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Damage to railway earth structures and foundations caused by the 2011 off the Pacific Coast of Tohoku Earthquake

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Abstract

Statistics are compiled on the damage to railway earth structures, soil retaining walls and bridge foundations caused by the 2011 off the Pacific Coast of Tohoku Earthquake in Japan and the subsequent tsunami. Several case histories are reported on the damage they created and the rehabilitation works implemented, including the collapse of a high cut slope, the excessive settlement of embankments in lowland areas, the significant scoring of the backfill soil of bridge abutments, the restoration works of tilted bridge foundations and the tsunami-induced collapse of soil-retaining walls and bridge foundations. The good performance of well-designed foundations, which were able to survive the impact of the earthquake, particularly the effects of the earthquake-induced liquefaction of the subsoil layers, is also described.

Keywords: Railway; Cut slope; Embankment; Retaining structure; Bridge foundation; The 2011 off the Pacific Coast of Tohoku Earthquake; Tsunami (IGC: E04/E06/E08)

1. Introduction

The 11 March 2011 off the Pacific Coast of Tohoku Earthquake, Japan, along with subsequent events, including a large tsunami, severely damaged many earth structures, including railway earth structures.

Tables 1 and 2 summarize the major damage to earth structures (cut slopes and embankments), soil retaining walls and foundations of the East Japan Railway and other railways, respectively. Data on the damage were compiled on the basis of information provided by the East Japan Railway Company (2011), Nozawa et al. (2012), Ministry of Land, Infrastructure, Transport and Tourism (2011), Iwamoto (2011), Mizutani et al. (2011) and Tetsudo.com (2012).

Including both major and minor sites, a total of about 220 earth structures belonging to the East Japan Railway Company were damaged, as summarized in Table 3. The total fee for reconstructing all types of damaged structures, including the earth structures, has amounted to 71.7 billion yen as of March 2012 (East Japan Railway Company, 2012). It should be noted that some of the damaged lines are still partially suspended; their reconstruction would thus require an additional fee. Also, the loss in profits due to reduced commercial activities has amounted to 111.0 billion yen as of March 2012, where most of the loss, as large as 107.0 billion yen, can be attributed to the suspension of railway operations (East Japan Railway Company, 2012).

In the case of the Sanriku Railway, which was severely affected by the tsunami, about 70 earth structures were

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Table 1
Major damage to earth structures and foundations of East Japan Railway.

Line	Original service length (km)	Types of damaged earth structures	First date of full re-operation (or percentage of re-operational length**)
Tohoku Shinkansen	713.7	R	April 29, 2011
Tohoku (including branch line for freight)	571.7	E, S, R, F	April 21, 2011
Joban	350.4	E*, F	(73%)
Senzan	58.0	E	April 23, 2011
Suigun	147.0	E, S, F	April 15, 2011
Narita (west side between Narita and Abiko stations)	32.9 [in total 119.1]	E	March 16, 2011
Hachinohe	64.9	E*	March 17, 2012
Yamada (coastal side)	55.4 [in total 157.5]	E*, F*	(65%)
Ofunato (ditto)	43.7 [in total 105.7]	E*, S*, F*	(65%)
Kesennuma	72.8	E*, F*	(24%)
Ishinomaki	44.9	E*	(80%)
Senseki	50.2	E*	(77%)

E: Embankment, S: Cut or natural slope, R: Retaining wall and F: Bridge foundation.
*Including tsunami-induced damage.
**Defined as a ratio of current to original service length (as of July 3, 2012).

Table 2
Major damage to earth structures and foundations of other railways.

Railway	Original total service length in total (km)	Types of damaged earth structures	First date of full re-operation (or percentage of re-operational length**)
Sanriku	107.6	E*, S*, R*	(24%)
Iwate-Kaihatsu	11.5	E*, S*, R	November 7, 2011
Sendai Airport Transit	7.1	F	October 1, 2011
Sendai-Rinkai	9.5	E*	March 13, 2012
Fukushima-Rinkai	5.4	E*	February 1, 2012
Kashima-Rinkai	72.2	E*, S, R	July 12, 2011
Keisei (main line)	69.3	E	March 12, 2011
Tsukuba Express	58.3	F	March 12, 2011

E: Embankment, S: Cut or natural slope, R: Retaining wall and F: Bridge foundation.
*Including tsunami-induced damage.
**Defined as a ratio of current to original service length (as of July 3, 2012).

Table 3
Approximate number of damaged sites of East Japan Railway (modified after East Japan Railway Company, 2011).

Category	Tsunami-affected lines*	Other lines	
Cause of damage	By tsunami and earthquake loads	By main shock load (March 11)	By aftershock load (April 7)
Track rails	210 sites (with 60 km-long tracks lost)	2200 sites	600 sites
Base ballasts	80 sites	220 sites	0
Platforms	40 sites	220 sites	40 sites
Earth structures	50 sites	170+1** sites	2 sites
Bridges and viaducts	30 sites (with 101 girders lost)	120+130** sites	30+40** sites
Tunnels	0	30 sites	2 sites
Rockfalls	1 site	20 sites	10 sites
Station buildings	25 stations (with 23 station buildings lost)	80 stations	10 stations
Electricity poles	950 sites	1150+540** sites	90+270** sites

As of April 5, 2011 for tsunami-affected lines and April 17, 2011, for other lines.
*A part of Hachinohe, Yamada, Ofunato, Kesennuma, Ishinomaki, Senseki and Joban lines (in total 325 km long).
**For Tohoku Shinkansen (bullet train) line.

damaged over a total service length of about 110 km, as summarized in Table 4. As of July 2012, railway operation has resumed for only 24% of the original service length (Table 2).

In this paper, we attempt to describe the features of the damage and the techniques used for their rehabilitation, by focusing on several case histories of cut slopes, embankments, retaining walls and bridge foundations of railway facilities. It is also shown that well-designed foundations were able to survive the impact of the earthquake, particularly the effects of the earthquake-induced liquefaction of the subsoil layers.

Table 4
Number of damages sites of Sanriku Railway (modified after Mochizuki, 2011).

	North Rias line	South Rias line
Service length (km)	71.0	36.6
Track rails	38 sites	96 sites
Earth structures	11 sites	61 sites
Bridges	15 sites	20 sites
Tunnels	0	4 sites
Stations and platforms	1 site	4 sites
Other facilities*	5 sites	62 sites

*Including electricity and telecommunication facilities.

2. Earthquake-induced damage to cut slopes and embankments

Fig. 1(a) shows the location of the sites at which earth structures suffered from major damage due to the earthquake load throughout the East Japan Railway network. Case studies of some of these sites are reported herein, along with their rehabilitation works.

2.1. Collapse of cut slopes

Fig. 2(a) shows the collapse of a cut slope (V:H = 1:1) along the JR Tohoku Line, located at 179k100m between Toyohara and Shirasaka Stations. It had a maximum height of about 23 m, and consisted of volcanic ash-origin soil called loam. Several boring surveys, conducted after the earthquake, have revealed that this soil layer exhibits typical SPT-N values of 2–4. As shown in Fig. 2(b), the collapsed soil fully covered the railway track, while the masonry soil-retaining wall that had been constructed at the toe of the cut slope was found intact.

In contrast, cut slopes in the adjacent areas consisting of the same soil type, which had a maximum height of 14 m, were found to have survived the earthquake. The apparent cohesion of this type of soil, mobilized by the suction effect under partially saturated conditions, may not have provided sufficient resistance against the earthquake load exerted on

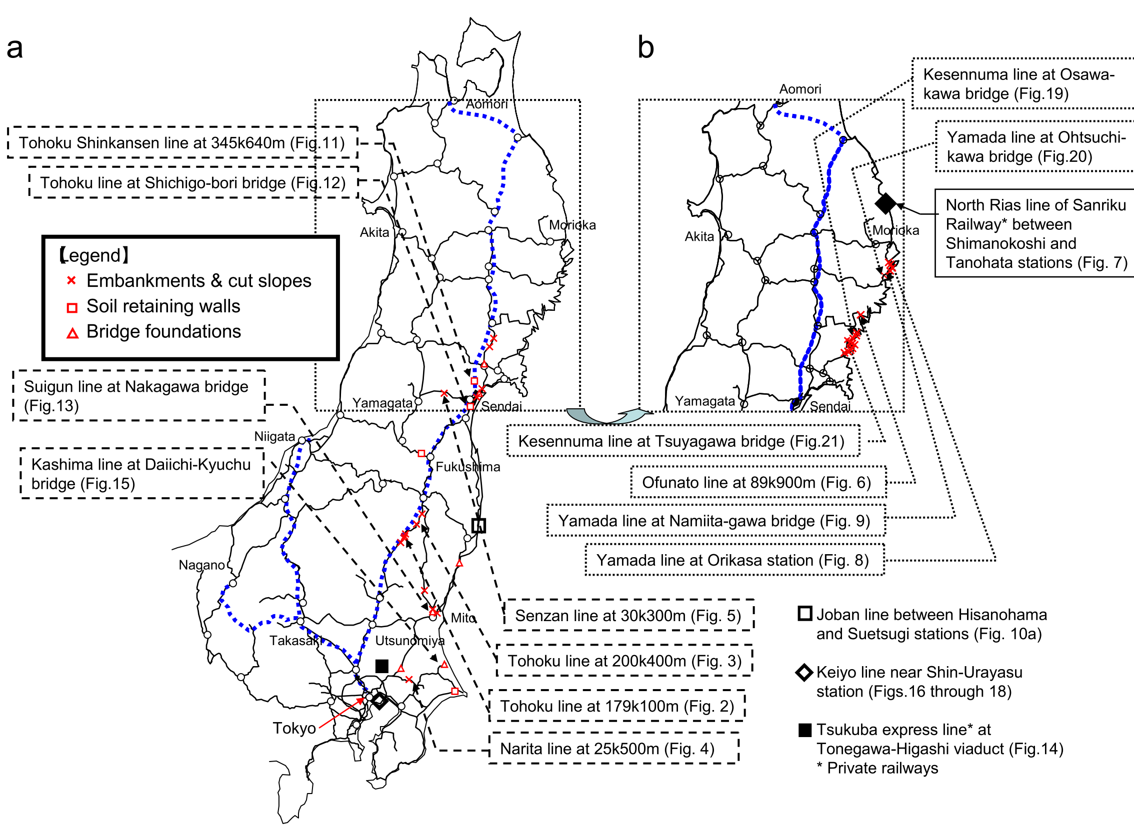

Fig. 1. Location of earth structures damaged by (a) earthquake loads and b) tsunami along the network of East Japan Railway.

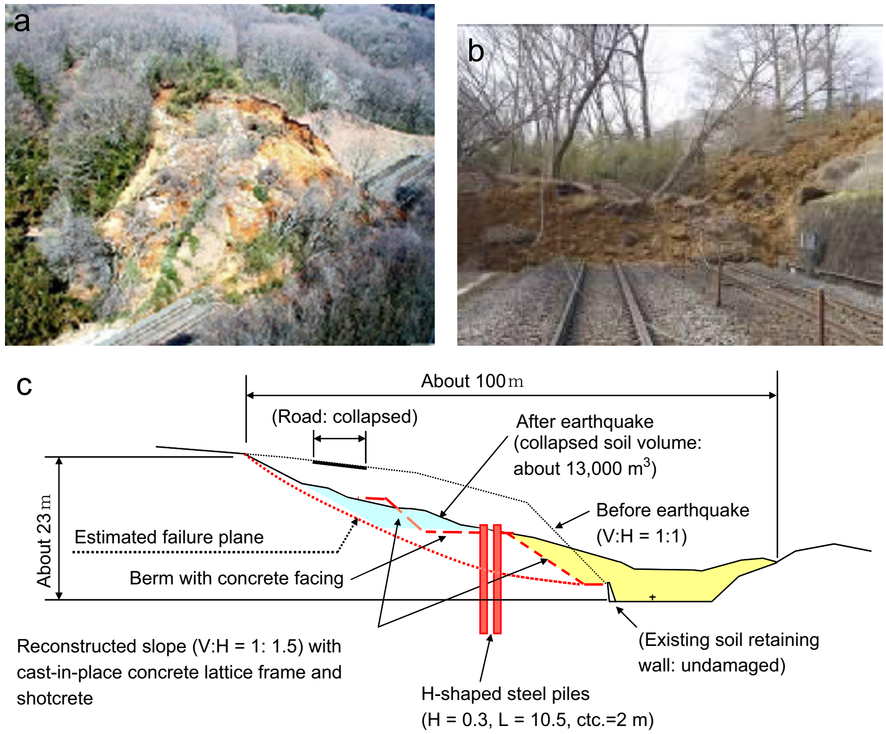

Fig. 2. (a) and (b) Collapse of cut slope along JR Tohoku line at 179k100m between Toyohara and Shirasaka stations and (c) its reconstruction.

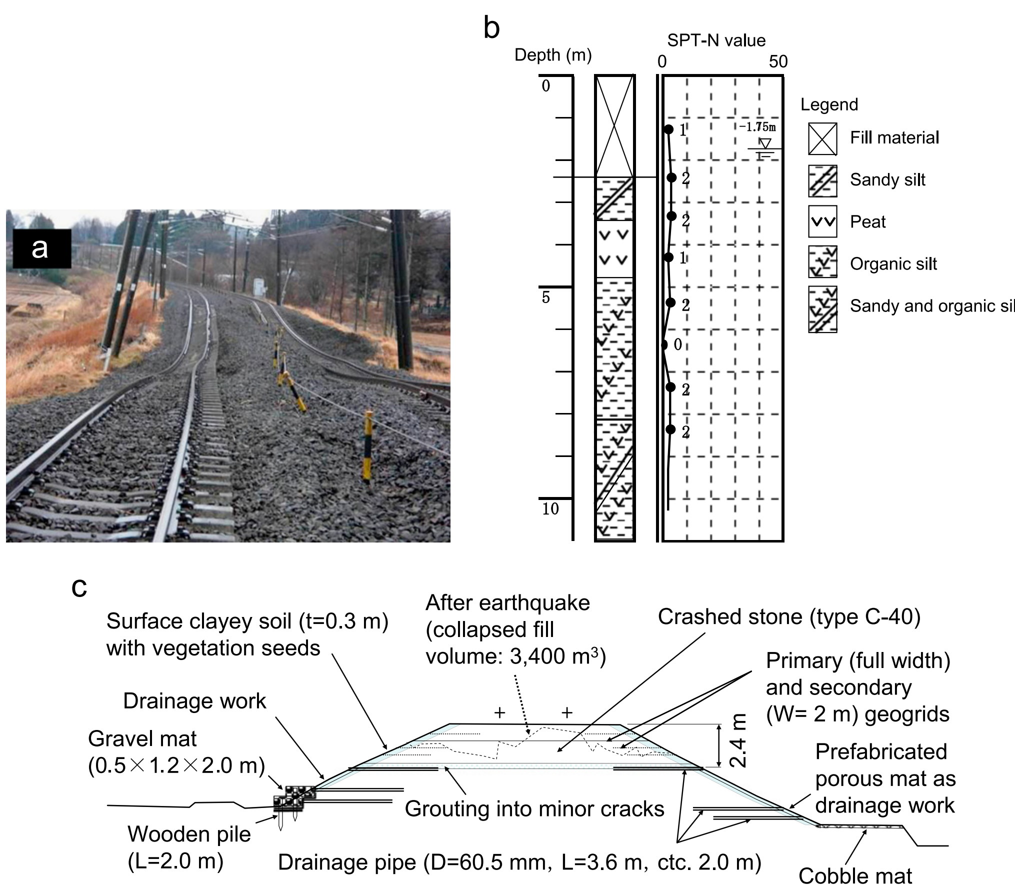

Fig. 3. (a) Excessive settlement of embankment along JR Tohoku line at 200k400m between Izumizaki and Yabuki stations, (b) results from boring survey conducted after earthquake and (c) its reconstruction.

the failed slope, while it may have been sufficient to support the other lower slopes.

As shown in Fig. 2(c), the failed slope was reconstructed into a more gentle slope (V:H = 1:1.5), which was covered with a cast-in-place concrete lattice frame and shotcrete. H-shaped steel piles were imbedded to increase the resistance to sliding failures.

2.2. Damage to embankments

Fig. 3(a) shows the excessive settlements of an embankment along the JR Tohoku Line, located at 200k400m between Izumizaki and Yabuki Stations. It had a height of about 5 m and consisted of alternative layers of sandy soil and clayey soil. It was filled on soft subsoil layers (with typical SPT-N values of 1 to 2) consisting of peat and organic silt in a lowland area.

As shown in Fig. 3(b), a boring survey, conducted after the earthquake, has revealed that the groundwater level was located within the filled soil layer above the subsoil layers, suggesting that the saturated part of the fill, consisting of a sandy soil, may have liquefied and induced a large deformation. The survey has also revealed that the subsoil layers consisted predominantly of organic soils, exhibiting SPT-N values equal to or less than 2.

As shown in Fig. 3(c), the failed embankment was reconstructed into a reinforced embankment having the same dimensions as the one before the failure, with a slope of V:H = 1:1.6 to 1:2.2. For the fill material, a gravelly soil consisting of crushed sand and/or volcanic stone particles was used, which was well compacted and reinforced by geogrids inserted at a vertical spacing of 30 cm. Full-width geogrids are used as primary reinforcements, while shorter and weaker geogrids with a width of 2 m are used as secondary reinforcements. The drainage capacity was also enhanced by using horizontal drainage pipes in the fill and gravel mats at the toe of the fill.

Fig. 4(a) shows the excessive settlement of an embankment along the JR Narita Line, which was located at 25k500m between Aziki and Kobayashi Stations. It had a height of about 3 m and was filled on sandy subsoil layers in a lowland area. After the earthquake, sand boiling from the subsoil level was observed at the level ground adjacent to the embankment. Therefore, the occurrence of liquefaction in the subsoil would have been the major cause of the excessive settlement of the embankment.

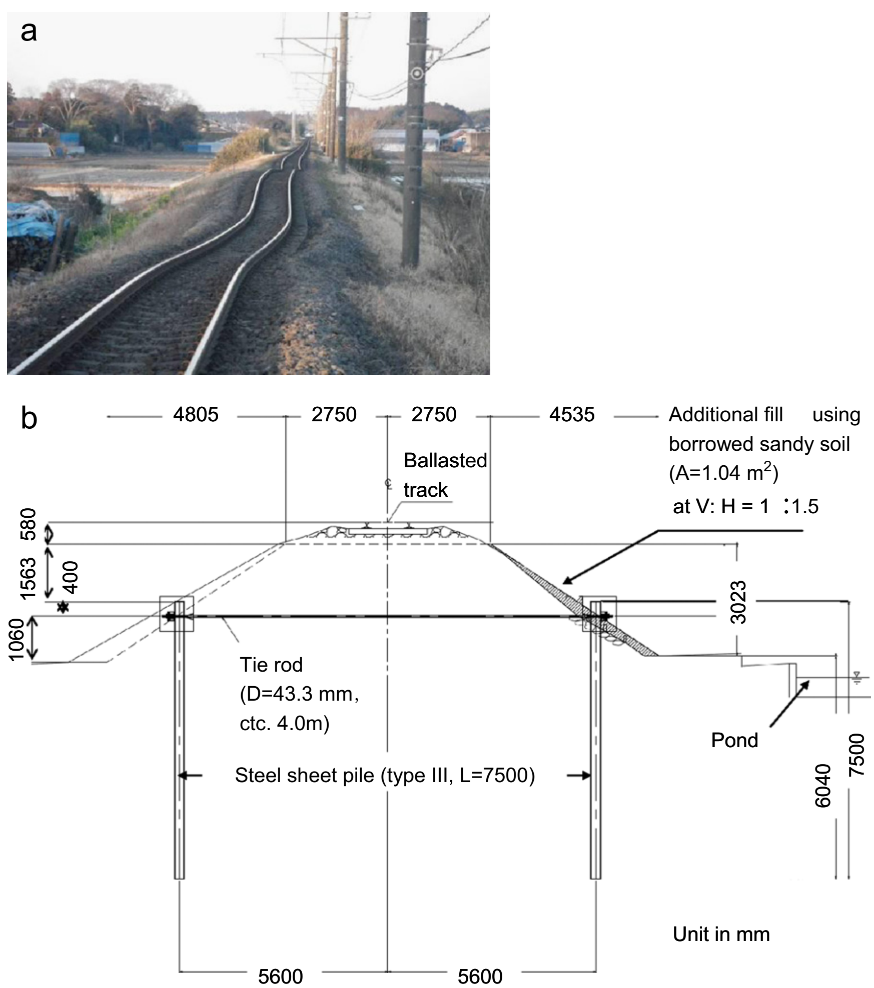

Fig. 4. (a) Excessive settlement of embankment along JR Narita line at 25k500m between Aziki and Kobayashi stations and (b) its reconstruction.

As shown in Fig. 4(b), the failed embankment was reconstructed into an unreinforced embankment, having dimensions which are similar to those before the failure, with a slope of V:H = 1:1.5. A pair of steel sheet piles, connected to each other at the top with a tie rod, was imbedded at the toe of the embankment. This measure is expected to prevent the possible deformation of the subsoil layers which may again liquefy during future earthquake-related events.

Fig. 5(a) shows the collapse of an embankment along the JR Senzan Line, which was located at 30k300m between Sakunami and Yatsumori Stations. It had a maximum height of about 10 m and was constructed by filling a valley in a mountainous area. The results from a boring survey, conducted after the earthquake to reveal the subsoil conditions, are shown in Fig. 5(b). The subsoil layers consisted of clayey and sandy silts, sandy gravel and soft rock. In particular, the soft rock was tuffaceous, occasionally sandwiching highly weathered clayey zones.

Due to the earthquake, the embankment suffered from sliding failure, which resulted in the loss of the top of the railway track. The collapsed soil at its toe part was found to be very soft, namely, consisting of a clayey material with high water content. It was reported that during the reconstruction work, some local groundwater escaped from one of the side surfaces of the failure plane at its middle height. Based on these observations, it may be inferred that the fill originally consisted of crushed mud–stone particles, which had been brought from a nearby tunnel excavation site, while a part of the fill had been deteriorated by slaking partially due to the supply of groundwater. Future investigations are required on the details of the local ground conditions, including the state of the groundwater, especially during and after heavy rainfall events.

As shown in Fig. 5(c), the failed embankment was reconstructed into a reinforced embankment having dimensions which are similar to the ones present before the failure, with a slope of V:H = 1:1.5. The lower part of the embankment is filled using a gravelly soil, consisting of crushed sand stone particles, with 2-m-wide geogrids as the secondary reinforcement. In order to reduce the use of gravelly soil, which requires long-distance transportation, the upper part is filled using a cement-treated soil, which is

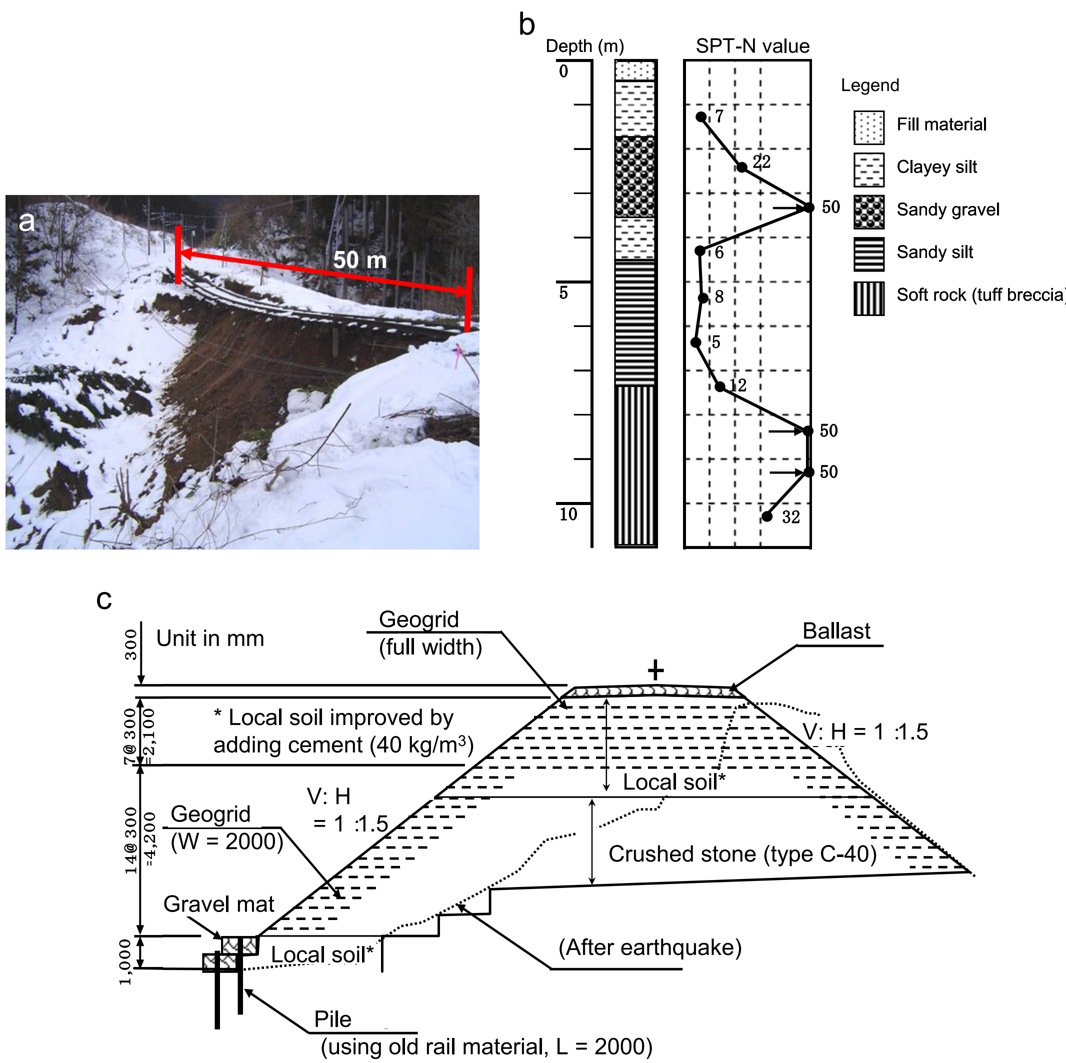

Fig. 5. (a) Collapse of embankment along JR Senzan line at 30k300m between Sakunami and Yatsumori stations, (b) results from boring survey conducted at the toe of embankment after earthquake and (c) its reconstruction.

available nearby. The upper part is further combined with full-width geogrids as the primary reinforcement. The drainage capacity was also enhanced by placing gravel mats at the toe of the fill on the downstream side of the valley.

3. Tsunami-induced damage to cut slopes and embankments

Fig. 1(b) shows the locations of sites at which earth structures were damaged by the tsunami along the East Japan Railway network. Typical case histories are reported herein, including damage to an embankment belonging to the Sanriku Railway. The respective locations of these sites are also indicated in the figure.

3.1. Damage to cut slopes

Fig. 6 shows the tsunami-induced damage to a cut slope along the JR Ofunato Line, which was located at 89k900m between Wakinosawa and Otomo Stations. The slope surface suffered from a shallow slide for a longitudinal length of about 100 m, among which shotcrete covering had been made for about 20 m.

When compared to the sites with embankments, the tsunami-induced damage to cut slopes was limited. In general, cut slopes are less affected by tsunamis because they are located at higher elevations than embankments. In addition, they appear to exhibit more resistance against tsunami-induced erosion than embankments; this is possibly due to the effect of natural cementation that has developed within the cut slopes.

3.2. Collapse of embankments

Fig. 7 shows the tsunami-induced damage to an embankment along the North Rias Line of the Sanriku Railway, which was located adjacent to the Hiraiga Tunnel between Shimanokoshi and Tanohata Stations. The overflow of the tsunami caused severe erosion of the ballasted track and the fill body. Similar damage patterns were observed at many other embankments, including railway stations constructed on embankments, as shown in Fig. 8.

Fig. 9(a) and (b) show the tsunami-induced damage to the backfill soil of a bridge abutment along the JR Yamada Line, which was located adjacent to Namiita-kaigan Station. In addition to the washing away of the bridge girders, the overflow of the tsunami caused severe scoring around the abutment body. As shown in Fig. 9(c), the top of the backfill soil of the abutment and that of the bridge girders were located at a height of about 6 m above the ground level.

It should be noted that, in cases where the tsunami did not overflow, there was no major induced damage to railway embankments, as typically shown in Fig. 10(a). Considering as well the good performance of highway embankments that were able to effectively block the tsunami, it is proposed that railway embankments be utilized as part of the multiple defense facilities against tsunamis (Miyagi Prefecture, 2011), as schematically shown in Fig. 10(b). In doing so, it is also proposed that recent geotechnical technologies, such as reinforced soil walls (Japanese Geotechnical Society, 2011 and Railway Technical Research Institute, 2011), be employed, as shown in Fig. 10(c).

Fig. 6. Tsunami-induced damage to cut slope along JR Ofunato line at 89k900m between Wakinosawa and Otomo stations.

Fig. 7. Tsunami-induced damage to embankment along North Rias line of Sanriku Railway between Shimanokoshi and Tanohata stations (adjacent to Hiraiga tunnel).

Fig. 8. Tsunami-induced damage to Orikasa station on embankment along JR Yamada line.

4. Earthquake-induced damage to soil-retaining structures and bridge foundations

Fig. 1(a) also shows the location of sites where soil-retaining structures and bridge foundations were damaged

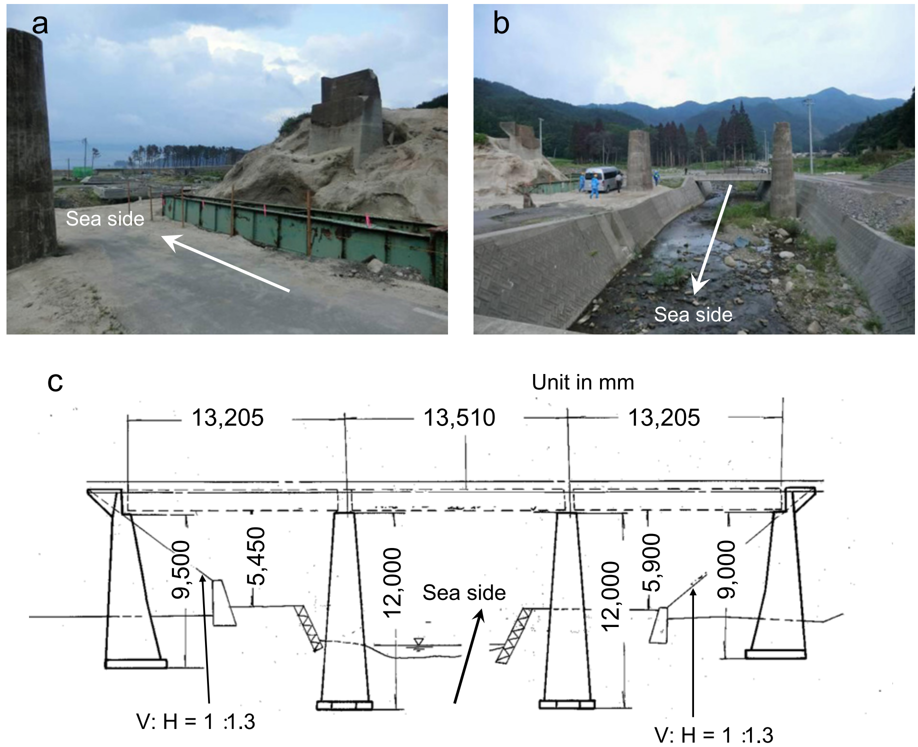

Fig. 9. (a) and (b) Tsunami-induced damage to backfill soil of Namiita-gawa bridge abutment along JR Yamada line near Namiita-Kaigan station and (c) original cross-section.

by earthquake motion along the East Japan Railway network. In general, the earthquake-induced damage to soil-retaining walls and bridge foundations as railway structures was limited. Among them, some case histories are reported herein, including damage to bridge foundations of the Tsukuba Express Line and no damage to viaducts of the JR East Keiyo Line located in ground that underwent liquefaction. The respective locations of these sites are indicated in the figure.

4.1. Damage to soil-retaining structures

Fig. 11(a) shows the inclination and the breach of a retaining wall, consisting of plain concrete. It is located in the face of a cut slope along the JR East Tohoku Shinkansen Line at 345k642m between Sendai and Furukawa Stations (East Japan Railway Company, 2011). It has a length of 58 m and a maximum height of 9 m, including the embedment. Due to the earthquake, the wall inclination, measured at its base, changed from 70.7° (which is the design gradient) to 74°. This resulted in an opening of 100–150 mm at the top of the wall. The wall body was breached at a height of about 1.0 m, forming a horizontal gap of about 150 mm at the construction joint, as shown in Fig. 11(b).

The above damage was possibly affected by the fact that the wall was relatively high, namely, about 7.4 m excluding the embedment. It can be inferred that the earthquake responses of the wall and the cut slope may have been different from each other, inducing an accumulation of the opening at the wall top and the breach of the wall body, which was accompanied by the formation of several cracks in the original ground behind the wall, as shown in Fig. 11(a).

In the restoration work, a part of the wall was removed, and the slope was cut with a gentle gradient and blown by shotcrete for surface protection, as shown in Fig. 11(c) and (d).

Fig. 12(a) shows a damaged retaining wall, which is located at the Shichigobori Bridge abutment along the JR East Tohoku Kamotsu Line at 350k047m between Nagamachi and Sendai Cargo Terminal Stations (East Japan Railway Company, 2011). A water channel existed in front of the wall, which had a height of 5.3 m from the base of the channel, as shown in Fig. 12(b). Both the wall and a part of the backfill soil collapsed due to the earthquake motion. The backfill consisted of sandy soil with gravel. The collapsed retaining wall was built with the bridge, and was one of four retaining walls on which no previous deformation had been recorded.

According to the records, there were some deformations and slides in the embankments around the bridge after the Miyagi-Ken-Oki Earthquake in 1978. Some drainage pipes (length of 3600 mm, outside diameter of 60.5 mm and interval spacing of 1000 mm) had been inserted into the embankment slope as countermeasures to increase both the drainage capacity and the shear strength of the embankments.

The above countermeasures seem to have acted effectively in reducing the extent of the damage to the embankments, which settled moderately by about 100 mm. On the other

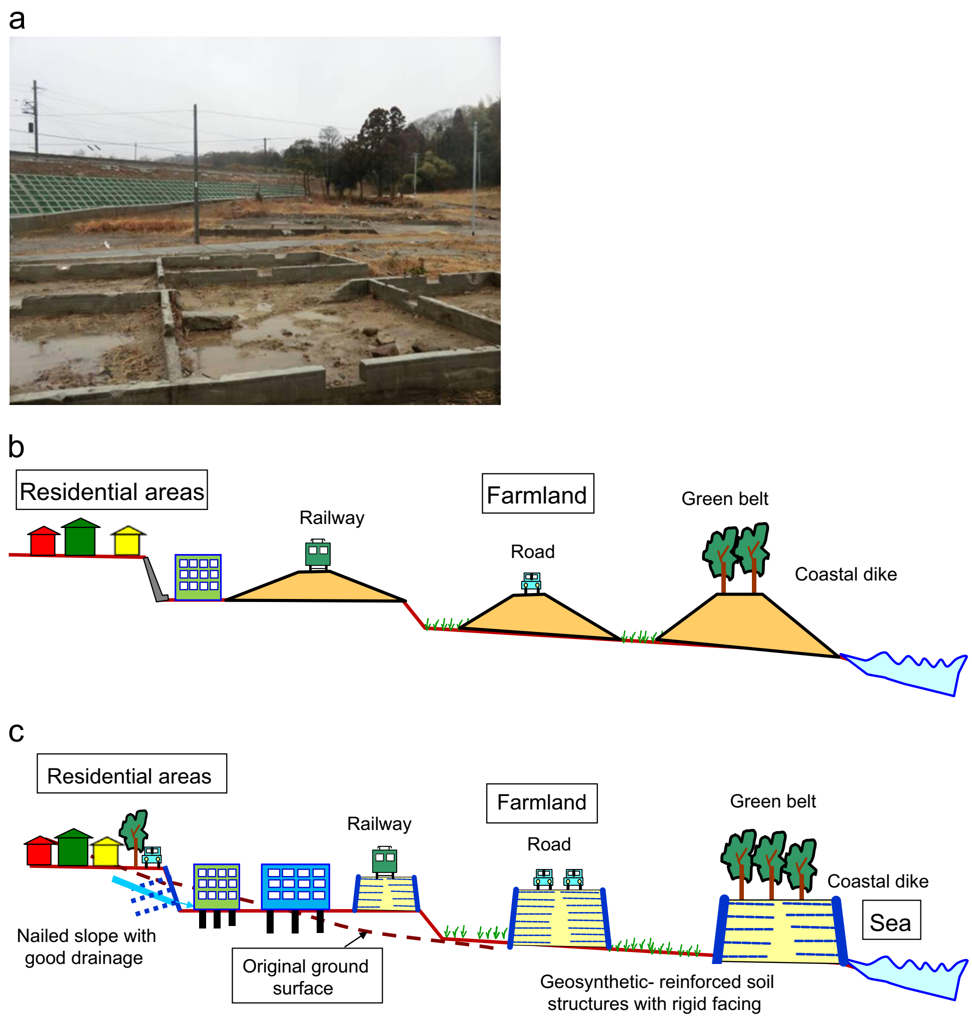

Fig. 10. (a) Embankment along JR Joban line between Hisanohama and Suetsugi stations that blocked the tsunami; and schematic diagrams of multiple tsunami defense facilities showing applications of (b) conventional and (c) recent geotechnical technologies to the restoration program (after Japanese Geotechnical Society, 2011).

hand, the wall and its backfill, beside the abutment, had been without any countermeasures, and thus, completely collapsed.

As shown in Fig. 12(c)–(e), during the restoration work, a geogrid-reinforced soil-retaining wall was used, which formed a part of the water channel revetment as well. The collapsed soil, from which grass and trees were removed, was reused as the backfill material. During the backfilling work, the water content of the backfill soil was controlled to exceed 95% of its optimum value. The compaction degrees of the backfill were measured as well; they exhibited minimum and mean values of 91.9% and 92.1%, respectively.

4.2. Damage to bridge foundations

Fig. 13(a) shows the inclination and the settlement of Pier 4P, located at the Naka-gawa Bridge on the JR East Suigun Line at 0k956m between Mito and Hitachi-Aoyagi Stations. This pier was supported by a wooden pile foundation resting on subsoil layers consisting of 11.15-m-thick silt to fine sand layers with SPT-N values in the range of 2–8, with an exceptional value of 32 measured at a depth of about 8.3 m, and a 2.4-m-thick gravelly layer with SPT-N values exceeding 50. They were underlain by a stiff mud–stone layer.

Due to the earthquake, the foundation moved 200 mm horizontally and settled 50 mm down at the top of the pier (East Japan Railway Company, 2011). As shown in Fig. 13(b), track deformation occurred with the pier displacement.

The bridge was restored by switching from the old bridge to a new bridge (Fig. 13(b)). It was reconstructed as part of the river improvement works.

Fig. 14(a) shows a side view of the Tonegawa-higashi Viaduct near 35k000m between Kashiwatanaka and Moriya Stations on the Tsukuba Express Line. The movement at the track surface was a maximum of 151 mm on the top of Piers 24P and 25P (Iwamoto, 2011; Iwamoto and Yonezawa, 2012).

The Tonegawa-higashi Viaduct is located at the Inatoi Balancing Reservoir of the Tone River Basin in Moriya City, Ibaraki Prefecture, and it has a continuous beam with a respective length of 20 m. Each pier is supported by

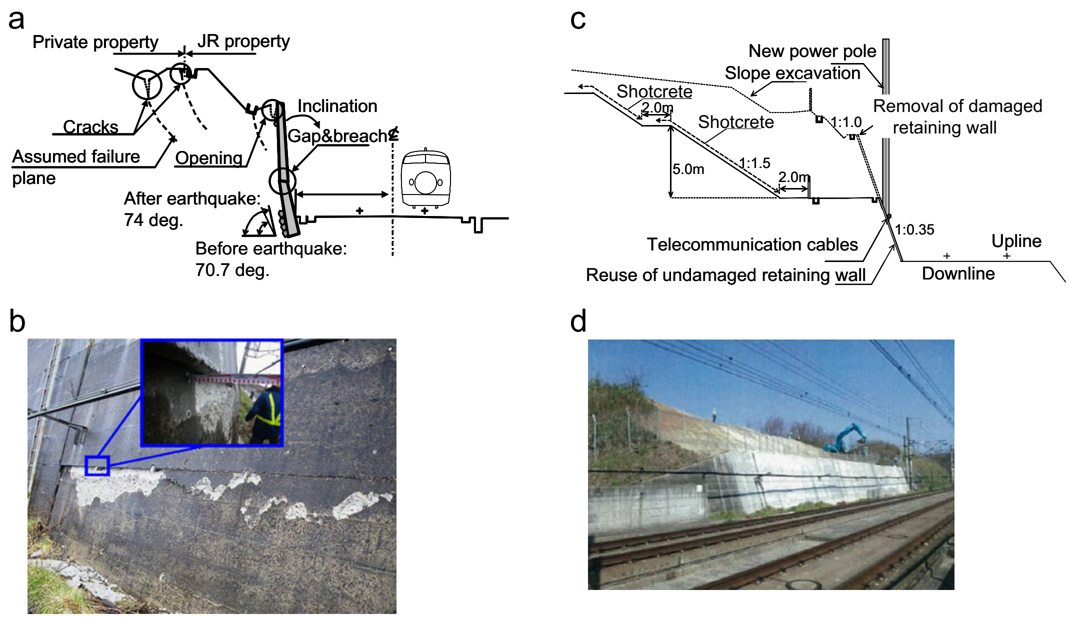

Fig. 11. (a) and (b) Inclination and breach of retaining wall along JR Tohoku Shinkansen line at 345k642m between Sendai and Furukawa stations and (c) and (d) its restoration (after East Japan Railway Company, 2011).

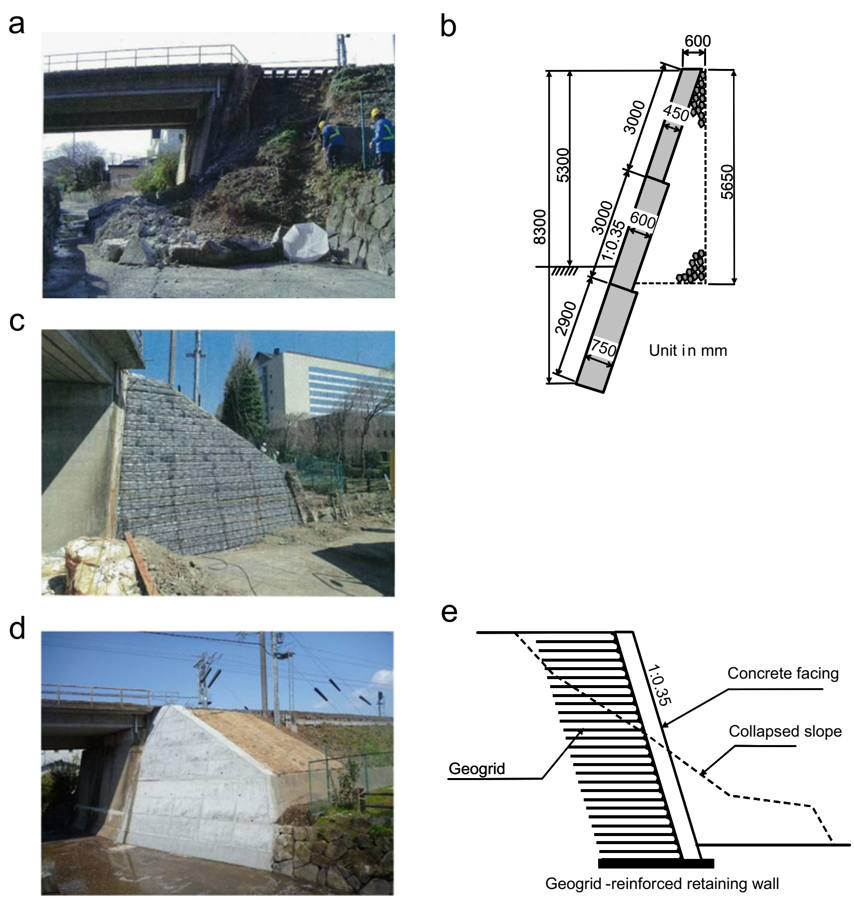

Fig. 12. (a) Collapse of retaining wall beside abutment of Shichigobori Bridge along JR Tohoku Kamotsu line at 350k047m between Nagamachi and Sendai cargo terminal stations, (b) its side view and (c), (d) and (e) its reconstruction by using geogrid-reinforced soil (after East Japan Railway Company, 2011).

four cast-in-place RC piles with a diameter of 1.5–1.8 m and a length of 19–22 m. The track is a straight line at an inclination of 1.4% towards Tsukuba Station. As listed in Table 5, a settlement of 80 mm and a lateral displacement of 132 mm occurred at the track surface at Pier 24P, and a settlement of 50 mm and a lateral displacement of 151 mm

Fig. 13. (a) Inclination and settlement of Pier no. 4 of Naka-gawa bridge along JR Suigun line at 0k956m between Mito and Hitachi-aoyagi stations and (b) rail track deformation on the bridge.

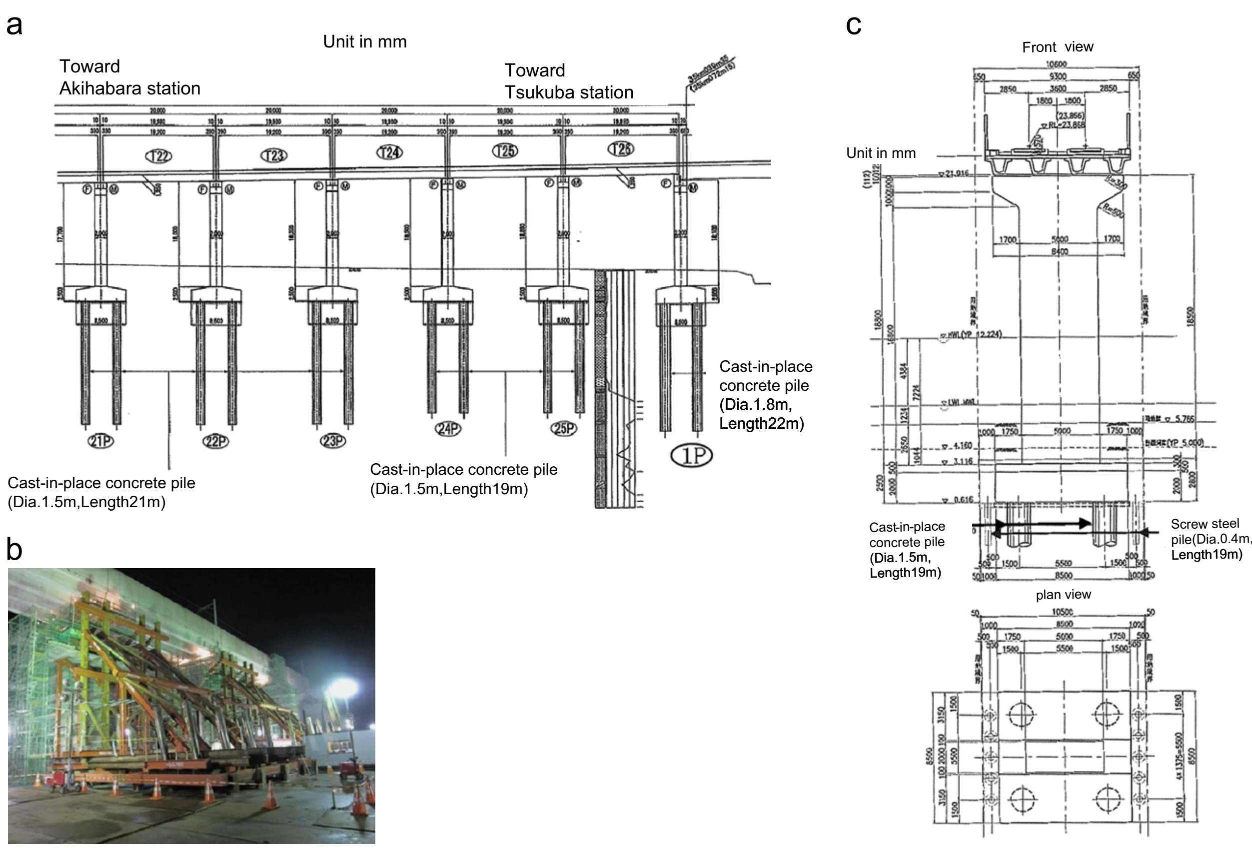

Fig. 14. (a) Side view of Tonegawa-Higashi viaduct along Tsukuba express line near 35k00m between Kashiwatanaka and Moriya stations, (b) reaction frames for recovery work of their piers and (c) provisional work (after Iwamoto, 2011; Iwamoto and Yonezawa, 2012).

at Pier 25P. Although no confirmation could be made during the restoration work, it is estimated that, due to the earthquake motion, a clearance may have been formed around the pile, which caused a decrease in its bearing capacity in terms of both skin friction and tip resistance.

As shown in Fig. 14(b), during the recovery work, Piers 24P and 25P were restored to their original positions using hydraulic jacks with a total capacity of 8000 kN that were set at a height of 11 m above the ground surface. Their reaction frame was temporarily made by H-section steel, supported by a 700-mm-thick RC base with 16 screw piles having a diameter of 400 mm and a length of 28 m. The maximum loads of 5511 and 6893 kN were applied to Piers 24P and 25P, respectively, and the horizontal movements at the track surface were 278.8 and 289.5 mm, respectively. After unloading, their residual lateral displacements could be

Table 5
Residual lateral displacements and settlements of the Tonegawa-higashi viaduct (modified after Iwamoto, 2011).

Pier no.	Lateral disp. on rail track (mm)	Settlement of rail track (mm)
22P	+1	0
23P	+9	50
24P	−132	80
25P	−151	50
1P (located next to 25P)	−17	0

reduced to 43 and 40 mm, respectively, which were within the adjustable ranges of the rail-fastening devices. In addition, the settled beams were jacked up, and spacers were inserted into the existing shoes.

To reinforce the foundation, 10 screw piles with a diameter of 400 mm and a length of 19 m were imbedded beside Piers 23P, 24P and 25P and connected to the footing, as shown in Fig. 14(c). In doing so, some of the screw piles that had been employed to support the temporary reaction frame, mentioned above, were reused.

4.3. Superstructure damage to skewed bridge

Fig. 15(a) shows the steel beam rotations of the Daiichi-Kyuchu Bridge on the JR East Kashima Line at 14k171m between Nobukata and Kashimajingu Stations. The bridge has 28-m-span steel beams with box sections (i.e., box girders). The piers have a skew angle of 60°with respect to the track line. They were supported by a pile foundation using pre-stressed concrete piles having a diameter of 40 cm and a length of 20–31 m. Between their footing and the supporting firm soil layers, with SPT-N values exceeding 50, there were subsoil layers consisting of about 3-m-thick fine sand layers with SPT-N values in the range of 4 to 15, about a 1-m-thick peat layer with an SPT-N value of 2, an approximately 16-m-thick clayey silt layer exhibiting SPT-N values of zero (i.e., the hammer settled down by its self-weight) and loose to medium-dense fine sand layers between which a 0.5-m-thick peat layer was sandwiched.

As shown in Fig. 15(b), one beam rotated by about 1350 mm at one side, with a fixed end, and by about 800 mm at the other side, with a movable end (East Japan Railway Company, 2011). Similarly, the other beam rotated by about 700 mm and 600 mm, respectively.

In general, the seismic response of the beams and the piers with a skew angle is asymmetric with respect to the track line, inducing a rotational excitation on a horizontal plane. As a result, the beam may suffer residual rotation. This seems to be the case with the above skewed bridge. Similar behavior was reported for road bridges in the 1995 Hyogo-ken Nanbu Earthquake.

During the restoration work, the beam was temporarily supported by a hydraulic jack and restored to its original position.

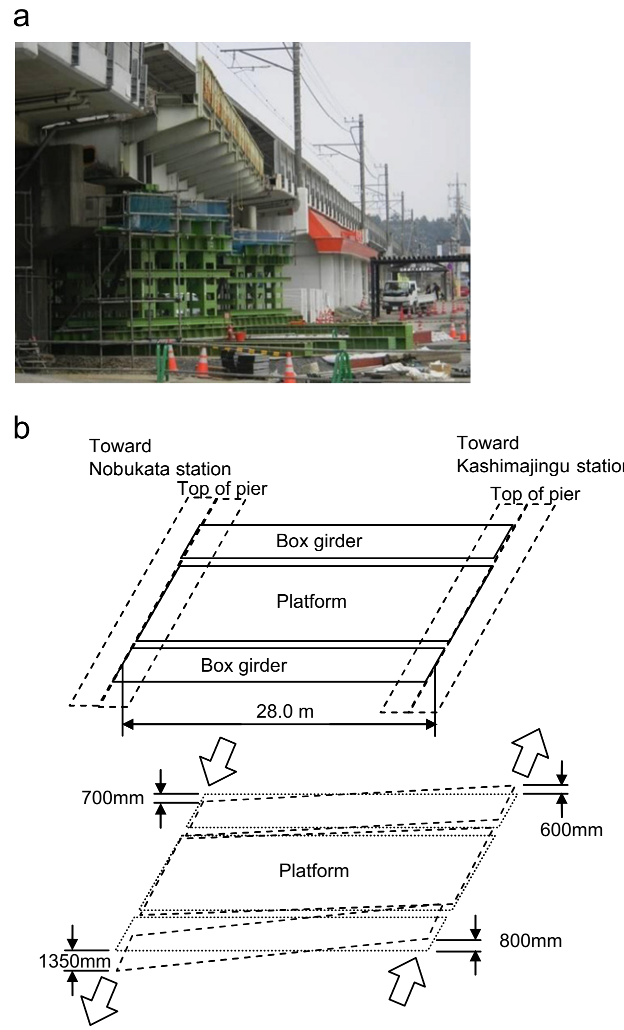

Fig. 15. (a) and (b) Steel beam rotation of Daiichi-Kyuchu bridge along JR Kashima line at 14kl71m between Nobukata and Kashimajingu stations.

Devices to limit earthquake-induced displacement were installed at the top of the piers instead of side blocks.

4.4. No damage to bridge foundation in liquefied subsoil

As shown in Fig. 16, the JR Keiyo Line in the region of Urayasu and Ichikawa Cities, Chiba Prefecture, including Shin-Urayasu Station, to be mentioned below, is constructed in a low land area at the mouth of the Edo River, which is at an elevation of 2 to 3 m above the Tokyo Pile (Tokyo Office of Japan Railway Construction Public Corporation, 1991). The ground consists of a landfill layer (B), Holocene sand layer (As), Holocene clay layer (Ac) and diluvium layers (Ds and Dc). The surface landfill layer consists of fine silty sand and sandy silt, which are both soft and exhibit SPT-N values ranging from 0 to 3. The Holocene sand layer consists of fine sand and fine silty sand, exhibiting SPT-N values of less than 10. It is estimated that the surface landfill layer and the Holocene sand layer were liquefied by the earthquake motion in the vicinity of Shin-Urayasu Station.

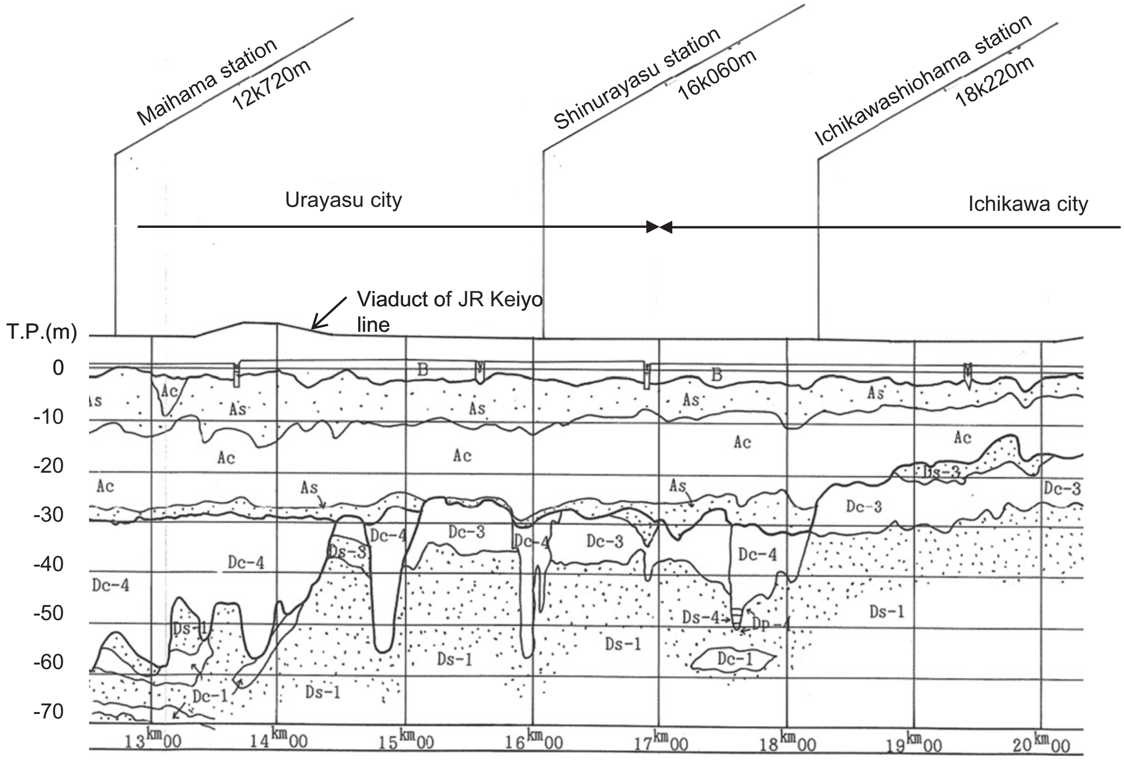

Fig. 16. Ground profile along JR Keiyo line (Tokyo Office of Japan Railway Construction Public Corporation, 1991).

Fig. 17(a) shows side and front views of the Daini-Irifune (rigid frame) Viaducts near Shin-Urayasu Station at 16k060m on the JR Keiyo Line (Tokyo Office of Japan Railway Construction Public Corporation, 1991). They are station viaducts supported by end-bearing pile foundations, which consist of steel tube concrete piles (SC piles) for the upper piles and pre-stressed high-strength concrete piles (PHC piles) for the lower piles. Considering the possible occurrence of liquefaction, they had been designed without considering the subgrade reaction of the soil layers from the surface to a depth of 10 m. Due to the earthquake, liquefaction did take place, inducing a residual ground surface settlement of 100–300 mm around these viaducts, while they did not suffer any structural damage, as shown in Fig. 17(b) and (c).

Fig. 18(a) shows side and front views of the Daini-Urayasu (beam type) Viaducts at 13k899m on the JR Keiyo Line (Tokyo Office of Japan Railway Construction Public Corporation, 1991). Except for the station viaducts mentioned above, the viaducts of the JR Keiyo Line in between Shinkiba and Ichikawa-Shiohama Stations are supported by pile foundations using long friction piles. They had been designed considering the effects of negative friction, caused by residual settlement, which would occur after the completion of the construction work. In addition, they had been designed without considering the skin friction to be mobilized in the uppermost layers from the surface to a depth of 10 m by assuming the possible occurrence of liquefaction. Due to the earthquake, liquefaction-induced ground surface settlement of 100 to 300 mm took place around the viaducts, while they did not suffer any structural damage, as shown in Fig. 18(b) and (c).

5. Tsunami-induced damage to soil-retaining structures and bridge foundations

Fig. 1(b) shows the locations of sites at which retaining structures and bridge foundations were damaged by the tsunami along the East Japan Railway network. Typical case histories are reported herein. Their respective locations are also indicated in Fig. 1(b).

5.1. Collapse of soil-retaining structure

Fig. 19(a)–(c) show the tsunami-induced damage to the retaining wall beside the Ohsawa-gawa Bridge along the JR Kesennuma Line at 54k098m between Motoyoshi and Koganezawa Stations (East Japan Railway Company, 2011). The wall fell down to the seaside, and the backfill soil was eroded by the tsunami.

The Ohsawa-gawa Bridge had a total length of 53.2 m, consisting of 4 T-type reinforced concrete beams, 3 piers and 2 abutments. Due to the tsunami, these beams and piers fell down into the river.

5.2. Damage to bridge foundations

Fig. 20(a) and (b) show the tsunami-induced damage to the Ohtsuchi-kawa Bridge along the JR Yamada Line at

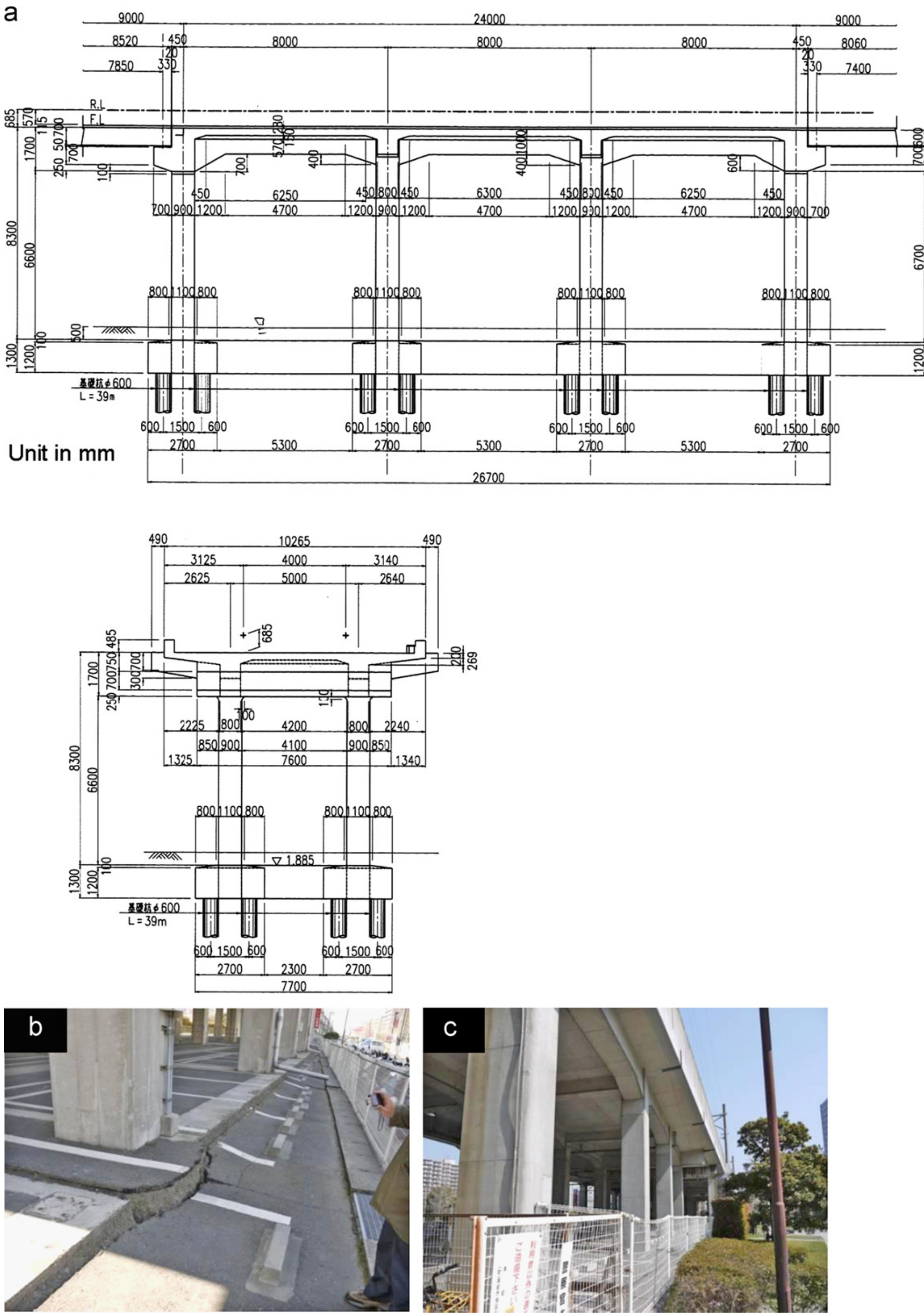

Fig. 17. (a) Side and front views of Daini-Irifune rigid frame viaducts near Shin-Urayasu station at 16k060m on JR Keiyo line (Tokyo Office of Japan Railway Construction Public Corporation, 1991), (b) ground settlement around the viaducts and (c) no damage to the viaducts.

143k279m between Kirikiri and Ohtsuchi Stations (East Japan Railway Company, 2011). The Ohtsuchi-kawa Bridge had a total length of 375 m, consisting of 23 simple steel beams, 22 piers and 2 abutments. All of the steel beams were washed away by the tsunami. Five piers, which had been on land, and two piers, which had been in the river, were also destroyed by the tsunami. The other piers suffered residual inclination into the upstream direction of the river.

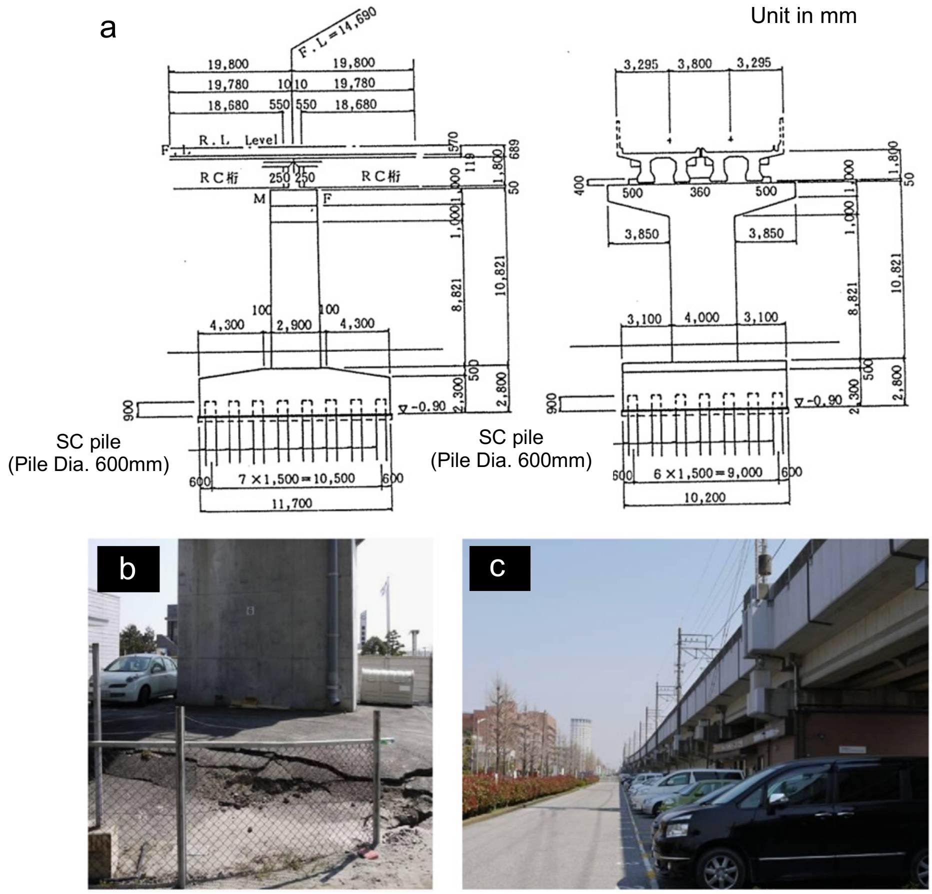

Fig. 18. (a) Side and front views of Daini-Urayasu beam type viaducts at 13k899m on JR Keiyo line (Tokyo Office of Japan Railway Construction Public Corporation, 1991), (b) ground settlement around the viaducts and (c) no damage to the viaducts.

Fig. 21(a) and (b) show the tsunami-induced damage to the Tsuya-gawa Bridge along the JR Kesennuma Line at 50k099m between Rikuzenkoizumi and Motoyoshi Stations (East Japan Railway Company, 2011). The Tsuya-gawa Bridge is 462 m long in total, consisting of 6 pre-stressed concrete beams (PC beams) and 13 reinforced concrete simple beams (RC beams), 17 piers and 2 abutments. All the PC beams, having a length of 35 or 40 m, were severely cracked and washed away by the tsunami. In addition, four piers fell down due to the tsunami. Each of the piers had been reinforced by 48 steel bars with a nominal diameter of 29 mm, while some steel bars were torn down by the tsunami. The backfill soil of one of the abutments was washed away by the tsunami as well. Fig. 21(c) shows the foundation scouring of a pier in a river bed, where the maximum depth of scouring was about 1 m.

6. Summary

In addition to compiling the statistics on the damage to railway earth structures, soil retaining walls and bridge foundations, some case histories on their performance have been described.

Case histories on the earthquake-induced damage to railway earth structures, including cut slopes and embankments, can be summarized as follows:

(1) A cut slope, with a height of about 30 m and consisting of a volcanic ash-origin soil called loam, collapsed. On the other hand, cut slopes in adjacent areas, consisting of the same type of soil and with a maximum height of 14 m, survived the earthquake.
(2) Embankments that had been filled on soft or liquefiable subsoil layers in lowland areas suffered from excessive settlement. In one case, with a soft subsoil layer, the groundwater level was found within the filled soil layer above the subsoil, suggesting that the saturated part of the fill consisting of a sandy soil may have liquefied and induced significant deformation. In another case with a liquefiable subsoil layer, sand boiling from the subsoil layer was observed, confirming the occurrence of liquefaction in the subsoil.
(3) An embankment that had been filled on a valley in a mountainous area suffered from sliding failure. The collapsed soil at its toe part was found to be very soft, namely, consisting of a clayey soil with high water content.

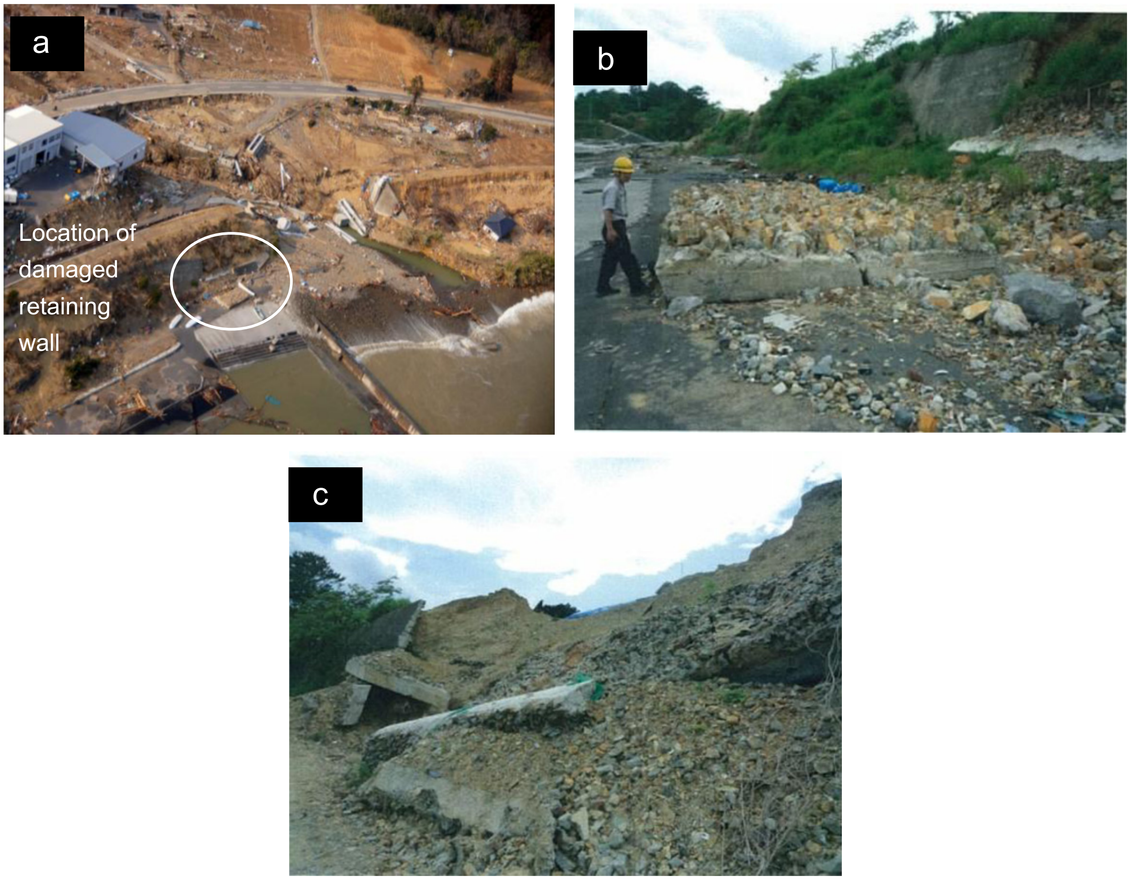

Fig. 19. (a), (b) and (c) Tsunami-induced damage to retaining wall beside Ohsawa-gawa bridge along JR Kesennuma line at 54k098m between Motoyoshi and Koganezawa stations.

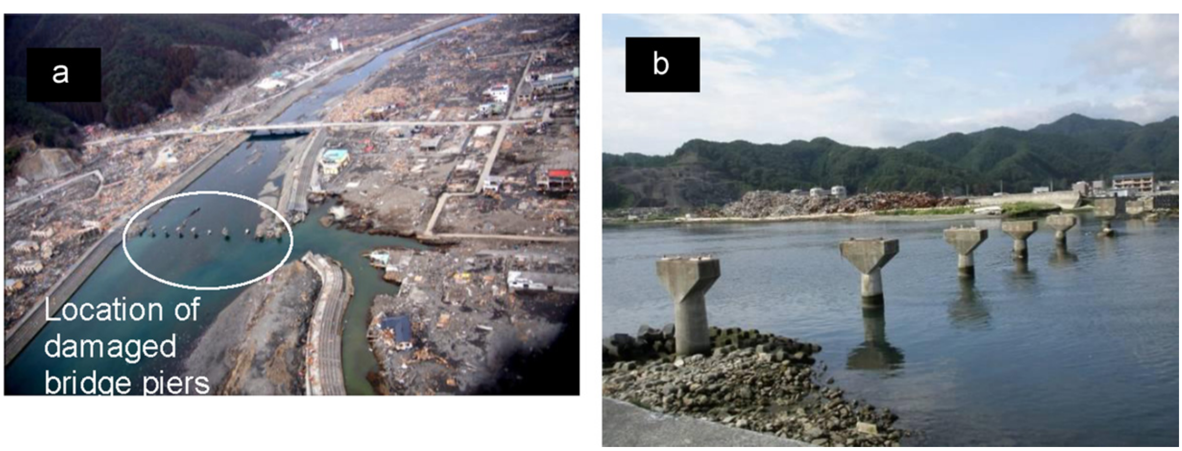

Fig. 20. (a) and (b) Tsunami-induced damage to Ohtsuchi-kawa bridge on JR East Yamada line at 143k279m between Kirikiri and Ohtsuchi stations.

The tsunami-induced damage to railway earth structures can be summarized as follows:

(1) Embankments that were subjected to the tsunami overflow suffered from erosion of the ballasted track on the top and the fill body itself. In particular, there was significant scoring at the backfill soil of bridge abutments. Railway stations constructed on embankments were also severely damaged.

(2) Without overflow, the tsunami induced no major damage to embankments in general. Considering the relatively good performance of the highway and railway embankments that were able to effectively block the tsunami, it is proposed that they shall be utilized as part of the multiple defense facilities against tsunamis, while employing recent geotechnical technologies, such as reinforced soil-retaining walls.

Fig. 21. (a), (b) and (c) Tsunami-induced damage to Tsuya-gawa bridge on JR East Kesennuma line at 50k099m between Rikuzenkoizumi and Motoyoshi stations.

The performance of the soil-retaining walls and the bridge foundations of railway facilities against earthquake loads can be summarized as follows:

(1) Damage to soil-retaining walls induced by earthquake motion was generally limited, while the inclination of a retaining wall on a cut slope and the collapse of a retaining wall at the side of a bridge abutment were observed. In both cases, the earthquake-response characteristics of the walls and their backfill soil may have been largely different from each other, affecting their poor performance.
(2) Earthquake-induced damage to bridge foundations was also limited. However, it was learned from the case history on the Tonegawa-higashi Viaduct that, once they were damaged, particularly when they underwent tilting, their restoration work required a significant amount of time and effort. A beam and piers, which had a skew angle against the track line, suffered from residual rotation, possibly due to the torsion behavior during the earthquake. Detailed attention should be given to such types of structures.
(3) Two types of viaducts, that had been designed considering the effects of liquefaction and constructed on reclaimed land, suffered no structural damage, despite the residual settlement of the surrounding ground by 100–300 mm due to liquefaction.

The performance of the soil-retaining walls and the bridge foundations of railway facilities during the tsunami can be summarized as follows:

(1) Soil-retaining walls, subjected to the overflowing of the tsunami, collapsed completely, and their backfill soils were washed away. They had not been designed to resist the effects of tsunamis. Even at the present time, it would be difficult to establish rational design procedures for them considering the effects of tsunamis. Use of a retaining wall structure that would perform in a ductile manner against the overflow of tsunamis, such as reinforced soil-retaining walls, is desirable.
(2) Bridge foundations in rivers and in dry river beds collapsed completely by the tsunami; they had not been

designed to combat the effects of tsunamis. When the tsunami overflowed them, their beams, piers and abutments were washed away. It is important to reduce the force of tsunamis acting on the beams and foundations, for example, by adopting thin beams, particularly when connecting the beam and pier rigidly.

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References

East Japan Railway Company, 2011. Special issue on the 2011 off the Pacific coast of Tohoku earthquake and railway structures, Structural Engineering Data, 37, 302p (in Japanese).

East Japan Railway Company, 2012. Accounting report as of March 2012 (in Japanese). Available from: 〈http://www.jreast.co.jp/investor/guide/pdf/201203guide1.pdf〉 (accessed 05.07.12).

Iwamoto, H., 2011. Recovering work on Tonegawa-higashi viaduct of Tsukuba Express. Journal of Japan Railway Civil Engineering Association 49 (10), 52–54 (in Japanese).

Iwamoto, H., Yonezawa, T., 2012. Damage to Tonegawa-higashi viaduct of Tsukuba Express and its recovering work. Kisoko 40 (4), 74–77 (in Japanese).

Japanese Geotechnical Society, 2011. Geo-hazards during earthquakes and mitigation measures-lessons and recommendations from the 2011 Great East Japan Earthquake, 84p.

Miyagi Prefecture, 2011. Miyagi prefecture disaster recovery plan. Available from: 〈http://www.pref.miyagi.jp/seisaku/sinsaihukkou/keikaku/index en.htm〉 (accessed 16.03.12).

Ministry of Land, Infrastructure, Transport and Tourism, 2011. Report of survey and restoration planning of tsunami-induced damage to medium- and small-scale private railways (in Japanese).

Mizutani, K., Suzuki, Y., Okada, N., 2011. Damage to Keisei Electric Railway and its restoration. Journal of Japan Railway Civil Engineering Association 49 (10), 48–51 (in Japanese).

Mochizuki, M., 2011. Damage to Sanriku Railway and its restoration activities up to today. Journal of Japan Railway Civil Engineering Association 49 (10), 43–45 (in Japanese).

Nozawa, S., Shirasaki, H., Wada, A., Tomori, M., 2012. Damage and restoration of the railway structures caused by the 2011 off the Pacific coast of Tohoku earthquake. Japanese Geotechnical Journal, Japanese Geotechnical Society 7 (1), 127–137 (in Japanese).

Railway Technical Research Institute, 2011. Technical proposals for restoration and rehabilitation works of earthquake-induced damage to railways, 94p (in Japanese).

Tetsudo.com, 2012. Summary of re-opening status of suspended railway lines (in Japanese). Available from: 〈http://www.tetsudo.com/special/disaster2011/?date=20120317〉 (accessed 05.07.12).

Tokyo Office of Japan Railway Construction Public Corporation, 1991. Keiyo line construction record, pp. 167–168 (in Japanese).