Geotechnical Extreme Events Reconnaissance (GEER)

Preliminary Observations of Levee Performance and Damage following the March 11, 2011 Tohoku Offshore Earthquake, Japan

by

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Acknowledgments

The authors had the opportunity to tour portions of the areas affected by the March 11, 2011 Tohoku Offshore Earthquake on the northern portion of Honshu, Japan between April 19-24, 2011, approximately 6 weeks after the main event. The principal purpose of the tour was to observe and document the performance of levees following the earthquake and tsunami events. The authors were greatly aided by the briefings and information provided by Drs. Jiro Takemura and Akihiro Takahashi, associate professors at Tokyo Institute of Technology (TIT), and by Toshiro Suzuki and Shingo Satou of Japan's Ministry of Land, Infrastructure, and Transportation (MLIT). Much of the information for levee performance and repair in the Tohoku and Kanto regions were provided by the MLIT and TIT. Their assistance was invaluable in developing the observations, and information included in this report. The GEER Team greatly appreciates the assistance and efforts provided by these colleagues.

Introduction

The principal purpose of this GEER Team reconnaissance was to document the performance of levees following the earthquake and tsunami. There are hundreds of kilometers of levees bordering several different rivers in the Tohoku and Kanto regions in northeastern Japan. The authors inspected levee performance in these two regions with particular focus on the eastern parts of Miyagi and Ibaraki prefectures (see Figure 1). The levee damage resulting from the earthquake and tsunami was documented immediately following these events by the MLIT. The extant body of knowledge on the locations and types of levee damage was graciously shared by both MLIT and TIT with the GEER Team, and enabled the authors to focus on specific areas during our limited field reconnaissance. As noted below, many of the sites with major damage had been already under repair at the time of the reconnaissance, thus limiting our assessments of original post-earthquake site conditions and possible damage mechanisms.

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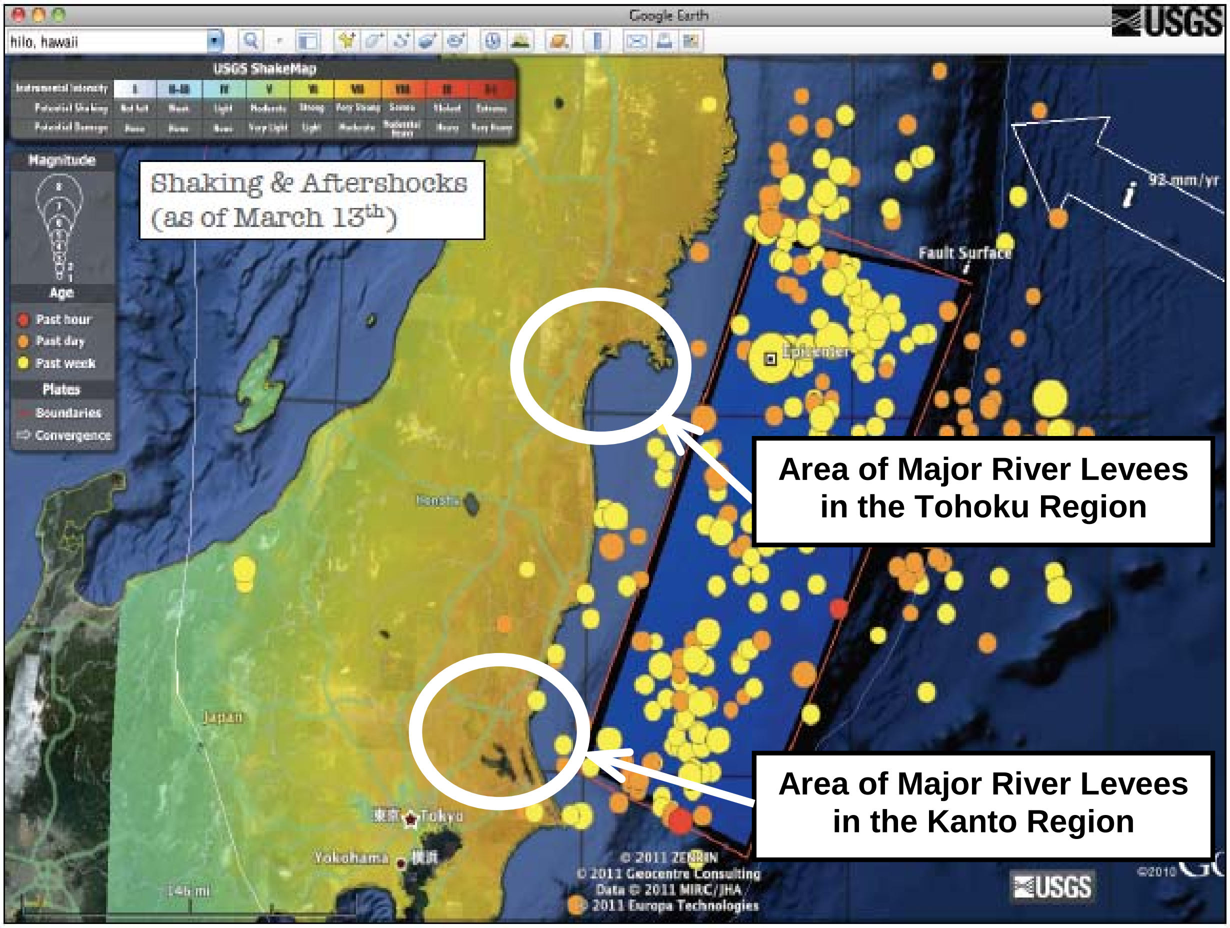


Figure 1: General Location of Major River Levees in the Tohoku and Kanto Regions Shown on USGS Shake Map (adapted from USGS, March 13, 2011)

At the time of the earthquake, the river levels were relatively low and within the channels and not on the levees themselves. Thus, the vast majority of levee embankments were not saturated at the time of the earthquake. Consequently, most levee reaches performed well with little or no damage or distress. However, there were numerous reaches with moderate to major damage (see Figures 2 and 3). For the most part, the damage was ascribed to foundation liquefaction. For these levee incidents, no flooding resulted because the water levels were low and within the channel. This was true even for levees that were almost totally destroyed by foundation liquefaction. However, near the coast, many river levees near their mouths were overwhelmed by tsunami waves that caused serious damage to the levees and commonly flooded and obliterated the communities behind the levees and floodwalls.

In some cases in the tsunami-affected areas of the river systems, it appeared that liquefaction-induced damage and settlement of the levee may have resulted in concentrations of overtopping flows by the subsequent tsunami that then resulted in more overtopping damage to the levee and adjacent areas.

Figure 2: Photograph of Major Slumping of Landside Slope of Naruse River Right Levee and Approach Road at River Kilometer 30.0 (N38.5307, E 141.0064, April 20, 2011) – see Figure 8 for additional views and aerial image

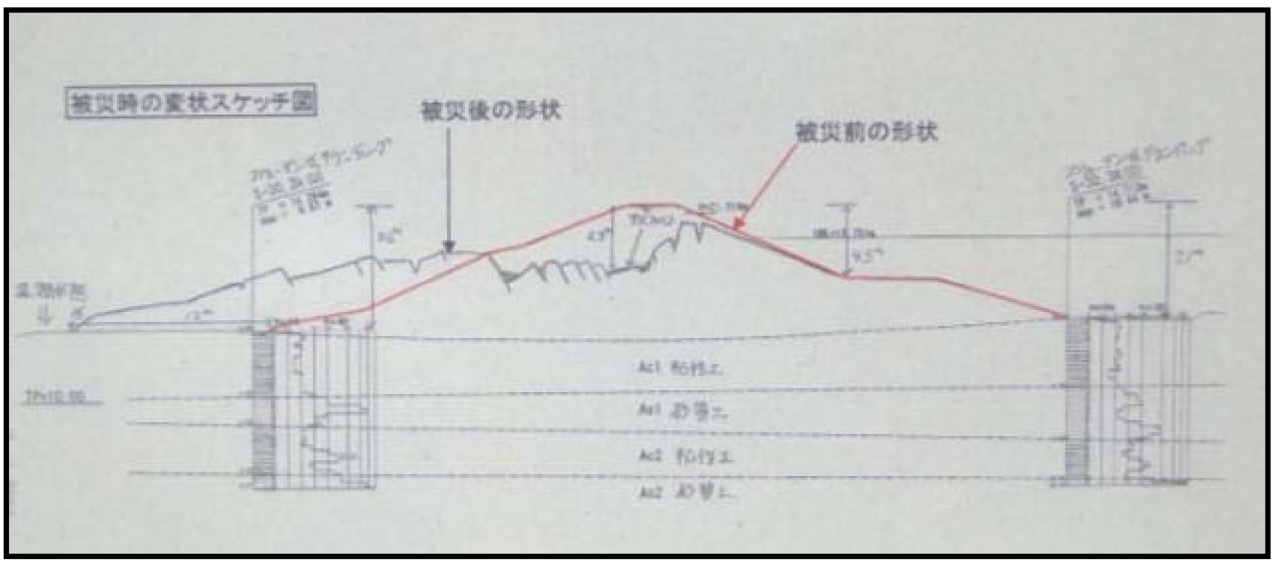


Figure 3: Drawing Depicting Major Levee Damage along Naruse River Due to Earthquake-Induced Foundation Liquefaction
(from MLIT, 2011)

Liquefaction was thought to have developed in either foundation sands or in the lower portions of a sandy levee embankment that had settled sufficiently into a clay foundation to be saturated by groundwater. At several distressed levee sections, sand boils were observed along cracks in the levee embankment, or in the foundation beyond the levee. At several sites, groundwater on the landward side of the levee appeared to be significantly higher than the water level in the river, indicating groundwater flow towards the river.

In most areas, the general settlement of even non-distressed levees appeared to be about 7 to 15 cm relative to hard structures such as bridge piers or buried water conveyance structures. However, in areas where liquefaction appeared to have occurred, general settlement was sometimes 20 to 40 cm relative to hard structures.

PERFORMANCE OF LEVEES IN MIYAGI PREFECTURE

Levee Observations Upstream of Tsunami Inundation

In the Tohoku region near Sendai, Japan, the MLIT, an agency of the federal government of Japan, is responsible for approximately 210 kilometers of levees/floodwalls. While the majority of levee reaches had little or no damage, the MLIT reported that it had documented 1,190 locations of levee/floodwall distress. Of these, approximately 25 were considered to represent major structural damage or failure. The classifications of damage are summarized in Table 1:

Table 1: Type of Levee Damage Documented by the MLIT in the Tohoku Region (from MLIT, 2011)

River System	Type and Number of Levee Damage Sites Reported							
	Failure	Settlement	Slope Slumping	Levee Cracking	Revetment /Wall Damage	Gate Damage	Other	Total
Mabuchi	0	1	1	1	5	1	5	13
Kitakami	13	62	47	278	121	67	58	646
Naruse	9	27	25	183	56	26	37	363
Natori	1	2	1	26	2	2	1	35
Abukuma	2	26	16	73	2	10	3	132
TOTAL	**25**	**118**	**90**	**561**	**186**	**106**	**104**	**1190**

Figures 4 and 5 present additional photographs of levee damage caused by foundation liquefaction in the Miyagi Prefecture. In this area, preliminary results from seismographic recordings indicated peak ground accelerations in this area generally ranging between 0.27g and 0.66g, with a maximum peak acceleration of 0.94g recorded at the coast near the town of Oshika.

(a)

(b)

(c)

Figure 4: (a) Moderate Landward Slumping and Cracking of Levee Crown (note interim repair of more seriously damaged reach in the background, see Figure 12), (b) 30-60 cm Bulge at Landside Toe, and (c) Residual Sand Boils on Landside Berm on Naruse River Left Levee at River Kilometer 11.3-11.1 (N38.4538, E141.1087, April 21, 2011)

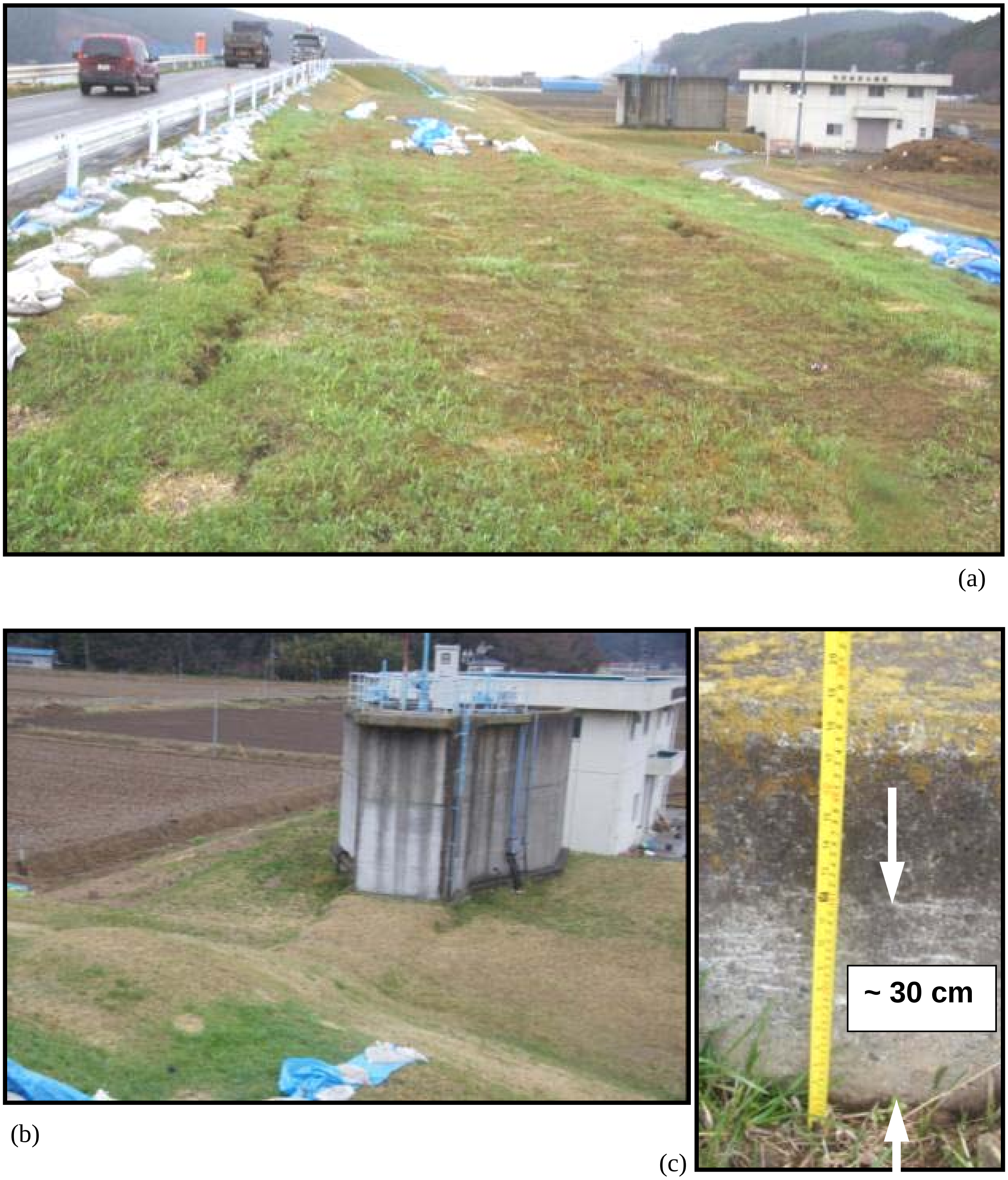
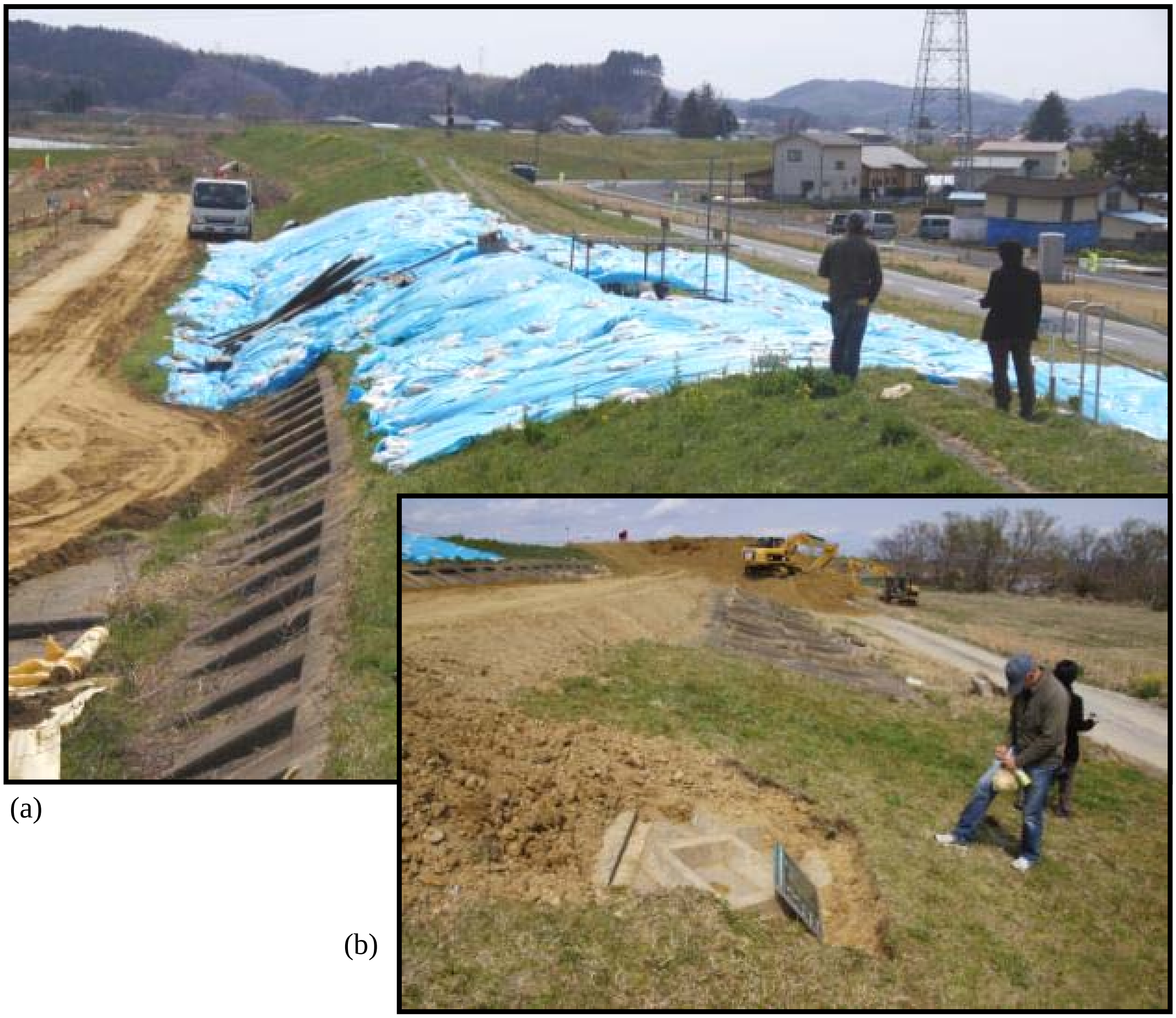


Figure 5: (a) Moderate Longitudinal Cracking and Slumping of Upper Landside Levee Slope, (b) Differential Settlement Over Reinforced Concrete Conduit on Lower Landside Levee Slope, and (c) Approximately 30 cm of Differential Settlement at Concrete Water Tank at Landside Levee Toe on Kitikami River Left Levee at River Kilometer 8.8 (N38.5320, E141.3687, April 22, 2011)

Along the Naruse River, the GEER Team also observed evidence of previous repairs of the right levee at River Kilometer 12 that had been damaged by the 2011 earthquake. Distress of the levee crest and waterside embankment during the 2011 includes cracked and thrusted concrete revetments and open cracks on the crest and side slopes (see Figure 6). Pre-2011 distress at this site is suggested by the exposure of a newer, damaged revetment that was inset locally into the older revetment. This location coincides with the mapped location (MLIT, 2011) of a former meander bend of the Naruse River that may extend orthogonally beneath this section of the levee (see Figure 7). This paleochannel may contain different soils than those in the surrounding areas and they may be more susceptible to losses in shear strength. This is important because of a common association of paleochannels with areas of repeated levee deformation in California's Central Valley.



(a)

(b)

Figure 6: (a) Photograph Looking Downstream of Longitudinal Cracking and Slumping of Levee Crown and (b) Photograph Looking Upstream of Exposed More Recent Revetment on Waterside Slope – Evidence of Previous Repair at Naruse River Right Levee at River Kilometer 12.0 (N38.4596, E141.1088, April 21, 2011)

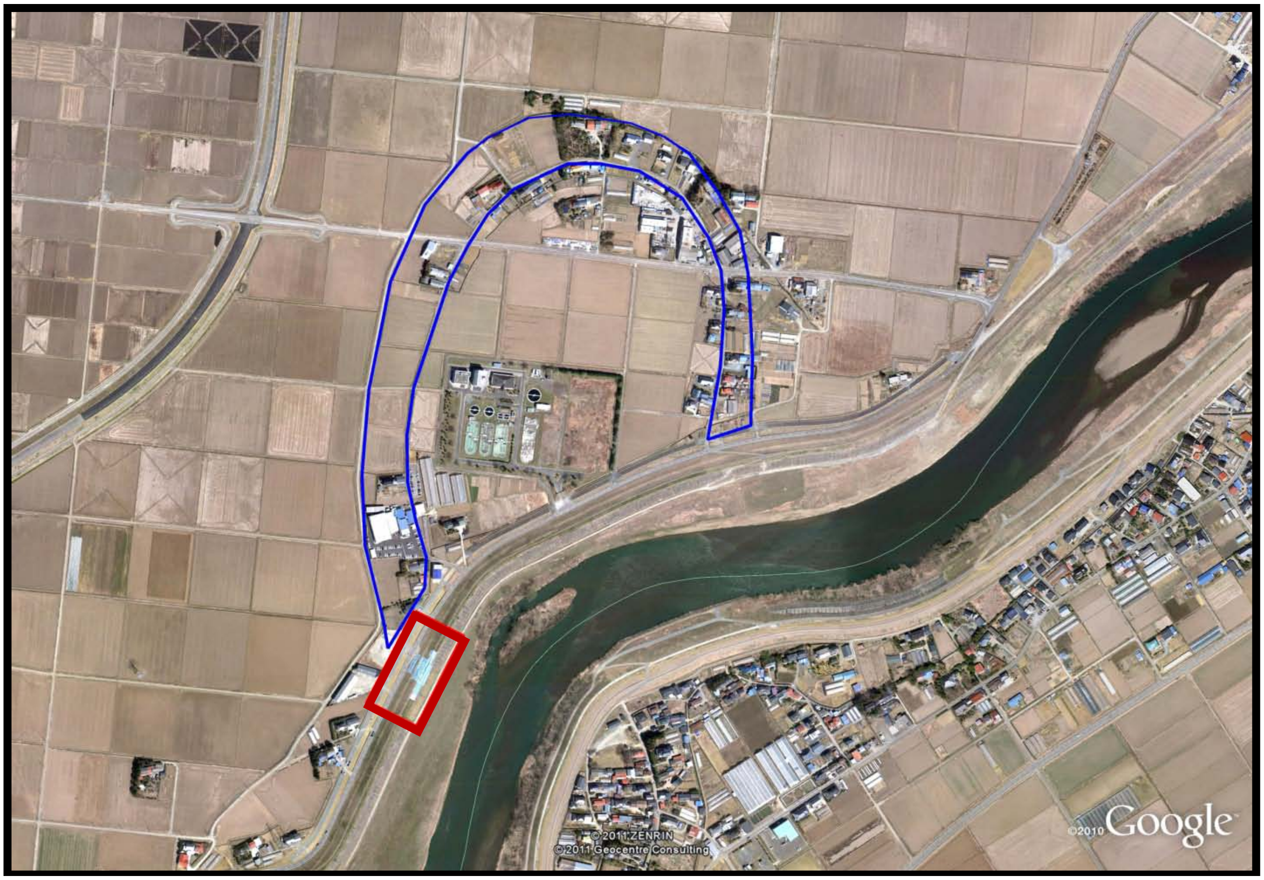


Figure 7: Aerial Image of the Naruse River near River Kilometer 12 Showing Repaired Area of Right Levee (red box) and Shallow Paleochannel with Geomorphic Expression on Northern Side of Levee (blue polygon) – adapted from Google Earth, 2011

Along the Naruse River near the town of Matsuyama (at River Kilometer 30.0), damage and distress of the right levee involved complex landward deformation with a connected approach road embankment to a concrete-span bridge (see Figure 8 and previously shown Figure 2). The roadway approached the levee crown from the southwest, and the combined embankment failed landward towards the south and damaged adjacent property. The right levee/abutment fill shows evidence of landward extension from the southernmost bridge span (see Figure 8b). The left (northern) levee/abutment fill also was damaged both upstream and downstream of the bridge, and experienced about 10 cm of settlement relative to the bridge (see Figure 8c). In addition, the bridge spans show evidence of small amounts of contraction at deck seams and broad arching (see Figure 8d).

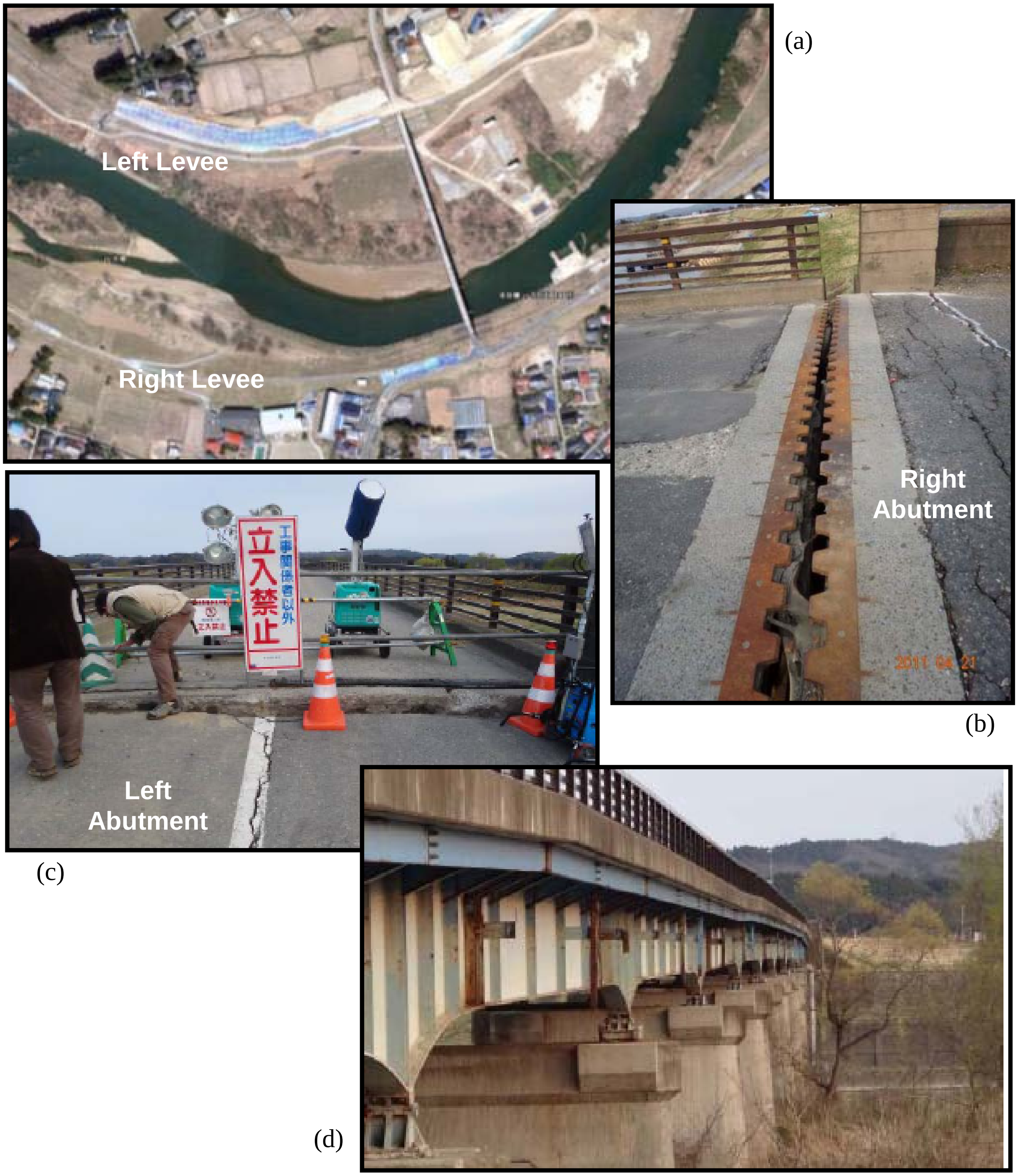


Figure 8: (a) Aerial View of Bridge and Levees (adapted from Google Earth, 2011), (b) View Looking Downstream (east) at Separation Between Bridge Span (on left) and Right Levee/Abutment Fill (on right), (c) View Looking South (across river) at Settlement and Separation of the Left Levee/Abutment Fill, and (d) View of Irregular Bridge Deck of the Matsuyama Bridge Across the Naruse River at River Kilometer 30.0 (N38.5322, E141.0059, April 21, 2011)

Repairs of Levees Damaged by Liquefaction

By the time the authors toured the area 6 weeks after the earthquake, interim repairs had been completed for most of the levees seriously damaged by liquefaction outside of the tsunami areas. The interim repairs generally consisted of the following:

- Removal of any broken revetments and paving
- Placement of new earth fill into cracks and bring levee section back up to original grade
- Place of new buttresses or berms where needed
- Placement of straw mats on landside slope to provide slope protection
- Placement of articulated concrete blocks (cabled together) on waterside slope and portions of restored levee crown to armor these areas
- Placement of gravel road base on center of levee crown

Figure 9 shows the construction of a large waterside berm as part of the initial phase of an interim repair for a levee on the Naruse River. This repair is on the left levee at River Kilometer 30.1, directly across the river from the slumping on the right bank shown in Figure 2 (see also aerial view of left levee in Figure 8a).

Figure 9: Photograph of Construction of Large Waterside Berm as Part of an Interim Repair of the Naruse River Left Levee at River Kilometer 30.1
(N38.5333, E 141.0050, April 20, 2011)

In some areas, a double row of sheetpiles filled with soil was used as an interim retaining structure instead of, or in addition to, the repair of the levee itself. Figures 10 and 11 present sketches illustrating the general approaches for interim repairs for the liquefaction-induced damage. Figure 12 presents a photograph of a completed interim repair on the Naruse River immediately adjacent to the moderately slumped levee shown in Figure 4.

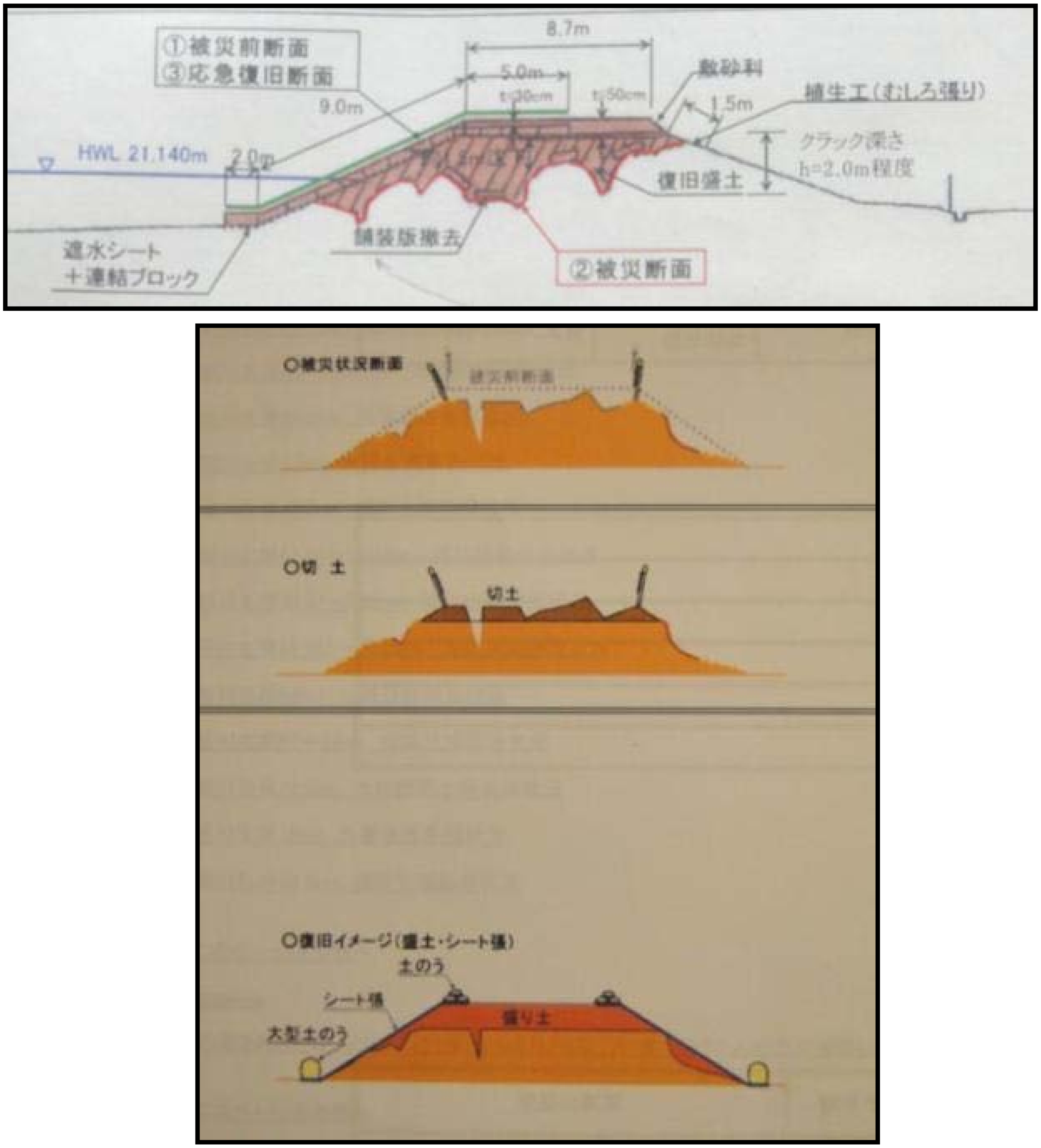


Figure10: Drawings Depicting Conceptual Approach for Interim Levee Repairs (from MLIT, 2011)

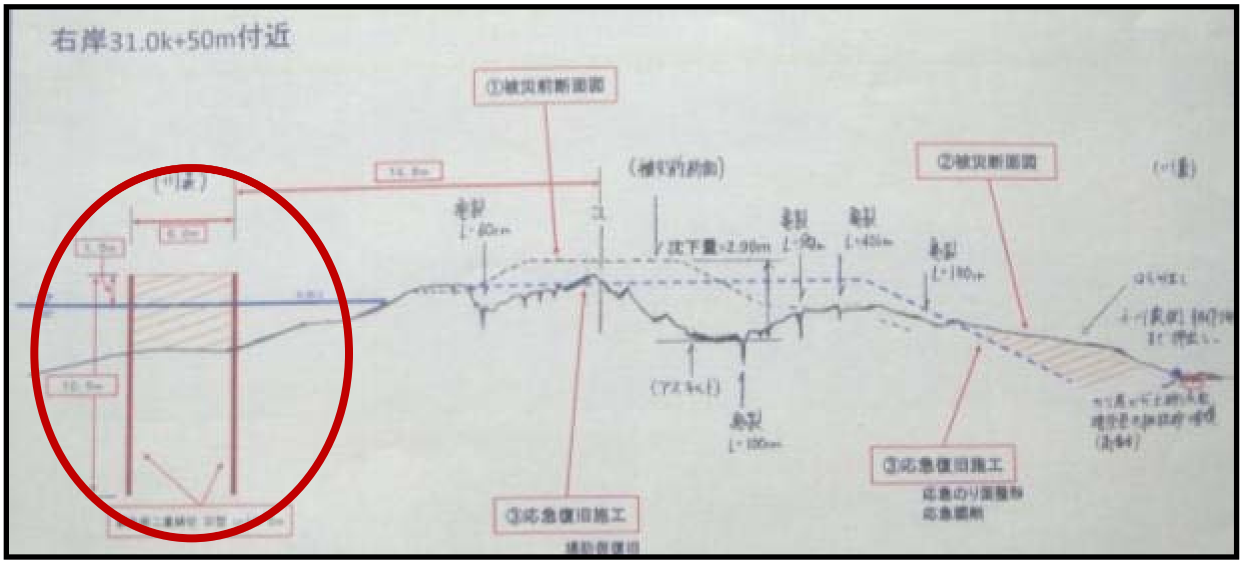


Figure 11: Drawing Depicting Sheetpile Interim Repair for Liquefaction-Related Damage on Abukuma River Levee at River Kilometer 31+50
(from MLIT, 2011)

Figure 12: Completed Interim Repair of Liquefaction-related Damage to Naruse River Left Levee at River Kilometer 11.3 (N38.4538, E141.1087, April 21, 2011)

For levee reaches with only minor to moderate damage, blue plastic tarps had been placed over the cracked and distressed areas and held down with sandbags with the apparent thought that these reaches would be repaired later after repairs to the more heavily damaged levees were completed.

The interim repairs are expected to allow the levees to perform adequately through the upcoming flood season in June through August. Following previous earthquakes, levees seriously damaged by foundation liquefaction locally were permanently repaired by removing the damaged levee and treating the foundation down to the depth of liquefaction (see Figure 13). The foundation treatment appears to have been mix-in-place columns of soil-cement across the entire levee footprint with columns basically constructed almost edge to edge. Following foundation treatment, the levee would be reconstructed back to the original height, but sometimes with a modified cross section. Following the 2003 Miyagi North Continuation Earthquake (M=6.2), this type of repair had been completed for several levee sections in the Tohoku region. All of these previously repaired sections with foundation treatment were reported to have performed well during the more powerful 2011 earthquakes with little or no damage observed.

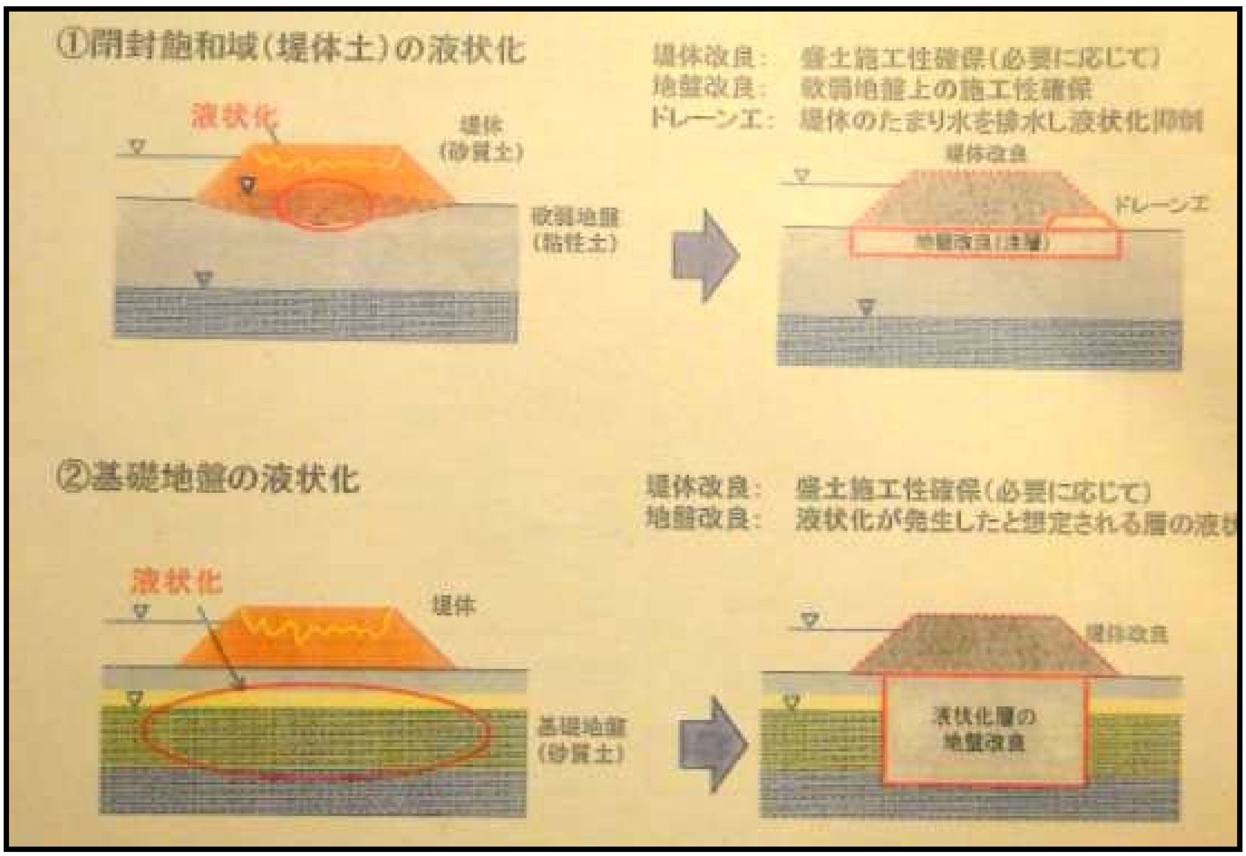


Figure 13: Drawing Depicting Permanent Repair Approach Using Foundation Treatment for Levees Seriously Damaged by Liquefaction
(from MLIT, 2011)

The authors were able to inspect four of the previous treatment sites along the Naruse River and were able to confirm no visual damage evident in the treated areas for the 2011 event:

- Naruse River Left Levee at River Kilometer 13.3 – 12.7 (N38.4637, E141.1230)
- Naruse River Left Levee at River Kilometer 12.5 – 12.1 (N38.4593, E141.1168)
- Naruse River Right Levee at River Kilometer 15.0 – 14.7 (N38.4784, E141.1257)
- Naruse River Right Levee at River Kilometer 13.1 – 12.9 (N38.4638, E141.1186)

For two of the previously treated levee reaches, levees on either side of the treated lengths developed foundation liquefaction and experienced minor to moderate levee cracking and slumping during the 2011 event. Figure 14 illustrates landside longitudinal cracking and slumping, together with transverse cracking at the levee crown, directly downstream of the treated reach of the Naruse River Right Levee at River Kilometer 14.7.

Tsunami Effects

Near the coast, large tsunami waves heavily damaged or destroyed levees and floodwalls. This caused great destruction to the communities lying behind the levees/floodwalls. The tsunami waves also increased river levels away from the coast with 10-cm water level increases or surges reported as far as 49 kilometers upstream of the river mouth (see Table 2, MLIT, 2011).

Table 2: Distances along Major Rivers in Miyagi Prefecture Inundated by Tsunami, Waves Upstream from Coastline (from MLIT, 2011)

River System	Distance Upstream from Coastline (km)			
	Tsunami Above Levee Crown	Tsunami on Levee Face	Tsunami Below Levee Toe	Tsunami Upstream Extent
Kitakami	0 to 5.5	to 17	to 49	49
Old Kitakami	0 to 12	to 19	to 33	33
Naruse	0 to 3.0	to 10	to 15	15
Yoshida	No data	No data	to 14	14
Natori	0 to 0.8	No data	to 7	7
Abukuma	0 to 2	to 11	to 13	13

For two rivers in the Tohoku region, the Abukuma and Kitakami Rivers, surge barriers constructed within the river system were successful in preventing any significant increases in river stage upstream of the barriers. The barriers had been constructed to prevent surges from typhoons, help prevent salt water intrusion, and control upstream water levels (see Figure 15). While the two surge barriers were reported to have sustained minor damage from the tsunami waves, they were reported to have remained functional. However, by the time the tsunami waves reached the barriers, located at 10 and 17 kilometers upstream of the river mouths, the tsunami waves were relatively small and already not a danger to the levee system (see Table 2).

Figure 13: (a) Aerial View of Treatment Area (adapted from Google Earth, 2011), (b) Longitudinal Cracking and Slumping of Waterside Levee Slope Downstream of Treatment Area, and (c) Transverse Cracking on Levee Crown at Downstream Edge of Treatment Area on Naruse River Right Levee At River Kilometer 15.0 - 14.7 (N38.4784, E141.1259, April 21, 2011)

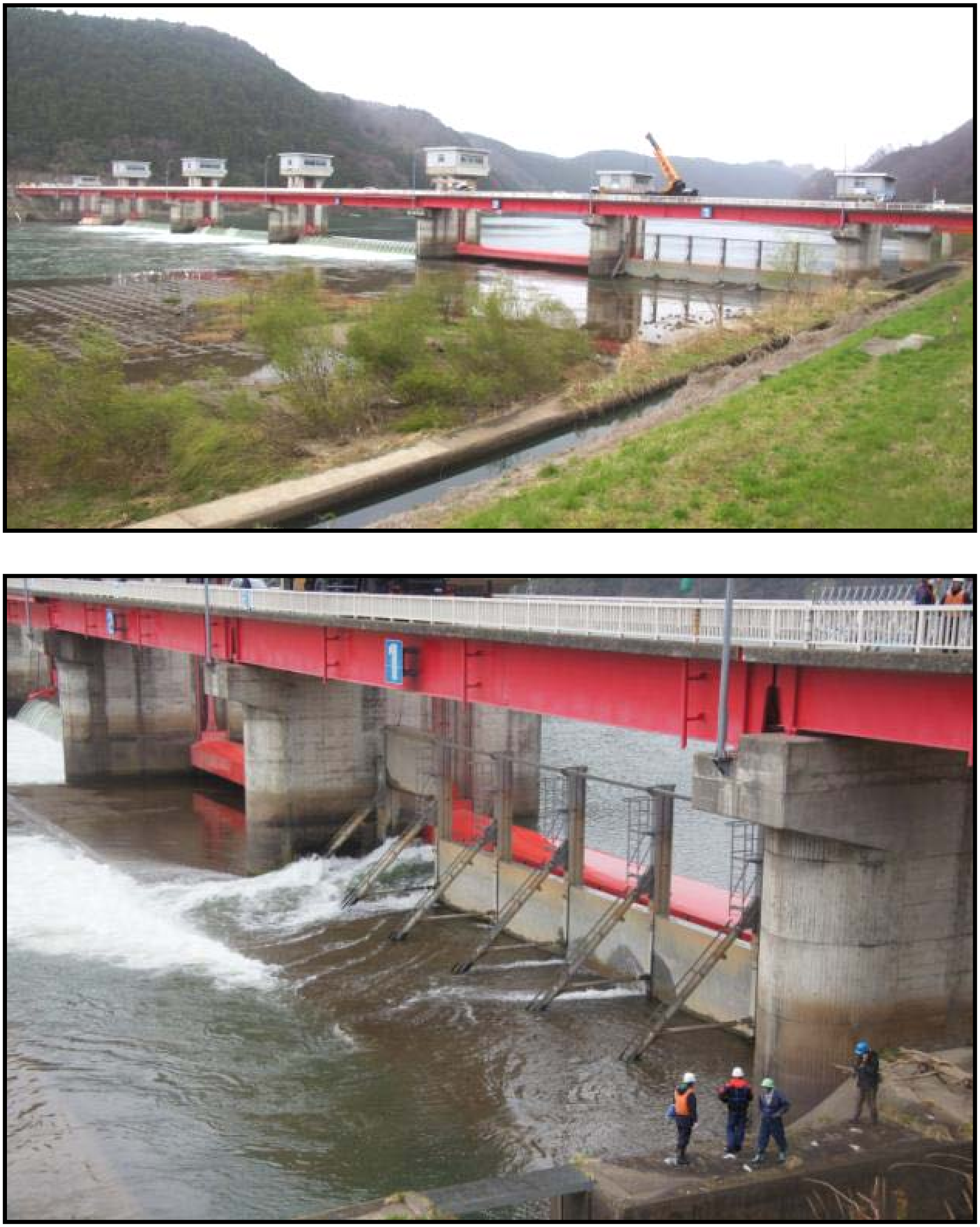


Figure 14: Views of Surge Barrier on Kitakami River at River Kilometer 17
(N38.5294, E141.3097, April 22, 2011)

Many of the floodwall/levee sections along the river systems near their mouths had been constructed with a sloping concrete floodwall on the waterside slope and rising about 60 cm above the top of an earthen levee. Levee crowns with such floodwalls were commonly only about 3 to 5 meters high with 3 to 8 meter crown widths. The tsunami waves commonly overtopped the floodwalls by several meters and caused major erosion of the earthen levee and scour at the levee's landside toe. In many cases, this was sufficient to undermine the floodwall and led to a complete breach. The overtopping and breach tsunami flows devastated areas behind the levees (Figures 15 through 22)..

Where overtopped, substantial landside scour occurred into levee embankments, and highlighted the absence of hardened erosion control on the landside surfaces. The damage on the landside contrasted greatly with that on the waterside, which typically exhibited only minor and local scour because of erosion-resistant designs. However, near the ocean, scour did occur on some waterside levee slopes as the tsunami flows receded back towards the river and ocean. Although little or no evidence of liquefaction remains in areas affected by tsunami waves, it seems likely that some of the areas that experienced tsunami overtopping had localized lower crown elevations that had resulted from liquefaction-related lateral spreading in advance of the tsunami waves. In short, in areas where tsunami inundation levels were equal to or higher than the levee crests, liquefaction-induced damage and/or settlement of the levee may have resulted in concentrations of overtopping tsunami flows, which then resulted in increased landside scour, aggravated incision into the embankment, and development of levee breaches that caused additional damage to adjacent landside areas.

The riverine floodwalls on top of the levees near the mouths of the river sometimes seemed smaller and lower than those placed along the adjacent coast (see Figures16 and 23). The riverine floodwall along the right levee of the Naruse River was found to be approximately 2 meters lower than the coastal floodwall to which it was connected (see Figure 16). The coastal floodwall at this location appeared to have only minor damage associated with perhaps limited overtopping. However, the much lower riverine levee was extensively damaged and breached by overtopping flows. If all of the riverine levees/floodwalls had the same heights as the coastal floodwalls they were connected to, the tsunami damage might have been smaller.

Nevertheless, with the exception of the dramatic and extremely damaging levee failures at or very near the coast, the levees generally protected landside property. On each of the major rivers visited by this team, there are several km of levee that effectively confined the tsunami wave to the floodplain, and protected landside property. As a result of the confinement of the tsunami wave in the channelized river system, the impacted area of tsunami inundation likely was smaller than what would have occurred in the absence of effective flood protection.

In addition, the pattern of tsunami deposits resulting from the 2011 earthquake may differ substantially from that of previous historical and pre-historical inundations, including those identified in the early historical and paleoseismic records, because the flow patterns and hydrodynamic properties of the 2011 waves were affected by the levee flood protection system as well as other modern engineered features and local topographic modifications.

(a)

(b)

Figure 15: (a) Waterside View and (b) Landside View of Levee/Floodwall Sections Damaged by Tsunami Waves Along Right Bank of Naruse River Near the River Mouth (N38.3775, E141.1716, April 20, 2011)

(a)

(b)

Figure 16: (a) View of Collapsed Levee/Floodwall Along Right Bank of Naruse River at River Mouth and Connection with Coastal Floodwall and (b) View Illustrating 2-meter Higher Crown Elevation of Coastal Floodwall Above Riverine Floodwall
(N38.3756, E141.1727, April 20, 2011)

(a)

(b)

Figure 17: (a) Aerial View (adapted from Google Earth, 2011) and (b) Photograph of Homes Behind Right Levee of Naruse River at the River Mouth Obliterated by Tsunami Waves ((N38.3763, E141.1711, April 20, 2011)

Figure 18: Photographs of Left Bridge Spans Destroyed by Tsunami Waves and Twisted Wreckage Upstream of Kitakami River Bridge at Approximately Kilometer 4 - Tsunami Height Above Bridge Deck ~170 cm (Based on Water Stains on Building on Left Kitakami Levee)
((N38.5485, E141.4201, April 22, 2011)

Figure 19: Photographs of Tsunami Debris and Pedestrian Deck/Railing Flipped Up and Against Downstream Side of Kitakami River Bridge at Approximately Kilometer 4 – Tsunami Height Above Bridge Deck ~170 cm (Based on Water Stains on Building on Left Kitakami Levee) ((N38.5458, E141.4257, April 22, 2011)

(a)

(b)

Figure 20: Photographs of Erosion and Scour of Levee Slope on (a) Left Levee and (b) Right Levee of Kitakami River at Immediately Downstream of Kitakami River Bridge at Approximately River Kilometer 4 – Tsunami Height Above Levee Crown ~170 cm (Based on Water Stains on Building on Left Kitakami Levee at Bridge) ((N38.5468, E141.4238, April 22, 2011)

Figure 21: Photographs of Tsunami Damage to Homes and Structures Behind Left Levee of Kitakami River near River Kilometers 2 to 0.5
(N38.5639, E141.4294, April 22, 2011)

Figure 22: Photograph of Nirashima School (Reinforced Concrete Buildings) Damaged by Tsunami Waves Behind Right Levee of Kitakami River Immediately Downstream of Kitakami River Bridge at Approximately River Kilometer 4 (N38.5460, E141.4283, April 22, 2011)

Figure 23: Photograph of Relatively Low Floodwall on Left Bank of Kitakami River Near River Kilometer 0.5 (N38.5763, E141.4546, April 22, 2011)

Interim Repairs to Tsunami Levee/Floodwalls

Interim repairs of levees and floodwalls for tsunami damage consisted mostly of placing new levee fill to restore the eroded sections, and placing various types of slope protection ranging between new concrete revetments, articulated concrete mats, or riprap (see Figures 24 and 25). In some cases, rows of large sand bags were being used to retain new fill before being covered over with additional fill and slope protection measures. At the time of our reconnaissance, much of this work was ongoing and much was still left to be done.

PERFORMANCE OF LEVEES IN IBARAKI PREFECTURE

Summary

There are numerous levees in the Ibaraki Prefecture providing flood protection along several different river systems. MLIT and TIT investigators have documented several levee reaches along the Tone, Ono, Tomoe, Wani, and Hinuma Rivers where minor to major damage was attributed to foundation liquefaction. At the time of this GEER reconnaissance, most of these sites had already been repaired. However, the authors were able to view the unrepaired portion of levee damage along the Hinuma River. We were also able to inspect a large lateral spread of reclaimed land at the Kaminoike Green Park. In these areas, preliminary results from seismographic recordings indicated peak ground accelerations generally ranging between 0.2 and 0.5g.

Figure 24: Photograph of Construction Equipment Being Used to Rebuild Landside Levee Section Eroded Along Left Kitakami River Levee by Tsunami Waves near River Kilometer 1.5 (N38.5703, E141.4384, April 22, 2011)

Hinuma River/Lake Hinuma

The Hinuma River flows from Lake Hinuma to the ocean near the town of Mito (see Figure 26), and is bordered on the west by levees that experienced relatively extensive damage from foundation liquefaction (see Figures 27 through 31). This levee, apparently founded on dredged fill/reclaimed land, was observed to have extensive cracking and slumping for over 2½ kilometers along the western margin of Lake Hinuma, a shallow, near-coastal lake. In some areas, new fill had been placed into limited reaches where it appeared that the river/lake might breach the slumped levee. The difference in the length of damage along this levee, as opposed to the more limited (but multiple) damaged reaches in the Miyagi Prefecture, and other locations in the Ibaraki Prefecture, appears to reflect the presence of man-made foundation materials and/or the presence of lake water that was high enough to saturate both the foundation and the lower portions of the embankment. In some lengths along the left levee, the Hinuma Lake/River water level was about a meter higher than the landside ground surface. Exposed embankment material in the numerous large cracks indicated that at least the upper fill was composed of clayey sands and gravels. However, the numerous sand boils found in the cracks were generally clean, fine to medium-grained sands – the latter material consistent with dredged or hydraulic fill. The long length of liquefaction damage has significant implications for saturated levees constructed of or on dredged material, such as those in the Sacramento-San Joaquin Delta in California's Central Valley.

Figure 25: Photographs of Construction Equipment Being Used to Provide Interim Flood/Tsunami Protection Along Left Kitakami River near River Kilometer 0.5 (N38.5739, E141.4498, April 22, 2011)

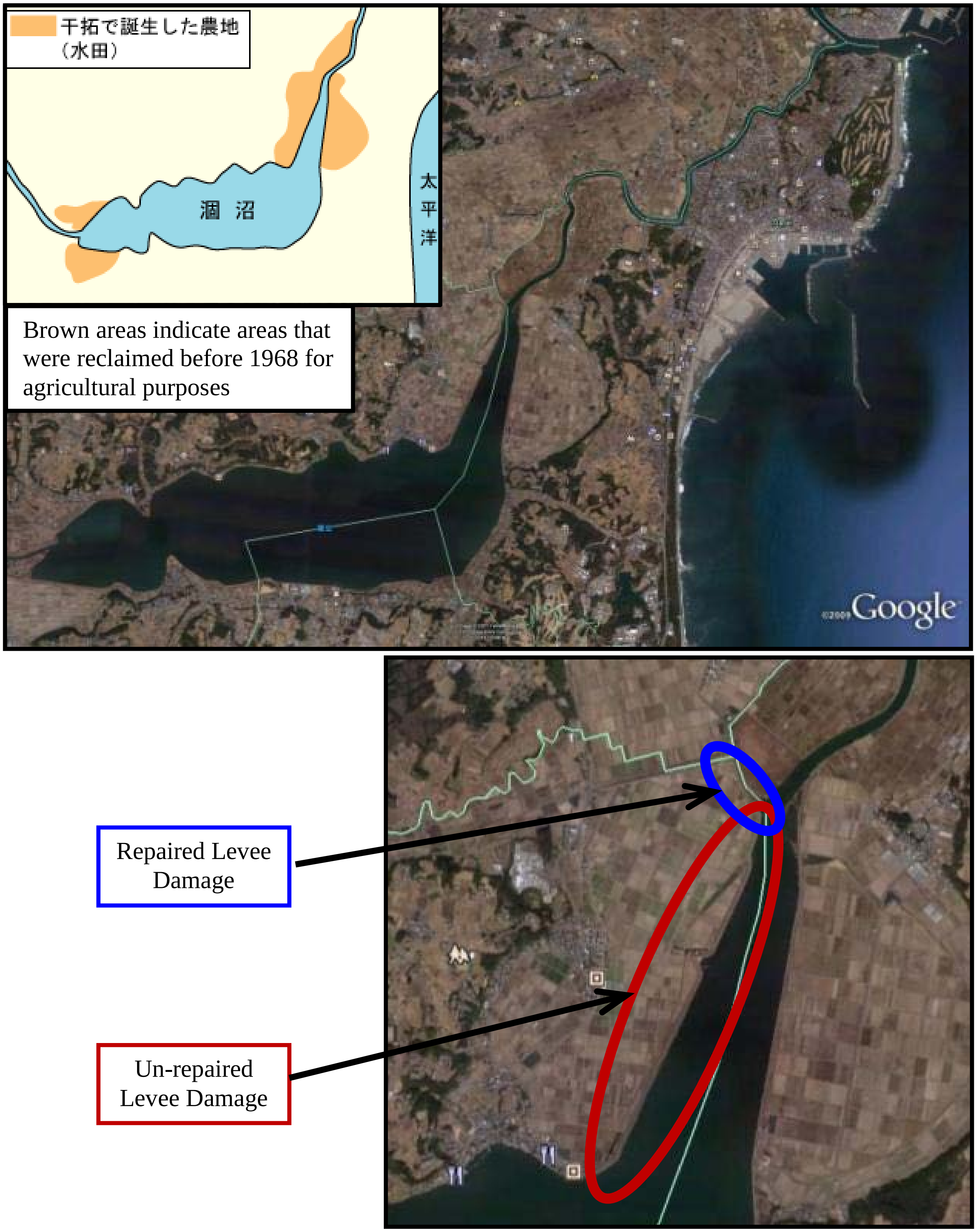


Figure 26: Aerial View of Lake Hinuma and Hinuma River near Mito, Ibaraki Prefecture (adapted from Google Earth, 2011)

Figure 27: View of Slumped Hinuma River Left Levee Induced by Liquefaction
(N36.2861, E140.5238., April 24, 2011)

Figure 28: View of Residual Sand Boils Partially Filling Large Crack/Graben
of Slumped Hinuma River Left Levee
(N36.2861, E140.5238, April 24, 2011)

Figure 29: Views of Hinuma River Left Levee Where Interim Repairs had been Completed (N36.3018, E140.5321, April 24, 2011)

Figure 30: Views of 4-Story Reinforced Concrete Apartment Building Landward of Hinuma River Left Levee Which Experienced Significant Damage and Approximately 20 cm of Ground Settlement Around the Building Foundation
((N36.2861, E140.5238, April 24, 2011)

Figure 31: Interior Views of Damaged 4-Story Reinforced Concrete Apartment Building Landward of Hinuma River Left Levee Which Experienced Significant Damage and Approximately 20 cm of Ground Settlement Around the Building Foundation ((N36.2861, E140.5238, April 24, 2011)

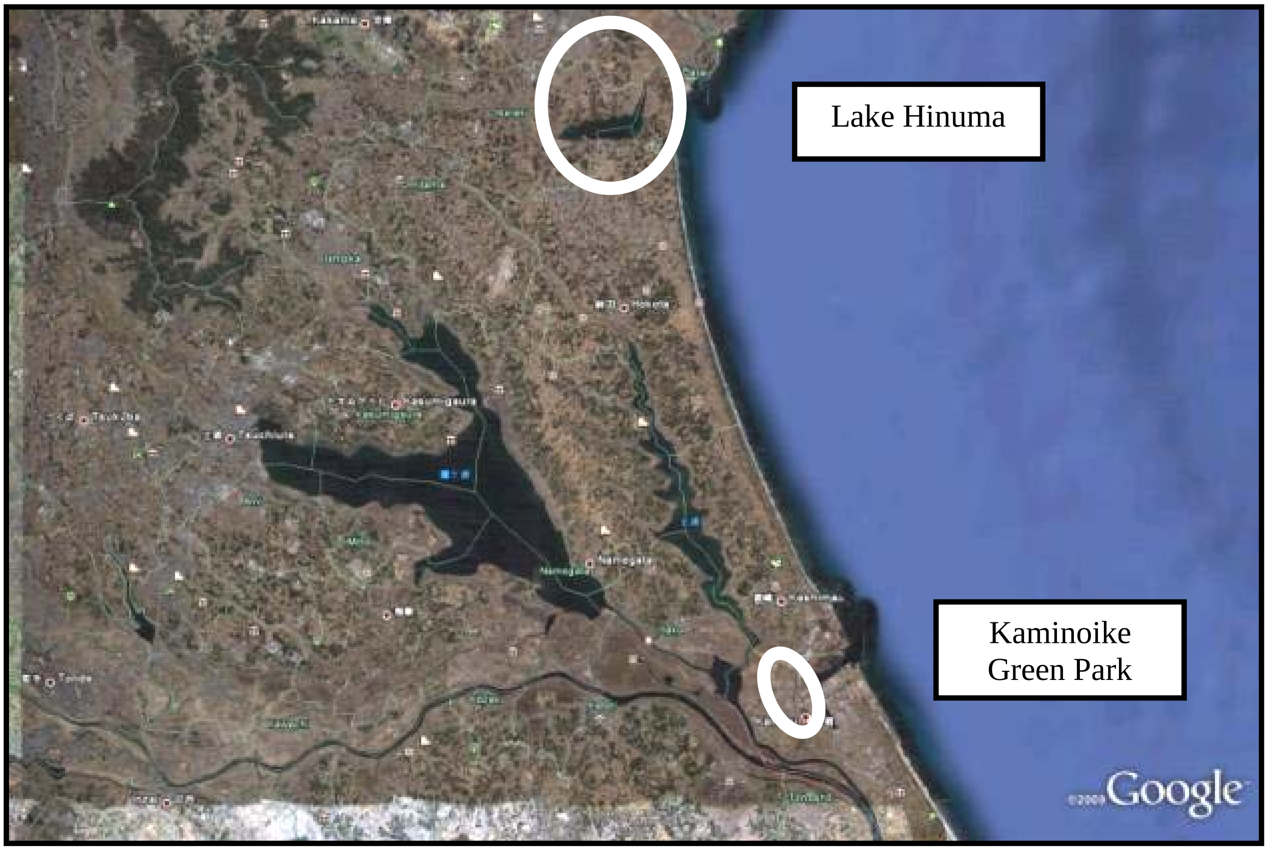
At the northern end of the damage along the Hinuma River levee, an interim repair had been completed for a limited reach. This reach apparently is consistent with the section of the levee that the MLIT is responsible for. However, most of the damaged levee was not repaired, apparently because this more southern reach is the responsibility of a local agency and that agency either did not have the resources or time to complete any significant repairs by the time that this reconnaissance took place.

The interim repairs completed by the MLIT are shown in Figure 29. The repaired levee crown is approximately 1½ meters above the unrepaired slumped levee section. If the repaired section restored only the previous height, then this suggests that the Hinuma River Left Levee had an overall general slump of 1½ meters, with additional cracking and slumping on top of this general slump; however, the 1½ meter of general slumping could not be confirmed.

Near the southern end of the damaged left levee, a 4-story reinforced concrete apartment building had been constructed near the landside levee toe. There was evidence of sand boils and liquefaction within the adjacent levee section, and there was differential settlement evident all around the building. There appeared to be about a 20 cm general settlement of the ground relative to the building all around it (see Figure 30). Inside the building, all of the windows had been broken, and much of the tile in the stairwells and other portions of the building had been shattered to small pieces (see Figure 31). The contents of the residents who had lived there had been almost completely removed. This all suggested that the building experienced both shaking and settlement damage related to the liquefaction of the reclaimed land which the building was founded on.

Kaminoike Green Park Liquefaction and Lateral Spreading

The Kaminoike Green Park is located near the coast near the town of Kamisu City (see Figure 32). The general topography and layout of the park suggests that much of the area is reclaimed land. Within the park along a linear lake, a significant lateral spread of almost flat ground occurred towards the lake. In some locations, the lateral spread appeared to have moved laterally towards the lake by at least as much as 3 meters. In the park area, numerous longitudinal cracks, some as much as a meter wide, paralleled the lake front. Numerous sand boils were also observed in the park area and along railroad tracks immediately behind the park. Compression and buckling of the rails indicated that the surface crust of the foundation had broken up into blocks and experienced ground oscillation and spreading not only towards the lake, but also parallel to the lake. Behind and parallel to the railroad tracks, relative settlement and minor damage was also apparent in a major roadway. Figures 33 and 34 illustrate some of the liquefaction-related damage in the park.



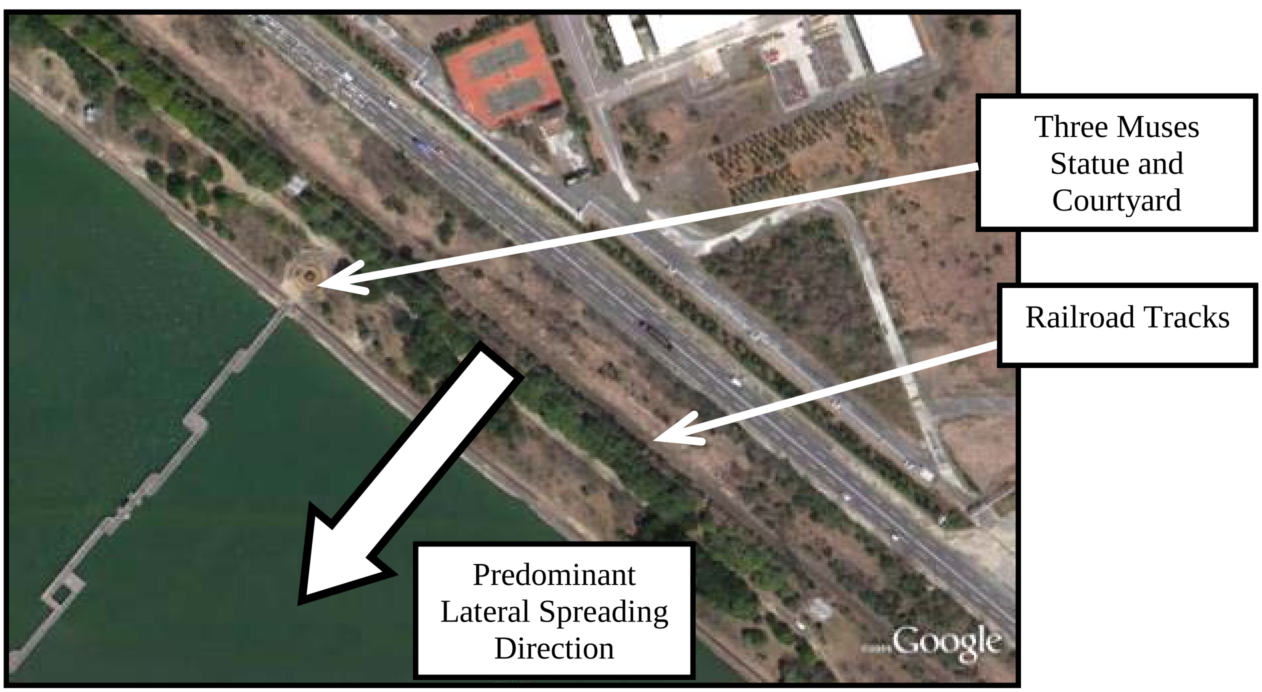


Figure 32: Aerial Views of Kaminoike Green Park near Kamisu, Ibaraki Prefecture (adapted from Google Earth, 2011)

Figure 33: Views of Liquefaction-Induced Lateral Spreading at Kaminoike Green Park
(N 35.8911, E140.6702, April 24, 2011)

Figure 34: Views of Liquefaction and Lateral Spreading in Three Muses Courtyard in Kaminoike Green Park (N 35.8915, E140.6696, April 24, 2011)

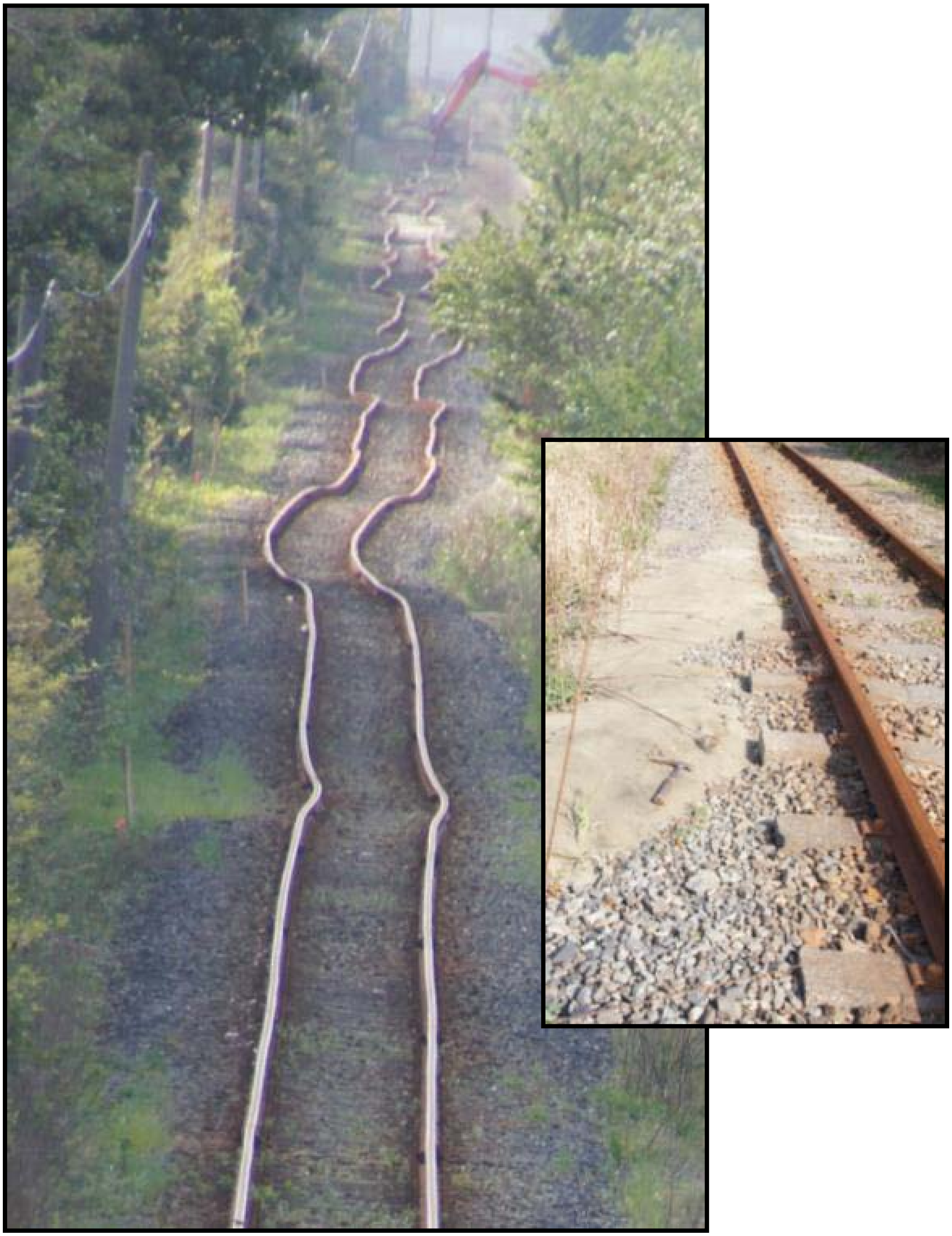


Figure 35: Views of Liquefaction, Lateral Spreading, and Compression along Railroad Tracks Behind Kaminoike Green Park
(N 35.8911, E140.6702, April 24, 2011)

SUMMARY OF PRELIMINARY OBSERVATIONS

1. Taken as a percentage of the total length of levees exposed to strong earthquake shaking, the majority of the levees experienced little or no damage following the 2011 Tohoku Offshore Earthquake. However, there were still many areas where foundation liquefaction, or liquefaction of the lower portions of the levee fills themselves, resulted in minor to major damage. While as a percentage of the total length of levees exposed to shaking this was a small percentage, there were still hundreds, if not thousands, of locations requiring immediate interim repairs.

2. Levees were generally not holding water at the time of the earthquake; consequently, there appears that there were no actual levee failures which lead to a complete breach of the levee and flooding of the protected areas. The exceptions to this were the areas within a few kilometers of the coast where tsunami waves overtopped the levees and floodwalls and devastated the communities behind them. Nevertheless, many of the levees seriously damaged by liquefaction should be considered to be complete structural failures.

3. For the most part, the levees which experienced significant damage due to liquefaction had relatively limited lengths of damage, commonly only 100 to 300 meters in length. This probably reflects the geomorphic conditions which lead to either having continuous liquefiable layers in the foundation, or for the presence of soft, compressible clays which allowed the lower portions of the liquefiable sandy embankment fills to settle into the ground below a shallow water table and be saturated at the time of the earthquake.

4. The exception to the limited lengths of liquefaction damage to levees was the extensive slumping and spreading of the Hinuma River Left Levee. This levee, apparently founded on dredged fill/reclaimed land, was observed to have serious damage for over 2½ kilometers. The difference in the length of damage reflects the difference between natural deposits and man-made fills. This has significant implications for levees constructed of or on dredged material, such as those in the Sacramento-San Joaquin Delta in California’s Central Valley.

5. The reconnaissance team was able to inspect 4 levee reaches along the Naruse River which had experienced major liquefaction damage during the 2003 Miyagi North Continuation Earthquake (M=6.2), and which had been repaired with a mix-in-place soil cement foundation ground improvement technique. All 4 sites appeared to have performed well with no observable damage for the much stronger 2011 earthquake sequence. In contrast, at two of the sites there was moderate liquefaction-related damage to the levee immediately beyond the limits of the ground treatment. While the cost for the 2003 treatment was probably significant, it was successful in preventing liquefaction-related damage.

6. While most of the serious damage to levees outside of the tsunami area has been attributed to liquefaction, the presence of numerous wide stability berms and the existence of compressible foundation clays suggest that it is possibly that some of the limited cracking and slumping observed in some levee reaches may be due to shearing and yielding of soft clays.

7. General settlement of the levees and adjoining ground appeared to be approximately 7 to 15 cm relative to hard structures such as bridge piers and water conveyance structures founded on deeper foundations. However, where liquefaction was present, general settlement exclusive of lateral spreading commonly ranged between 20 and 40 cm.

8. The tsunami waves which devastated the coast were obviously much higher than what was planned for in designing the tsunami and levee floodwalls in the coastal areas. The levees and floodwalls were simply overwhelmed. However, it was puzzling why in some cases the river levees/floodwalls at the river mouths were set as much as 2 meters lower than the adjoining floodwalls facing the ocean (e.g. see Naruse River Right Bank Levee/Floodwall at River Mouth). Tsunami waves hitting the river mouths would seem to be essentially the same as those hitting the coast around the corner and have similar wave heights and forces. There is much to be learned from the tsunami wave damage, including how to better design and armor the levee/floodwall systems to better protect those who live behind them.

10. Where overtopped by tsunami waves, substantial landside scour occurred on the levee surface, and highlighted the absence of hardened erosion control on the landside surfaces. The damage on the landside contrasted greatly with that on the waterside, which exhibited only minor and local scour because of erosion-resistant designs. In locales where overtopping-related scour was the primary failure mode, there is an opportunity to learn how to better prevent subsequent breaching of the levee.

11. Although little or no evidence of liquefaction generally remained in areas affected by tsunami waves, it seems likely that some of the areas that experienced local tsunami overtopping had lowered crown elevations resulting from liquefaction-related lateral spreading prior to the arrival of the tsunami waves.

12. With the exception of a few dramatic yet extremely damaging levee failures at or very near the coast, the levees generally protected landside property. On each of the major rivers visited by this team, there are several kilometers of levee that effectively confined the tsunami wave to the floodplain, and protected landside property. As a result of the confinement of the tsunami waves in the channelized river system upstream of the river mouths, the impacted area of tsunami inundation was likely smaller than what would have occurred in the absence of effective flood protection.

14. In addition, the pattern of tsunami deposits resulting from the 2011 earthquake will likely differ substantially from that of previous inundations, including those identified in the early historical and paleoseismic records, because the flow patterns and hydrodynamic properties of the 2011 waves were affected by the levee flood protection system.

OPPORTUNITIES FOR SUBSEQUENT RESEARCH

The impacts of this earthquake on the levee system provide several opportunities for improving our understanding of levee performance during strong ground motions and tsunami inundation:

- With the full range of minor to serious slumping and spreading, there appears to be significant opportunities to improve our field correlations between liquefiable soils and residual shear strengths. In particular, the generally good performance of most of the levee reaches for a strong earthquake with an extremely long duration would probably not have been predicted if these reaches had been evaluated in advance of the earthquake. This suggests that many of our current approaches for the prediction of liquefaction and liquefaction-related shear strength losses may be conservative. There may be a great opportunity to document that medium dense to dense soils do not lose most of their shear strength and do not develop large strains following even the strongest of ground shaking. Sites to be considered for detailed evaluations of a full range of behavior include:
    - Naruse River Left and Right Levees at Kilometer 30.0 near and away from the Matsuyama Bridge (see Figures 2 and 8).
    - Naruse River Left Levee at Kilometer 11.3 where major damage, moderate damage, and little or no damage occurred within distinct reaches (see Figures 4 and 12).
- Collection of design and cost information for areas of successful ground improvement would be very beneficial.
- The GEER reconnaissance team was not able to visit sites where the MLIT has instrumented levee embankments and foundations. Compilation of strong ground motion and piezometric data from 11 instrumented levee sites maintained by MLIT within the Miyagi, Iwate, and Ibaraki prefectures, and collection of detailed site conditions and damage information at these sites, to evaluate levee response to strong ground shaking of long duration.
- There are several areas where ground settlement induced by liquefaction could be further investigated. Sites where ground settlement relative to hard structures include those shown in Figures 5 and 30.
- In areas of minor to moderate levee cracking and settlement, no indication of foundation liquefaction, and the presence of stability berms indicating soft soils, the cause of the distress may be a loss in shear strength within soft clay. A few such areas should be investigated. One of these would be the Naruse River Left Levee at approximately River Kilometer 14.5 (N38.4739, E141.1293)
- Characterization of near-surface paleochannel deposits and associated areas of levee damage along the Naruse River Right Levee (River Kilometer 12), would be beneficial in assessing the effects of variable subsurface characteristics on levee liquefaction and settlement (see Figures 6 and 7). In areas where liquefaction-related damage was on both sides of the river, investigations of geomorphology and paleochannels would provide a stratigraphic framework for understanding the influences of near-surface foundation materials on levee performance.

- In locales where tsunami overtopping-related scour was the primary failure mode, there is an opportunity to learn how to better prevent subsequent breaching of the levee.
- Characterization of areas that experienced foundation liquefaction and levee damage adjacent to Lake Hinuma, and comparison with levee characteristics in analogous areas of extreme consequence in the California Central Valley may be very beneficial in developing remediation alternatives and emergency response plans for the latter region.

Other opportunities will become clearer as additional reconnaissance efforts visit affected regions and damage is further documented, including the performance of dams (e.g., failures of embankments on the Fujinuma irrigation pond), possible surface fault rupture, and additional levee waterside loading during the upcoming rainy (typhoon) season.

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