsunami wave force was reduced to some extent, and the neighboring wood house with store avoided being carried away, as shown in Photo 7.4-13 (5). It might be possible for the survived low-rise building to make wave force reduce.

In the south east of Hiroura bridge (6), there was protect forest (Photo 7.4-14:7) of the pine trees with about 20 cm diameter at breast-height. The water depth was estimated to be about 5-6 m by the flotsam attaching to trees. A part of this protect forest fell down completely, in the downstream of this, the wood house (Photo 7.4-15:8) was washed away. On the other hand, in the downstream of survived protect forest, wood houses were selectively carried away and an example of the remained house was shown in Photo 7.4.16 (9). It seems to be generally thought that protect forest reduces wave force. However, because it cannot be thought that the strength of trees falling down continually was quite different by their location, it would be natural to think that the wave force or the speed of the tsunami were different by factors such as the depth of water or the submarine topography in this case. There was a house (Photo 7.4-17:10) remained in the area where there was no building and no protect forest existed in the direction of the wave. In addition, the relatively new Japanese conventional post and beam wood house (Photo 7.4-18 :11) and light frame construction house (Photo 7.4-19 :12) were confirmed at the location where there were no survived buildings in the direction of waves. Besides, in the downstream of the former, another Japanese conventional post and beam wood house (13) remained in. The water depth was estimated to be about 3.5 m in these locations.

In the downstream of large RC building, houses with low structural specification (Photo 7.4-20 :14) also remained, as shown in Photo 7.4-20. On the other hand, in the location where was the downstream of the relatively large factory building (Photo 7.4-21 :15), the wood house (16) with relatively better structural specifications avoided being carried away, selectively.

Photo 7.4-10. Wood house (1) that was carried away with the base in Yuriage, Natori city.

Photo 7.4-11. Steel tube pile left at the the original position (2) of house in photo 7.4-10.

Photo 7.4-12. Heavily damaged temple (3) building in Yuriage, Natori city.

Photo 7.4-13. Wood house with store (5) remained in the down-stream of the survived buildings in Yuriage.

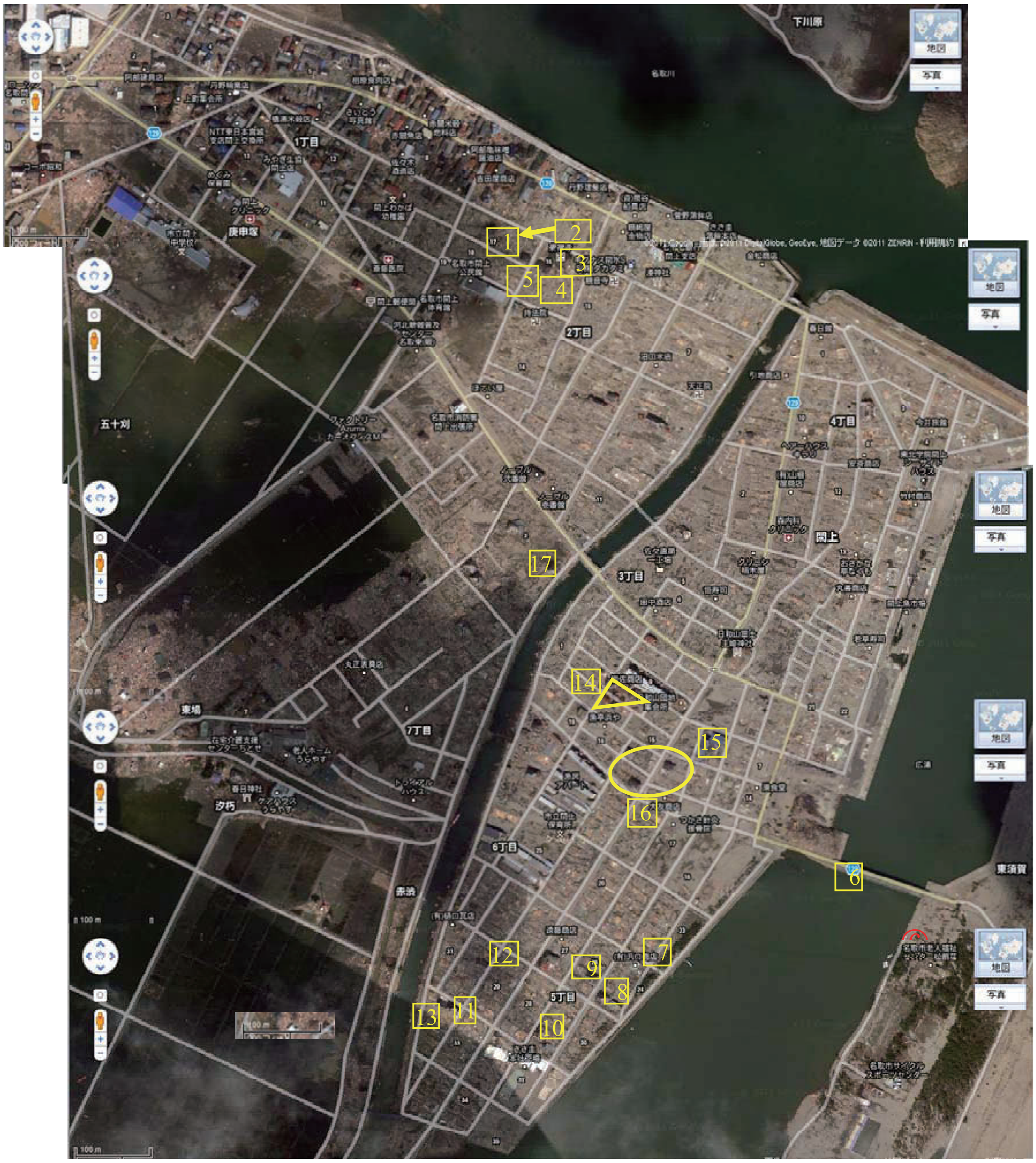

Fig. 7.4-2. Aerial photograph and the location related to surveyed buildings in Yuriage, Natori city.


Photo 7.4-14. Protect forest (7) in Yuriage, Natori city.


Photo 7.4-15. Fallen Protect forest and wood house (8) washed away in Yuriage, Natori city.


Photo 7.4-16. Protect forest and wood house (9) remained in Yuriage.


Photo 7.4-17. Wood house (10) remained without the effect of protect forest.


Photo 7.4-18. Japanese conventional post and beam wood house (11) remained alone.


Photo 7.4-19. Light frame construction wood house (12) remained alone

Photo 7.4-20. Group of wood houses (14) which were not washed away in the downstream of a RC apartment house in Yuriage

Factory building

Photo 7.4-21. Wood houses (15) which were not washed away selectively in the downstream of a factory building.

(4) Remained wood buildings in Arahama, Watari town

Arahama district in Watari town is surrounded with sea shore and faces the Pacific Ocean in the east, and there is a port in the south side, as shown in Fig. 7.4-3. In the area between Pacific Ocean and Arahama port, most of wood houses were washed away. In the north area of the Arahama port, the water depth was estimated about 6 m. Many of wood houses were washed away. On the other hand, in the west area of the Arahama port, the water depth was estimated about 4 m. Many of wood houses remained. Remained parts, for example foundation, sill, and so on, were as mentioned in (1).

In the area between Pacific Ocean and Arahama port, remained wood buildings were Glulam frame structure (Photo 7.4-22) and a mixed structure (Photo 7.4-23) which has 1st story of RC structure and wooden 2nd story. In other cases, the part of the L-shaped wood house (Photo 7.4-24) whose part with short horizontal length in the direction of wave pressure was washed away, and another part with long horizontal length remained. It was confirmed that metal fasteners were used in the column end joints, and considered that the structural performance of this house was better.

In the north area of the Arahama port, a 3-story wood house (Photo 7.4-25) remained. The reason might be that the lateral strength of 1st story in 3-story building was larger than that in 2-story building.

In the west area of the Arahama port, it was confirmed that the wood house (Photo 7.4-26) was crashed by two ships but remained. The reason was that the wave pressure was low and the structural performance of the house was high because the house was relatively new.

Fig. 7.4-3. Aerial photograph and the water depth estimated in Arahama, Watari town.

Photo 7.4-22. Glulam frame structure remained in Arahama, Watari town.

Photo 7.4-23. Mixed structure which has 1st story of RC structure and wooden 2nd story.

Photo 7.4-24. L-shaped wood house whose part was washed away in the east of Arahama port.

Photo 7.4-25. 3-story wood house remained in the north of Arahama port.

Photo 7.4-26. Wood house remained in spite of ships' crashing in the west of Arahama port.

7.4.4 Damage in Slope Land

The damage in Akasaki-cho, Oofunato city was reported as an example of the tsunami damage in several surveyed slope lands. Akasaki-cho is located in the east of Oofunato bay, and is a gradual slope land. Fig. 7.4-4 shows the aerial photograph and the locations related to surveyed buildings. Similar to plain areas, many of wood houses were washed away by tsunami here in Oofunato. According to the resident of a house (Photo 7.4-27:1) located just near the shore, the height of the tsunami reached to the top of 2nd story, and the house went under the water completely. The house was damaged in a part, however it remained. The neighbouring work shed (2) whose sill came off from floor concrete moved. On the other hand, a 2-story wood house (Photo 7.4-28:3) opposite to the house (1) across the street along the sea suffered almost no damage. Two houses next to the house (1) and shed (2) remained. There is a hill in the back of them (in the north side), and there is a possibility that the hill affected the strength of the wave force caused by the tsunami. A Japanese traditional post and beam frame house (Photo 7.4-29:5) built on the street along the sea remained under the water depth of about 5-6 m, in spite of partial failure of walls. Close to this house, a wood house (Photo 7.4-30:6) remained under about 6 m water depth in spite of partial failure in the roof system. It was considered that this failure caused by the floating materials. There was a house (7) remained in the next, but a house which was guessed to have many hold down fasteners (8) was washed away. The house with hold down fastener may not remain by severe tsunami.

At the location where we went up the slope land from these houses, a light steel-frame house (9) remained in under the about 5 m water depth. In the next of this house, the 1-story old wood house (Photo 7.4-31:10) whose structural specification was not so good, but the anchor bolts were installed remained. In addition, a warehouse with mud walls (Photo 7.4-32:11) was remained and an old wood house without anchors (Photo 7.4-33:12) turned and moved horizontally. Because the wood house under about 5 m water depth were almost washed away in plain areas, it might be possible for the slope land to make lateral force caused by tsunami a little smaller.

Fig. 7.4-4. Aerial photograph and the locations related to surveyed buildings in Akasaki-cho, Oofunato city.

Photo 7.4-27. Wood house (1) remained under the water depth of over 7 m in Akasaki-cho, Oofunato city.

Photo 7.4-28. Wood house (3) without damage under the water depth of over 7 m in Akasaki-cho, Oofunato city.

Photo 7.4-29. Japanese traditional wood house (5) which was not carried away under about 5 m water depth in Akasaki-cho, Oofunato city.

Photo 7.4-30. Wood house (6) which was not carried away in spite of damage on 1st floor roof system in Akasaki-cho, Oofunato city.

Photo 7.4-31. Survived house (9) which seemed to have comparatively slight structural specifications in Akasaki-cho, Oofunato city.

Photo 7.4-32. Survived soil warehouse (10) which seemed to have comparatively slight structural specifications in Akasaki-cho, Oofunato city.

Photo 7.4-33. Survived old house (12) which rotated and moved horizontally in Akasaki-cho, Oofunato city.

7.4.5 Survey summaries

Results of surveys are summarized as follows;

1) Not all of the low-rise wood houses were washed away by the tsunami.
2) In the downstream of survived buildings more than a middle-rise or higher buildings, many wood houses remained regardless of structural specifications.
3) In the downstream of survived low-rise buildings, or at the location far from survived middle-rise buildings, only the wood houses with excellent structural specification remained.
4) In the location where there were almost no survived buildings in the direction of tsunami, there were some cases that a wood house remained alone. In that case, there were many examples that some columns or walls were carried away in the direction where tsunami came.
5) Having metal fastener or not in the column end joints such as the hold down fastener didn't decide whether the house was carried away or remain in.
6) It was possible for the slope land to make lateral force caused by tsunami a little smaller than in plain areas.

7.5 Conclusion

This paper classified the damage patterns for different structural categories and briefly discussed the factors that had caused various types of damage. Based on the results of the relevant investigation, the survey team is now conducting an additional site investigation as required and collecting design documents for damaged buildings, while further evaluating the effects of building openings and buoyancy and proceeding with the elucidation of mechanisms for causing damage and the identification of tsunami loads on buildings.

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8. Damage of Buildings, etc. due to Fire

8.1 Objective of Survey

Large number of fires occurred in wide area due to the earthquake and tsunami brought severe damage to buildings. The entire image of the fires is analyzed in this chapter. Investigation has been conducted in order to grasp the circumstances of the fire spreading and fire stopping in large city fires and the damage of building fires.

8.1.1 Number of Fire Occurrence

In this earthquake disaster, enormous tsunami damage occurred, but large number of fires were also identified in the areas damaged by tsunami. This is a major feature of fire damage in this earthquake disaster.

The total 345 fires including non-building fires reported (as of April 20, 2011) by Fire and Disaster Management Agency (FDMA) of Ministry of Internal Affairs and Communications (MIC)[8.1-1]. Table 8.1-1 shows the number of fires in each prefecture. In Miyagi, more than half of the total number of fires was occurred. These 345 fires include not only fires occurred in the mainshock at 14:46 on March 11, but also ones in aftershocks.

Table 8.1-1 Number of Fires by prefectures

Prefecture	Number of Fires
Aomori	5
Iwate	26
Miyagi	194
Akita	1
Fukushima	11
Ibaraki	37
Gunma	2
Saitama	13
Chiba	14
Tokyo	35
Kanagawa	6
Shizuoka	1
Total	345

(FDMA, as of April 20)

8.1.2 Seismic Intensity and Fire Occurrence

In Japan, the relation between fire break-out ratio and seismic intensity has been often discussed in order to identify the feature of earthquake fire[8.1-2].

The relation between seismic intensity and fire break-out ratio in this earthquake is shown in Fig. 8.1-1 and Table 8.1-2. The numbers of fires in some municipalities without seismic intensity data are omitted.

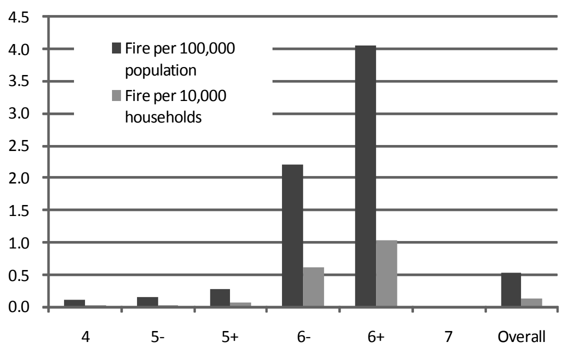


Fig. 8.1-1 Relation between fire break-out ratio and seismic intensity

Table 8.1-2 Seismic intensity, number of fire and fire break-out ratio

Seismic intensity	Population	Number of households	Number of fire	Fire per 100,000 population	Fire per 10,000 households
4	11,156,088	4,225,871	12	0.108	0.028
5−	19,042,953	8,292,245	31	0.163	0.037
5+	20,092,544	8,381,820	56	0.279	0.067
6−	4,254,959	1,543,580	94	2.209	0.609
6+	3,115,586	1,213,129	126	4.044	1.039
7	74,938	23,441	0	0.000	0.000
Overall	59,928,945	24,482,678	320	0.534	0.131

And the distribution of seismic intensity, number of fires and municipalities damaged by tsunami are geographically shown in Fig. 8.1-2.

Total data of the maximum seismic intensity by municipalities is based on the reports on seismic intensity released on May 30 and April 25, 2011 by the Japan Metrological Agency (JMA) of MLIT.

For this totaling, the municipalities in the prefectures which seismic intensity were 5 lower (5-) or more are included and the municipalities where seismic intensity has not been obtained or not yet been investigated are excluded from this totaling.

In only one area where seismic intensity 7 was observed, however, no fire was reported. The tendency that the higher the seismic intensity, the higher the fire break-out ratio, is observed in the municipalities where seismic intensity 6 lower (6-) or less was recorded.

In the cases of the 1995 Hyogo-ken Nambu (Kobe) earthquake and the 2004 Niigata-ken Chuetsu earthquake, in which seismic intensity 7 were recorded, fire ratio per 10,000

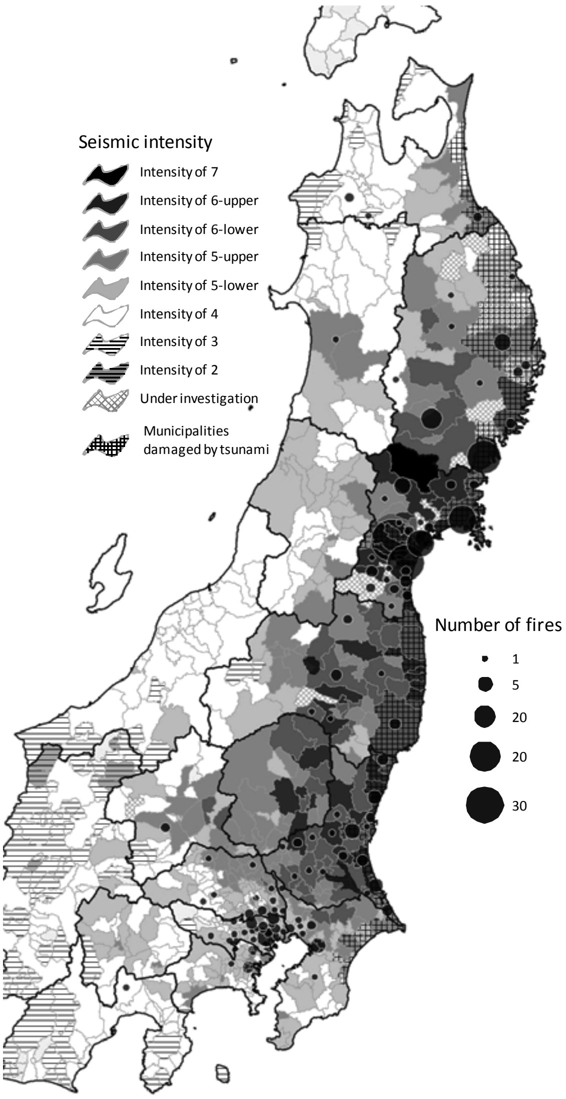


Fig. 8.1-2 Distribution of seismic intensity, number of fires and municipalities damaged by tsunami

households was 2~6 cases, but as for the 2011 Tohoku earthquake, the fire break-out ratio has become lower than the ratio for the 1995 Hyogo-ken Nambu earthquake.

However, in the areas of seismic intensity 6 upper (6+) in 2004 Chuetsu Earthquake, the ratio was around 0.7. Therefore, fire break-out ratio of 1.0 in the area of seismic intensity 6 upper of this earthquake is regarded as the same or a little higher value. The principal reason why the ratio of this earthquake is the same or a little higher, may be due to that many fires broke out in the damaged area by tsunami.

8.2 Damage by Fire due to Tsunami

There should be a distinction between fire occurred in areas damaged by tsunami (hereinafter referred to "tsunami fire") and fire occurred in other areas (hereinafter referred to "earthquake fire"), however at present, detailed information about the fire scene are not provided. Therefore, this report do not distinguish tsunami fire from earthquake fire out of the 345 fires.

Table 8.2-1 Number and break-out ratio of tsunami fire

Seismic intensity	Population	Number of households	Area of tsunami invasion [km^2]	Number of fire	Number of fire per 1km2 area of tsunami invasion	Fire per 100,000 population	Fire per 10,000 households
4	86,147	32,875	14	0	0.000	0.000	0.000
5−	207,519	73,107	16.5	3	0.182	1.446	0.410
5+	680,002	252,323	44.5	13	0.292	1.912	0.515
6−	1,492,701	557,650	280.5	68	0.242	4.556	1.219
6+	1,580,722	660,780	179	108	0.603	6.832	1.634
Not available	122,413	45,838	27	21	0.778	17.155	4.581
Total	4,169,504	1,622,573	561.5	213	0.379	5.109	1.313

Therefore, it is assumed the fires reported in the municipalities damaged by tsunami as tsunami fires and the fires reported in other municipalities as earthquake fires. The features of each fire on fire occurrence circumstance will be reported. Table 8.2-1 illustrates the list of number and break-out ratio of tsunami fire. The data has been acquired by totaling of the number of fire occurrence by the municipality areas of tsunami invasion.

It would be said that the features of tsunami fire which was reported in damaged area by tsunami, the area of fire spread extended to wider area where the

Photo 8.2-1 Tsunami fire at an elementary school (Ishinomaki city, Miyagi prefecture)

debris of buildings etc and automobiles which drifted and crashed would become cause of fire and fire spreading route.

Ishinomaki, one of the coastal cities of Miyagi prefecture, had huge damage due to tsunami and also had large fire that spread widely. As for the investigation soon after the earthquake disaster, the joint survey team could not find any information about the initiation of the fire; however, the team identified the range of fire spread.

Photo 8.2-1 shows a fire scene of an elementary school building located at about 1 km from the coast. Almost all of the 3-story school building had been burnt by the flame flared up from cars, combustible debris and oil and so forth that drifted and accumulated by tsunami in the schoolyard in front of the building.

Building at a port was one of the most damaged buildings by tsunami with not only tidal wave but also debris, cars and ships and so forth drifted by tsunami (Photo 8.2-2 and 8.2-3). Several hundred automobiles which have been parked in a parking zone, being drifted to a port warehouse by the tsunami, caused fire at the place where it accumulated.

The cause of the fire is unclear, but it is assumed that the car collided severely each other, the gasoline tank of the cars were damaged, and sparked by malfunction of the electrical system by the seawater. There was no spread of fire in the interior of the building, only the external wall has been damaged by fire.

Photo 8.2-4 shows the fire at a coastal village after several hours of tsunami invasion. The fire continued for

Photo 8.2-2 Tsunami fire at a port warehouse (Sendai city, Miyagi prefecture)

Photo 8.2-3 Vehicle fire due to tsunami at a parking lot (Iwanuma city, Miyagi prefecture)

Photo 8.2-4 Fire at a site of 8 buildings due to tsunami (Noda-village, Iwate prefecture), Courtesy of Noda-village

over 12 hours. Firefighters could not access to the site because the road had been destroyed by the tsunami.

8.3 Damage by Fire due to Earthquake Motion

Concerning the fires reported in the municipalities which did not have the damage of tsunami, the feature of fire occurrence circumstance as an earthquake fire is shown below.

Major cause of the fire was heat sources contacting surrounding combustibles with the earthquake motion and electric fires at the recovery of power supply from power failure and misuse of the candle which was used for the light in the midst of blackout nights which were also seen as the past cases.

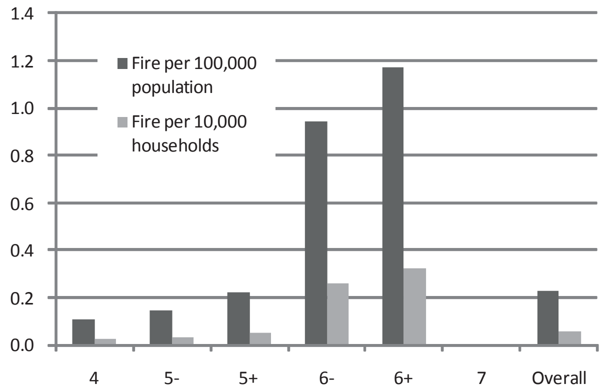


Fig. 8.3-1 Relation between break-out ratio of fire due to earthquake motion and seismic intensity

Table 8.3-1 Number and break-out ratio of fire due to earthquake motion

Seismic intensity	Population	Number of households	Number of fire	Fire per 100,000 population	Fire per 10,000 households
4	11,069,941	4,192,996	12	0.108	0.029
5−	18,835,434	8,219,138	28	0.149	0.034
5+	19,412,542	8,129,497	43	0.222	0.053
6−	2,762,258	985,930	26	0.941	0.264
6+	1,534,864	552,349	18	1.173	0.326
7	74,938	23,441	0	0.000	0.000
Overall	55,881,854	22,905,943	128	0.229	0.056

The relation between seismic intensity and break-out ratio of fire due to earthquake motion is shown in Fig. 8.3-1 and Table 8.3-1. Mass media have reported intensively fire due to tsunami, but many fire cases due to earthquake motion were also identified by this data. Some building fires were presented in the following.

Photo 8.3-1 shows a house fire scene of one victim in an inland rural

Photo 8.3-1 Fire scene of a house (Oushu city, Iwate prefecture)

district. The fire broke out not soon after the mainshock but at 10 pm of the same day. The cause of the fire has not been identified clearly, but, it is thought to be by the spark or hot exhaust gas leaked from the gap of smoke duct of a boiler for heating and bathing, due to earthquake motions.

Photo 8.3-2 shows a factory building fire in which half of the building burned. The cause of the fire is assumed to be ignition by falling of fluorescent light on the ceiling to the floor where the thinner spilled due to earthquake motions by the mainshock.

Photo 8.3-3 shows another house fire case in which two wooden houses were completely burnt out and three houses were partly burnt. The cause of fire is assumed to be misuse of candlelight for lighting in the midst of power failure on the night of the next day of the mainshock.

For a condominium fire, one case has been investigated: the fire broke out when electricity supply has been recovered at the night of the next day of the mainshock. The fire broke out on the 7th floor of a 17-story medium scale condominium. The residents of the room of fire origin were absent at the time, but some neighbors were aware of the fire and informed the fire station. Because of early suppression by firefighters, there was no spread of fire to the upper floor and the next rooms (Photo 8.3-4).

Photo 8.3-2 Fire scene at a factory building (Oushu city, Iwate prefecture)

Photo 8.3-3 Fire scene at a house (Oushu city, Iwate prefecture)

Photo 8.3-4 Fire scene at a condominium (Sendai city, Miyagi prefecture)

References

8.1-1) FDMA, MIC: http://www.fdma.go.jp/bn/higaihou/pdf/jishin/109.pdf (in Japanese, accessed September 1, 2011)

8.1-2) Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster: Report on the Hanshin-Awaji Earthquake Disaster, Building Series Volume 6, Fire Damage and Civil Activities, Damage to Information Systems, AIJ, ISBN: 4-8189-2006-1, pp.51, October, 1998 (in Japanese)

9. Response of Seismically Isolated Buildings

9.1 Outline of Surveyed Buildings

Miyagi prefecture and nearby areas have experienced disastrous earthquakes frequently, thus there are many seismically isolated buildings (hereinafter referred to as SI buildings) constructed in those areas. The Joint Survey Team was dispatched on 1st and 2nd June, 2011 to observe performance of SI buildings during the earthquake and asked persons in charge of the buildings about the damage. In total, 16 SI buildings in Miyagi prefecture and one SI building in Yamagata prefecture were surveyed. Table 9.1-1 shows the list of SI buildings surveyed.

Table 9.1-1 List of SI buildings surveyed on 1st and 2nd June, 2011

	Usage	Year of Construction	Super-Structure Type*1	Super-Structure # of Floors	Isolation Device*2	Existence of Record: Displacement (scratch)	Existence of Record: Acceleration	JMA Seismic Intensity at the nearest observatory
A	Office	2009*3	SRC	9	HRB	○	○	6 lower
B	Warehouse	1996	S	1	HRB	○		6 lower
C	Condominium	2007	RC	14	NRB, LD, USD			6 lower
D	Condominium	2011	RC	12	LRB, USD			6 lower
E	Condominium	2009	RC	15	LRB, ESB	○		6 lower
F	Condominium	2009	RC	10	HRB, ESB			6 lower
G	Hospital	2001	RC	6	LRB, ESB			6 lower
H	Office	1999	RC	18	NRB, ESB	○	○	6 lower
I	Hotel	1998	RC	12	NRB, LD, LSD			6 upper
J	Fire station	2006	S	3	LRB, SB, OD			6 upper
K	Hospital	2002	RC	5	LRB, NRB, OD			6 upper
L	Fire station	2008	RC	3	LRB, ESB, USD	○		6 lower to 6 upper
M	Hospital	2006	S	6	NRB, NRB+USD, USD, ESB	○		5 upper
N	Fire station	2007	RC	3	NRB, ESB, OD	○		5 upper to 6 lower
O	Hospital	2003	RC	4	NRB, LRB, ESB, LSD			6 lower
P	Hospital	2000	RC	10	NRB, LD, LSD		○	4
Q	Hospital	2002	SRC	4	LRB, SB, OD	○		5 upper

*1 SRC: Steel Reinforced Concrete, RC: Reinforced Concrete, S: Steel

*2 NRB: Natural Rubber Bearing, LRB: Lead Rubber Bearing, HRB: High-damping Rubber Bearing, ESB: Elastic Sliding Bearing, SB: Sliding Bearing, LD: Lead Damper, USD: U-Shaped Steel Damper, LSD: Loop-Shaped Steel Damper, OD: Oil Damper (Hereinafter referred to as above abbreviations)

*3 Newly constructed in 1982 and retrofitted by seismic isolation in 2009.

9.2 Behavior of Seismically Isolated Buildings

In this section, 5 SI buildings (A, B, C, L and M in Table 9.1-1) are picked up to describe typical damages and situations under the 2011 Tohoku earthquake (mainly at mainshock).

9.2.1 SI building (A)

(1) Building information

The SI building (A) is a steel reinforced concrete office building with 9-story super-structure and 2-story basement, located in Miyagino ward in Sendai city (Photo 9.2-1). The building was retrofitted by using base isolation technique putting isolation devices on the top of columns in B1F. The floor plan has the 26.4 m × 54 m rectangular shape and 44 HRBs are installed.

(a) Overview of the building (b) Sign board to warn about seismic gap

Photo 9.2-1 SI building (A) – SRC office building –

(2) Building performance during the earthquake

Observation results are summarized as follows:

a) According to the person in charge of the building, no furniture was turned over and no structural damage was observed.
b) However, some damage was observed at the cover-panels of fire protection and the expansion joints near the boundary between isolated and non-isolated floors (Photo 9.2-2). It seems that parts of expansion joints were not well operated due to the large displacement of SI floor during the earthquake.
c) The ground surrounding the building partially subsided around 10 cm.

(a) Damage to the panel (b) Damage to the expansion joint

Photo 9.2-2 Damage near the boundary between isolated and non-isolated floors

(3) Earthquake motion records

Accelerometers were installed in this building at B2F, 1F and 9F (top floor). A scratch board was also installed in B1F to record the displacement of isolation interface. Furthermore, there is an accelerometer installed by JMA in the basement of an adjacent building. The maximum acceleration values of these accelerometers at the mainshock are listed in Table 9.2-1.

Table 9.2-1 Maximum acceleration values

Location	Direction		
	NS [gal]	EW [gal]	Vertical Z [gal]
Basement of adjacent building	409.9	317.9	251.4
B2F (below SI)	289.0	250.8	234.9
1F (above SI)	120.5	143.7	373.7
9F	141.7	169.9	523.9

From the trace on the scratch board installed on the SI floor (Photo 9.2-3), the maximum displacement was estimated as around 18 cm at the mainshock on 11 March, 2011 and around 10 cm at an aftershock on 7 April, 2011 (Photo 9.2-4).

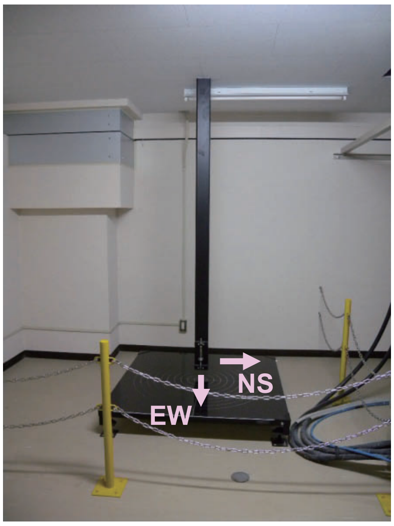
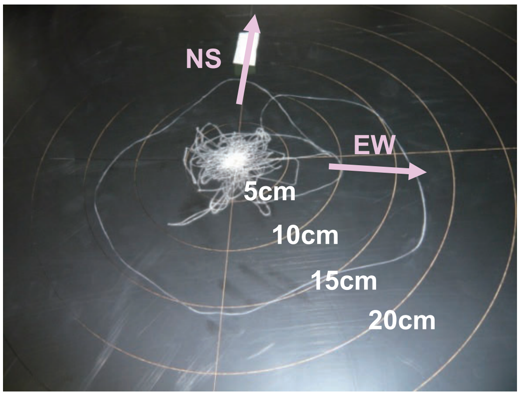
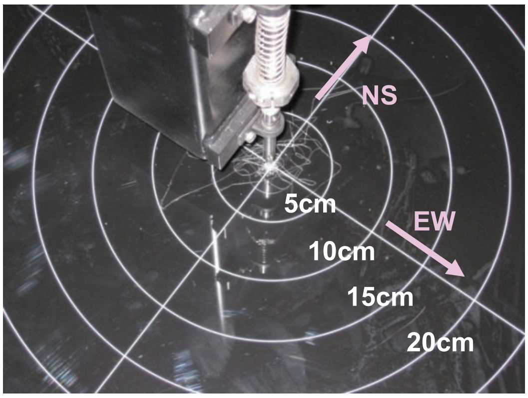


Photo 9.2-3 Scratch board installed on the SI floor





(a) Trace at the mainshock on 11 Mar. (b) Trace at an aftershock on 7 Apr.

Photo 9.2-4 Trace of displacement of SI floor during earthquake

9.2.2 SI building (B)

(1) Building information

The SI building (B) is a one-story steel warehouse constructed in 1996, located in Miyagino ward in Sendai city (Photo 9.2-5). The building height is 30 m. There are 20 HRBs with diameter 850 mm and 4 HRBs with diameter 800 mm arranged in the basement with 51.6 m × 31.7 m rectangular shape.

Photo 9.2-5 SI building (B) – Steel warehouse -

(2) Building performance during the earthquake

Since the building is located near the Sendai-Shiogama bay, tsunami reached the building and the SI floor was submerged under water. The building also suffered the damage to outer walls by the collision of floating debris (Photo 9.2-6). Observation results are summarized as follows:

a) According to the person in charge of the building, other warehouses nearby had trouble of cargo-shift or collapse of stuff by the earthquake. On the contrary, this SI warehouse had no such trouble at all. Since this warehouse is a freezer, tsunami water entered in the freezer space was frozen. It took 16 days to remove the water from the SI floor.

b) Tsunami height was estimated around 4.0 m from the trace of water on the wall (Photo 9.2-7) and damage situation of surrounding buildings (Photo 9.2-8). There was no information about the direction and impact force of tsunami.

c) The ground was excavated in northeast corner of the building around 1.0 m depth, probably because of the water flow from the building at the moment of tsunami (Photo 9.2-9).

d) From visual inspection, there was no harmful scratch or inflation of the rubber of HRB, however, severe rust was observed at the steel plates and bolts (Photo 9.2-10).

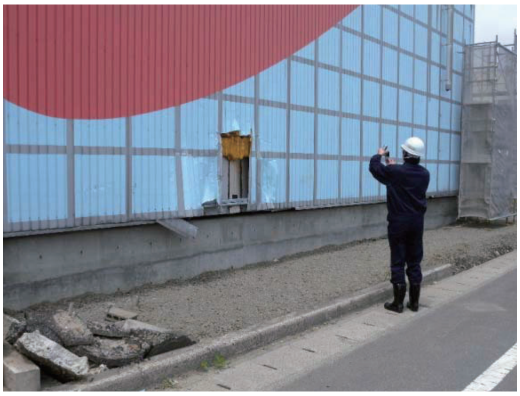


Photo 9.2-6 Damage due to debris

Photo 9.2-7 Trace of tsunami water

Photo 9.2-8 Tsunami damage to surrounding buildings

Photo 9.2-9 Excavation of ground

Photo 9.2-10 Rust of High-damping rubber bearing

(3) Earthquake motion records

From the trace on the scratch board in the SI floor, the maximum displacement was estimated as around 21 cm at the mainshock (Photo 9.2-11).

Photo 9.2-11 Trace of displacement of the SI floor on the scratch board

9.2.3 SI building (C)

(1) Building information

The SI building (C) is a 14-story reinforced concrete building used for condominium, located in Miyagino ward in Sendai city (Photo 9.2-12). The building has U-shaped plan and corners of the building are separated by expansion joints. There are 24 NRBs, 8 LDs and 13 USDs installed in the SI floor.

(a) Overview of the building (b) Sign board to warn about seismic gap

Photo 9.2-12 SI building (C) – RC condominium building –

(2) Building performance during the earthquake

Observation results are summarized as follows:

a) According to the person in charge of the building, no furniture was turned over and no structural damage was observed inside of rooms. However, the damage to the expansion joint was observed.
b) Drop of the ceramic tiles on outer wall (Photo 9.2-13) and shear crack on the wall in

the first floor parking space (Photo 9.2-14) were observed. The subsidence of ground around 10 cm was observed around the building.

c) No damage was found to RBs by visual inspection (Photo 9.2-15), however, paint of USDs was peeled off (Photo 9.2-16) and many cracks were found on LDs (Photo 9.2-17).

Photo 9.2-13 Drop of ceramic tiles

Photo 9.2-14 Shear crack on the wall

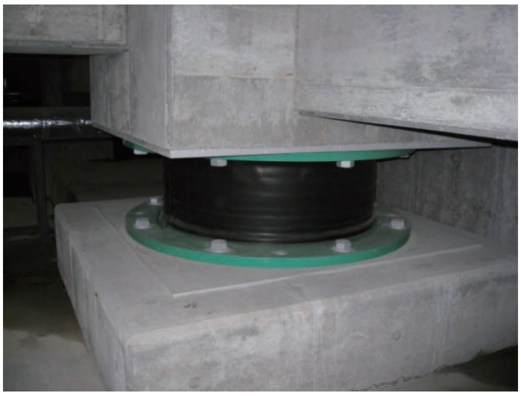


Photo 9.2-15 Natural rubber bearing

Photo 9.2-16 U-shaped steel damper

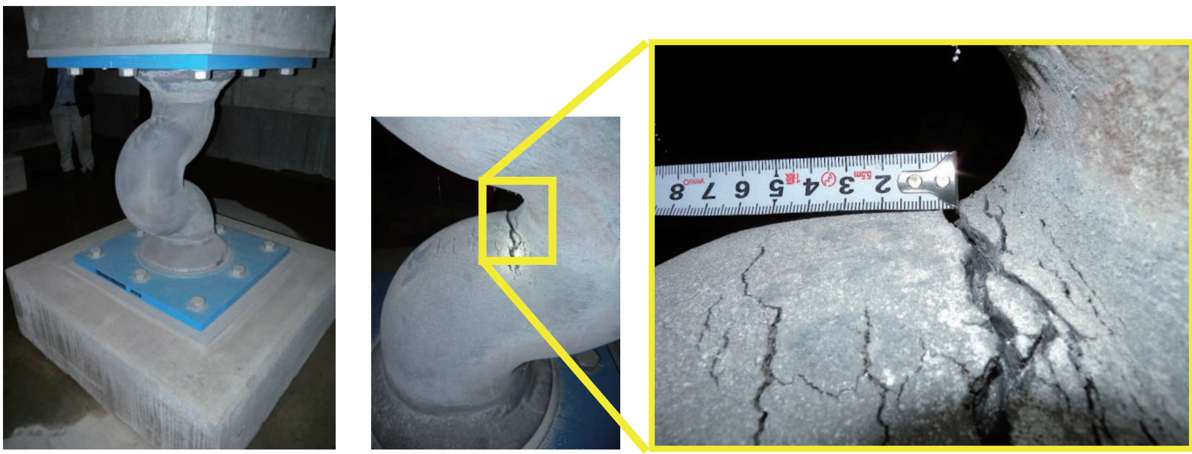


Photo 9.2-17 Lead damper and cracks on the surface

9.2.4 SI building (L)

(1) Building information

The SI building (L) is a 3-story reinforced concrete building used for fire station, located in Tome city (Photo 9.2-18). The following SI devices are installed in the basement with L-shaped plan; 61 m in the east-west direction and 58 m in the north-south direction:

- 34 LRBs (6 with diameter 650 mm and 28 with diameter 700 mm)
- 11 ESBs (6 with diameter 500 mm and 5 with diameter 600 mm)
- 8 USDs

(a) Overview of the building

(b) Sign board to warn about seismic gap

Photo 9.2-18 SI building (L) – RC fire station building –

(2) Building performance during the earthquake

Observation results are summarized as follows:

a) According to the person in charge of the building, no furniture was turned over and no structural damage was observed.

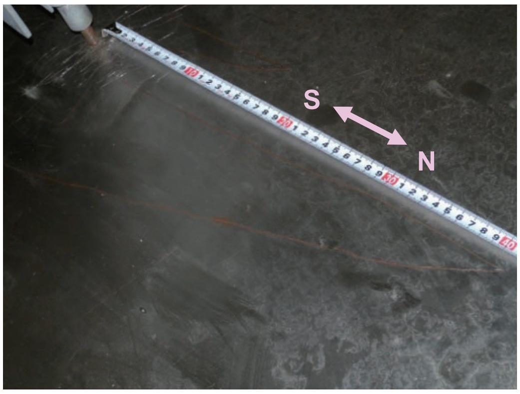
b) Because of the movement of the SI floor during the earthquake, the bolts of steel dampers became loose and the paint on the dampers was peeled off widely. Furthermore, a large amount of residual deformation of steel was remained (Photo 9.2-19).

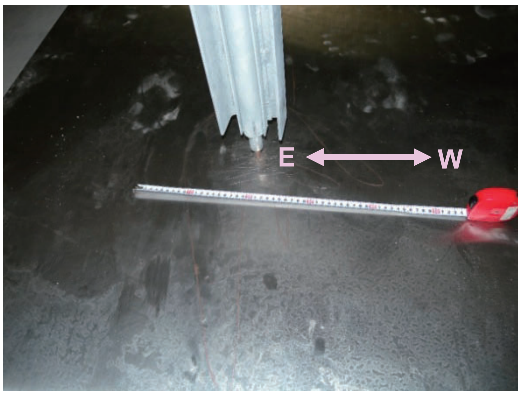
(3) Earthquake motion records

According to the scratch board in the SI floor, the maximum displacement was estimated as around 40 cm northward (Photo 9.2-20). The displacement was also confirmed from the trace of scratch found at the expansion joint outside of the building.

(a) Peeling off of paint (2) Deformation of steel

Photo 9.2-19 Deformation of U-shaped steel damper





(a) Around 40 cm northward (b) Around 15 cm eastward and 22 cm westward

Photo 9.2-20 Trace of displacement of the SI floor on the scratch board

9.2.5 SI building (M)

(1) Building information

The SI building (M) is a 6-story steel building with one story basement used for hospital, located in Ishinomaki city (Photo 9.2-21). Lower part of the building up to second story has the 100 m × 100 m square plan and higher part has 100 m × 25 m plan. The following SI devices are installed in the basement:

- 6 NRBs with diameter 1000 mm
- 16 NRBs with diameter 1000 mm with USD
- 74 ESBs (30 with 400 mm diameter, 25 with 600 mm diameter, 11 with 800 mm diameter and 8 with 900 mm diameter)

(2) Building performance during the earthquake

Observation results are summarized as follows:

a) According to the person in charge of the building, up-down shaking happened together with horizontal shaking during the earthquake. On the 6th floor, contents inside of the rooms such as refrigerators and shelves were moved or turned over, and the fire protection steel door moved to open and hit against the ceiling by vertical shaking causing the damage to the lamp covers. Above the 4th floor, PC monitors were turned over.

b) In the penthouse, anti-vibration rubber of a power generator was moved and the bottom part of a water tank was broken.

c) Because of the movement of the SI floor during the earthquake, the bolts of the steel dampers became loose and the paint on the dampers was peeled off (Photo 9.2-22).

d) The ground around the building subsided around 20 cm.

(a) Overview of the building (b) Sign board to warn about seismic gap

Photo 9.2-21 SI building (M) – Steel hospital building –

(3) Earthquake motion records

From the trace on the scratch board in the SI floor, the maximum displacement was estimated as around 25 cm westward (Photo 9.2-23). The displacement was also confirmed from the trace of displacement of the ESB (Photo 9.2-24).

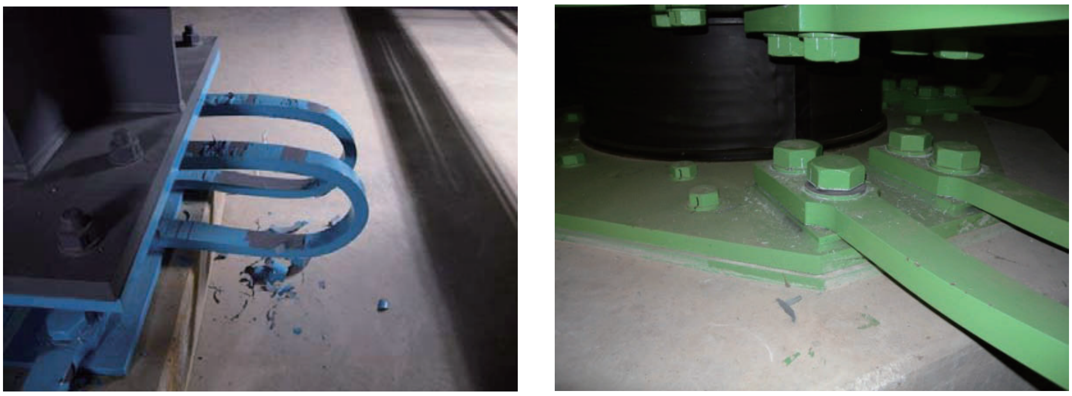


Photo 9.2-22 Peeling off of paint and loose of the bolts of U-shaped steel dampers

Photo 9.2-23 Trace of displacement of the SI floor on the scratch board

Photo 9.2-24 Trace of displacement of elastic sliding bearing

9.3 Results of Survey

Investigation results of 16 SI buildings in Miyagi prefecture and one SI building in Yamagata prefecture are summarized as follows:

a) Super-structures of the SI buildings suffered almost no damage even under strong shaking with JMA intensity 6 upper. It verifies the performance of the SI buildings.

b) There are 8 buildings with scratch boards to measure displacement of the SI floor.

In most cases, the maximum displacement has been estimated as around 20 cm. There was one case with the maximum displacement estimated over 40 cm.

c) In some buildings, damage was observed at the expansion joints. It seems that parts of expansion joints were not well operated due to the large displacement of the SI floor during the earthquake.
d) Subsidence of ground around the building was observed in some buildings.
e) Many cracks were found in lead dampers. A number of cracks might be increased by aftershocks.
f) Peeling off of paint was observed widely for U-shaped steel dampers. In some cases, residual deformation of steel remained.

10. Concluding Remarks

Although more than five months have passed after the earthquake occurred, approximately 90,000 evacuees still live in difficulties and whole damage of the disaster cannot be captured. These facts make us realize that the disaster was unprecedented huge one. It was also the first experience for us that the investigation areas needed to be limited considering the influence of the accident in the Fukushima-dai-ichi nuclear power plant and that we had to be concerned with the safety of staff members against frequent aftershocks including large ones.

This report summarized the survey results described in our quick report already published in Japanese with some additional survey results on the seismically isolated buildings. The outline of each chapter is as follows;

The first chapter forms “Introduction” to briefly figure how NILIM and BRI cooperated to prepare the system (The Joint Survey Team on building damage) in order to respond to the support requests of affected areas and how the team conducted various surveys and researches after occurrence of the earthquake.

The second chapter titled "Outline of Research and Field Survey" describes the outline of the researches and field surveys and the names of the staff members who were in charge of the works.

The third chapter titled as “Overview of Damage” reviews outline of the 2011 Tohoku earthquake, applied situation of enforcement of the laws related to disaster management, data on human and physical damage and situation of provision of temporary houses etc. mainly based on the officially announced data as of April 20 when this report was summarized (if new data becomes available, this report uses updated data indicating new date).

The fourth chapter, “Outline of Earthquake and Tsunami”, provides research results on earthquake source, models of tsunami source and maximum height of tsunami and so on.

The fifth chapter describes “Earthquake Motion Observation and Results” that includes characteristics of earthquake records from BRI strong motion observation network etc. It is noteworthy that the data of above-mentioned BRI earthquake data was referred globally as the first seismic data of the earthquake, since the data network system of the National Research Institute for Earth Science and Disaster Prevention (NIED) that was usually one of the first data resource from earthquake did not work well because damage to network facilities had occurred immediately after the earthquake.

The sixth chapter titled “Damage to Buildings by Earthquake Motions” summarizes the policy of the investigation and the results of damage surveys on wood, steel frame, and reinforced concrete structures, residential land, foundation and non-structural elements. The results are summarized as follows.

1) Wood houses: The damage of upper structure was observed in several areas however the damage to wood houses seemed not so heavy as an impression in Kurihara city where seismic intensity 7 was recorded. Many damage of structure were observed due to deformation of developed residential land in Sendai city, Miyagi prefecture and Yaita city, Tochigi prefecture. The damage to roof tiles could be more observed in both Fukushima and Ibaraki prefectures than in Miyagi prefecture where major earthquakes frequently occurred since the 1978 Miyagi-ken-oki Earthquake. The damage types are similar to those of the past earthquakes.

2) Steel frame structures: There was almost no damage to main steel structure members such as columns and beams. Damage of vertical braces’ rupture etc. was observed in the school gymnasium that was constructed in the years of old seismic code (before 1981) however the damage ratio was smaller than the case of the 2004 Niigata-ken Chuetsu Earthquake. On the other hand, damage to non-structural elements including falling of ceilings was observed comparatively more than the past cases.

3) Reinforced concrete structures: Most of structural damage to reinforced concrete structure was observed in the buildings designed with the previous seismic code. The number of damaged reinforced concrete buildings was not so large as considered with the seismic intensity observed nearby. The damage types were mostly similar to the past seismic damages that included severe damage such as loss of axial force bearing capacity due to shear failure of columns.

4) Residential land, Foundation: Liquefaction occurred in so wide areas that could not be seen during the past earthquakes in Japan. Research on the mechanism and considerations of counter-measures will be necessary not only for individual buildings but also for infrastructure like roadway structures, water supply and sewage systems. In some residential lands, heavy damage such as ground failure was observed similar to the damaging earthquakes in the past.

5) Damage to non-structural elements of buildings of comparatively old construction types was confirmed in many cases. In addition, break and falling of non-structural elements at rather higher parts were also confirmed.

The seventh chapter describes “Damage to Buildings in Inundation Areas Induced by Tsunami” that includes research on the existing guidelines regarding the building design methodologies against tsunami. This chapter introduces conducted surveys on remaining, collapsed or washed away buildings in the major tsunami affected areas from the north in Yamada town, Iwate prefecture to the south in Yamamoto town, Miyagi prefecture. The surveys included measuring damage of buildings, depth of tsunami and structural element data for calculating horizontal load bearing capacity and other values. After verification of existing guidelines, a proposal was prepared in order to make the guidelines more rationalized ones.

The eighth chapter on “Damage of Buildings, etc. due to Fire” summarizes results of field surveys on fires in tsunami affected areas and shake-induced fires in other areas and clarifies the features of damage. The result shows that many usual type of fires due to earthquake happened even though fires in tsunami affected areas were noticed and reported more.

The ninth chapter summarizes “Response of Seismically Isolated Building” including outline of surveyed buildings and the behavior of seismically isolated buildings.

The damage surveys in this report were conducted as carefully as possible, using around 200 person-days (130 persons). However, whole damage of the earthquake may not be covered, considering the damage of wide areas. Further surveys will be continuously carried out.

Recovery and rehabilitation of the affected areas have advanced slowly but steadily, while the introduction (Section 1) of this report says that whole damage cannot be grasped yet. The government set up the Reconstruction Design Council on April 11, which submitted its report of recommendation in June, 2011. The MLIT also established various working committees. In the field of buildings, the Building Structural Code Committee (chaired by Prof. Tetsuo Kubo, the University of Tokyo) that aims to review draft structural code of buildings in the NILIM, is analyzing the damages and promote related technical reviews and so on in cooperation with BRI in order to secure the safety of buildings based on damages caused by the 2011 Tohoku earthquake.

NILIM and BRI would like to contribute to the society through this report and the advanced technical knowledge. It will be very much appreciated if related organizations and individuals will cooperate with us continuously in the future.

Lastly, NILIM and BRI would express deepest condolence to the victims of the tsunami and earthquake and their family members as well as sufferers affected 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.

Note 1: A comment via e-mail sent from U.S.A. dated on March 17,
“I learned that the NIED servers were out, so the shaking must have been pretty bad. I was able to see the BRI ground motions and some reports on buildings. Very good and quick work”

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