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Damage statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage)

Motoki Kazama[a], Toshihiro Noda[b,*]

[a]Department of Civil and Environmental Engineering, Tohoku University, Japan
[b]Disaster Mitigation Research Center, Nagoya University, Japan

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Abstract

The 2011 off the Pacific Coast of Tohoku Earthquake, which occurred on March 11, 2011, caused enormous damage, particularly to the strip of land along the Pacific Ocean from the Tohoku Region to the Kanto Region, due to seismic motion and the tsunami it triggered. This report presents an outline of the earthquake and summarizes the associated seismic damage to social infrastructure facilities.

Keywords: The 2011 off the Pacific Coast of Tohoku Earthquake; Damage statistics; Summary of the earthquake; Social infrastructure facilities; Tsunami

1. Introduction

Summary of the Earthquake (Japan Meteorological Agency (JMA), 2011) At 14:46 JST (05:46 UTC) on March 11, 2011, a moment magnitude (M) 9.0 earthquake occurred with an epicenter off the coast of Sanriku. This was the strongest earthquake experienced by Japan since the country began taking measurements, and the JMA named it "The 2011 off the Pacific Coast of Tohoku Earthquake." The disaster caused by this earthquake was given the name the "Great East Japan Earthquake Disaster" by Cabinet decision.

According to JMA, the epicenter of the earthquake was 130 km east-southeast of the Oshika Peninsula at 38° 06.2' north latitude and 142° 51.6' east longitude and at a depth of 24 km. It was a large ocean-type reverse fault earthquake occurring at a plate boundary with a west-northwest to east-southeast compression axis.

The epicentral location of the main earthquake, and that of the larger aftershocks (moment magnitude of M 6), are shown in Fig. 1. The largest aftershock occurred on the same day at 15:15 off the coast of Ibaraki Prefecture. On March 9, two days prior to the main earthquake, an M 7.3 earthquake, which should be regarded as a foreshock, occurred off the coast of Sanriku; this is also shown in the figure. The aftershock activity of this earthquake was extremely vigorous, namely, in the three months between March 11 and June 11, there were five aftershocks that were M 7.0 or higher, 82 aftershocks that were M 6.0 or higher, and 506 aftershocks that were M 5.0 or higher.

In addition, tsunamis associated with the earthquake were measured over a wide area, from Hokkaido to Okinawa, mainly along the Pacific side of the Tohoku Region and the northern part of the Kanto Region, as shown in Fig. 2 (The 2011 Tohoku Earthquake Tsunami

*Corresponding author.
E-mail address: noda@civil.nagoya-u.ac.jp (T. Noda).
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Joint Survey Group, 2011). Very high tsunamis were measured at Soma in Fukushima Prefecture, of 9.3 m or higher, and at Ayukawa in Ishinomaki City, Miyagi Prefecture, of 8.6 m or higher (Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2011a).

Ground settlement due to crustal movement also occurred over a wide area (Geospatial Geospatial Information Authority of Japan (2011)). At the electronic control point in Onagawa, extremely large crustal movement was measured, namely, about 5.3 m in the horizontal direction and about 1.2 m in the vertical direction. GSI has installed electronic control points at about 20-km intervals in 1240 locations throughout the country for continuous observation using GPS satellites. It was found that after the main shock, gentle crustal movements, that were small compared with those of the main shock, continued to occur (see Fig. 3).

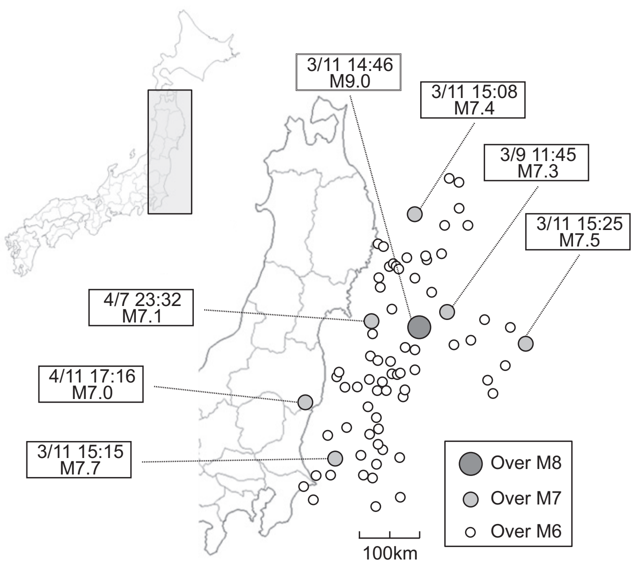

Fig. 1. Main earthquake and foreshock/aftershocks M6 and higher (from a document published by Japan Meteorological Agency (JMA), 2011).

2. Summary of the damage

2.1. Statistics concerning human casualties and damaged houses

According to an announcement by the National Police Agency (NPA) (2011), as of September 11, six months after the earthquake, 15,782 people had died as a result of the earthquake (including the tsunami and aftershocks), and 4086 people were still missing. The breakdown, according to prefectures, shows that almost all of these people were in Iwate, Miyagi, and Fukushima Prefectures, as can be seen in Fig. 4. In the Kanto Region, the number of deaths (persons missing) was in the double digits in Ibaraki and Chiba Prefectures, namely, 24 (1) and 20 (2), respectively. More than 60% of the dead and missing persons were aged 60 years or older; many firefighters and police were also among the victims.

As of September 11, six months after the earthquake, the number of houses considered to have been totally destroyed or half destroyed were 128,530 and 240,332, respectively. As can be seen in Fig. 5, the number of houses thought to have been totally destroyed in Miyagi Prefecture is conspicuously high in the breakdown according to prefectures.

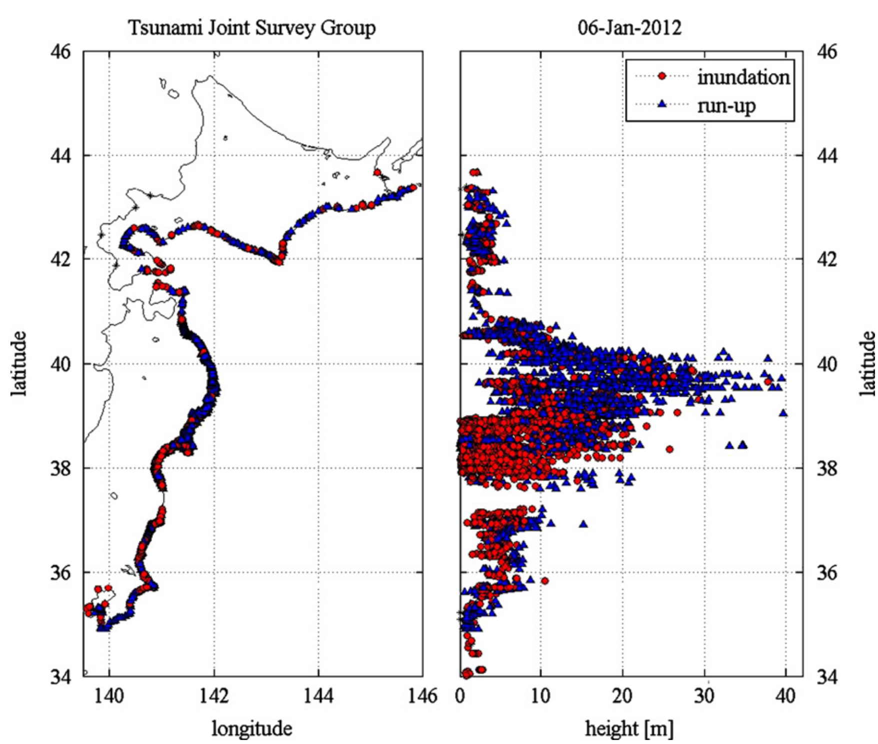

Fig. 2. Measured values of the tsunami inundation and run-up (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011).

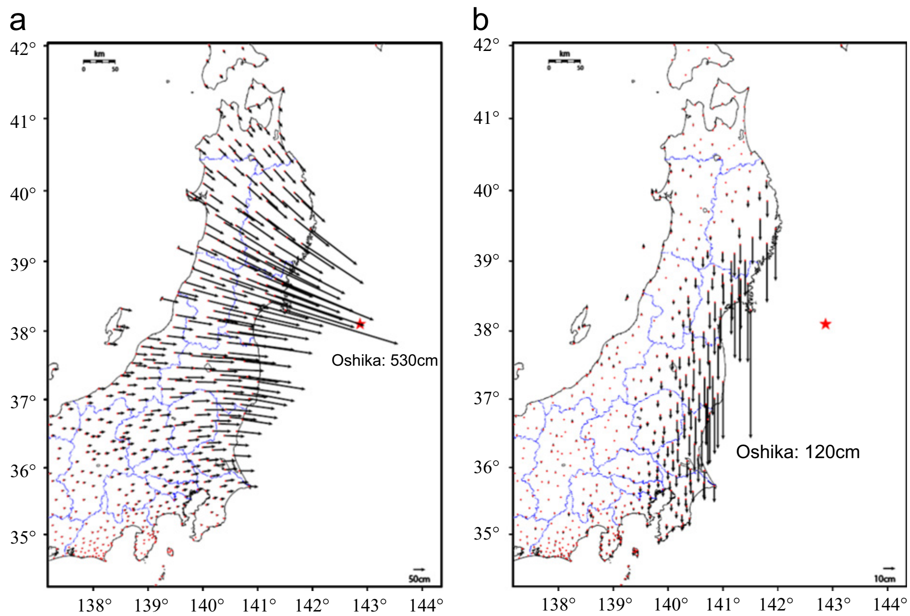

Fig. 3. Tectonic deformation by the main earthquake (from a document published by GSI(2011)). (a) Horizontal displacement. (b) Vertical displacement.

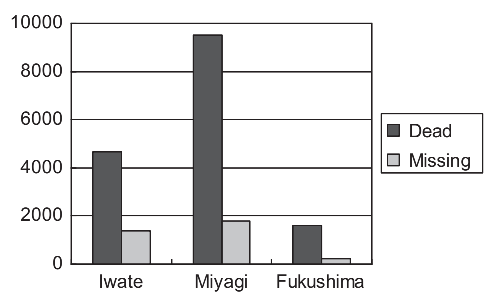

Fig. 4. Human casualties (from a document published by National Police Agency (NPA) (2011)).

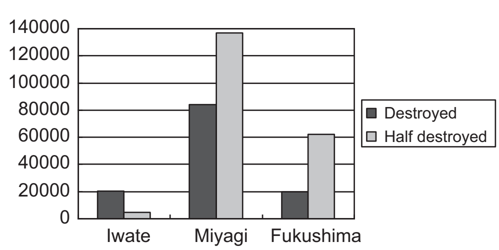

Fig. 5. Number of damaged houses (from a document published by National Police Agency (NPA) (2011)).

The damage to private housing is broadly divided into houses along the coast that were washed away by the tsunami and houses along the coast and inland that were damaged by seismic motion. In the former case, there were many places where whole areas were destroyed. In the latter case, there were many cases of damage due to foundation deformation in residential land formed in hilly areas and damage due to liquefaction on old river courses and reclaimed land in the Kanto Region. The damage due to seismic motion alone was relatively small, in spite of the large magnitude of the earthquake. This is considered to be because the periodic properties of the seismic motion did not directly result in damage to buildings despite the large magnitude of the earthquake.

3. Estimated cost of the damage

An overall perspective of the earthquake damage has still not been sufficiently produced, but Table 1 shows the amounts estimated by the Cabinet Office (2011) of Japan as of June 24. The range in estimates in the middle column of the table arose from the estimated rates of damage to buildings assuming about twice as much damage in the tsunami-afflicted areas as that in the Great Hanshin-Awaji Earthquake Disaster or a substantially larger amount.

3.1. Damage to social infrastructure facilities

3.1.1. Road facilities (MLIT, 2011a)

The tsunami caused damage to road facilities, particularly to National Route 45, which connects the Pacific coastal part of the Tohoku Region running north-south . Since the main north-south route along the coast was closed, MLIT's Tohoku Regional Development Bureau (2011b) adopted a road-opening strategy that was referred to as the "teeth of a comb strategy." The strategy was to first open the inland National Route 4, along the backbone of the Tohoku Region, and then to secure road transport to the disaster-stricken areas along the coast, like the teeth of a comb (see Fig. 6).

Figs. 7 and 8 show the damaged parts of the road facilities on National Route 45 and National Routes 4 and 6, respectively. The main forms of damage were the erosion of embankments at bridges ((1) Namiita Bridge: Otsuchicho, Iwate Prefecture), road embankments washed away by the tsunami ((2) Kamaishi City, Iwate Prefecture), bridge decks washed away ((3) pedestrian bridge over a

Table 1
Comparison of estimates of damage (Cabinet Office, 2011).

		Great East Japan earthquake disaster (Cabinet office, disaster management)	Great East Japan earthquake disaster (Cabinet office, economic analysis)	Great Hanshin-Awaji earthquake disaster (MLIT)
Buildings, etc. (housing, residential land, shops, offices, factories, machinery, etc.)		About ¥10.4 trillion	About ¥11–20 trillion (due to the difference in estimated rates of damage to buildings)	About ¥6.3 trillion
Lifeline facilities (water supply, gas, electricity, communications, broadcasting facilities)		About ¥1.3 trillion	About ¥1 trillion	About ¥0.6 trillion
Social infrastructure facilities (rivers, roads, ports, sewage works, airports, etc.)		About ¥2.2 trillion	About ¥2 trillion	About ¥2.2 trillion
Others	Agriculture, forestry, and fisheries production	About ¥1.9 trillion	About ¥2 trillion	About ¥0.5 trillion
	Others	About ¥1.1 trillion		
Total		About ¥16.9 trillion	About ¥16–25 trillion	About ¥9.6 trillion

Note: Classification of stock uses estimates of the Cabinet Office (Disaster Management Section).

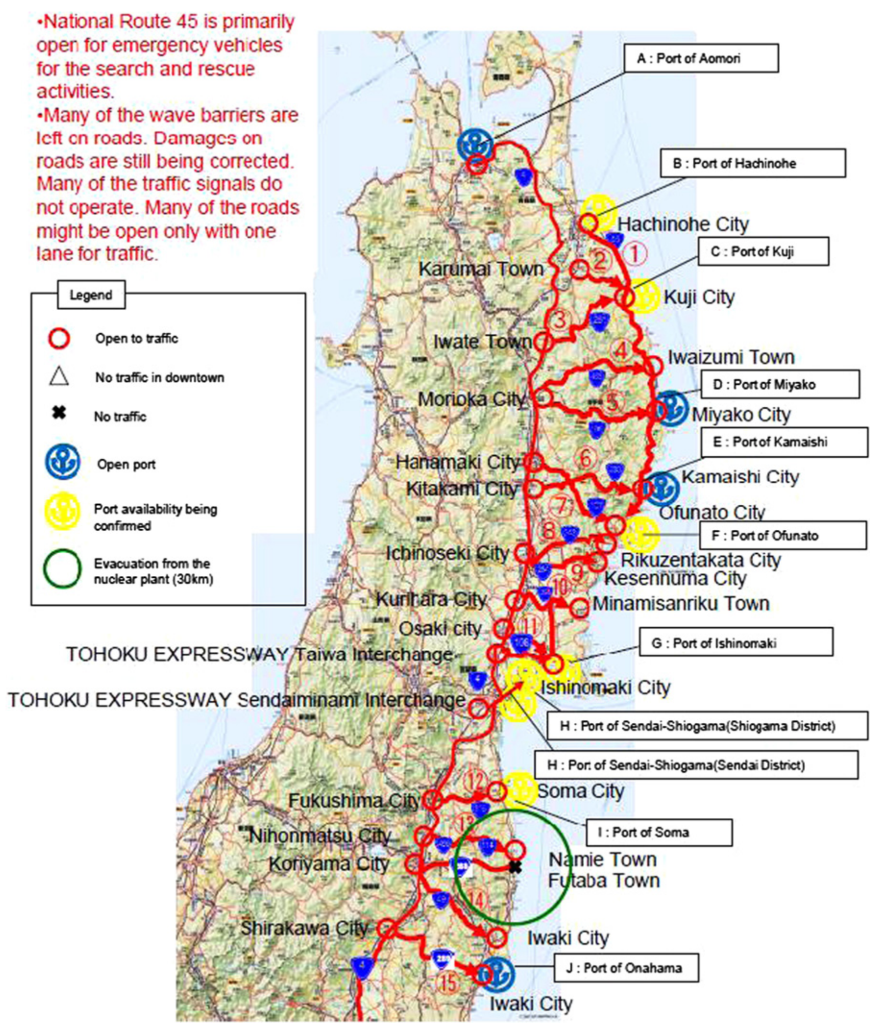

Fig. 6. "Operation COMB" used for opening roads(status of roads open as of 18th March) (MLIT, 2011b).

railway in Numata, (4) Kawahara River bridge, (5) Kesen Ohashi ((3)–(5) in Rikuzen-Takada, Iwate Prefecture), (6) Koizumi Ohashi, (7) Sodeogawa Bridge, (8) Nijuichihama Bridge ((6)–(7) in Kesennuma City, Miyagi Prefecture), (9) Utatsu Ohashi, and (10) Mizushiri Bridge ((9)–(10) in Minamisanrikucho, Miyagi Prefecture)), the collapse of slope surfaces ((11) Ishinomaki City, Miyagi Prefecture), the collapse of road embankments and slopes ((12) Ishinomaki City,

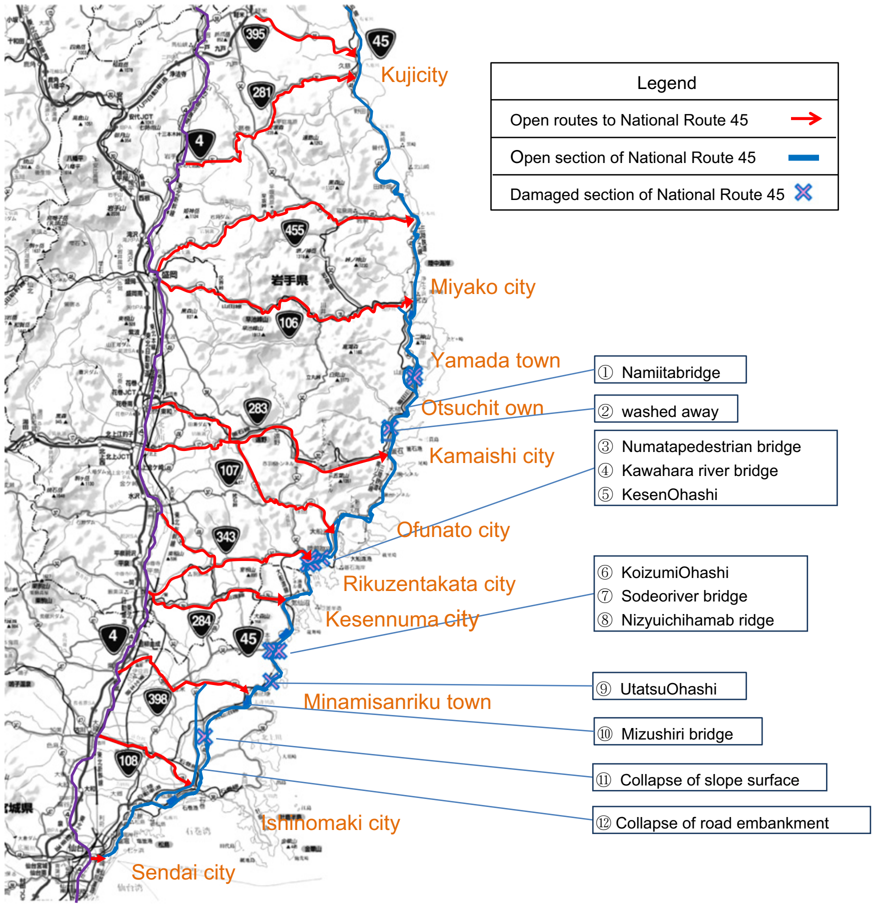

Fig. 7. Damage to National Route 45 (MLIT Tohoku Regional Development Bureau, 2011b).

Miyagi Prefecture, (13) Fukushima City, Fukushima Prefecture, and (14) Hirono Town, Fukushima Prefecture), etc.

On the other hand, damage was caused to a total of 20 stretches of expressways with a total length 870 km (East Nippon Expressway Company Limited, 2011). The main damage includes the collapse of main roads and road surfaces at two locations, the large-scale cracking of main roads at 13 locations, the subsidence of the road surface at 23 locations (maximum depth of 30 cm), the difference in road surface levels of 2 cm or more at 174 locations, the damage to bridge bearings, five bearings on three bridges, the damage to bridge joints at 56 locations on 46 bridges, interchange damage, and so on. There was no major damage to bridges or tunnel structures, so by March 24, emergency repairs were completed for about 813 km of the above damaged stretches (about 93%). (Restoration of the approximately 10-km section between Sendai Wakabayashi JCT on Sendai Tobu Road and the Sendai Port North IC and the approximately 4-km section from Sanriku Jidoshado Sendai Port IC to Rifu JCT were completed by March 30.) In addition, as a result of a slope collapse caused by an earthquake that occurred at 17:16 on April 11, 2011, with an epicenter near Hama Dori in Fukushima Prefecture, the Joban Expressway again became impassable between Iwaki Nakoso IC and Iwaki Yumoto IC (emergency repairs were completed on April 14).

3.1.2. River levees and coastal facilities (MLIT Tohoku Regional Development Bureau, 2011a; MLIT Kanto Regional Development Bureau, 2011; Japan Institute of Construction Engineering, 2011).

Of the 12 water drainage systems managed by the Tohoku Regional Development Bureau, 1195 locations among five water drainage systems and along nine rivers were damaged on the Pacific Ocean side. Emergency construction was carried out to restore 29 of these locations for which the scale of the damage was particularly large, and by July 11, all the emergency construction was complete. On the other hand, ten rivers in four water drainage systems managed by the Kanto Regional Development Bureau were damaged. The damaged locations increased with the occurrence of aftershocks, and 939 locations had been damaged as of July 31. Of these, emergency construction was carried out to restore 24 locations for which the damage was particularly large, and by June 2, emergency construction at all 24 locations was complete (see Table 2).

The causes of the damage in almost all cases were the tsunami at the mouths of the rivers and liquefaction in the inland areas. Fig. 9 shows the positions of the major damage along the Kitakami River drainage system and the Naruse River drainage system in the Tohoku Region. Also, almost all the damage in the Kanto Region was

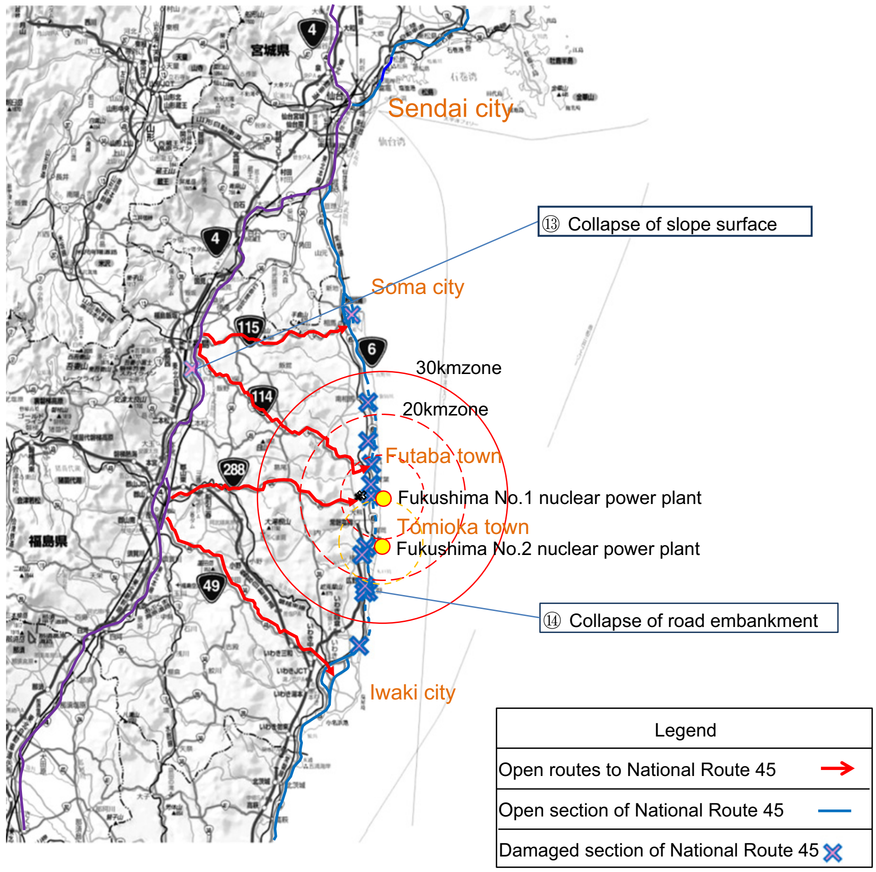

Fig. 8. Damage to National Route 4 and 6 (MLIT Tohoku Regional Development Bureau, 2011b).

Table 2
Locations of emergency restoration of river levees under direct management. (MLIT Tohoku Regional Development Bureau, 2011b, MLIT Kanto Regional Development Bureau, 2011).

Water drainage system name	No. of locations
Abukuma River	6 (Miyagi, 5)
Naruse River	9 (Naruse River, 7; Yoshida River, 2)
Kitakami River	14 (Kitakami River, 5; Eai River, 8; Shineai River, 1)
Tohoku Region	29 locations in total
Tone River	16 (Tonegawa downstream, 11; Tonegawa upstream, 1; Edo River, 2; Kokai River, 2)
Naka River	2 (Naka River, 1; Hinuma River, 1)
Kuji River	2
Kasumigaura	4 (Nishiura, 1; Sotonasakaura, 1; Hitachi River, 1; Yokotone River, 1)
Kanto Region	24 Locations in total

caused by liquefaction (see Fig. 10). On the other hand, it was reported that in areas where countermeasures had been taken against liquefaction, there was either no damage or the damage was slight.

Regarding coastal facilities, major damage was caused mainly on the southern coast of Sendai Bay, where almost all sections of the coastal levee were either completely destroyed or half destroyed. As a result, the major damage consisted of the washing away of houses along the coast, the flooding of agricultural land, etc. Therefore, emergency work was carried out to restore about 20 km at seven locations directly managed by the national government. Details of this work are given in Table 3.

3.2. Port facilities

Port structures were subjected to the external forces of the seismic motion and the subsequent tsunami. Whether the cause of the damage was one or the other, or a combination of causes, is not clearly known at present. Generally speaking, breakwaters (including tsunami barriers) were mainly damaged by the tsunami, and quay

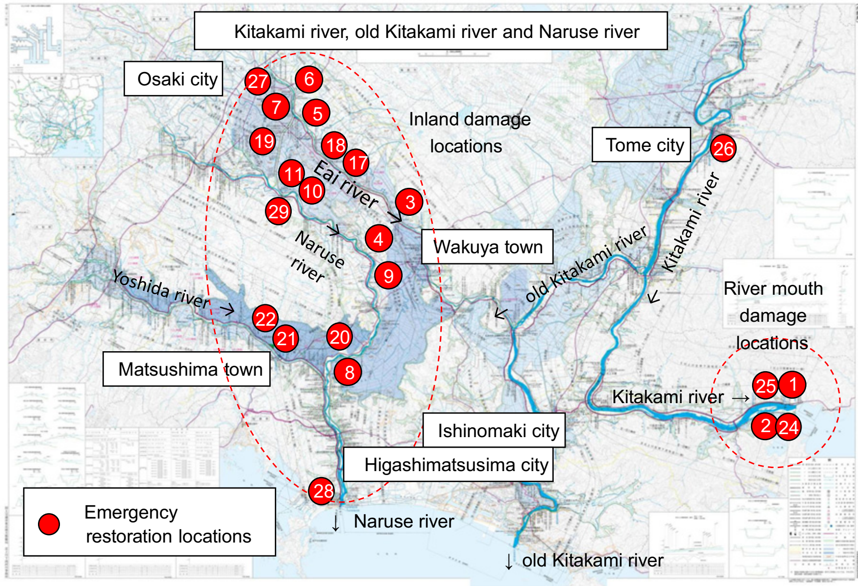

Fig. 9. Major damage locations along the Kitakami and Naruse River drainage systems (MLIT Tohoku Regional Development Bureau, 2011b).

walls were mainly damaged by the seismic motion and liquefaction. Also, the effect of the tsunami on the ports in the northern Tohoku Region was large, and the effect of the earthquake force was large south of Ishinomaki and Sendai Shiogama Ports. Table 4 presents an outline of the damage. In this table, the possible causes of the damage are shown.

Normally, traces of liquefaction on coasts that have been subjected to the effects of a tsunami are wiped out by the tsunami, so traces of sand boils cannot be used as evidence of the occurrence or non-occurrence of liquefaction. However, it is known that liquefaction occurred to a certain extent based on the liquefaction that occurred during the aftershocks, as well as the many photographs and images taken of sand boils caused by liquefaction before the tsunami.

3.3. Railway facilities (JR-EAST)

Various types of damage were caused to the Tohoku Shinkansen (Bullet Train), including the bending, slanting and cracking of electrification columns, the severing of overhead wires, damage to elevated bridge columns, the displacement and damage of tracks, the breakdown of transformer facilities and the falling down, tilting, detaching, etc. of noise barriers. However, as a result of the Urgent Earthquake Detection and Alarm System, no Shinkansen trains operating at high speeds derailed during the earthquake. In the main earthquake, there was damage to electrification columns at about 540 locations. As of April 7, restoration work at about 60 locations remained unfinished; however, the aftershock on April 7 damaged 270 new locations (East Japan Railway Company (JR-EAST), 2011b). Among these locations were locations that had already been restored from previous damage, so a large amount of work had to be done again.

After the Great Hanshin-Awaji Earthquake Disaster, the columns and piers of elevated bridges of the Tohoku Shinkansen were steadily seismically retrofitted, so in this earthquake disaster, there was no catastrophic damage, such as the toppling over or the collapse of elevated bridges, which would have lengthened the restoration period. However, there was a very large number of bent, tilted, or cracked electrification columns, which are ancillary facilities, and because of the large number of damaged facilities, the area's high-speed mass passenger transport was damaged for a long time. The main damage to the Tohoku Shinkansen, as announced by JR-EAST, is shown in Table 5. Also, the main damage to regular train lines that were not affected by the tsunami is shown in Table 6. In addition, there was significant damage to seven local lines that were affected by the tsunami (Hachinohe, Yamada, Ofunato, Kesennuma, Ishinomaki, Senseki, and Joban Lines), and 325 km of these seven lines were damaged (JR-EAST, 2011d). The economic effect of the disaster, as announced by JR-EAST Japan, amounted to an estimated cost of ¥67 billion, excluding the lines damaged by the tsunami (JR-EAST, 2011a).

3.3.1. Communication facilities (Oka, 2011)

Tables 7 and 8 show the scale and the cost of communication-related damage announced by NTT East. The damage to communication facilities from this earthquake is classified as follows:

1) Suspension of service due to damage to or depletion of power supply devices.
2) Communication buildings damaged/ flooded/ washed away by the tsunami.

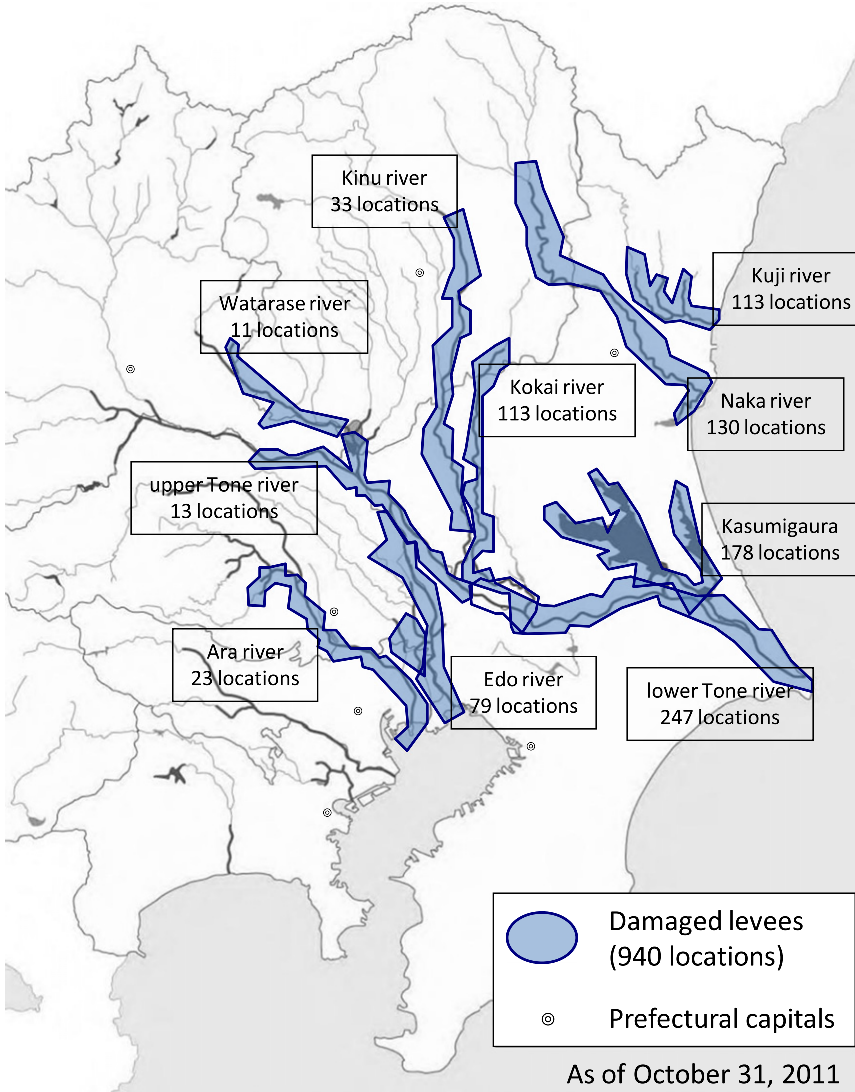

Fig. 10. Locations of damage to river levees in Kanto Region (MLIT Kanto Regional Development Bureau, 2011).

Table 3
Locations of emergency restoration of coastal levees on the south coast of Sendai Bay. (MLIT Tohoku Regional Development Bureau, 2011b).

	No. of locations (length)
Sendai Coast	2 locations (L=2740 m)
Natori Coast	1 location (L=3010 m)
Iwanuma Coast	2 locations (L=6020 m)
Yamamoto Coast	2 locations (L=8200 m)

3) Relay network severed by the tsunami.
4) Overhead cables to customers' homes severed or electricity poles collapsed.

In the Tohoku Region, the effect of the tsunami was large, while in the Kanto Region, liquefaction damage was the main cause of the interruption of service.

3.3.2. Electrical power facilities (Ministry of Economy, Trade and Industry, 2011)

Of the 20 fossil-fired and geothermal power stations of Tohoku Electric Co. Ltd. (TE) that were operating, 12 stopped operating immediately after the earthquake. As a result, the gross capacity (plant capacity) of the fossil-fired and geothermal plants was reduced by 4.926 gigawatts (GW) (about 55%). Of the four fossil-fired power stations on the Pacific Coast (Hachinohe, Sendai, Shin Sendai, and Haramachi), three of the four plants that were operating shut down due to the earthquake, and one shut down due to the tsunami. The damage caused by the earthquake included the shifting of vibration isolators, etc. In addition, the tsunami caused major damage to coal unloaders, and it was reported that this damage also occurred at two of the power stations that were shut down (TE, 2011b). Of the 63 fossil-fired power stations of Tokyo Electric Power Company (TEPCO) that were operating, 13 were shut down

Table 4
Summary of the main damage to port facilities (abstracted and partially summarized from a document from the Committee to Study Technical Measures Against Tsunami and Earthquake Damage in Tohoku Ports).

Port name	Area name	Facility name	Main damage
Hachinohe	Hattaro	North breakwater	Wave-dissipating blocks moved, scouring of mounds in the port, sliding of coverings due to the tsunami
	Outer harbor	Central breakwater, etc.	Collapse due to scouring by the tsunami
		No. 2 port breakwater	Dispersal of covering blocks and split stones caused by the tsunami
Kuji	Hanzaki	Wave break	Sliding and collapse due to the tsunami
	Mizoguchi	Breakwater (north–south)	Scouring due to the flow rate of the tsunami
Miyako	Desaki	Breakwater	Sliding and collapse due to the tsunami
		Shallow draft quay, etc.	Settlement and cracking of aprons due to seismic motions
	Ryujinsaki	Breakwater	Scouring due to the flow rate of the tsunami
	Fujiwara	Breakwater	Collapse due to the flow rate of the tsunami, sliding and collapse of caissons, etc.
		−12 m quay wall, etc.	Settlement and cracking of aprons due to seismic motions
Kamaishi	Harbor mouth	Harbor mouth breakwater	Sliding and collapse of caissons due to the wave power of the tsunami and damage to steel cells due to uplift of the opening caused by the flow rate of the tsunami
Oofunato	Harbor mouth	Breakwater	Sliding and collapse of caissons due to the wave power of the tsunami and damage to steel cells due to uplift of the opening caused by the flow rate of the tsunami
	Nagahama, Nonoda	−13 m quay wall, etc.	Damage to jetties and retaining walls caused by the seismic force and the level differences with hinterland
Onagawa		Tsunami barrier	Sliding and collapse of caissons due to the wave power of the tsunami
Soma	Main port	Sea breakwater	Sliding and collapse of caissons due to the wave power of the tsunami during the drawback
Ishinomaki	Hibarinocho	Central wharf quay wall, etc.	Settlement and cracking of aprons due to seismic motions
Sendaikamaishi	Nakano, Koyo	−12 m quay wall, etc.	Settlement and cracking of aprons and bulging of the normal line due to seismic force
Onahama	5–6 wharf	−14 m quay wall, etc.	Apron pavement damage and crane foundation damage due to seismic force
	Fujiwara wharf	−12 m quay wall	Damage to apron pavement and scour protection due to seismic force
	No. 3 wharf	Quay wall, etc.	Apron pavement damage, crane foundation damage, and bulging of sheet piling due to seismic force
	No. 4 wharf	Quay wall, etc.	Damage to apron pavement and scour protection due to seismic force
	No. 7 wharf	−13 m quay wall, etc.	Sliding of caissons and apron pavement damage due to seismic force
	Otsurugi Wharf	−10 m quay wall, etc.	Damage to apron pavement and scour protection due to seismic force

Table 5
Main damage to the Tohoku Shinkansen (JR-EAST, 2011b).

Main damage	3/11 Main earthquake	4/7 and Subsequent aftershocks
Bending, tilting, and cracking of electrification columns	About 540 locations	About 270 locations
Severed overhead lines	About 470 locations	About 200 locations
Damage to elevated bridge columns, etc.	About 100 locations	About 20 locations
Displacement and damage of tracks	About 20 locations	About 20 locations
Breakdown of transformer facilities	About 10 locations	About 10 locations
Falling down, tilting, detaching, etc. of noise barriers	About 10 locations	2 locations
Damage or falling down of ceiling materials	5 stations	2 stations
Shifting of bridge beams	2 locations	7 locations
Damage to bridge beam supports	About 30 locations	About 10 locations
Track damage within tunnels	2 locations	–
Total	About 1200 locations	About 550 locations

No collapses of elevated bridges, bridges, or tunnels occurred.

Table 6
Main damage to the local line (JR-EAST, 2011c).

Main damage	March 11 main earthquake	April 7 and subsequent aftershocks
Displacement of tracks	About 2200 locations	About 620 locations
Bending, tilting, and cracking of electrification columns	About 1150 locations	About 90 locations
Road bed ballast washed away	About 220 locations	1 location
Platform deformation	About 220 locations	About 50 locations
Deformation of earthwork facilities such as embankments, cuttings, etc.	About 170 locations	About 10 locations
Breakdown of signal communication equipment	About 130 sections	About 10 sections
Damage to elevated bridges	About 120 locations	About 30 locations
Damage to station buildings	About 80 stations	About 20 stations
Tunnel damage	About 30 locations	2 locations
Breakdown of transformer facilities	About 30 locations	About 10 locations
Fallen rocks	About 20 locations	About 20 locations
Damage to facilities where trains stop, such as overhead pedestrian bridges, etc.	About 20 locations	4 locations
Severed overhead lines	About 10 locations	About 10 locations
Total	About 4400 locations	About 850 locations

Excludes damage to the 7 lines affected by the tsunami.

Table 7
Comparison of the scale of damage to NTT East (Oka, 2011).

Item	Great East Japan earthquake disaster	Great Hanshin-Awaji earthquake disaster
Peak traffic	About 9 times normal	About 50 times normal
(Number of mobile phone subscribers)	(About 119.54 million)	(About 4.33 million)
Number of lines with service interruption	About 1.5 million	About 285,000
Time required for restoration	About 50 days	About 2 weeks
Damaged equipment		
Relay transmission routes	About 90 routes	–
Communication buildings	12 totally demolished and 16 flooded	–
Telephone poles	About 65,000	About 3600
Pipe ducts	About 3000 km	About 220 km
Manholes	About 2800 no.	About 2650
Overhead cables	About 6300 km	About 330 km
Underground cables	About 1700 km	About 25 km

Note: Telephone poles and overhead cables: coastal damage only.Time for restoration: excludes nuclear power plant area and evacuation area. Relay transmission routes: excludes nuclear power plant area.

Table 8
Cost of damage to NTT East (NTT East Corporation, 2011).

Loss 2010 and 2011	Emergency restoration, restoration to original condition, cost of personnel and material support, cost of removal of damaged equipment, making the disaster-stricken area free of charge	¥40 billion yen (including a special loss of about ¥20 billion in 2010)
Construction 2011-	Full-fledged Restoration	¥40 billion
	Restoration for improvement of reliability	α
Total		¥80 billion $+\alpha$

immediately after the earthquake. As a result, the gross output of the fossil-fired power stations (plant capacity) was reduced by 8.475 GW (about 30%). In the three fossil-fired power stations along the Pacific Coast (Hirono, Hitachinaka, and Kashima), a total of seven units that were operating were shut down. It was reported that in addition to liquefaction damage, electrical equipment was flooded by the tsunami at five plants that were not operating (TE, 2011a). Table 9 summarizes the announced damage to electrical power facilities. The areas where liquefaction occurred included areas along the coastline and reclaimed land. Damage to electrical power equipment at power stations included the exposure of foundation piles due to the settlement of the foundation soil, the lateral flow of shore protection, the tilting of tanks and other structures, etc. Damage to electricity transmission facilities included damage to connections in buried structures, and the tilting, damage, and collapse of electricity poles, etc.

Fig. 11 shows the variation in the number of homes without electricity with time within the TE area. As can be seen from this figure, after electricity was restored to the 4.4 million homes that suffered power outages due to the

Table 9
Damage to electrical power facilities (Ministry of Economy, 2011).

Facility		Tohoku electric	Tokyo Electric
Hydroelectric generating facilities	Dams	0 locations	2 locations
	Water courses	19 locations	3 locations
	Power stations	4 locations	1 location
	Transformers	1	0
	Isolators	0	1
	Other equipment	4	1
Substations	Substations	75 (9) locations	134 locations
	Main transformers	90 (23)	156
	Breakers	177 (171)	33
	Isolators	403 (331)	268
	Other equipment	917 (848)	162
Transmission facilities	Damage overhead transmission lines		
	Damage to transmission towers	37 (37)	1
	Insulators	23	108
	Electrical and other cables	9 spans	115 spans
	Others	221 lines	—
	Underground transmission lines		
	Cables	14 (11)	20
	Pipe ducts	1 location	4 locations
	Cable tunnels	0 locations	2 locations
	Others	37 locations	—
Distribution facilities	Electricity poles (tilted, fallen over)	Others	9946
	Electricity poles (washed away, destroyed)	15,681	
	High voltage lines	20,523 locations	212 locations
	Column transformers	8714	699
	Overhead closers	220	18

Data in parentheses ( ) indicate tsunami damage.

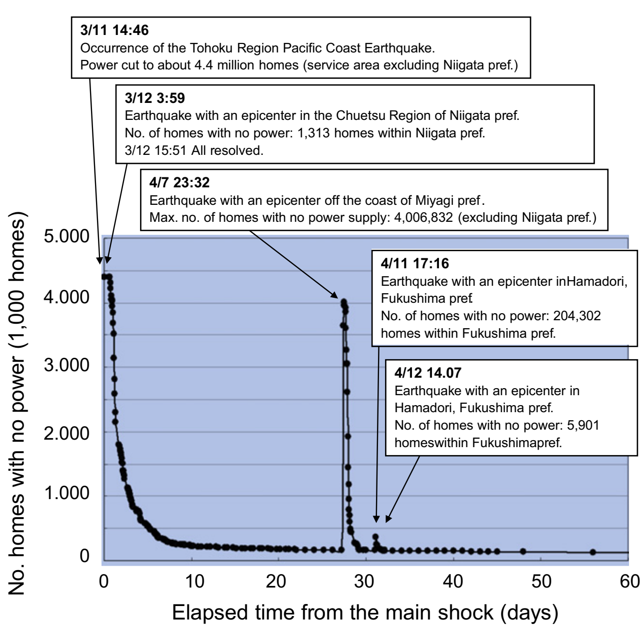

Fig. 11. Variation in number of homes without electricity with time in the TE area ((TE, 2011c), data converted into a graph).

main earthquake on March 11, power outages occurred again due to the aftershock on April 7. This aftershock affected not only the electricity supply, but also other lifelines, such as the water supply.

Regarding the nuclear power stations, TE reported that "at TE's Onagawa Nuclear Power Station in Miyagi Prefecture, Unit No. 1 and Unit No. 3 were operating normally, and the Unit No. 2 nuclear reactor was starting up. When the earthquake occurred, all units automatically shut down. The measured acceleration was 567.5 Gal" (TE, 2011c). At present, the accident at TEPCO's Fukushima No. 1 Nuclear Power Station is still ongoing, and no detailed summary of the situation has been provided. Therefore, it is omitted from this report.

3.3.3. Other lifelines (gas, water, and sewage works) (Japan Society of Civil Engineers Tohoku Branch, 2011)

Gas is supplied in Sendai City by the Gas Bureau, City of Sendai; the supply of gas was restored to about 310,000 homes by April 16. In the eastern areas along the coast that were damaged by the tsunami and in hilly areas within the city containing large-scale areas of developed residential land (Oritate 5-chome and part of Midorigaoka 4-chome), restoration had still not been achieved even after seven months. Restoration activities were carried out with the support of 100,000 workers from 49 gas companies from all over Japan, from Hokkaido to Kyushu, including members of the Japan Gas Association (Japan Society of Civil Engineers Tohoku Branch, 2011).

Regarding the water supply, the peak number of cities, towns, and villages to which the water supply was cut off was 187, and the water supply was cut off to about 2.3 million homes (survey by the Ministry of Health, Labor and Welfare). In Miyagi Prefecture, there was damage to water distribution pipes for several kilometers downstream of the water purification plants for the Sennan and Senen region waterworks, the Ishinomaki region waterworks, and the Osaki region waterworks. Also, leakage and the separation of the joints of ductile cast iron water distribution pipes occurred (Gas Bureau, 2011).

Regarding sewage works, the end of most of the flow sewage treatment plants are located along the Pacific Coast, so they were subject to major damage caused by the tsunami. According to the MLIT, damage was confirmed at 72 sewage treatment works in 12 prefectures and the Kanto area, and as of April 6, 22 of these sewage treatment works were still not operational. Most of the facilities switched to a simple treatment system, and sewage treatment is now being carried out by this system (Japan Society of Civil Engineers Tohoku Branch, 2011). Besides treatment problems, there have been problems with transporting sludge, reducing the volume of sludge, and disposal locations.

3.3.4. Liquefaction damage

The scale of the liquefaction damage caused by this earthquake was the largest recorded anywhere in the world, extending about 500 km along the coast from southern Iwate Prefecture to Kanagawa Prefecture. In the Tohoku Region, typical damage seen everywhere included such things as sand boils, floating manholes, tilting apartment buildings, damaged housing, the collapse of levees, the collapse, subsidence, cracking, and irregularity of roads, and the tilting of electricity poles. However, it is considered that, in most cases, the traces of liquefaction along the coastal areas of Iwate, Miyagi, and Fukushima Prefectures had been washed away by the tsunami. Even in these cases, however, liquefaction was caused by the aftershocks, so it is inferred that liquefaction was also caused by the main earthquake. In fact, in many places, it was confirmed that liquefaction had recurred due to the aftershocks. In addition, liquefaction occurred even at mine tailing dams.

In the seven prefectures that make up the Kanto Region, liquefaction damage was confirmed in 96 cities, towns, and villages and was concentrated along the coast of Tokyo Bay and the basin of the Tonegawa River (MLIT 2011b). Liquefaction occurred relatively frequently in reclaimed land, old river courses, old swamps, and drained land. However, almost no liquefaction damage was seen in grounds where countermeasures against liquefaction, such as sand compaction piles, etc., had been taken.

There was a very large amount of liquefaction damage. The damage is described in this special issue of Soils and Foundations.

3.3.5. Quantity of generated disaster waste and status of transport (Ministry of the Environment, 2011)

As of December 13, 2011, the estimated quantities of disaster waste in Iwate, Miyagi, and Fukushima Prefectures were about 4.76 million tons, 15.69 million tons, and 2.03 million tons, respectively, giving an approximate total for the three prefectures of about 22.47 million tons. In terms of the quantity of normal waste disposed of in one year, this corresponds to about 11 years worth of waste for Iwate Prefecture and about 19 years worth of waste for Miyagi Prefecture. Looking at the amounts in terms of cities, towns, and villages, the maximum amount was in Ishinomaki City, with about 6.16 million tons, followed by Higashi Matsushima City, with about 1.66 million tons, Kesennuma City, with about 1.37 million tons, Sendai City, with about 1.35 million tons, and so on. All together, 67% of the estimated quantity of disaster waste in Iwate, Miyagi, and Fukushima Prefectures has been transported to luggage temporary debris. The percentage, according to prefecture, is the highest in Iwate Prefecture, at 84% (74%), followed by Miyagi Prefecture, at 64% (55%), and Fukushima Prefecture, at 53% (47%). The values within the parentheses represent the values as of October 4, 2011, which means that waste removal has progressed by 8–10 % in about two months. Also, the disaster waste has been used in the construction of embankments after confirming at the sorting stage that it contained no harmful substances in order to ensure safety and durability (Japan Road Association, 2010).

Acknowledgments

Seismic geotechnical engineering is a branch of knowledge that is based on the experience gained from numerous disasters and for which improvements are continuously being made. As long as there is room for even a little advancement in the methods used to date, by learning from disasters and then moving in a positive direction with improvements, a policy that does not allow for stagnation in this field of research will exist. If there is nothing new that can be learned from the experience of the March 11 disaster, then it seems as though we can only blame ourselves, the engineers and researchers, for being negligent.

We have been commissioned by the Editorial Committee to write the Preface to this special edition of the Japanese Geotechnical Journal regarding the disaster, but it is just a bird's eye view of the diverse damage covering a wide area that is difficult to summarize. In the main text, we have tried to indicate the data concerning the earthquake and the damage it caused using numbers as much as possible. Unfortunately, we do not think we were able to provide enough numerical data. For further information regarding the damage to facilities, we suggest that the readers refer to the detailed reports which address each individual specialty.

Finally, we would like to express our deep gratitude to all those who have provided us with valuable information, particularly the Tohoku Regional Development Bureau.

It is worth mentioning that this paper is based on previous papers submitted to the Japanese Geotechnical Journal (Kazama, 2011), has produced graphs from some tables, and has introduced several new items.

References

Cabinet Office, 2011. ⟨http://www.bousai.go.jp⟩ "Estimate of the Cost of Damage in the 2011 off the Pacific coast of Tohoku Earthquake Disaster" 2011.6.24. (in Japanese).

East Japan Railway Company, 2011a. April 27 Announcement Regarding the Effect of the 2011 off the Pacific coast of Tohoku Earthquake Disaster and Difference in Projected Operating Results, http://www.jreast.co.jp/investor/financial/2011/pdf/kessan_03.pdf. (in Japanese).

East Japan Railway Company, 2011b. Main Damage and Status of Restoration of the Above Ground Facilities of the Tohoku Shinkansen (as of April 17, 2011), JR-EAST HP:http://www.jreast.co.jp/pdf/restore02.pdf. (in Japanese).

East Japan Railway Company, 2011c. Main Damage and Status of Restoration of the Above Ground Facilities of Regular Train Lines (as of April 17, 2011), JR-EAST HP: http://www.jreast.co.jp/pdf/restore.zairai.0.2.pdf. (in Japanese).

East Japan Railway Company, 2011d. Main Damage and Status of Restoration of the 7 Lines Affected by the Tsunami (as of April 17, 2011), JR-EAST HP: ⟨http://www.jreast.co.jp/pdf/check.pdf⟩. (in Japanese).

East Nippon Expressway Company Limited, 2011. ⟨http://www.e-nexco.co.jp/pressroom/tohoku_eq/restoration.html⟩. (in Japanese).

Gas Bureau, 2011. City of Sendai, Status of Restoration of Gas after the 2011 off the Pacific coast of Tohoku Earthquake, ⟨http://www.gas.city.sendai.jp/top/disaster/2011/10/000447.php#jokyo⟩. (in Japanese).

Geospatial Information Authority of Japan, 2011. Crustal Movements of Electronic Control Points Obtained From Continuous GPS Measurements, ⟨http://www.gsi.go.jp/chibankansi/chikakukansi40005.html⟩. (in Japanese).

Japan Institute of Construction Engineering, 2011. Document from the Committee to Investigate Emergency Seismic Resistance Measures for River Levees, ⟨http://www.jice.or.jp/sinsai/kasen/⟩. (in Japanese).

Japan Meteorological Agency, 2011. Preliminary Report on Earthquake and Tsunami Disasters, the 2011 off the Pacific coast of Tohoku Earthquake, ⟨http://www.jma.go.jp/jma//kishou/books/saigaiji/saigaiji_201101/saigaiji_201101.pdf⟩, August 17, 2011. (in Japanese).

Japan Road Association, 2010. Road Earthworks Guidelines for Embankments, p. 15. (in Japanese).

Japan Society of Civil Engineers Tohoku Branch, 2011. First Report of the Tohoku Branch Technical Joint Investigation Committee, Damage to Water Supply and Water Works, ⟨http://www.i.l.co.jp/jsce_shinsai/index.html⟩, 2011.4.28. (in Japanese).

Kazama, M., 2011. Overview of the damages of the 2011 off the Pacific coast of Tohoku Earthquake and its geotechnical problems, the Japanese Geotechnical Journal 7 (1), 1–11 in Japanese.

Ministry of Economy, Trade and Industry, 2011. General Resource and Energy Committee Nuclear Power Safety and Security Committee Nuclear Power Safety Sub-committee, 27th Document, 2011.7.21, ⟨http://www.meti.go.jp/committee/summary/0002540/027_haifu.html⟩. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism, 2011a. The 2011 off the Pacific coast of Tohoku Earthquake Disaster (92nd Report), Prepared at 10:00 on September 26, 2011, ⟨http://www.mlit.go.jp/saigai/saigai_110311.html⟩. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism, 2011b. Liquefaction Countermeasure Technology Investigation Committee Investigation Results, ⟨http://www.mlit.go.jp/common/000169750.pdf⟩. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism Kanto Regional Development Bureau, 2011. Prepared on November 1, 2011 (Status of River Damage, 8th Report) ⟨http://www.ktr.mlit.go.jp/ktr_content/content/000045914.pdf⟩. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism Tohoku Regional Development Bureau, Damage to River and Coastal Facilities in the 2011 off the Pacific coast of Tohoku Earthquake Disaster and Status of Restoration (as of July 11, 2011) ⟨http://www.thr.mlit.go.jp/Bumon/B00097/K00360/taiheiyouokijishinn/hukyuu/0711.pdf⟩. (in Japanese).

Ministry of Land, Infrastructure, Transport and Tourism Tohoku Regional Development Bureau, 2011b. ⟨http://www.thr.mlit.go.jp/road/jisinkannrenjouhou_110311/110315_17_kokudou.pdf⟩. (in Japanese).

Ministry of the Environment, 2011"Status of Progress in Processing of Disaster Waste in Cities, Towns, and Villages along the Coast," ⟨http://www.env.go.jp/⟩. (in Japanese).

National Police Agency, 2011. The 2011 off the Pacific coast of Tohoku Earthquake Damage Status and Measures by the Police, Public Information Document ⟨http://www.npa.go.jp/archive/keibi/biki/higaijokyo.pdf⟩. (in Japanese).

NTT East Corporation , 2011. Status of Recovery from the Damage of the 2011 off the Pacific coast of Tohoku Earthquake Disaster and Future Initiatives, ⟨http://www.ntt-east.co.jp/release/detail/20110427_02.html⟩, (accessed 27.04.11) (in Japanese).

Oka, M., 2011. NTT East Corporation, Research Institute of Electrical Communication, Tohoku University Symposium "Thoughts Concerning an Information Communication Network that is Strong Against Disasters," Damage to the Communication Service caused by the 2011 off the Pacific coast of Tohoku Earthquake and Efforts Towards Restoration and recovery–Joining Together for Tomorrow–, ⟨http://www.riec.tohoku.ac.jp/sympo201106/⟩, (accessed 15.06.11) (in Japanese).

The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011. The 2011 off the Pacific coast of Tohoku Earthquake Tsunami Information, ⟨http://www.coastal.jp/ttjt/⟩, (accessed 06.05.11).

Tohoku Electric, 2011a. Power Stoppages and Other Effects of Earthquake, ⟨http://www.tohoku-epco.co.jp/emergency/1/index.html⟩. (in Japanese).

Tohoku Electric, 2011b. Status of Nuclear Power Stations in the 2011 off the Pacific coast of Tohoku Earthquake, ⟨http://www.tohoku-epco.co.jp/information/1182212_821.html⟩. (in Japanese).

Tohoku Electric, 2011c. Status of Power Stoppages Due to the 2011 off the Pacific coast of Tohoku Earthquake, Status of Nuclear Power Stations, ⟨http://www.tohoku-epco.co.jp/information/1182212_821.html⟩. (in Japanese).