Geotechnical Extreme Events Reconnaissance (GEER)

LiDAR and Field Investigation Of the March 11, 2011 M9.0 Great Tohoku Offshore Earthquake, and April 7, 2011 M7.4 Aftershock.

Robert Kayen[1], YasuoTanaka[2], Hajime Tanaka[3], Takahiro Sugano[4], Ivan A. Estevez[5], Sean S. Cullenward[6], Winnie Yeh[3], Davis Thomas[3]

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Tohoku Earthquake Reconnaissance

The great magnitude 9.0 Tohoku Earthquake affected an 800 km long portion of Honshu Island from Tokyo City and Chiba Prefecture in the South, to the Oma Peninsula of Aomori Prefecture in the north. Three weeks after the earthquake, GEER Reconnaissance Team 2 (Reconnaissance-2) conducted a field activity from April 3 to April 14. This reconnaissance effort started in Tokyo City on the Kanto Plain and concluded in Aomori City, in Aomori Prefecture at the north end of Honshu Island. During Reconnaissance-2, LiDAR data was collected at nine locations to preserve noteworthy geotechnical damage, as well as photographs, GPS locations, and observations at 52 sites. Damage observations from the earthquake and tsunami are the result of the main magnitude 9.0 event that occurred on March 11, 2011, and also from a large M7.4 aftershock that occurred on April 7, 2011. The aftershock of April 7 triggered liquefaction at all but one of the SASW test sites previously tested by the first author in Miyagi Prefecture. At several of these locations, new sand fissures and sand boils were clearly deposited on liquefaction features from the main M9.0 event.

The reconnaissance team was led by Robert Kayen and included Professor Yasuo Tanaka of Kobe University, Takahiro Sugano of the Port and Airport Research Institute (PARI), and Hajime Tanaka, a recent Masters graduate of Tokyo University. Within a 50 mile exclusion zone around the Fukushima nuclear power plant, reconnaissance investigations at the ports of Soma and Onahama, Fukushima Prefecture, were made by the Japanese participants from PARI.

Acknowledgements

The authors had the opportunity to visit the entire effected region from Tokyo to Aomori following the March 11, 2011 Tohoku Offshore Earthquake over a 2 week period in April. The principal purpose of the visits was to observe and document the geotechnical failures and gather LIDAR imagery. The authors were greatly aided by the field reports and advice of Professors Konagai and Towhata (University of Tokyo), and the resources of Professor Yasuo Tanaka and the Research Center for Urban Safety and Security, Kobe University (RCUSS). The contributions of the phase 1 GEER reconnaissance teams that produced early reports allowed us to focus our efforts on specific targets of lidar data collection. We greatly appreciate the hard work and observations shared by these colleagues. The US-NSF provided funding through the core GEER activity and Rapid award CMMI-1138203.

[1] Research Civil Engineer, United States Geological Survey, Menlo Park, California
[2] Prof., Dept. Civil and Environmental Engineering, Kobe University, Japan
[3] Graduate, Dept. Civil and Environmental Engineering, Tokyo University, Japan
[4] Civil Engineer, Port and Airport Research Institute, Yokuska, Japan
[5] Student, City College of New York.
[6] Student, UCLA, Los Angeles, CA

LiDAR data collection occurred in Chiba, Ibaraki, and Fukushima Prefectures. Data were gathered at the following sites:

- Site RK3: Yoko-Tone (lateral to Tone river)
  - N35.92559301°, E140.4884430°
  - Lateral spread embankment failure and liquefaction of secondary levee and NTT cell communications tower

- Site RK4; JS23: Isobe
  - N35.63474°, E140.047557°
  - Lateral spread

- Site RK5; J26: Sodegaura Elementary School
  - N35.66958°, E140.02742°
  - Lateral spread, including sewer and storm water uplift in liquefied soil

- Site RK6; J27: Urayasu Cemetary
  - N35.63797°, E139.933455°
  - Lateral spread.

- Site RK8; JS7: Hinuma Lake South Shore
  - N36.268697°, E140.50896°
  - Embankment failure

- Site RK10; JS10: Hitachinaka Port Road
  - N36.344817°, E140.603443°
  - Landslide, settlement, lateral spread

- Site RK13: Shirakawa Village
  - N37.138857°, E140.21866302°
  - Landslide

- Site RK15a: Fujinuma Dam Failure – A,
  - N37.298934°, E140.194661°
  - Reservoir dam failure area and damaged upstream face of auxiliary dam

- Site RK15b: Fujinuma Dam Failure – B:
  - N37.298902°, E140.188743°
  - Multiple failures of the reservoir slope and concrete facing along the park perimeter on the west side of the reservoir

- Site RK34: Koguchi, Miyagi Prefecture, Route 257
  - N38.533777°, E141.21575796°
  - SASW site was a levee road failure that involves crest settlement and embankment widening near the town of Koguchi.

Table 2: All sites visited and logged during the Phase 2 Investigation.

Site Number	Location	Prefecture	Latitude (N)	Longitude (E)	Description	Common Site Names
RK1	Katori-Shi Central District	Chiba	35.925493	140.488454	River channel through central Katori City- suffered liquefaction, lateral spreading, river shortening	
RK2	Banks of Tone River	Chiba	35.899295	140.504429	Liquefaction of river soil and park facilities on river's edge. Incipient failure of wide section of levee	
RK3	Yokotone (lateral to Tone River)	Chiba	35.925593	140.488443	[LiDAR Site] Lateral spread, embankment failure, and liquefaction of secondary levee and NTT cell communication tower. Extensive liquefaction in rice fields along Yokotone river banks, damaged houses, tilted communication tower	
RK4	Isobe, Tokyo Bay	Chiba	35.634893	140.047328	[LiDAR Site] Lateral spread ground failure along river wall at mouth of the Isobe River at Tokyo Bay	JS23
RK5	Sodegaura School	Chiba	35.669618	140.028616	[LiDAR Site] Storm drainage and sewer uplift in liquefied soil. Possible lateral deformation occurred near the school foundation, which LiDAR did not cover.	JS26
RK6	Urayasu	Chiba	35.638003	139.933951	[LiDAR Site] Liquefaction foundation failures, structural tilting, and lateral spreads. LiDAR collected at area of maximum collection at cemetery boundary and waterfront park	JS27
RK7	Hokotashi	Ibaraki	36.153528	140.51211	Liquefaction along canal banks, lateral spreading, settlement in residential/commercial district affecting structural foundations, sand boils	
RK8	Hinuma Lake South Shore	Ibaraki	36.268519	140.512227	[LiDAR Site] Embankment failure w/ base widening and crest settlement, crest crack extends 800 meters	JS7
RK9	Hinuma Cemetery	Ibaraki	36.270052	140.529176	Cemetery within 5km of Site RK8. Collapse ratio appears to be less than 5%	
RK10	Hitachinaka Port	Ibaraki	36.344134	140.602386	[LiDAR Site] Shallow landslide beneath large retaining wall damaged road along head scarp of the failure.	JS10
RK11	Nasukarasuyama	Tochigi	36.683199	140.075043	Landslide originating from a terrace above cut bank of river valley. Slopes are forested native landscapes, Total displacement volume estimation~ 70,000 cubic meters	
RK12	Nasukarasuyama Village Cemetery	Tochigi	36.685898	140.072041	No observable collapsed tombstones	
RK13	Shirakawa Village	Fukushima	37.138857	140.218663	[LiDAR Site] Large landslide off a forest slope onto agricultural village, impacting several houses, covering and crossing the narrow valley	
RK14	Naganuma Town Cemetery	Fukushima	37.291635	140.173633	Tombstone collapse ratio of approximately 70%	
RK15	Fujinuma Dam	Fukushima	37.298934	140.194661	[LiDAR Site] Complete dam failure,	

					causing the uncontrollable release of the entire reservoir. Slope deformations & failures around reservoir, some liquefaction induced .	
PARI16/ PARI17	Soma Port	Fukushima	37.8468	140.951	Tsunami damage, estimated height was 10-15m at site. PARI office destroyed, heavily damaged seawall, caisson tilting, erosion due to initial flooding and drawdown, severe damage on corner areas of port wharves, wharf collapse	
PARI18/ PARI19/ PARI20	Onahama Port	Fukushima	36.9396	140.863	Tsunami damage, estimated height ranges from 0.4-3.0m, typically 1.5-2.9m. Harbor floor erosion, major tanker terminals remained closed in the region, Berthing and port facilities have been destroyed	
RK21	Abukuma Edgetsu	Miyagi	38.07	140.90	Tsunami damage along banks of Abukuma River several miles inland of the coast	
RK22	Watari District, Arahama Waste Water Plant	Miyagi	38.041982	140.919474	Liquefaction, lateral spreading, sand boils, and fissures due to aftershock from April 7, 2011. Tested using SASW prior to main earthquake event in 2001.	SASW 74ARA
RK23	Natori River Banks, Yuriage District	Miyagi	38.190032	140.934949	Liquefaction from April 7, 2011 aftershock. Sand boils and reduced gray sand. Direct evidence of liquefaction from main earthquake event is masked by debris, hydraulic re-working, and tsunami soil deposits. Tested with SASW in 2001.	SASW 75YUR
RK24	Natori Town	Miyagi	38.181450	140.944432	Liquefaction from April 7, 2011 aftershock. Sand boils and reduced gray sand on riverbank surface. Direct evidence of liquefaction from main earthquake event is masked by debris, hydraulic re-working, and tsunami soil deposits. Fissures are evident. Significant scour along piers.	SASW 76YUR
RK25	Nakamura Dike	Miyagi	38.198564	140.935332	North bank of Natori River on Sendai side. Liquefaction from April 7, 2011 aftershock. Sand boils. Tested with SASW in 2001.	SASW 77SEN (SENDAI)
RK27	Nakajima Wharf	Miyagi	38.415133	141.266074	Liquefaction from April 7 aftershock. Evidence of liquefaction from main event is completely obscured by tsunami damage. Scoured soil beneath pile supported foundation base of tanks. Buoyant tank floated off one base pad	SASW 79ISHI
RK28	Hiyori Wharf, Port of Ishinomaki	Miyagi	38.416907	141.274377	Liquefaction on wharf	SASW 84HIYO
RK29	Shiomi Wharf	Miyagi	38.418015	141.285865	Liquefaction from April 7 aftershock	SASW 78ISHS
RK30	Shiomi-Minami Wharf	Miyagi	38.411363	141.274197	No liquefaction from April 7 aftershock	SASW 83SHIO

RK31	Ishinomaki	Miyagi	38.420379	141.264363	Tohoku Electric Company electrical substation. Evidence of direct impact of tsunami wave on structural support frames. Significant scour.	
RK32	Embankment Highway 257 at Koguchi	Miyagi	38.51205	141.233755	[LiDAR Site] Settlement, fissures	
RK33	Kitawabuchi	Miyagi	38.531519	141.220286	Liquefaction during April 7 aftershock, overlapping evidence of liquefaction from aftershock & main event, sand boils,	SASW 82KITA
RK34	Kitawabuchi	Miyagi	38.533777	141.215758	Liquefaction during April 7 aftershock, overlapping evidence of liquefaction from aftershock & main event, sand boils,	SASW 81KITA
RK35	Matsushima	Miyagi	38.3508	141.047	Tsunami damage, height was significantly lower than at Ishinomaki. Tsunami sand deposits. No apparent geotechnical damage	
RK36	Shiogama City	Miyagi	38.315	141.035	Eastern harbor of the city was much less impacted by tsunami. Waves were no more than 1-2m. Western part of the city more severely impacted	
RK38	Shakushi	Miyagi	38.534151	141.183253	Agricultural embankment failure	
RK39	Kubota	Miyagi	38.553818	141.194932	Minor liquefaction feature at embankment highway	
RK41	Minamisanriku	Miyagi	38.647528	141.43895	Tsunami damage: 15m high debris in some cases, no other geotechnical damage	
RK42	Minamisanriku	Miyagi	38.793604	131.504912	Tsunami damage impacted about 30% of the community, no other geotechnical damage	
RK43	Rikuzentakada Bridge	Iwate	39.009923	141.617137	Tsunami damage. Bridge deck swept off piers. Soil supported piers are scoured. No other geotechnical damage.	
RK44	Rikuzentakada Railroad Yard	Iwate	39.008701	141.650046	Tsunami waves folded guard rail over the road deck	
RK45	Ofunato Town	Iwate	39.096144	141.707197	Largely unscathed by tsunami. Port district had the most damage. No other apparent geotechnical damage aside from tsunami related incidents	
RK46	Otsuchi Town	Iwate	39.374555	141.942422	Very badly impacted by tsunami waves, ~15m at harbor.	
RK47	Yamada-machi Miyako Town	Iwate	39.460713	141.955392	Tsunami damage. Overturned seawall, fire in city center after tsunami	
RK48	Port of Miyako	Iwate	39.631514	141.968452	Tsunami damage at port, fire	
RK49/ RK50	NODA Town	Iwate	40.114714	141.81999	Tsunami damage but no geotechnical damage at low elevations of the city	
RK51	Oma Peninsula	Aomori	40.71592	141.418383	Tsunami deposits and debris	
RK52	Ohata, Oma Peninsula	Aomori	41.134095	141.391803	No tsunami or geotechnical damage. First town in 400 miles without impacts	
RK53	Oma Point, Oma Peninsula	Aomori	41.524059	140.900698	No tsunami or geotechnical damage	
RK54	Aomori Old	Aomori	40.832633	140.736101	No Liquefaction at historic ground	SASW

	Train Station				failure site.	64AOMO

Reconnaissance Method

GEER Reconnaissance Team 2 is one of six sponsored by the Geo-Engineering Earthquake Reconnaissance (GEER) activity of the NSF was organized and sent to the epicentral region 21 days after the earthquake to assess the geo-engineering and soil-related structural damage aspects of the earthquake. The field reconnaissance team members were Robert Kayen (Reconnaissance team leader; USGS), Yasuo Tanaka (Professor, Kobe University), Hajime Tanaka (University of Tokyo) and Takahiro Sugano (during the Soma and Onahama port investigations. Port and Airport Research Institute). LiDAR data was processed and modeled in California by Sean Cullenward (UCLA), Ivan Estevez (CCNY), Davis Thomas (UCLA), Winnie Yeh (UCLA), and Robert Kayen (USGS/UCLA). The GEER team's main goal was to quantify the spatial extent and magnitude of ground failures, soil liquefaction, landslides, and damage to bridges, piers, ports, harbors, lifeline systems, and critical structures.

During the 12-day reconnaissance, one vehicle was used to traverse the roads of the epicentral region. The vehicle was equipped with handheld two-way radios, phones, digital cameras, maps, computers for recording site logs, LiDAR imager, and GPS units for recording track logs and site locations. In the evening, the reconnaissance team met to merge the GPS data, site logs, and digital photos into a common database. In the field, a Google Earth KML markup language file was generated to display all the written observations on dynamic digital maps. By observing damage in the Google Earth program, the team identified unexplored areas for the next day's reconnaissance, spatial trends in the observations, and any errors in the GPS logs and typed observations.

The authors of this report recommend downloading and opening the GEER .kmz Google Earth map file for this earthquake to navigate through the report observation sites as they are described in the text. Clicking on the individual site name in the waypoints folder will direct the program to fly to that site.

High-resolution topographic data sets of the most significant damage to earth dams and tunnels were collected to preserve the event by using the USGS terrestrial Light Detection and Ranging (LiDAR) system. The terrestrial LiDAR data collection technique consists of sending and receiving laser pulses to build a point file of 3-D coordinates of virtually any reflective surface. The time of travel for a single pulse reflection is measured along a known trajectory in such a way that the distance from the laser and consequently the location of a point of interest is computed. The USGS system consisted of a Riegl Z420 instrument mounted on a tripod platform. The instrument captured data at approximately 12,000 points per second, with a typical range of 700-1000 meters and at an accuracy of 15 mm for each point. Project coordinate system georeferencing was performed with the assistance of LiDAR reflectors. Project georeferencing was done by placing LiDAR reflectors in the field of view of the project scans. Data from these sites will be made available in digital format once they are processed. This reconnaissance report is organized chronologically as the team moved from Tokyo through prefectures to the east and north. Observations are presented in the following order:

1) Chiba Prefecture; 2) Ibaraki Prefecture; 3) Tochigi Prefecture, 4) Fukushima Prefecture; 5) Miyagi Prefecture; 6) Iwate Prefecture; 7) Aomori Prefecture

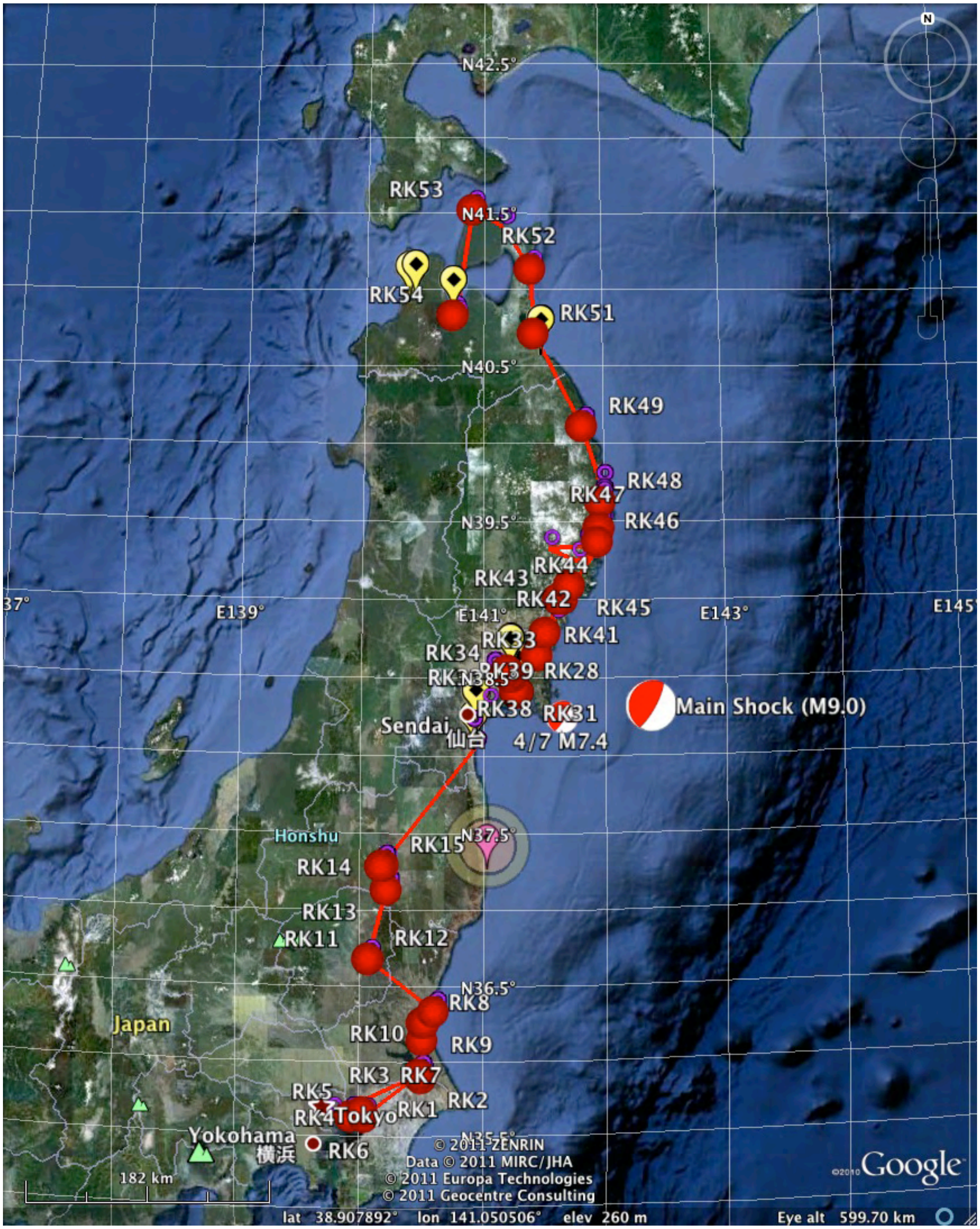


Figure QR6-1: Path of investigation from April 3 to April 14. Red dots are sites of post-earthquake investigation; yellow markers are sites of SASW testing done prior to the earthquake. The Fukushima Daiichi nuclear power plant is marked with a pink flag and surrounded by rings of radius 20 kilometers and 30 kilometers.

Observations on the Kanto Plain, Chiba Prefecture:

April 3, 2011:

Site RK1:,Katori-Shi Central District

The river channel running through central Katori city suffered liquefaction, lateral spreading and river shortening (narrowing). The river channel filled with liquefied sand, and the perimeter of the canal had differential settlements in the sub meter range. Several bridges crossing the canal suffered compression and minor buckling but could still convey traffic. At the time of the reconnaissance some dredging of the canal had occurred.

Figure QR6-2: Central canal in Katori City with river shortening and lateral spreading.

Figure QR6-3: Liquefied sand filling the canal near a small bridge pier.

Site RK2: Bank of Tone River, Katori City

Liquefaction of river soil and rotational failure of wide section of the outboard levee slope. This wide section of Levee had a rotational failure with a headscarf near the crest of Levy and the toe in the playground adjacent to the base of the slope. At the time of the reconnaissance this portion of the levy was covered in blue tarps. Along the inboard side of the levee, the Park perimeter of the Tone River border had spatially extensive soil liquefaction on baseball fields, tennis, soccer fields and other nonstructural park facilities along the river's edge.

Figure QR6-4: Top of levee at Tone River

Figure QR6-5: Toe of slump at Tone river levee.

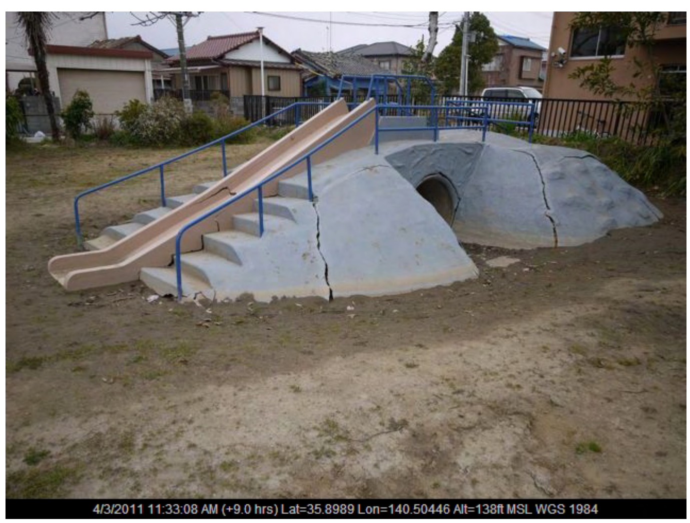


Figure QR6-6: Toe of slump and damage to structures at Tone river levee failure.

<u>Site RK3: Yoko-Tone (lateral canal to the Tone River) [LiDAR Site]</u>

In the area around the Yoko-Tone Canal and Tone River there is evidence of widespread liquefaction in the native river deposits. A noteworthy embankment failure occurred along a drivable levee parallel to the canal separated by planting Fields. Lidar data was captured along a segment of the most damaged portion of the lengthy in the vicinity of a wildlife wetland pond and the telecommunications tower. The NTT cell communications tower suffered tilting and settlement. The tower itself is pile supported. The generator structure and small building on the foundation pad are tilted about 20°. House structures surrounding the wetland pond lost roof tiles, and in some cases settled and tilted due the liquefaction foundation failures. Large sand boils, up to tens of meters across, were found along the adjacent rice fields on the bank of the canal. A minor secondary levee separating the residential district from the river and a wetland pond has one area (800m) of significant embankment bank failure. As much as 1 meter of crest settlement and 2.0-2.5 meters of lateral expansion occurred on the pond side of the embankment.

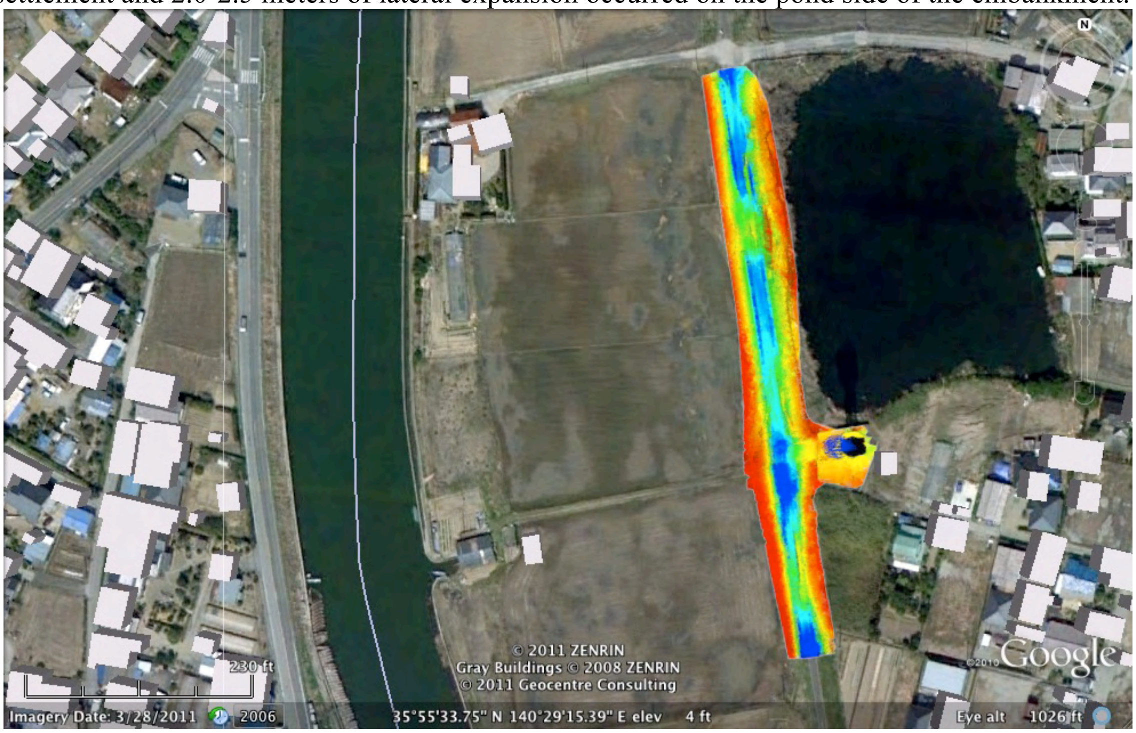


Figure QR6-7: LiDAR scanning at Yoko-Tone River. LiDAR coverage of the levee adjacent to the Yoko-Tone River. The data also covers a telecommunications tower pad. Lateral spreads were observed on the pond side of the embankment.

Figure QR6-8: LiDAR scanning at Yoko-Tone River at section B (see below)

Figure QR6-9: LiDAR scanning at Yoko-Tone River River at section B (see below)

Figure QR6-10: LiDAR scanning at Yoko-Tone River River at section A (see below)

Figure QR6-11: LiDAR scanning at Yoko-Tone River River at section D (see below)

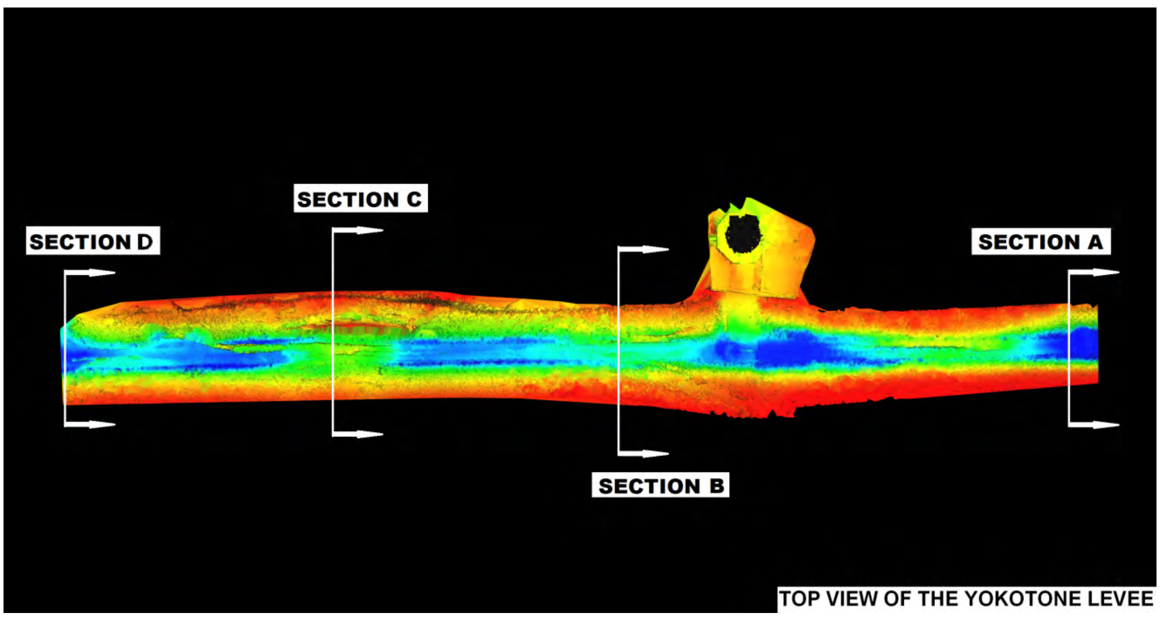


Figure QR6-12: Plan view map of the cross sections through the levee embankment near the Yoko-Tone River. Section A is the unfailed zone.

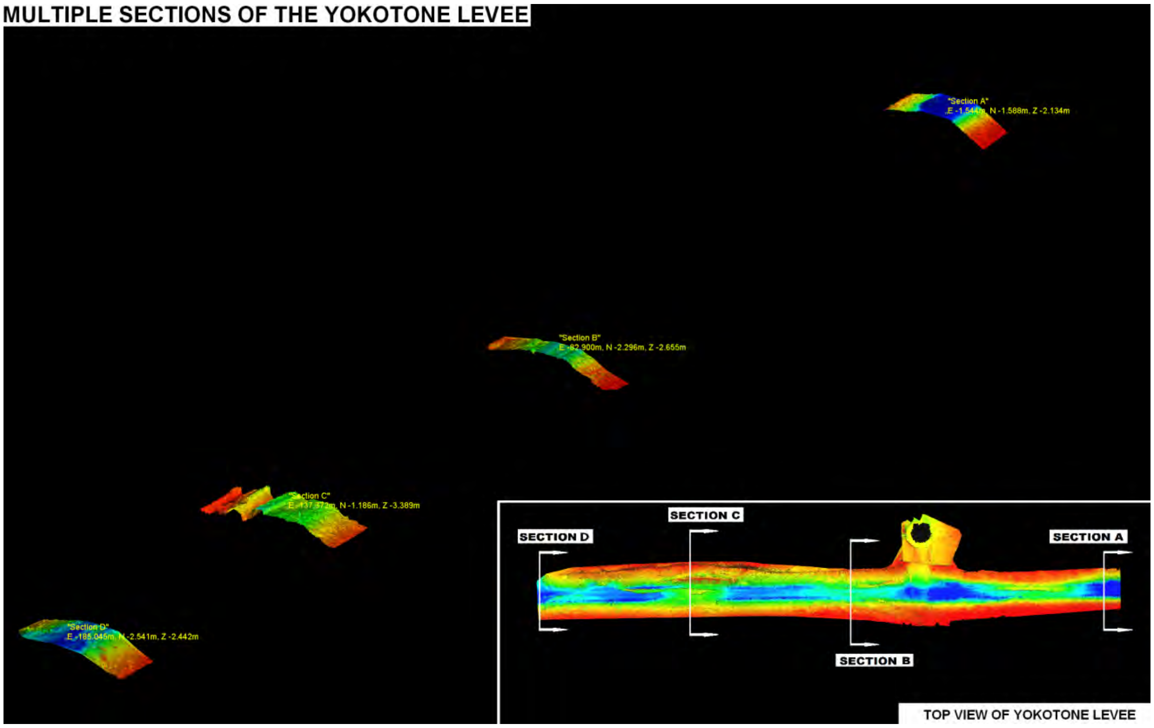


Figure QR6-13: Oblique view of cross sections A (unfailed), B (near tower), C (maximum deformation zone), and D (failed near cross road)

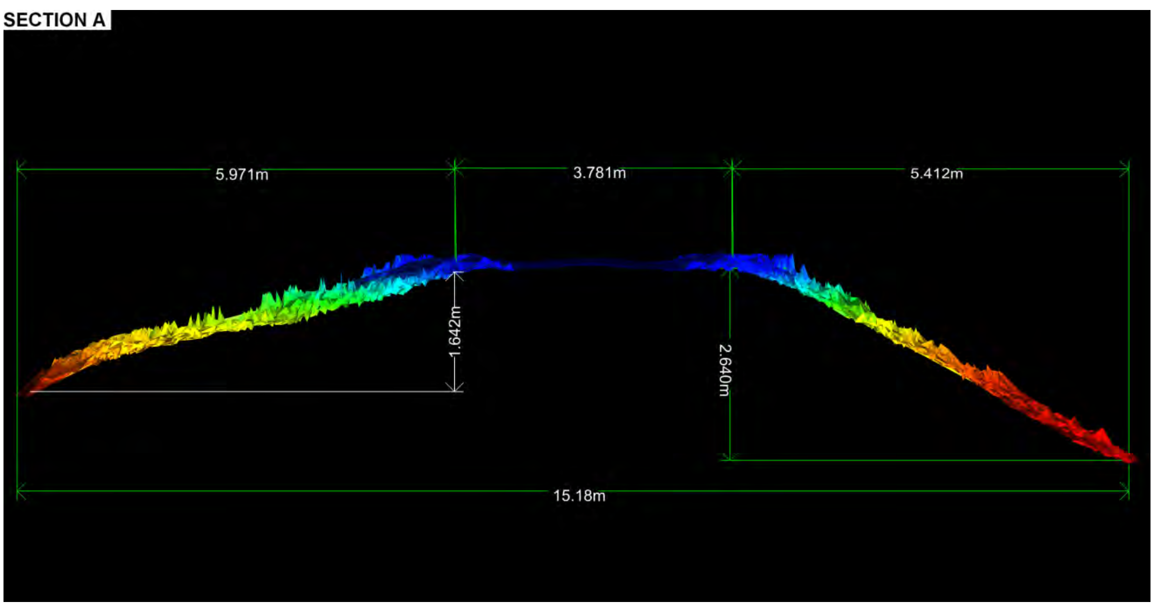


Figure QR6-14: Cross section A across the unfailed zone.

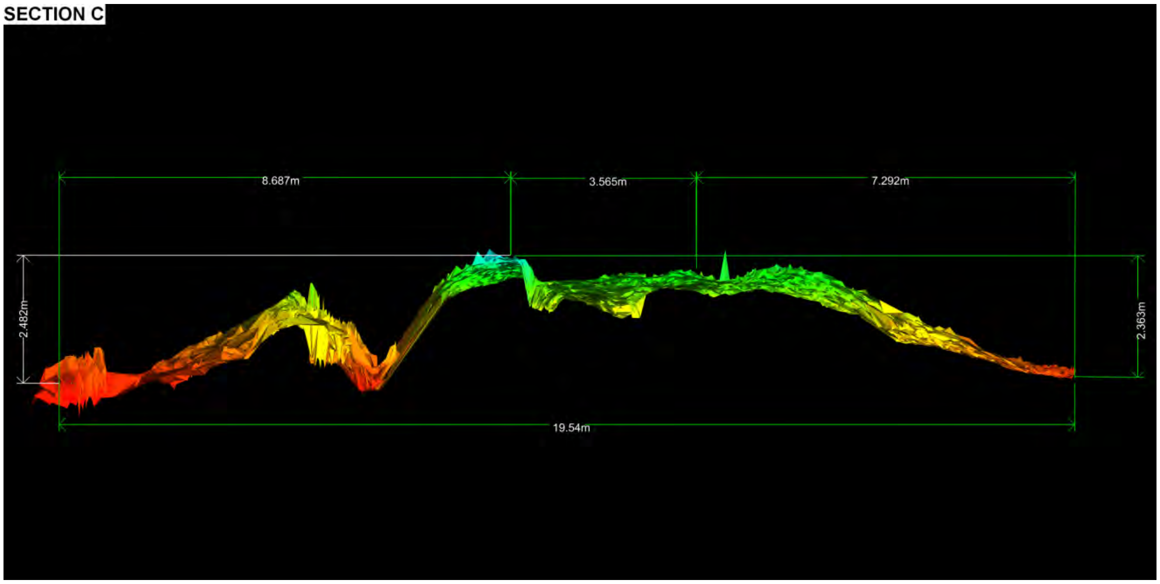
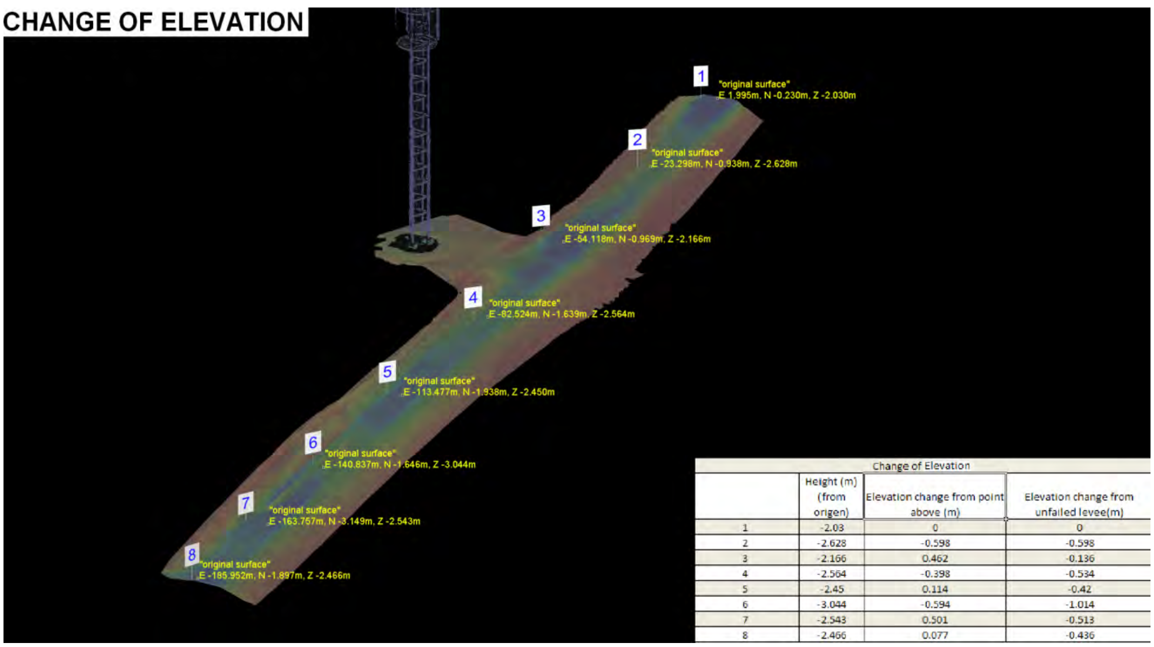


Figure QR6-15: Cross section C, lateral spread is towards the pond.



Change of Elevation

	Height (m) (from origen)	Elevation change from point above (m)	Elevation change from unfailed levee(m)
1	-2.03	0	0
2	-2.628	-0.598	-0.598
3	-2.166	0.462	-0.136
4	-2.564	-0.398	-0.534
5	-2.45	0.114	-0.42
6	-3.044	-0.594	-1.014
7	-2.543	0.501	-0.513
8	-2.466	0.077	-0.436

Figure QR6-16: Differential elevations across the levee crest. A maximum crest slumping of 1.01 meters was observed in the LiDAR data.

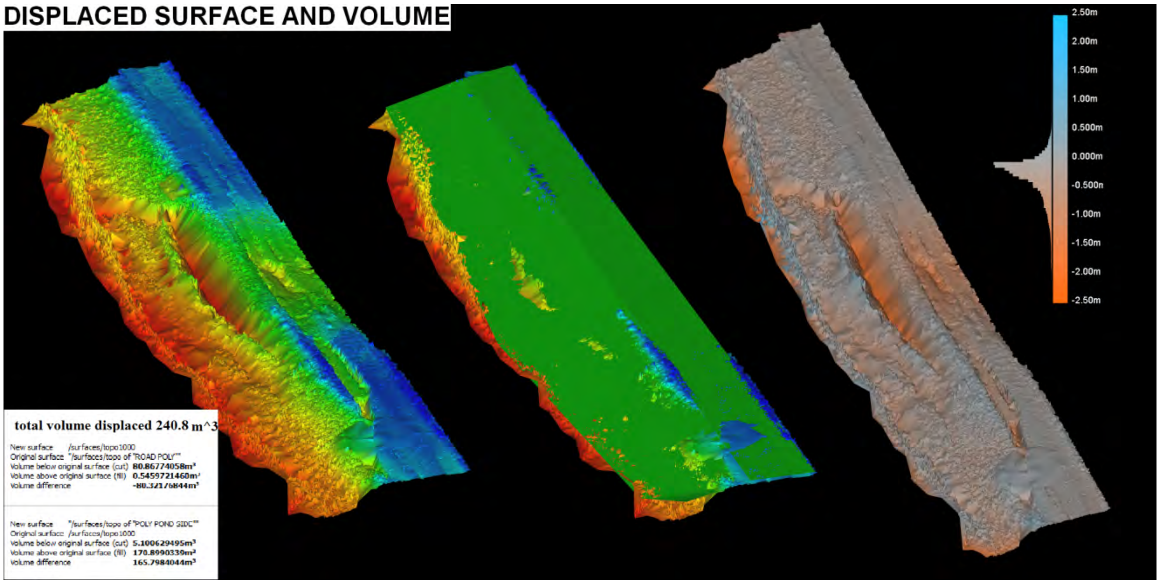


Figure QR6-18: Failure zone LiDAR data for section C (left), modeled pre-failure levee geometry (center), and change detection model that is the difference between the left and central models. The histogram indicates the distribution function for vertical deformations. Positive values represent gains in elevation from accumulation of soil at the toe of the spread or lateral movement toward the slope.

Site RK4 (Also Site JS23): Isobe, Chiba, Lateral Spread [LiDAR Site]

This is a lateral spread ground failure along the river wall at Isobe, Chiba Prefecture, near the mouth of the Isobe river at Tokyo Bay. The lateral spread is described by Stewart et al Quick Report 1. Quick Report. We took our LiDAR measurements from one position on the bridge looking diagonally down at the lateral spread from an excellent vantage point. We took one panorama scan at 0.12 deg. resolution and then a high-resolution scan from the same position at 0.03 deg. Resolution.

Figure QR6-19: LiDAR scanning at Isobe River from the bridge crossing

Figure QR6-20: Lateral spread and wall failure at the Isobe

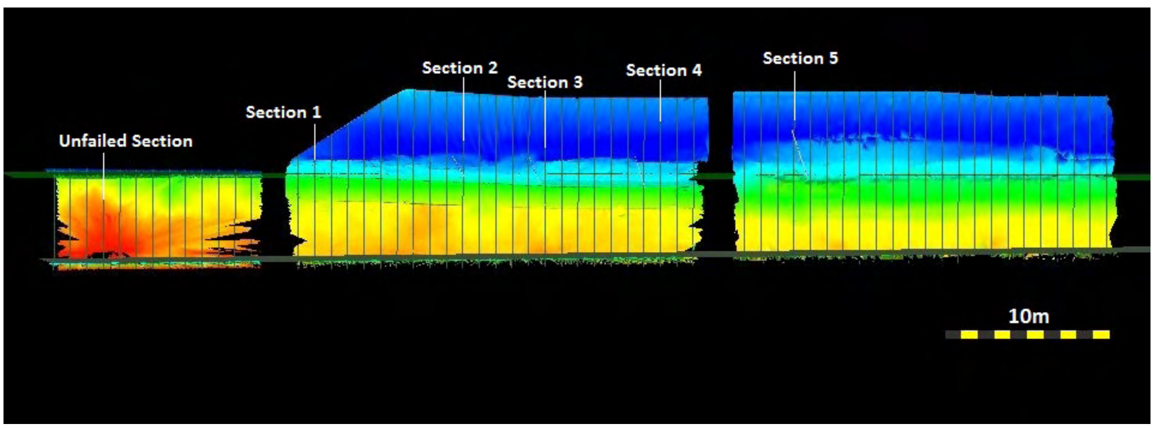


Figure QR6-21: Cross sections across Isobe

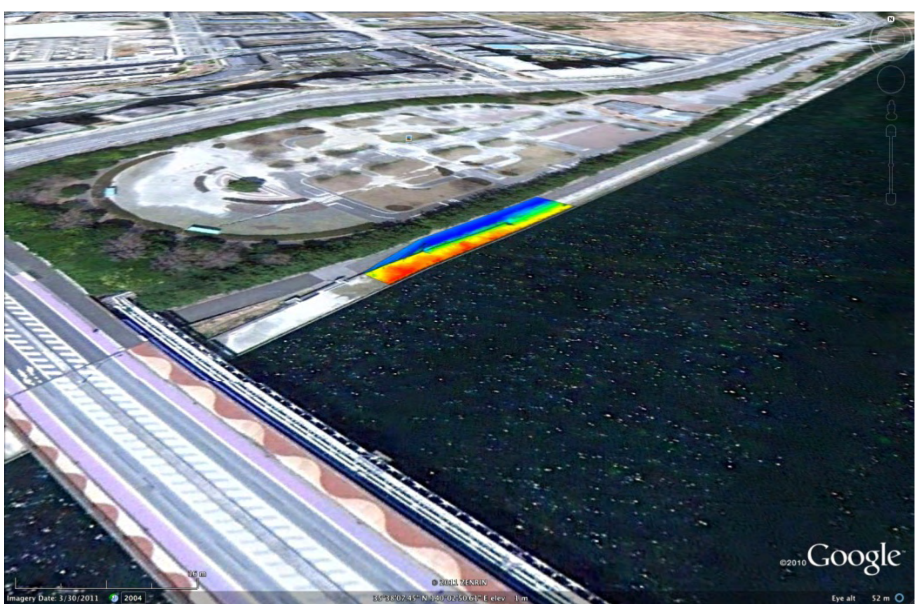


Figure QR6-22: LiDAR coverage along the Isobe River, Chiba Pref. on Google Earth imagery

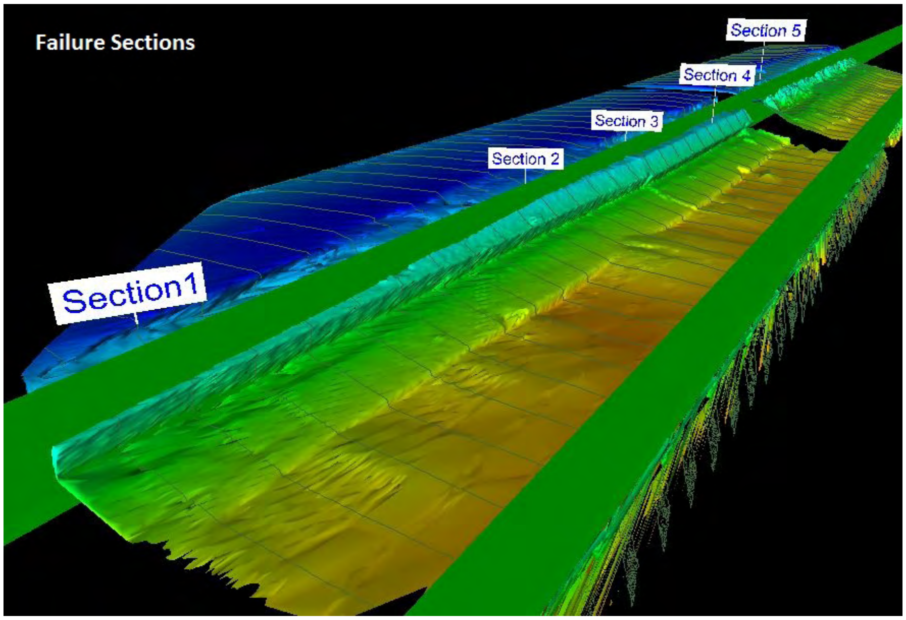


Figure QR6-23: Cross sections along the Isobe River. Section 1 is the first failed section after the unfailed section

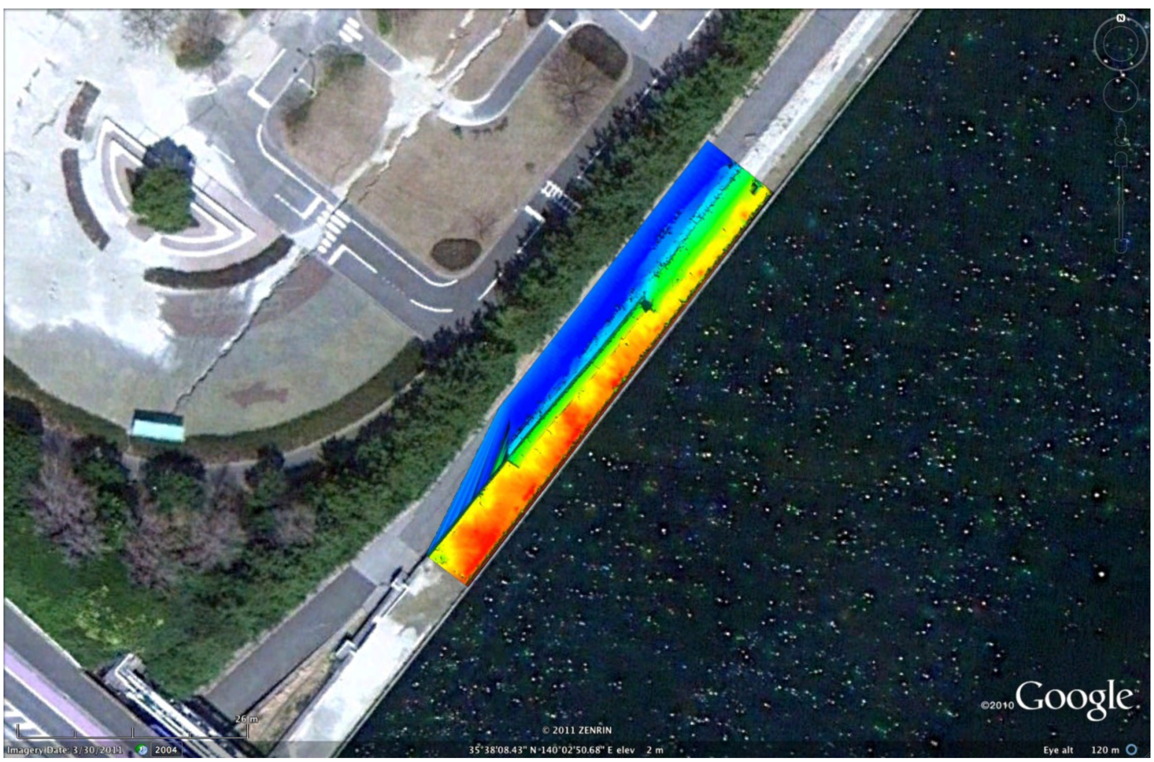


Figure QR6-24: LiDAR data in plan view along the Isobe River

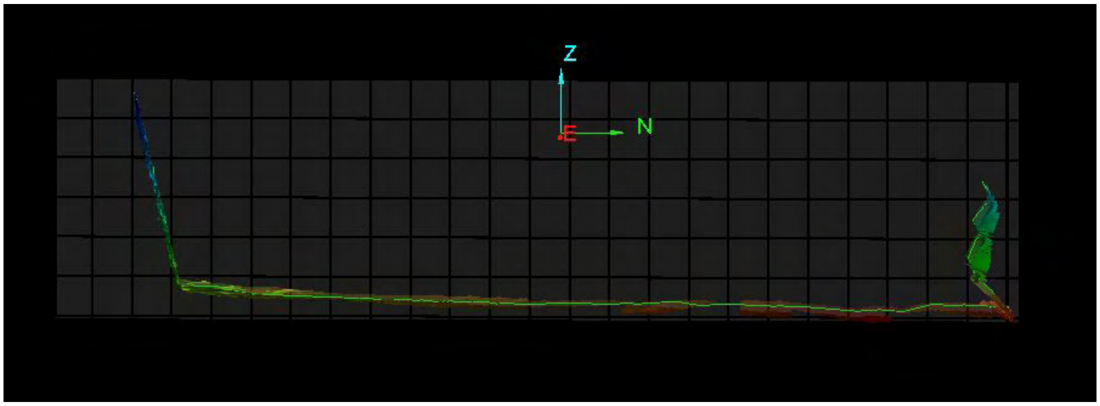


Figure QR6-25: Cross section views of the unfailed zone (before Section 1)

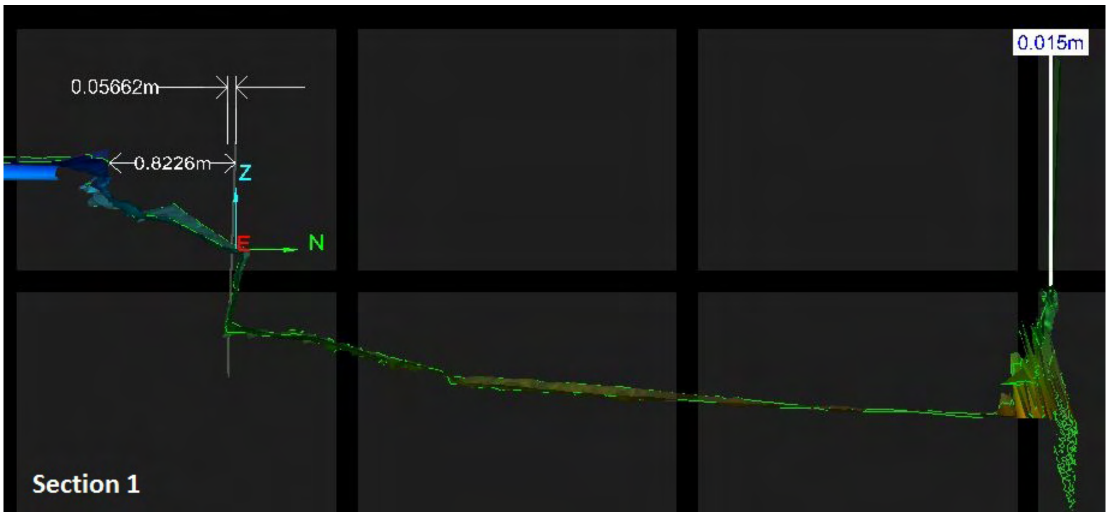


Figure QR6-26:. Failed cross section 1. Horizontal displacement of ground in the vicinity of the wall was 0.057m, failure zone width behind the wall was 0.823m, and river front railing displacement was 0.015m.

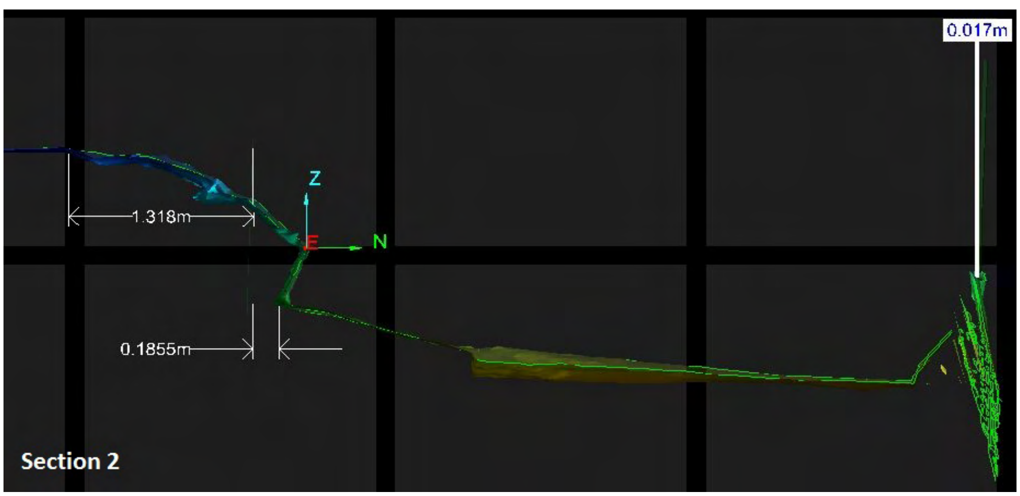


Figure QR6-27: Failed cross section 2. Horizontal displacement of ground in the vicinity of the wall was 0.19m, failure zone width behind the wall was 1.32m, and river front railing displacement was 0.017m.

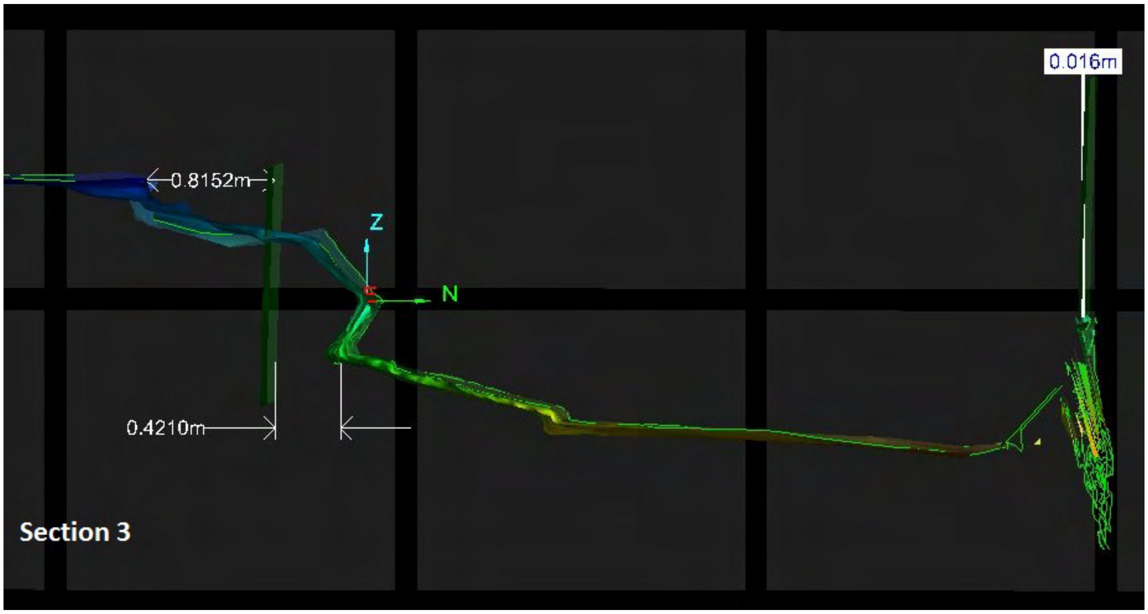


Figure QR6-28: Failed cross section 3. Horizontal displacement of ground in the vicinity of the wall was 0.42m, failure zone width behind the wall was 0.82m, and river front railing displacement was 0.016m

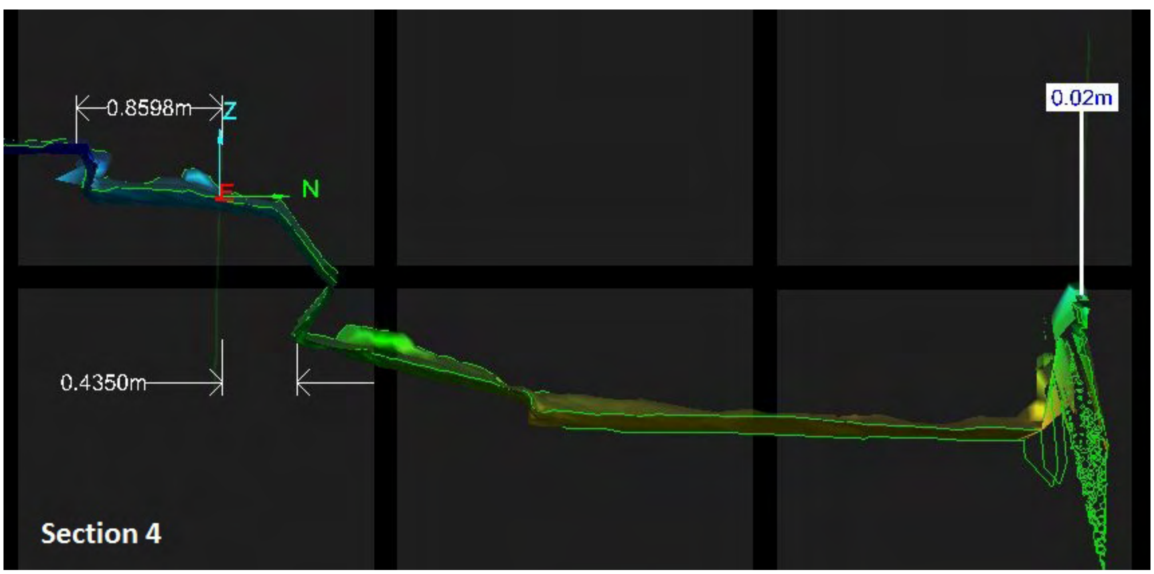


Figure QR6-29: Failed cross section 4. Horizontal displacement of ground in the vicinity of the wall was 0.44m, failure zone width behind the wall was 0.86m, and river front railing displacement was 0.02m.

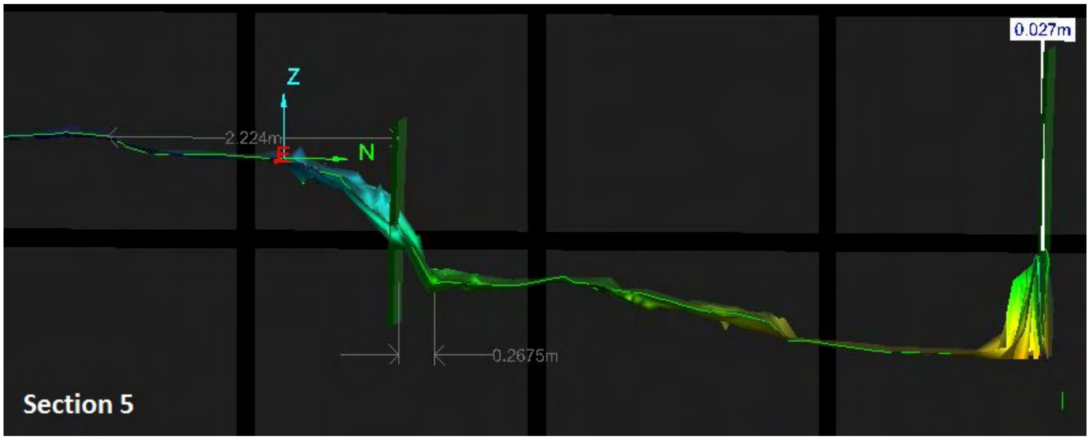


Figure QR6-30: Failed cross section 5. Horizontal displacement of ground in the vicinity of the wall was 0.27m , failure zone width behind the wall was 2.22m , and river front railing displacement was 0.027m. The river wall settlement in this zone is 0.08m.

Site RK5 (Also Site JS26): Sodegaura School, Chiba [LiDAR Site]

The LiDAR data was measured along the perimeter road on the south side of the elementary school. This area suffered storm drainage and sewer uplift in liquefied soil. On the surface, the centerline of the asphalt covered narrow road/path was lifted up. A light metal and construction block wall adjacent to the path on the north side marked the perimeter of the school, and this wall was not disturbed. At least in the vicinity of the public there does not appear to be lateral deformation occurring at this site. Jon Stewart noted that there may be lateral deformation occurring near the school foundation. Our LiDAR data does not cover that damage.

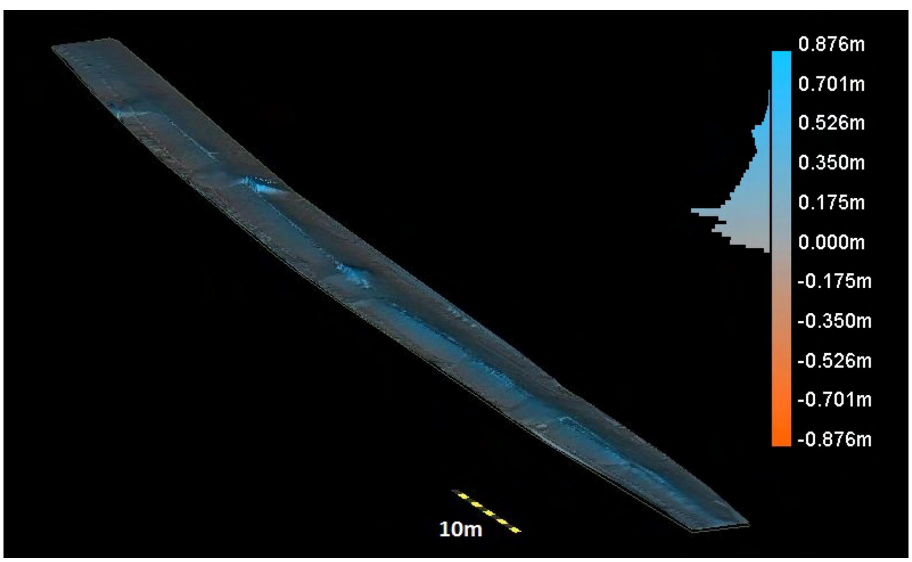


Figure QR6-31:. Histogram of uplift along path behind Sodegaura school due to buoyancy of buried storm water and sewer lines. The maximum uplift was approximately 0.70m.

Site RK6 (Also Site JS27): Urayasu, Chiba Prefecture Lateral Spread [LiDAR Site]

A large area in this field development suffered liquefaction foundation failures, structural tilting, and lateral spreads. At the southeast end of the filled peninsula is a cemetery adjacent to the bayfront park and Tokyo Bay. We collected LiDAR data along the area of maximum deformation at the boundary of the cemetery and the waterfront park.

Figure QR6-32: Lateral spread at Urayasu, Chiba

Figure QR6-32: Lateral spread at Urayasu, Chiba

Figure QR6-33: Lateral spread at Urayasu, Chiba

Figure QR6-34: Lateral spread at Urayasu, Chiba

Figure QR6-35: Lateral spread at Urayasu, Chiba

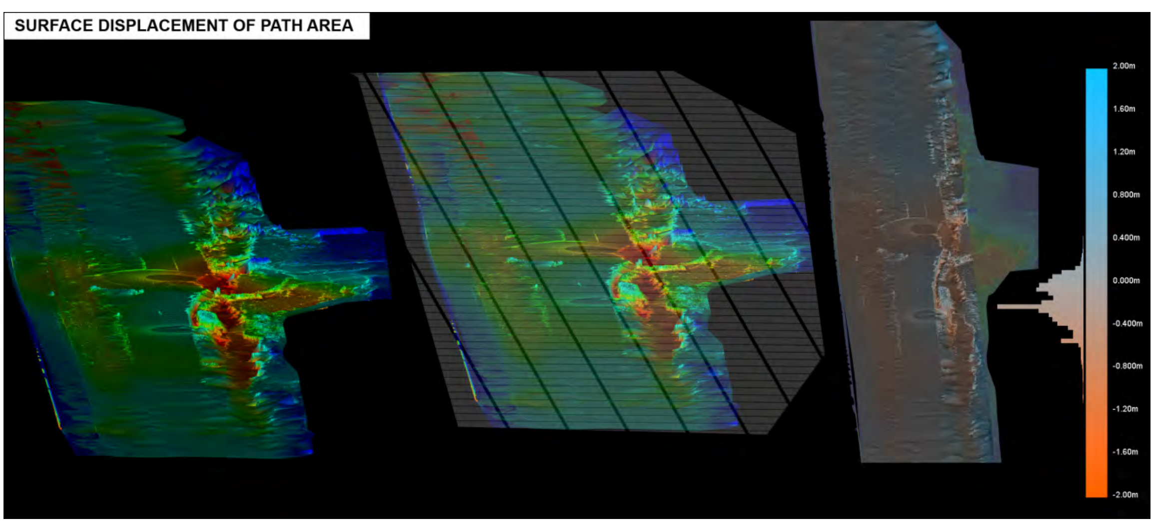


Figure QR6-36: Post failure surface (left), overlay of prefailure surface (middle) and histogram of vertical elevation change (right)

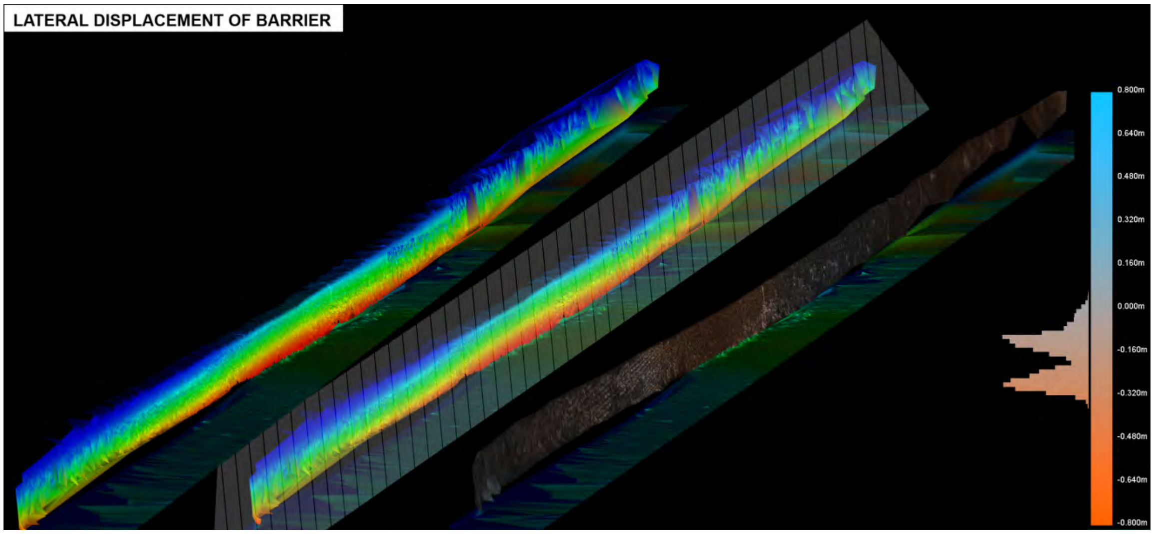


Figure QR6-37: Lateral sea wall displacement. The maximum horizontal wall movement was 0.35m.

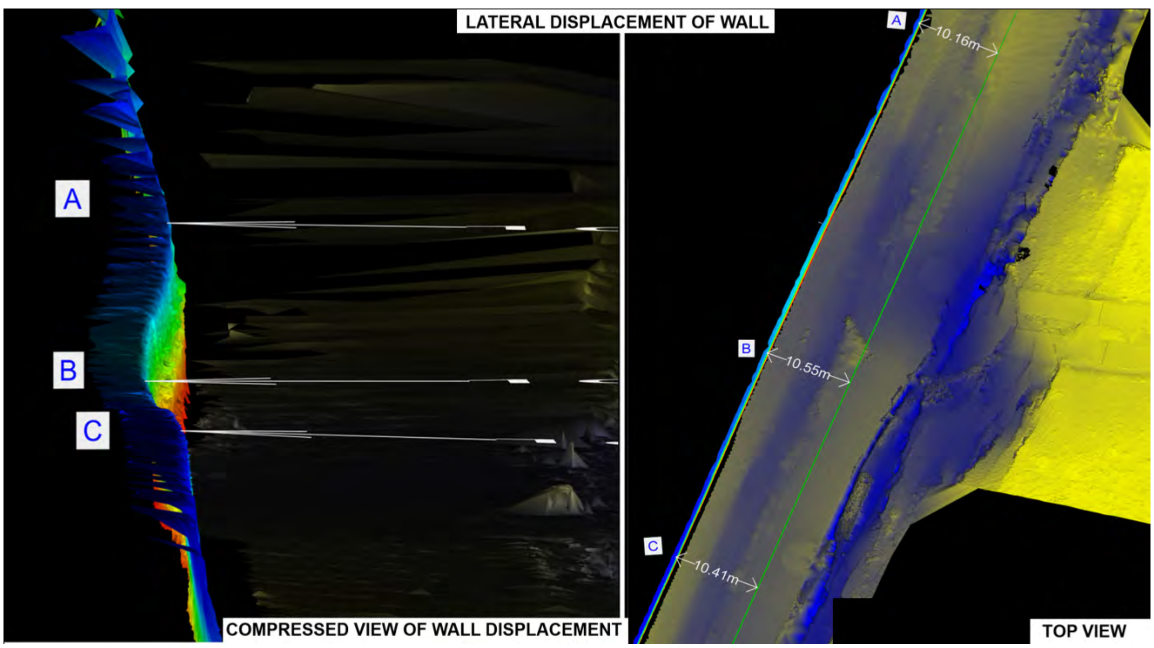


Figure QR6-38: Zone of maximum lateral displacement of the seawall (0.35 m)

Observations in Ibaraki Prefecture :
April 4, 2011:

Site RK7: Hokota City, Ibaraki Prefecture.
This site experienced liquefaction along the banks of the canal, running through the center of the town. Lateral spreading was typically 0.1-0.5m, resulting in canal shortening. Settlement in the residential/commercial district has affected structural foundations. Empty lots have sand boils, minor lateral spreading, and ground cracking. This is a worthwhile SASW site for additional study.

Figure QR6-39: Liquefaction and settlement at Hokota

Figure QR6-40: Liquefaction and wall deformation at Hokota

Figure QR6-41: Liquefaction and structural damage at Hokota

Site RK8 (Also Site JS7): Hinuma Lake South Shore Levee [LiDAR Site]

The site is an embankment failure with base widening and settlement of crest. We scanned the site from two positions at the location with the greatest amount of deformation. The crest crack extends for 800 meters.

Figure QR6-42: LiDAR scanning the Lake Hinuma embankment

Figure QR6-43: LiDAR scanning the Lake Hinuma embankment

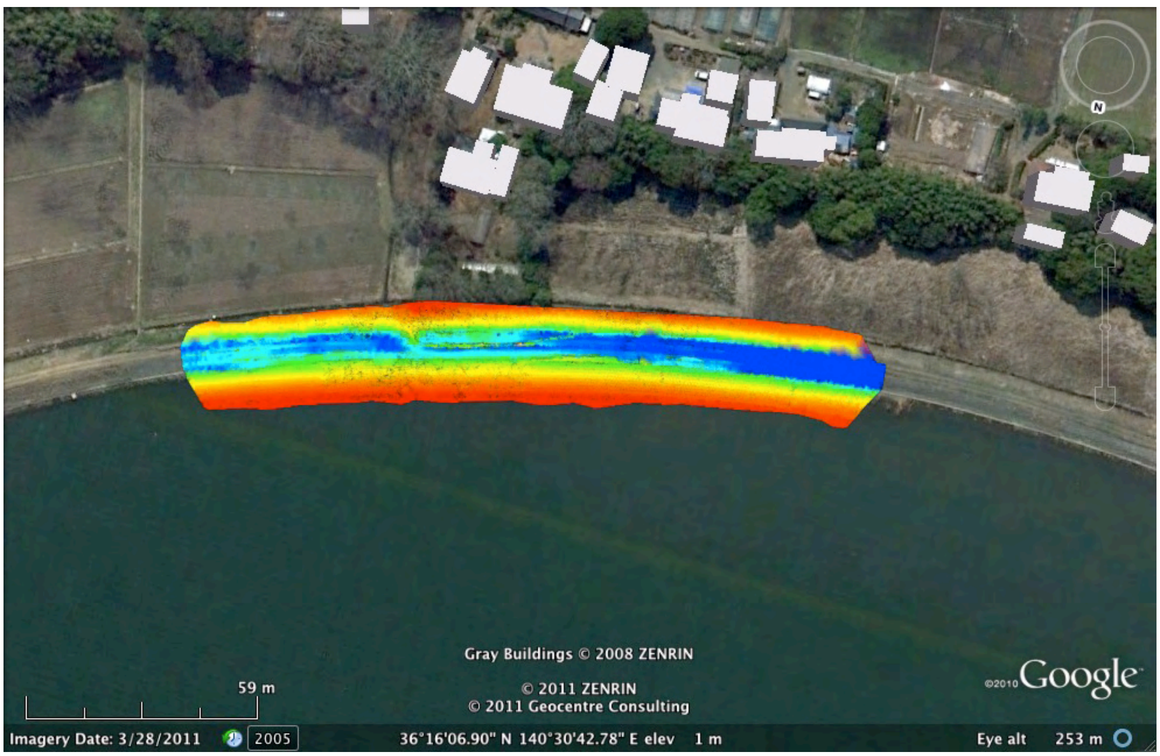


Figure QR6-44: LiDAR data and Google Earth map for the Lake Hinuma embankment

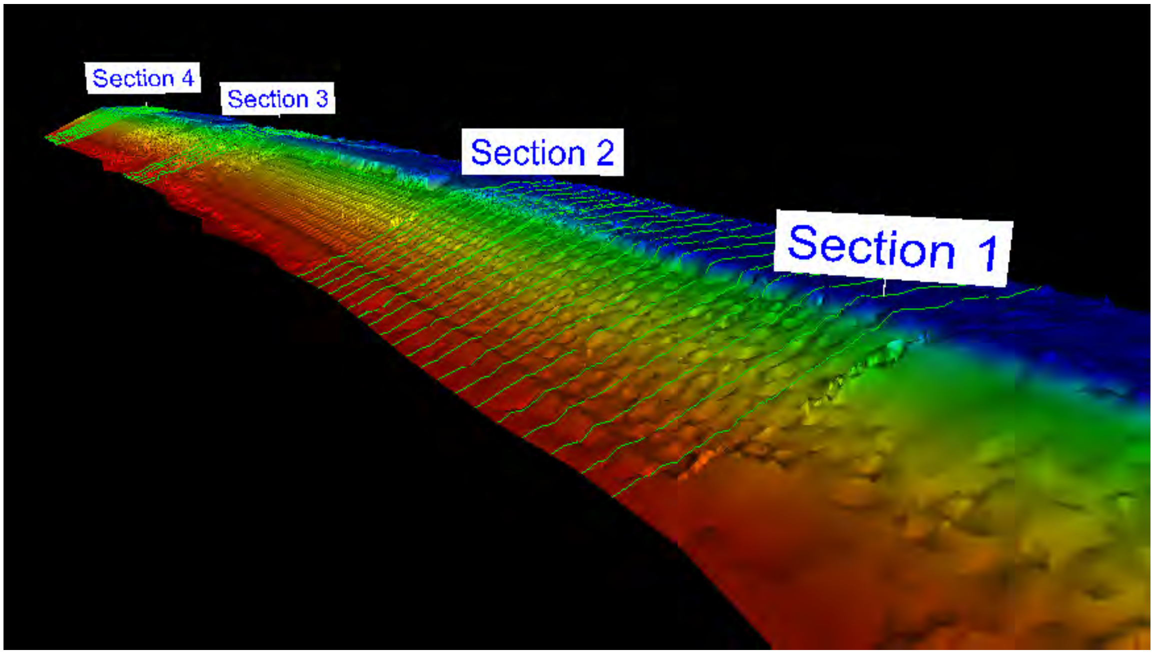


Figure QR6-45: Lake Hinuma levee cross sections 1 (unfailed) through 4

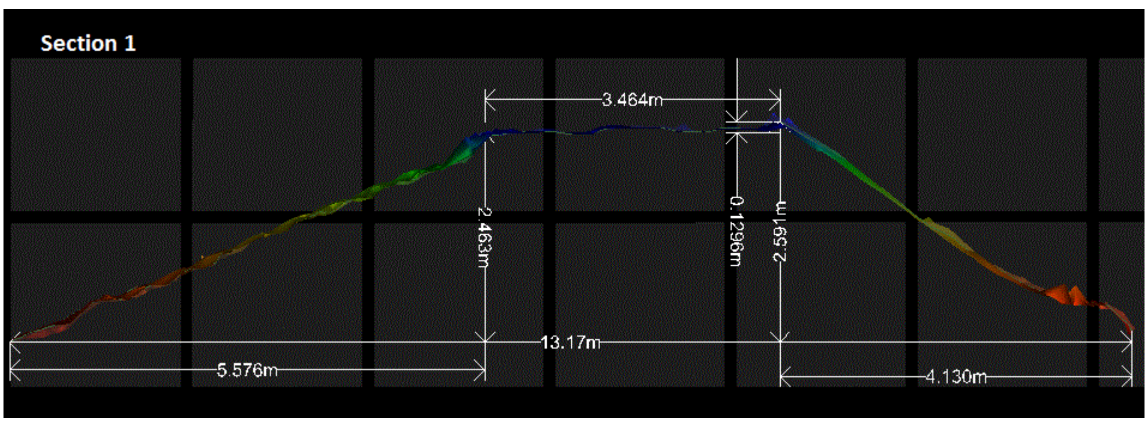


Figure QR6-46:Unfailed section 1 area of levee along Hinuma Lake, Has a crest width of 3.64m and a base width of 11.1m. [Wrong Figure]

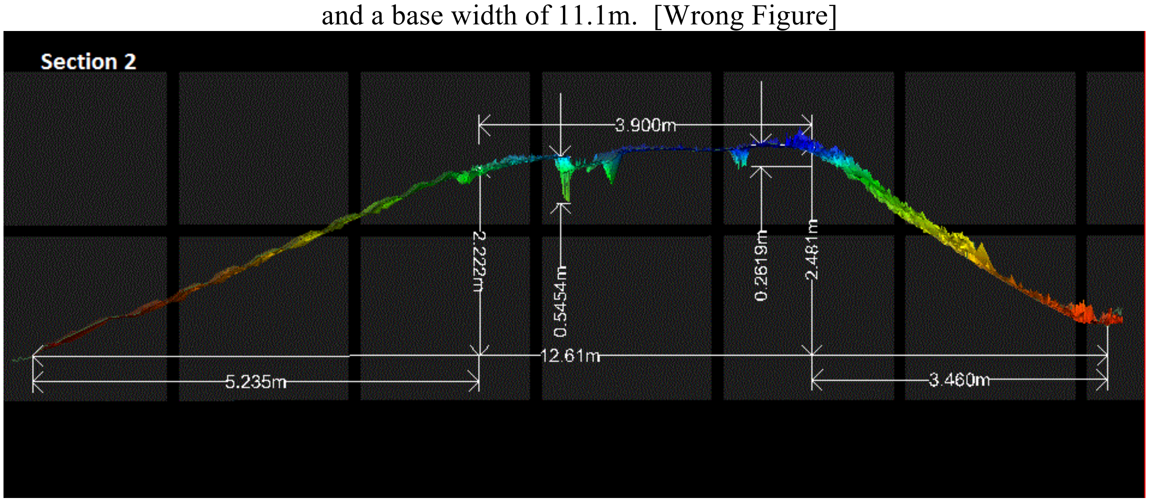


Figure QR6-47: Cross section 2 is a failed zone with open fissures measureable to a depth of 0.41m. The crest width and base have widened to 4.00 m and 11.50 m Respectably [Wrong Figure]

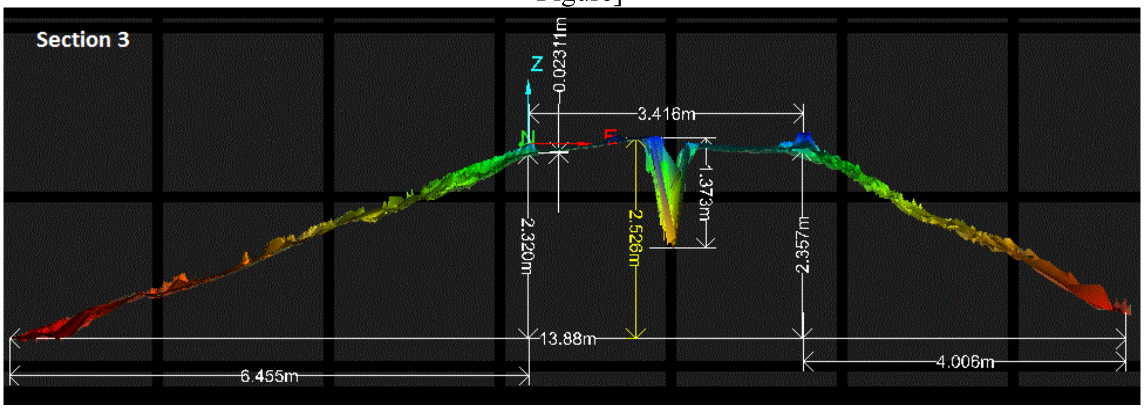


Figure QR6-48: Old Figure [Replace]

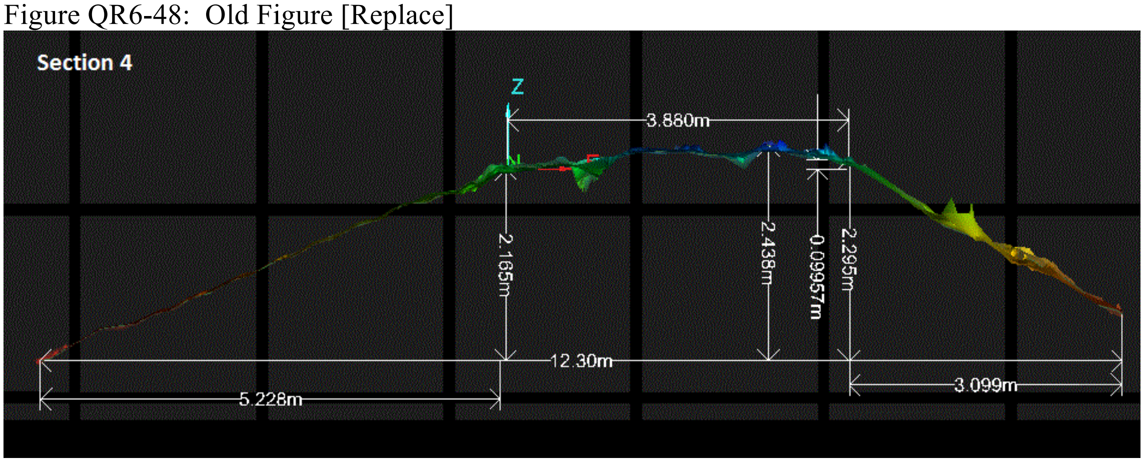


Figure QR6-49. [Old Figure, Replace]

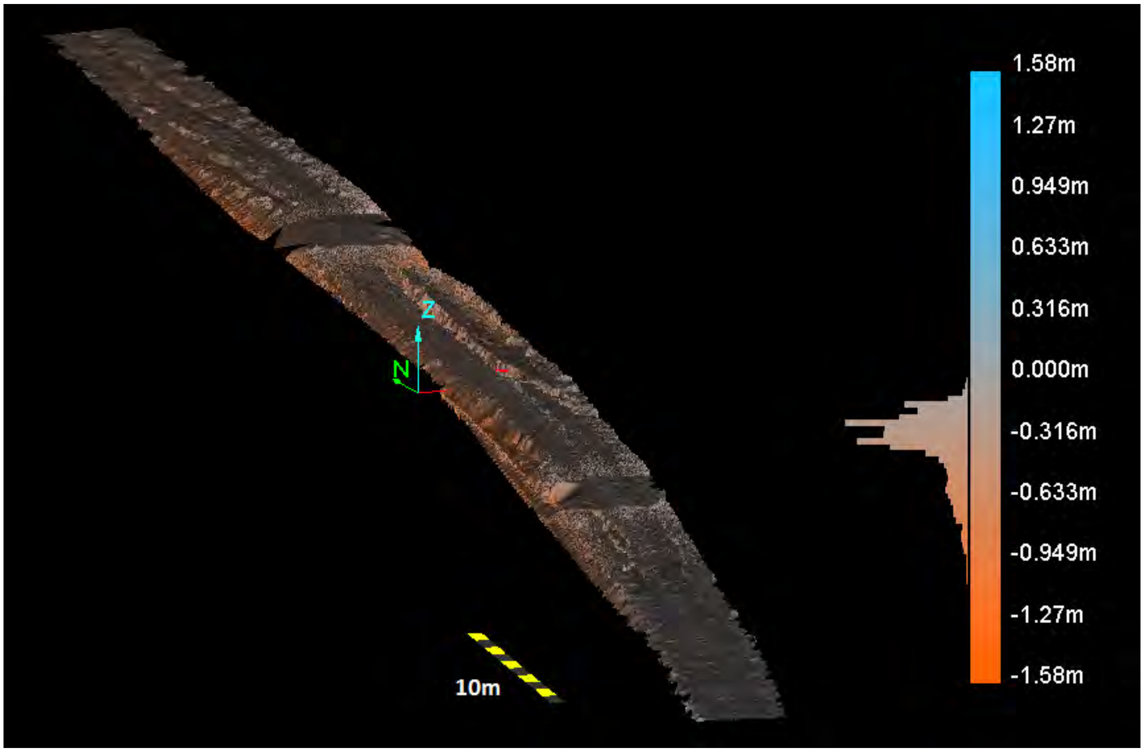


Figure QR6-50: Elevation difference map and histogram between post-earthquake and estimated pre-earthquake levee. Maximum recorded difference is approximately 1 meter.

Site RK9: Hinuma Cemetery (within 5 km of Site RK8)

The photographs were taken at the cemetery and the GPS location was taken from the track log based on the same time. The collapse ratio appears to be less than 5%, which was based on quick observation.

Figure QR6-51: Standing tombstones at Hinuma

Figure QR6-52: Standing tombstones at Hinuma

Site RK10 (Also JS10): Hitachinaka Port Landslide [LiDAR Site]

This site has a shallow rotational landslide in young coastal sediment beneath a large natural slope.   The headscarp of the landslide is a narrow zone along the base of the natural slope and the first lane of the adjacent roadway. The landslide toe is at the back and side of a port facility building. Four LiDAR scans were taken at the site. More details can be found in the description JS10.

Figure QR6-53: LiDAR scanning at Hitachinaka Port Landslide

Figure QR6-54: Lidar scanning at Hitachinaka Port Landslide

Figure QR6-55: LiDAR scanning at Hitachinaka Port Landslide

Figure QR6-56: LiDAR scanning at Hitachinaka Port Landslide

Figure QR6-57: LiDAR scanning at Hitachinaka Port Landslide

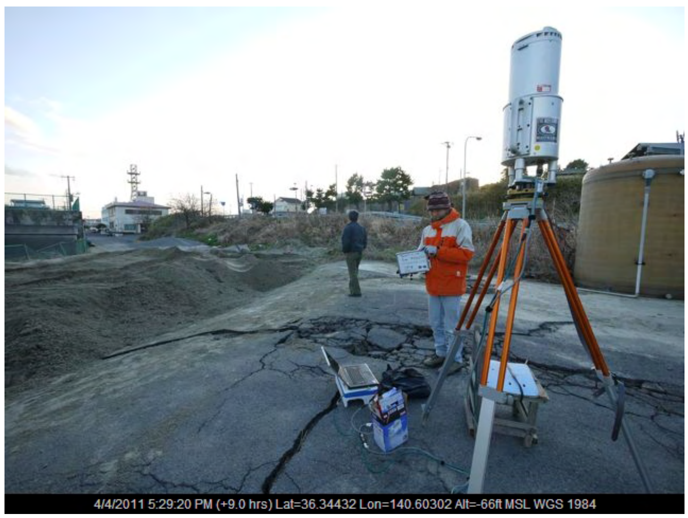


Figure QR6-58: LiDAR scanning at Hitachinaka Port Landslide

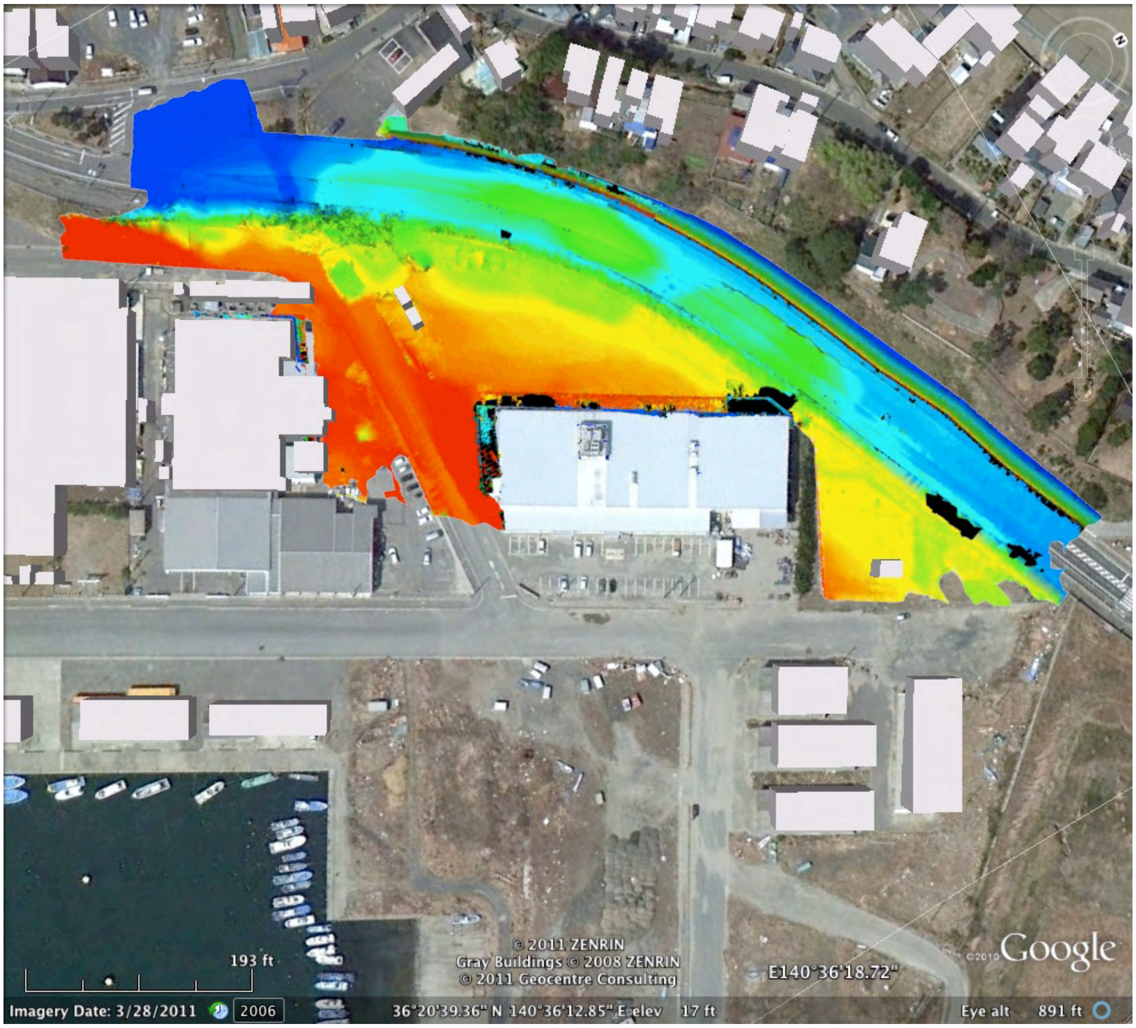


Figure QR6-58: Plan view Google Earth image of the LiDAR data captured at Hitachinaka Port.

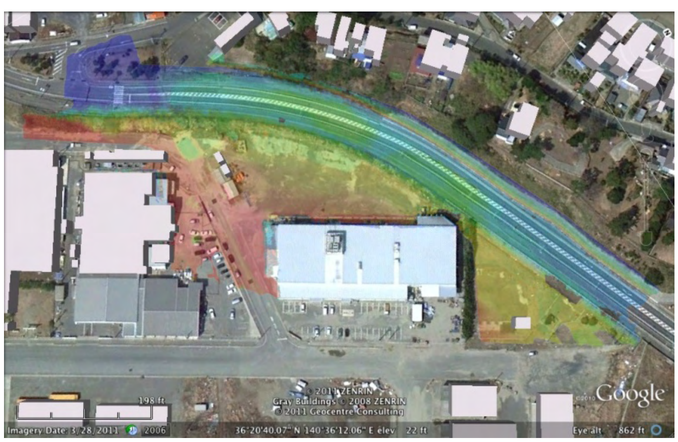


Figure QR6-59: Plan View Google Earth Image of the landslide at Hitachinaka Port with a LiDAR data transparency

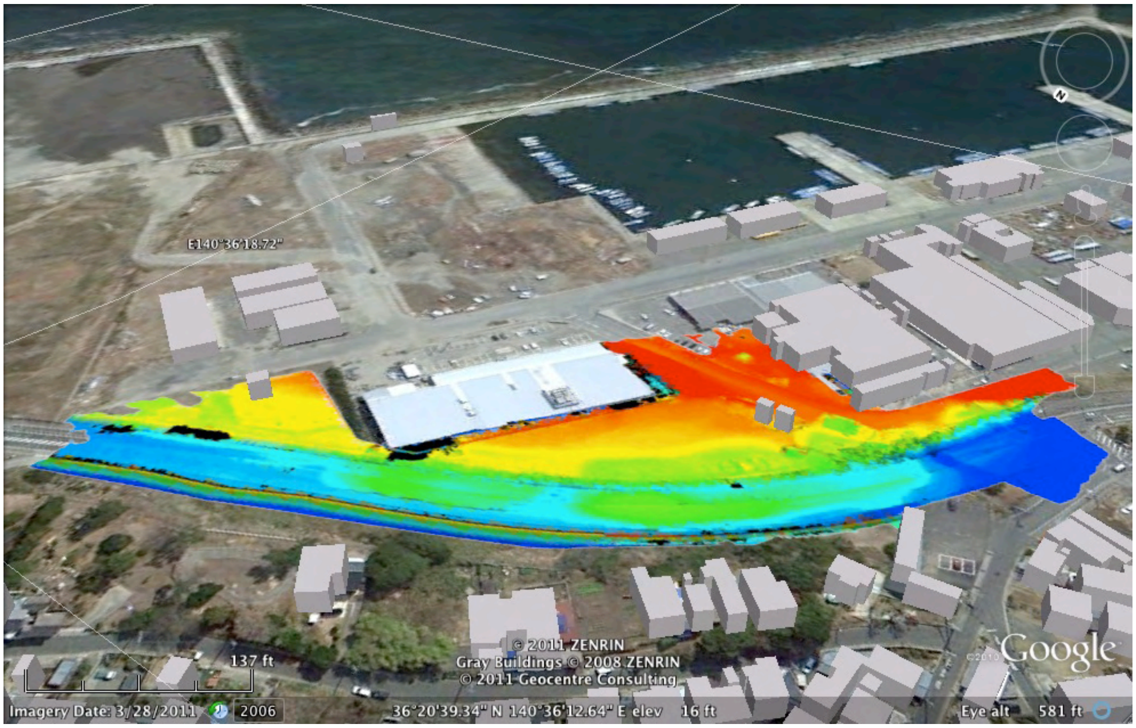


Figure QR6-60: Oblique view Google Earth image of the LiDAR data capture at Hitachinaka Port

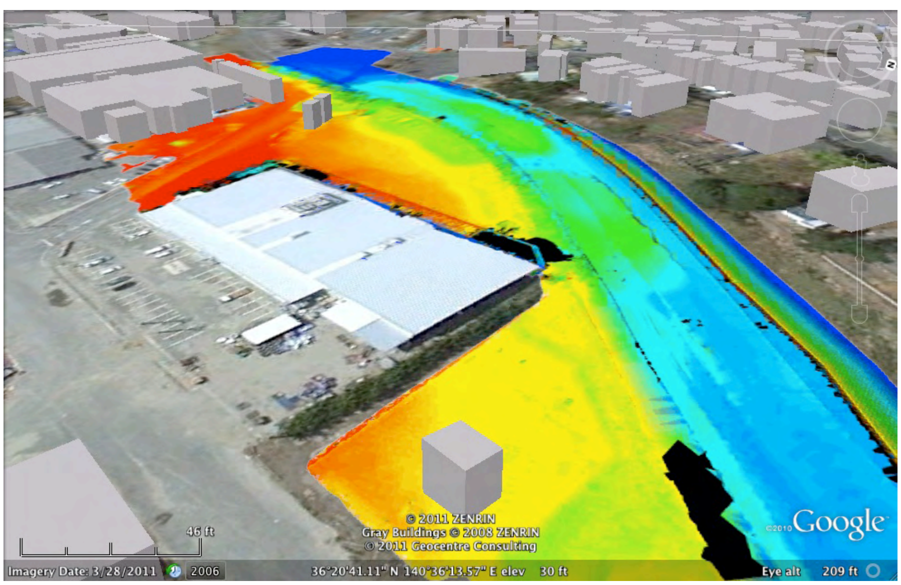


Figure QR6-61: Oblique view Google Earth image of the LiDAR data capture at Hitachinaka Port

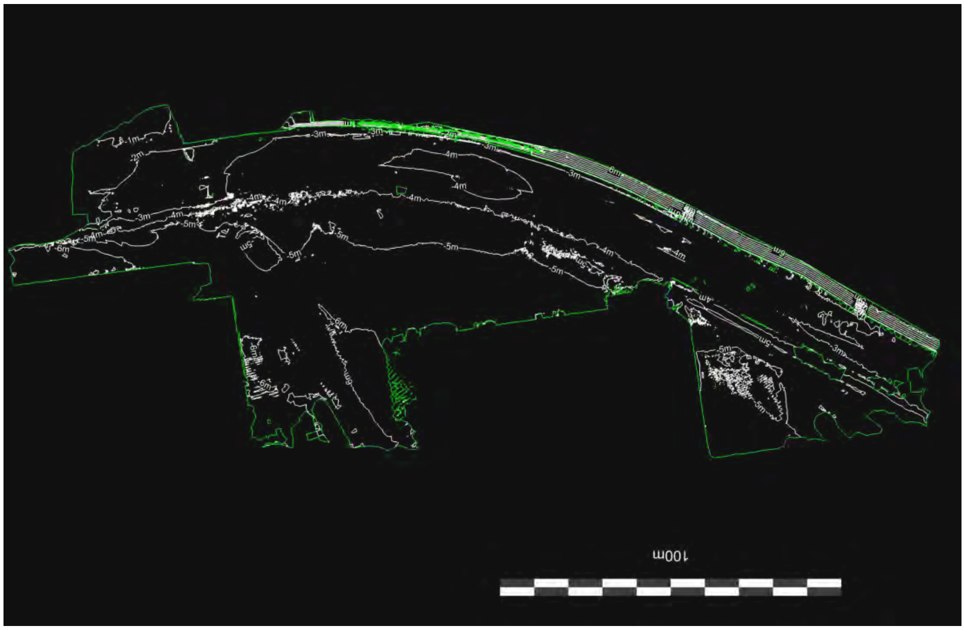


Figure QR6-62: Contour map at 1m of the Hitachinaka Landslide

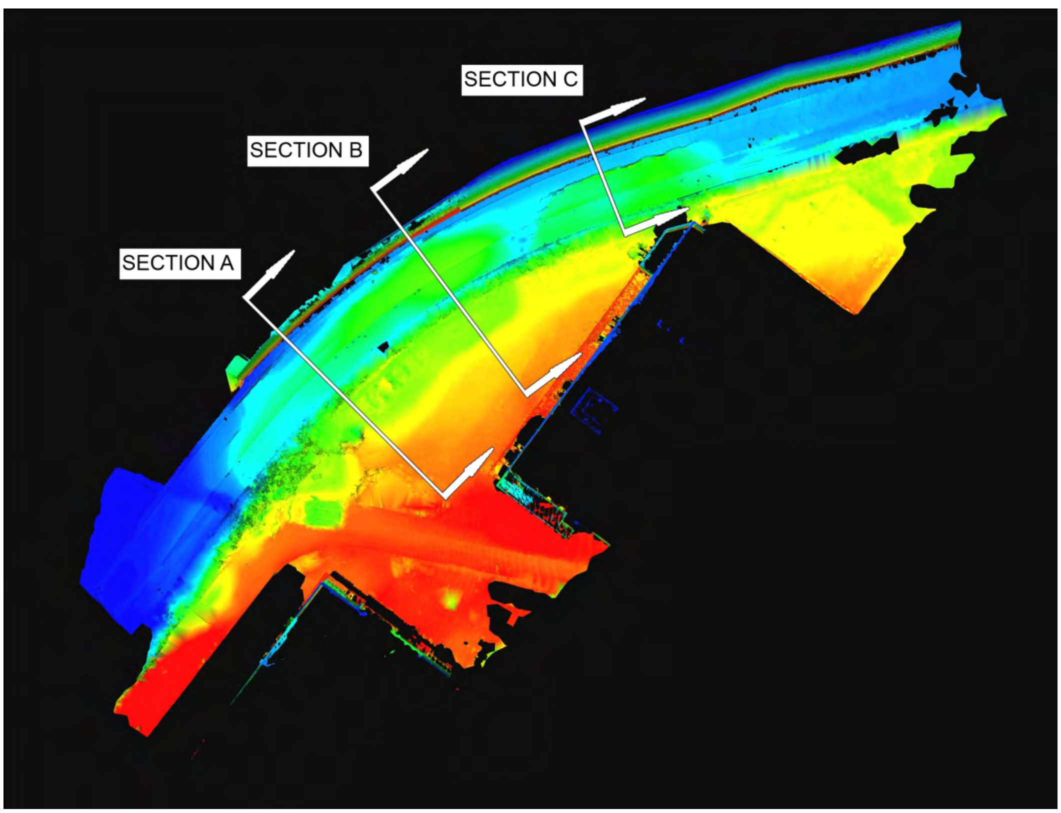


Figure QR6-63: Plan view of Hitachinaka Port Road with failure zone cross section locations

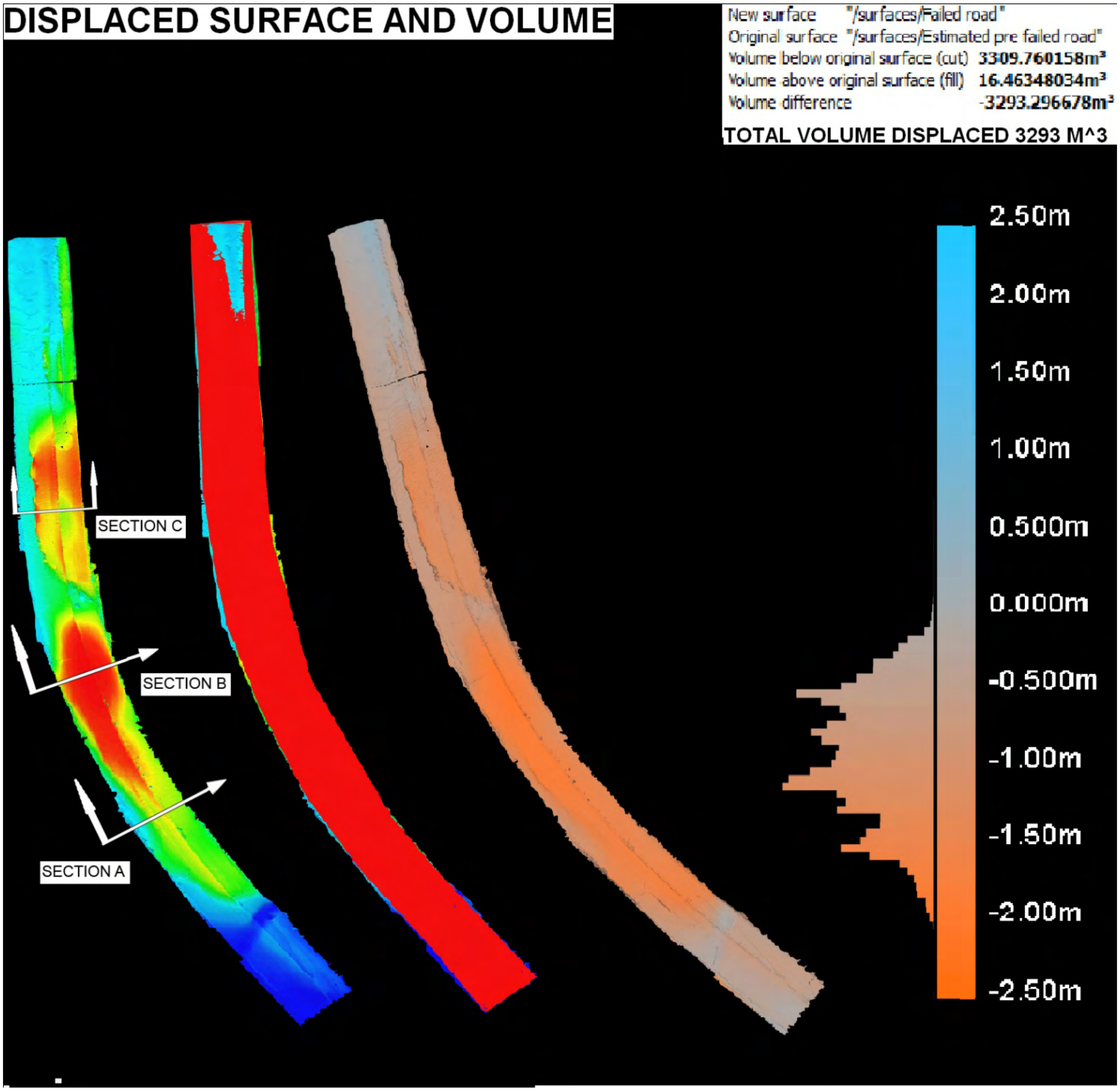


Figure QR6-64: Failure model (left), unfailed estimate model (center), and elevation difference map (right). The maximum settlement of the road at the headscarp of the landslide was 2 meters, but generally road settlements were on average 1 meters across the scanned area.

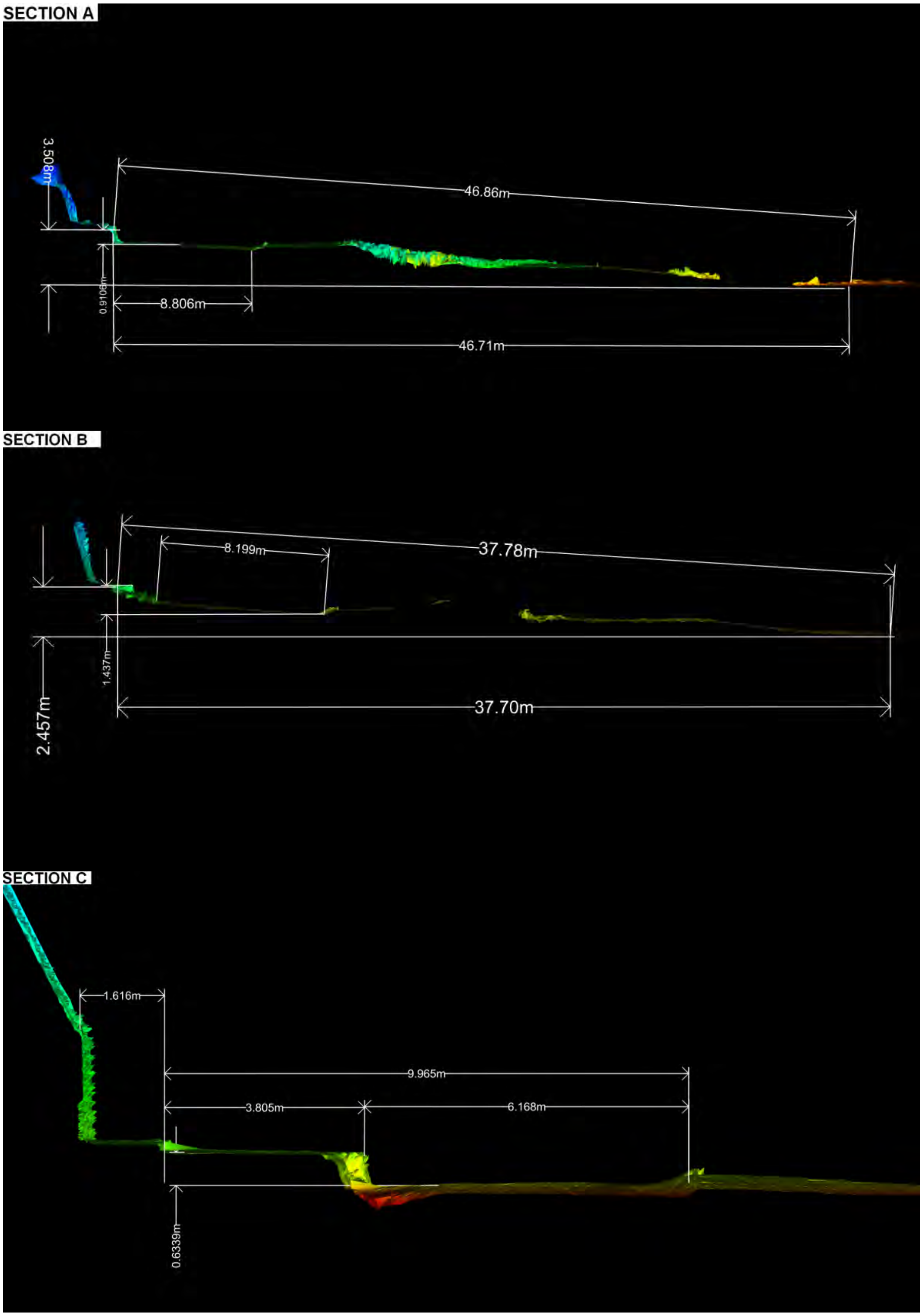


Figure QR6-65: Sections A, B, and C cross failure zones at Hitachinaka. Vertical settlment at the headscarp on the road is 0.91m on section A; section B 1.437m; and at Section C 0.633m.

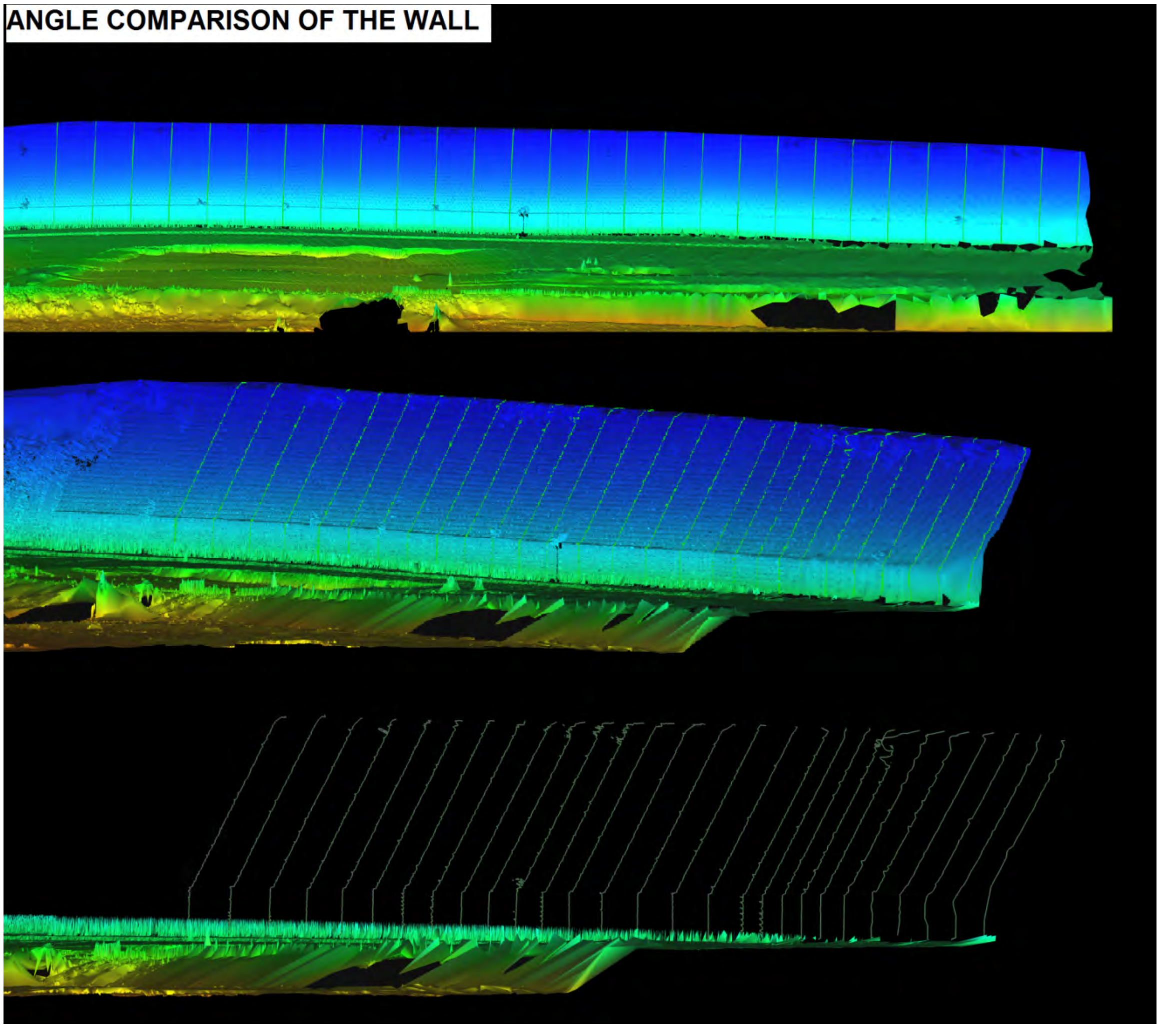


Figure QR6-66: Cross-sections along with the cut slope terrace deposits, faced with concrete indicates no deformation was observed above the landslides scarp.

Observations in Tochigi Prefecture :

April 5, 2011:

Site RK11: Nasukarasuyama Landslide

Originating from a terrace above a cut bank of a river valley. Terrace areas slope was forested native landscape. The top of the terrace is the tree farm crest scarp is approximately 250m wide by 150m long and perhaps with an average depth of 2m of material: total volume estimated at ~70,000 m^3. (W15)

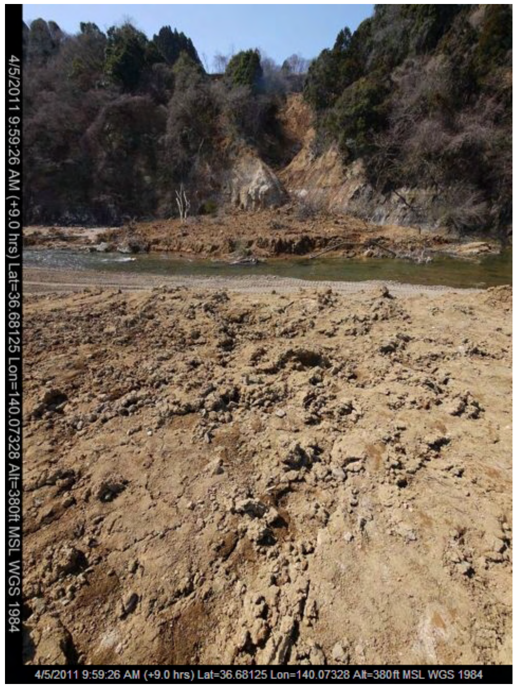


Figure QR6-67: Landslide debris crossing a local stream at Nasukarasuyama Landslide. No LiDAR data was captured at the site.

Figure QR6-68: Distant view of landslide debris and headscarp. At the time of the visit some movement of the debris had begun to prevent a landslide dam from flooding rice fields.

Site RK12: Cemetery in Nasukarasuyama Village, Tochigi Prefecture.

No observable collapsed tombstones at the cemetary. GPS coordinates stamped on the image is the vehicle's location, the cemetery site is N36.685898°, E140.072041°.

Figure QR6-69: No observable tombstone collapses, Nasukarasuyama Village, Tochigi Prefecture

Figure QR6-70: No observable tombstone collapses, Nasukarasuyama Village, Tochigi Prefecture

Observations in Fukushima Prefecture :

April 5, 2011

Site RK13 Shirawkawa Village landslide

This large landslide impacted a village in the southwestern Fukushima Prefecture. We collected three LiDAR scans on April 5. This landslide appears to emanate from a slope of an accumulation of volcanic ash or pumice(?). Samples are lightweight, white in color or oxidized brown. The landslide initiated on a forest slope and came down onto an agricultural village impacting several houses and resulting in fatalities. The landslide covered the valley floor and crossed to the far side. Estimates from the LiDAR scans indicate that approximately 25,000 cubic meters of material slid from the slope. Approximately half of that material (11,000 cubic meters) are accounted for on the valley floor. The disparity is due to incomplete LiDAR coverage of the valley floor, and re-creating efforts that remove soil from the main debris area.

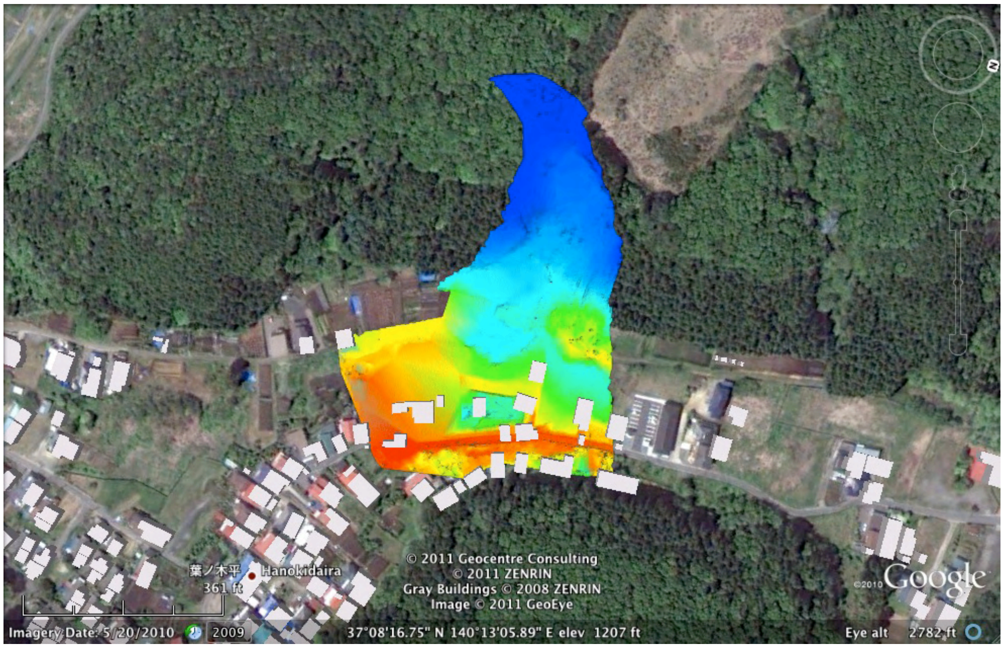


Figure QR6-71: Google Earth image of the Shirakawa landslide area with the LiDAR data overlay. Low lying structures in the south end were not impacted by the landslide. Approximately 10 residential and out-structures structures (garages, sheds, etc.) were impacted directly.

Figure QR6-72: Professor Tanaka (Kobe University) walking on debris from Shirakawa landslide

Figure QR6-73: An emergency road was bulldozed through a landslide debris at the toe of the failure, and to gain access to the location of homes buried by debris.

Figure QR6-74: A destroyed home at the north perimeter of the toe of a landslide.

Figure QR6-75.: Landslide scan position 1 on the north end of the debris field

Figure QR6-76: Shirakawa landslide scan position 2 at the slope break in the central portion of the landslide .

Figure QR6-77: Shirakawa landslide scan position 3 toward the south end of the debris field along the emergency access road.

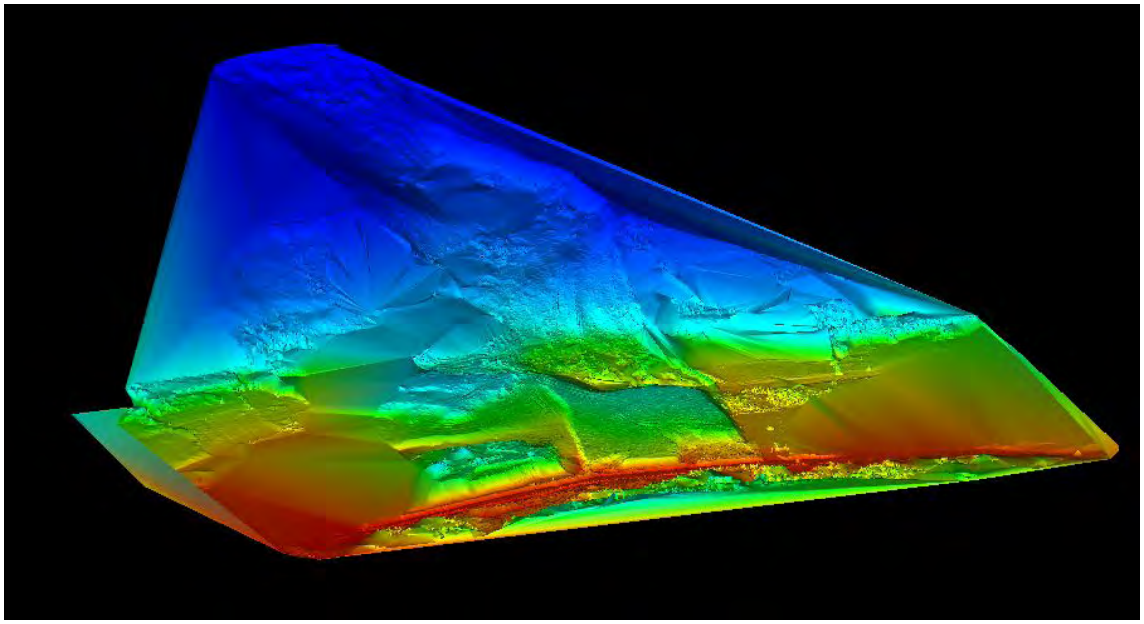


Figure QR6-78: Oblique LiDAR scan from the southeast of the landslide area. The rainbow shade indicates high elevation areas in blue and low elevation areas in red. The landslide scour is clearly evident in the slope. Some regarding of the landslide debris is evident in the valley floor along with the emergency access road cut.

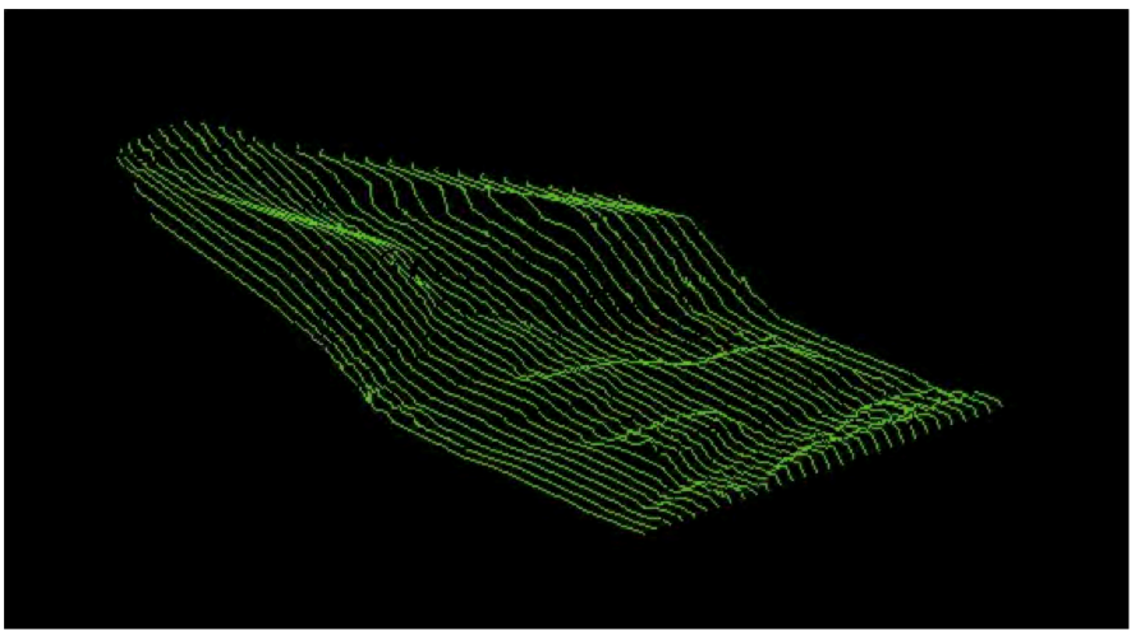


Figure QR6-79: Cross sections through the landslide and adjacent slopes

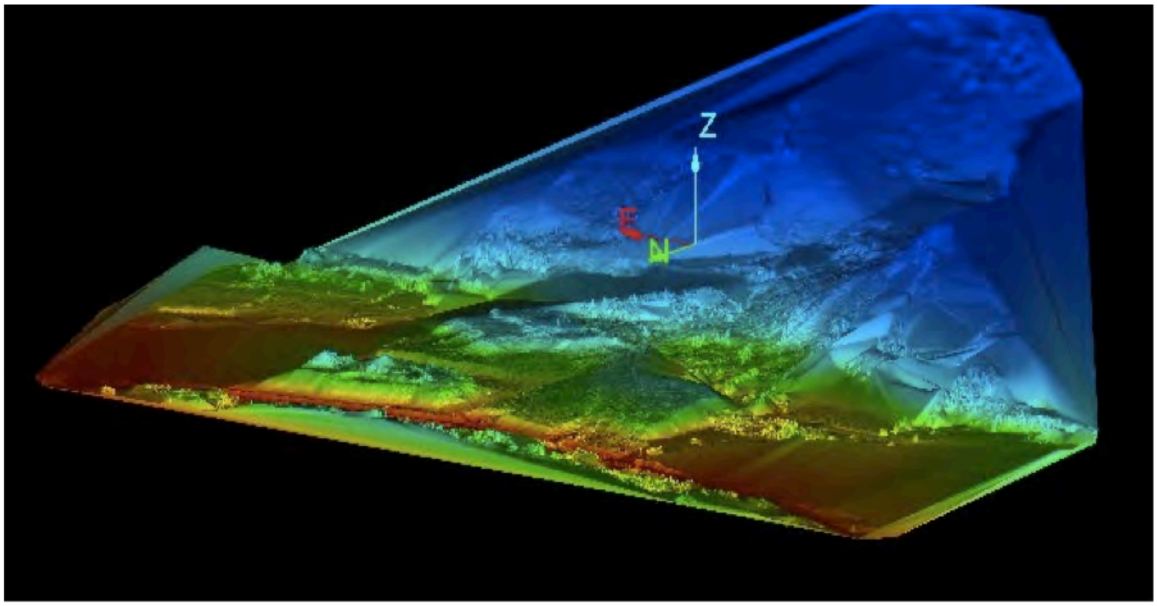


Figure QR6-80: Oblique LiDAR scan from the northeast of the landslide area. The rainbow shade indicates high elevation areas in blue and low elevation areas in red. The landslide scour is clearly evident in the slope. Some regarding of the landslide debris is evident in the valley floor along with the emergency access road cut.

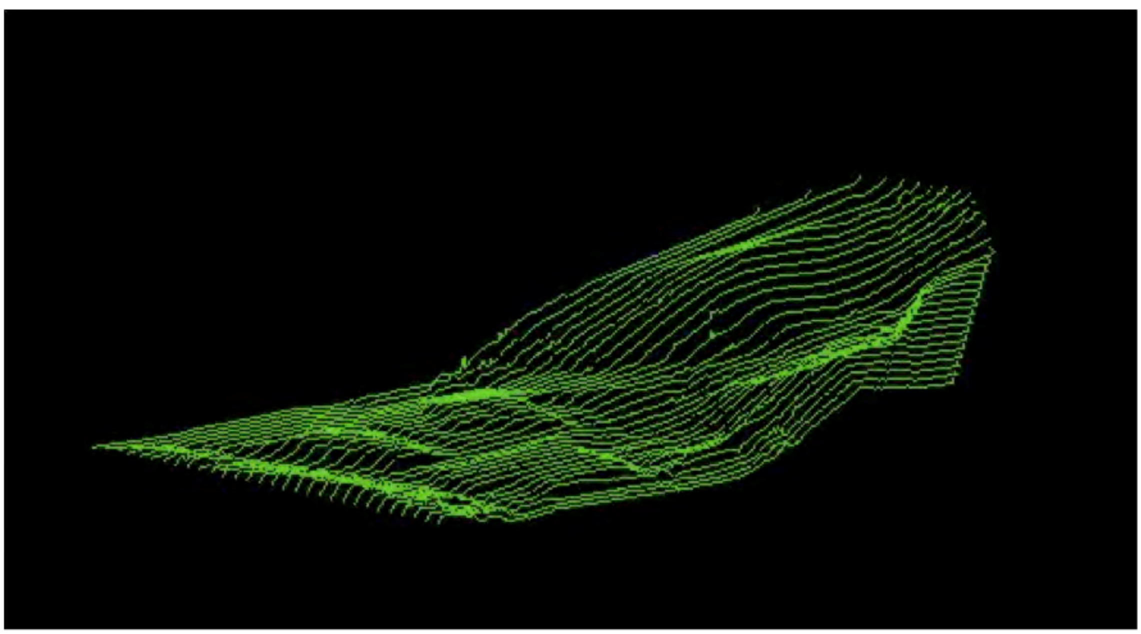


Figure QR6-81: Cross-sections of a landslide area from the Northeast

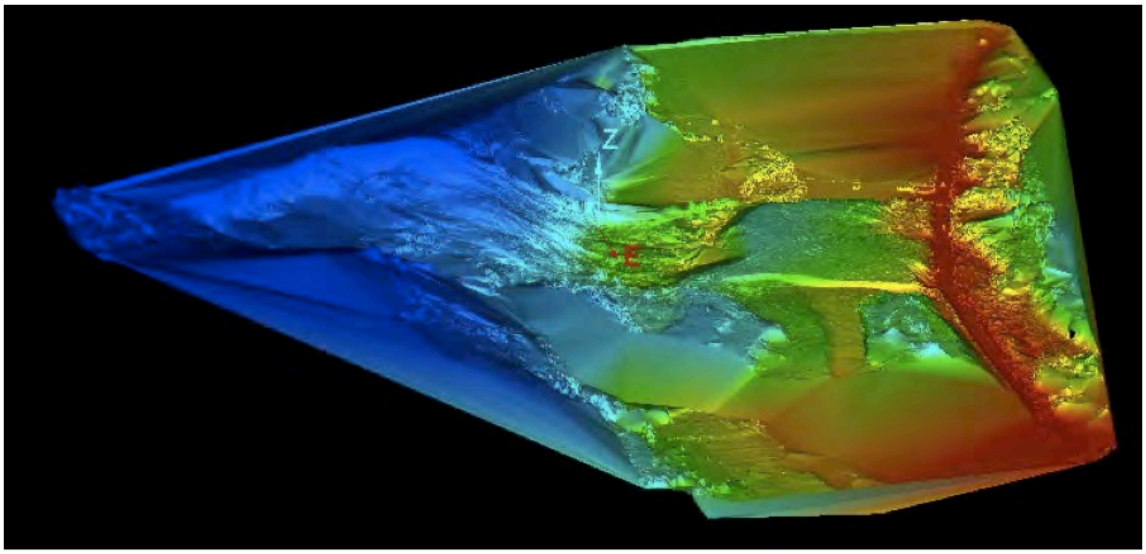


Figure QR6-82: Oblique LiDAR image from the South with filtered topography

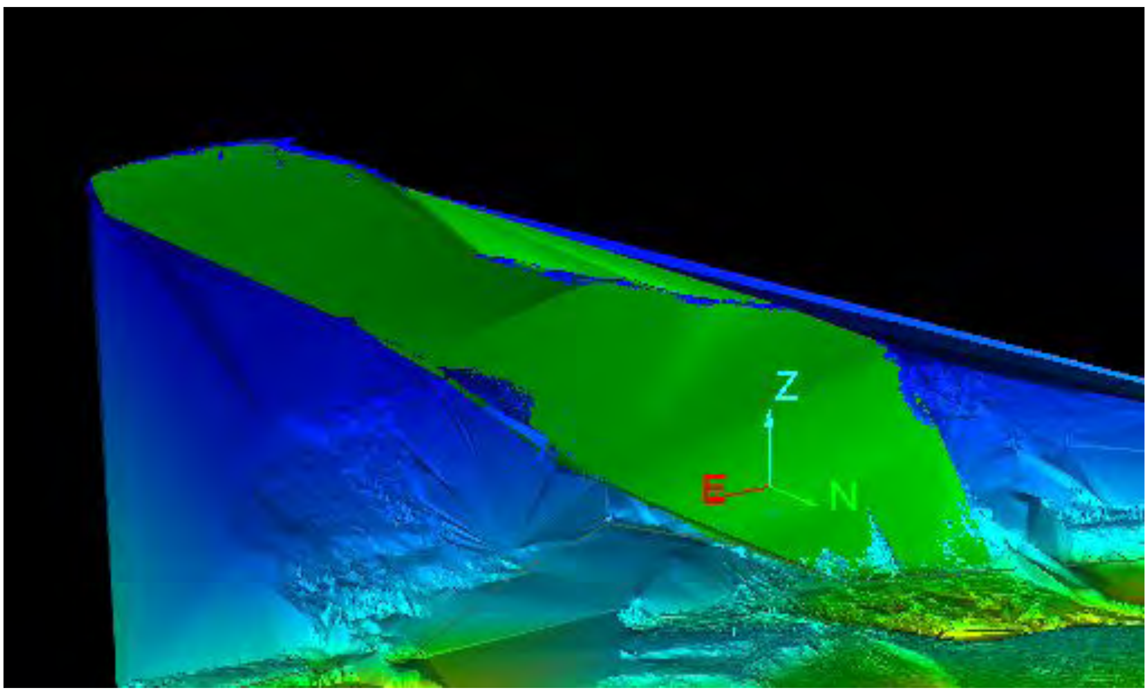


Figure QR6-83: Pre-earthquake model surface across the slope used to estimate the volume of material moved. Approximately 25,000 cubic meters of material were involved in the landslide.

Site RK14: Naganuma Town Cemetery with collapse ratio of approximately 70%.

Figure QR6-84: Professor Tanaka among collapse tombstones of a village outside Naganuma. The collapse ratio is approximately 70%

Figure QR6-85. : Tombstones of a village outside Naganuma. . The collapse ratio is approximately 70%.

Site RK15: Fujinuma Dam, Fukushima [LiDAR Site]

Fujinuma Dam is an embankment dam located in southern Fukushima Prefecture that failed shortly after the earthquake. The failure of the dam resulted in the uncontrolled release of the entire reservoir, which flowed downstream into a small village and killed 8 people (Matsumoto, 2011; Towhata et al., 2011).

Fujinuma Dam had a maximum height of about 18.5 meters and had a maximum reservoir volume of approximately 1.5 million cubic meters (~1,200 acre-feet). It has sometimes been referred to as Fujinuma-ike, which means it was considered to be a pond-retaining structure because the dam was not on a regulated river (Matsumoto, 2011).   Details regarding the failure of the dam are covered in greater detail in Quick Report 5: GEER Association Report No. GEER-025e (June 6, 2011), Preliminary Observations of the Fujinuma Dam Failure Following the March 11, 2011 Tohoku Offshore Earthquake, Japan by Harder et al. 2011 .(http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Tohoku_Japan_2011/Quick%20Report_5_index.html.

Report No. GEER-025e found that construction began in 1937 and was completed in 1949. A cross-section of the modern dam is posted on the diagram on the left abutment of the dam. We use this cross-section to construct a model pre-failure geometry in order to estimate the volume of material lost during the dam failure. The main shock of the earthquake occurred at 2:46 PM local time on March 11, 2011. A strong motion station at night a new month located 2.8 km away from the dam registered a peak horizontal acceleration of 0.315g. The breach of the damn occurred near the right abutment corresponding to the thalweg of the reservoir, observed after the failure.

This report covers the LiDAR data collection for the dam at three locations of slope deformation and failure, the main 18.5 m dam, a second 6m auxiliary dam, and liquefaction induced deformations of the embankment slopes along the park frontage at the western end of the reservoir.

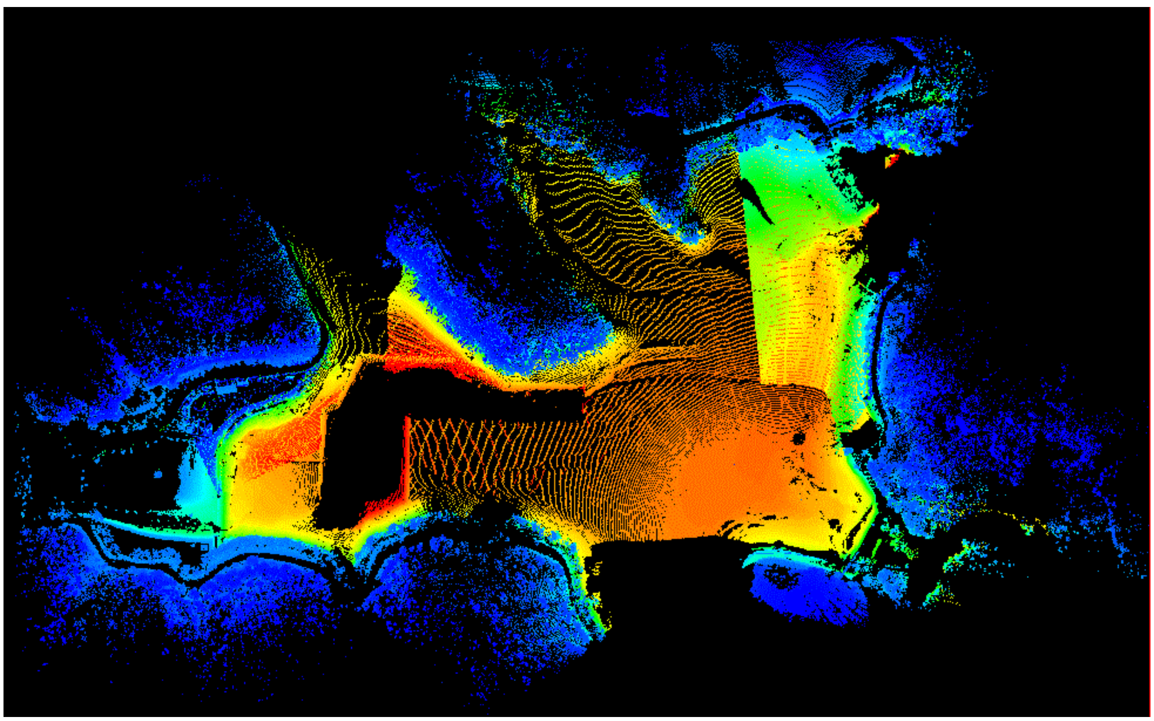


Figure QR6-86: Three areas of LiDAR coverage are the main dam in the upper right of the image above, the auxiliary damn in the lower right, and the embankment slopes along the park frontage on the left side.

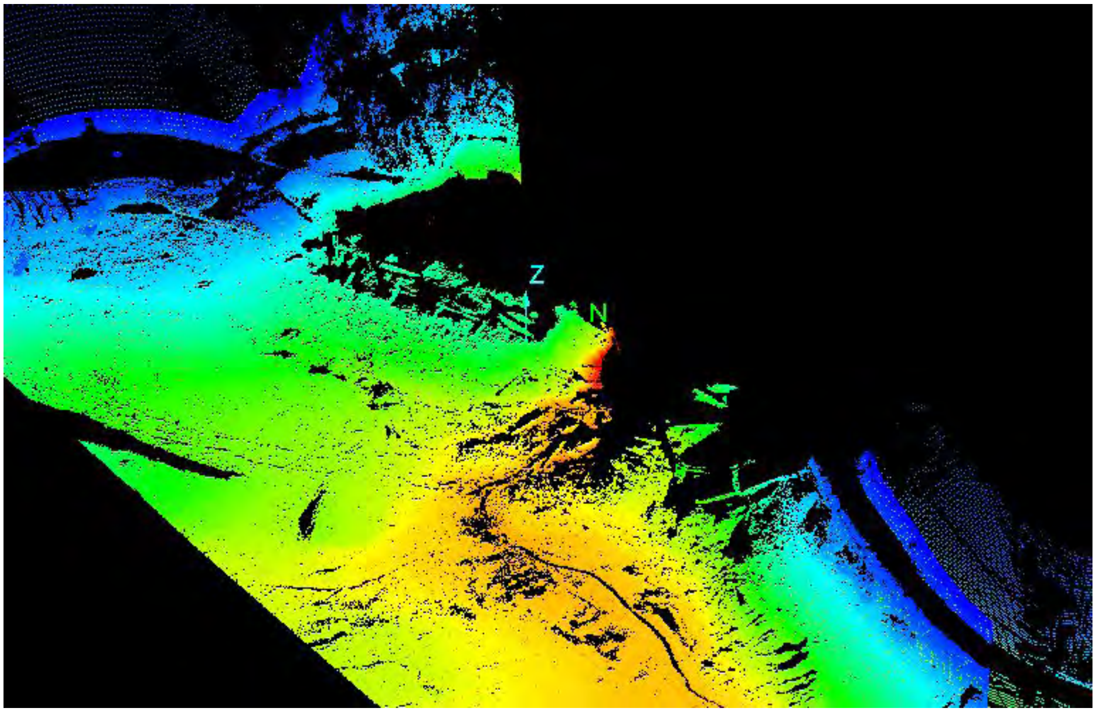


Figure QR6-87: LiDAR data coverage of the main dam includes the upstream slope and remaining crest, but is missing from sections of the downslope face where they still remain.

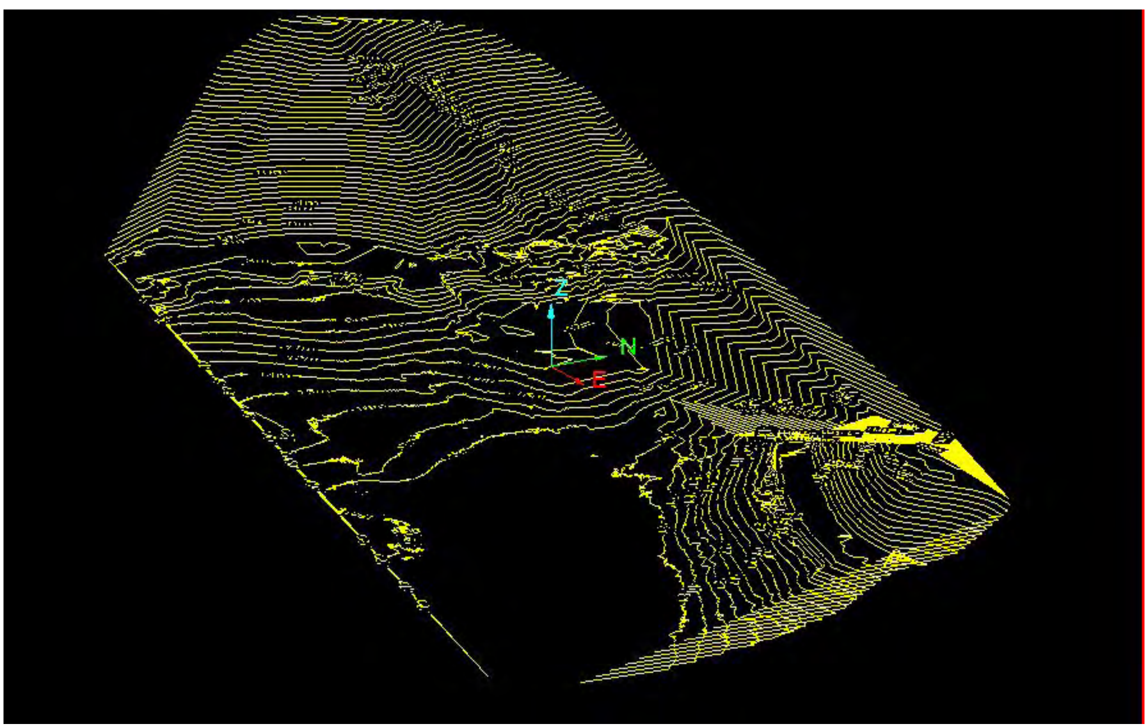


Figure QR6-88: Contour map includes portions of the lighter coverage and modeled portions of the downslope face.

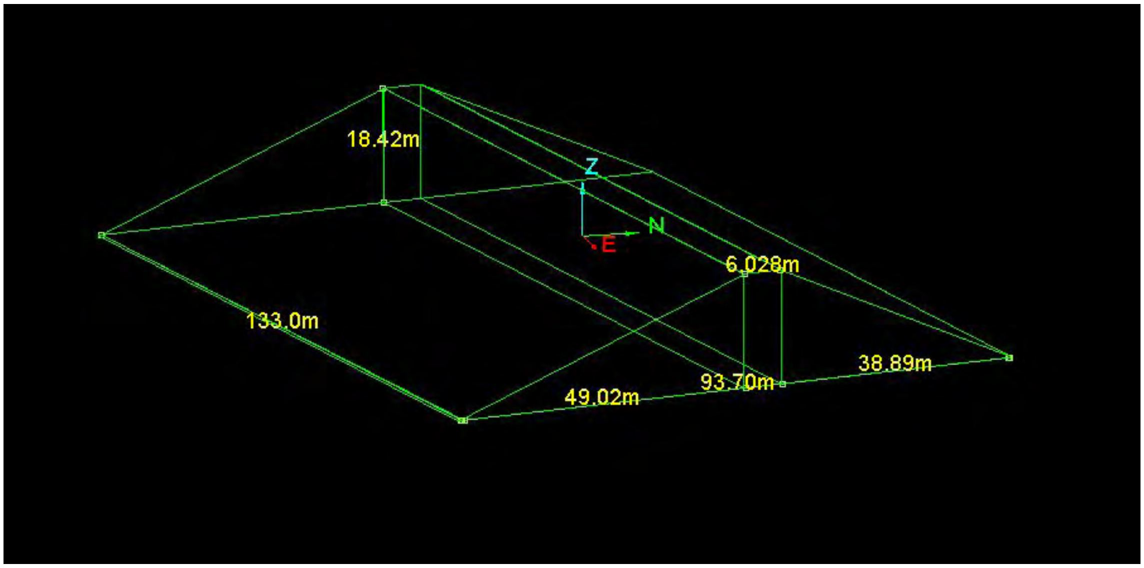


Figure QR6-89: Based on the diagram at the site, a model was developed for pre-dam geometry.

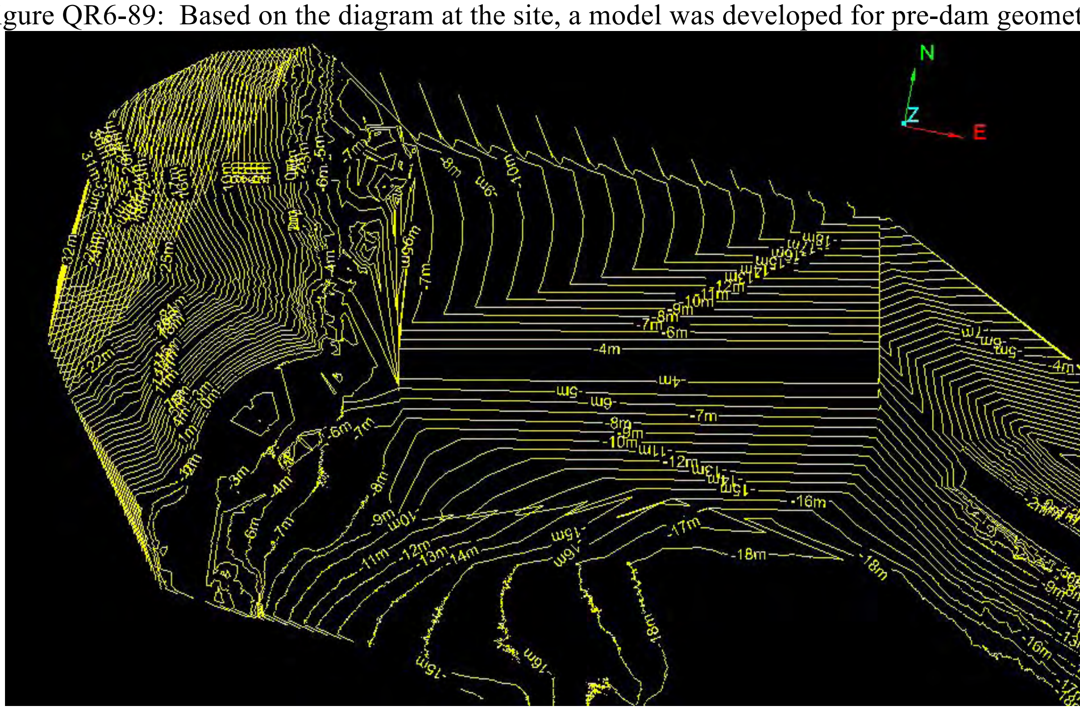
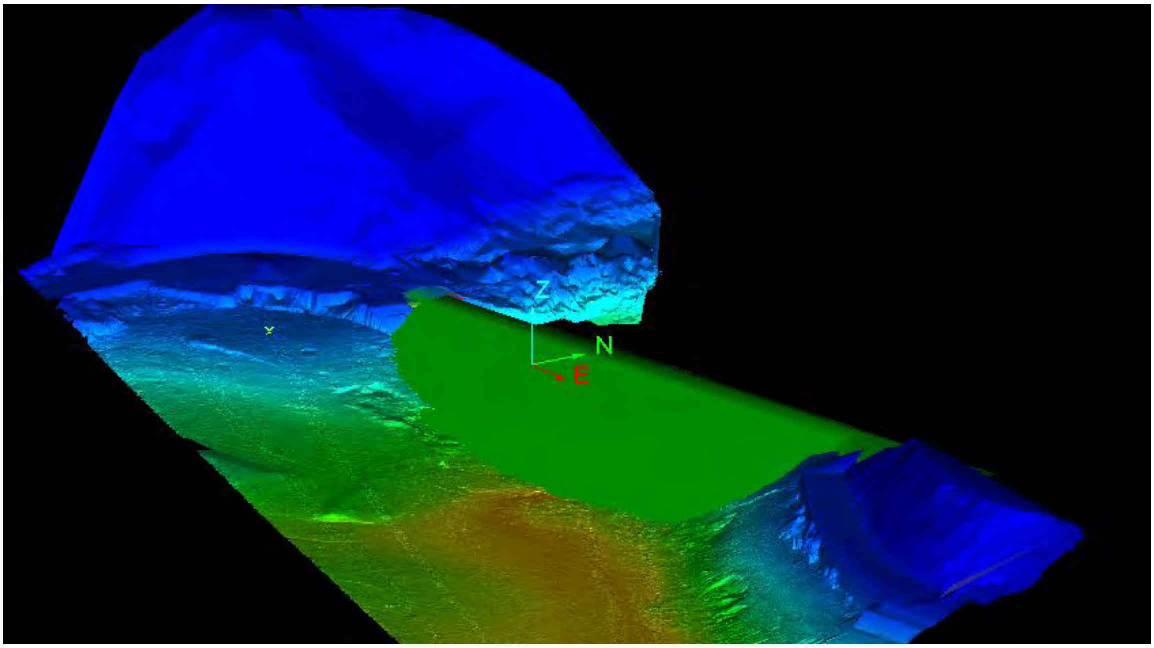


Figure QR6-90: Estimated contour map of the pre-failed dam and surrounding reservoir slopes



. Figure QR6-91: Oblique model of the LiDAR data and dam before failure.

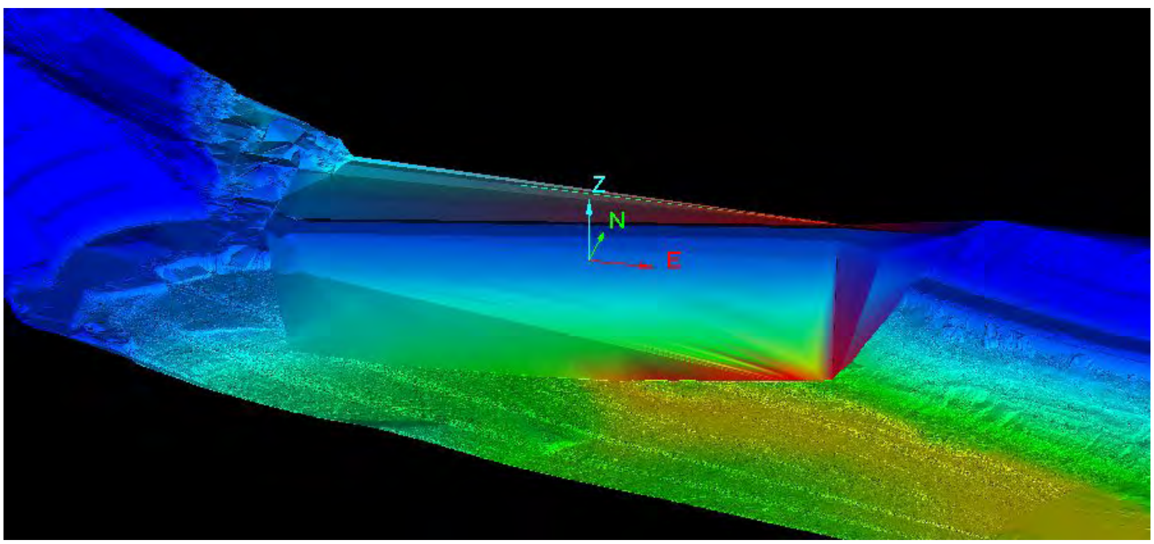


Figure QR6-92: Oblique model of the LiDAR data and dam before failure.

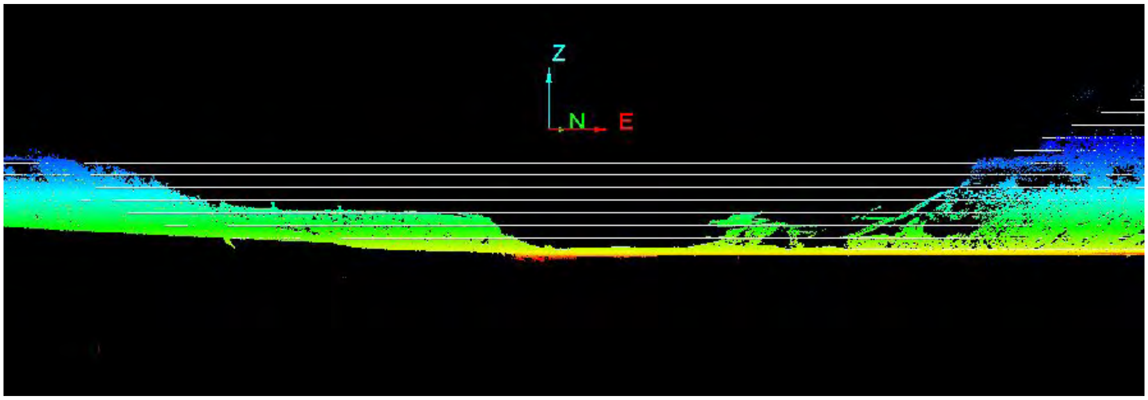


Figure QR6-93: LiDAR data plotted against 2m contours of the original dam surface looking directly at the dam from the reservoir side. At the maximum zone of cut down approximately 14m of embankment was lost. On the left about 8m of embankment was lost.

Auxilliary Dam

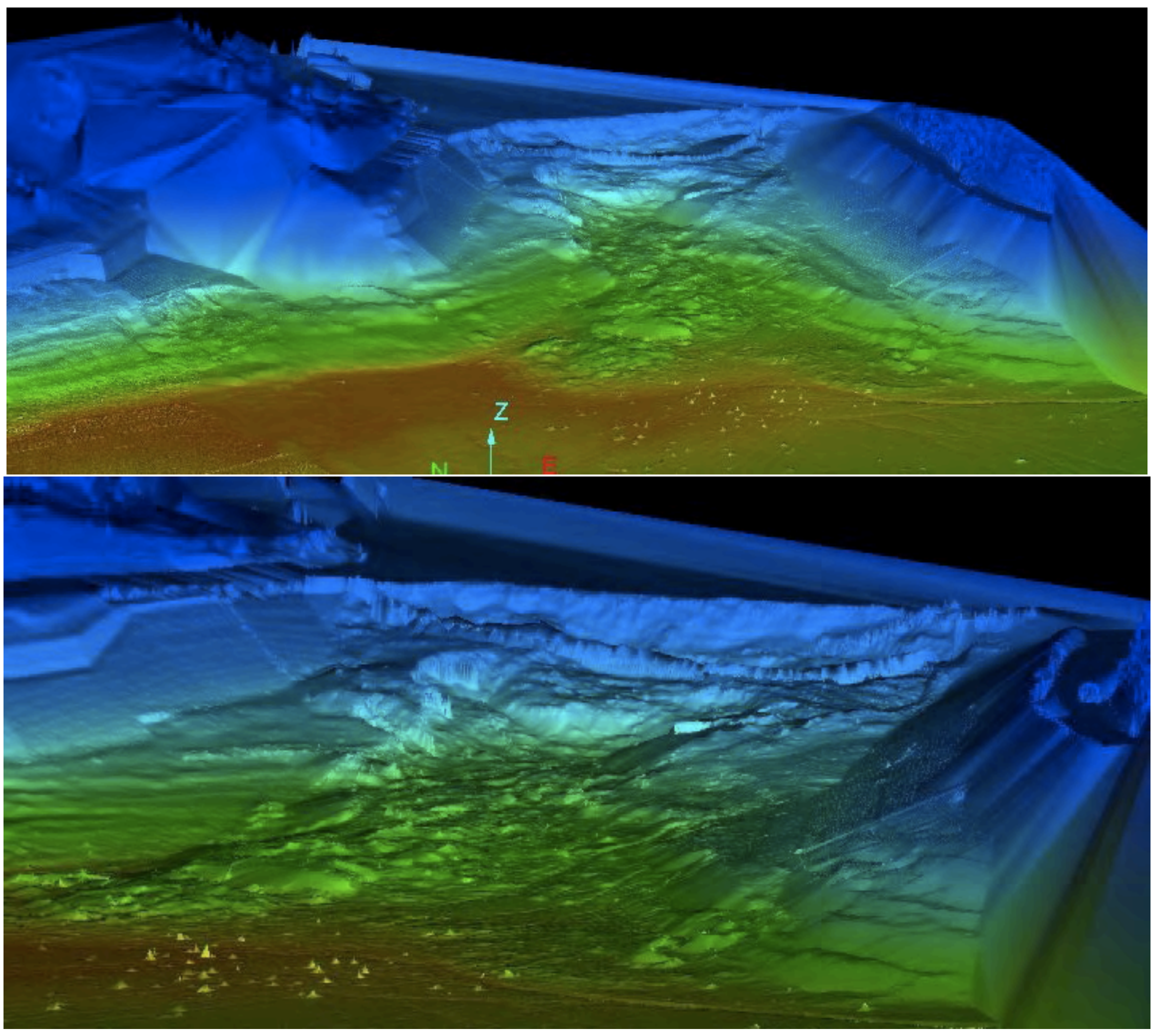


Figure QR6-94: Oblique LiDAR images of the auxiliary dam slope failure.

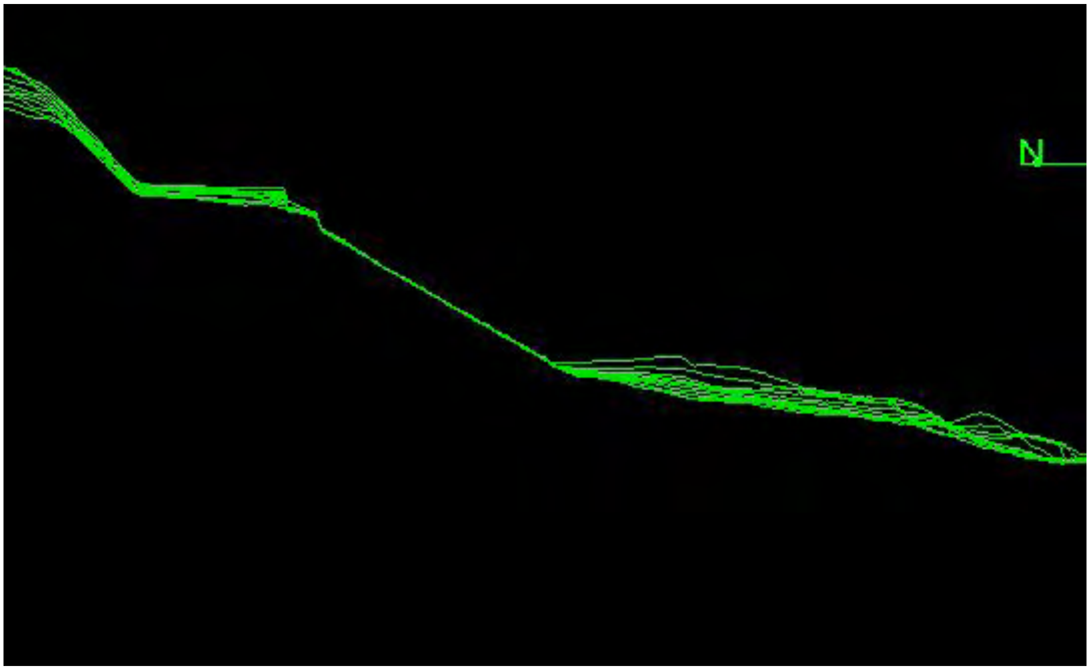


Figure QR6-95: Cross sections of the intact left slope adjacent to the auxiliary dam. Little deformation was observed on the slope.

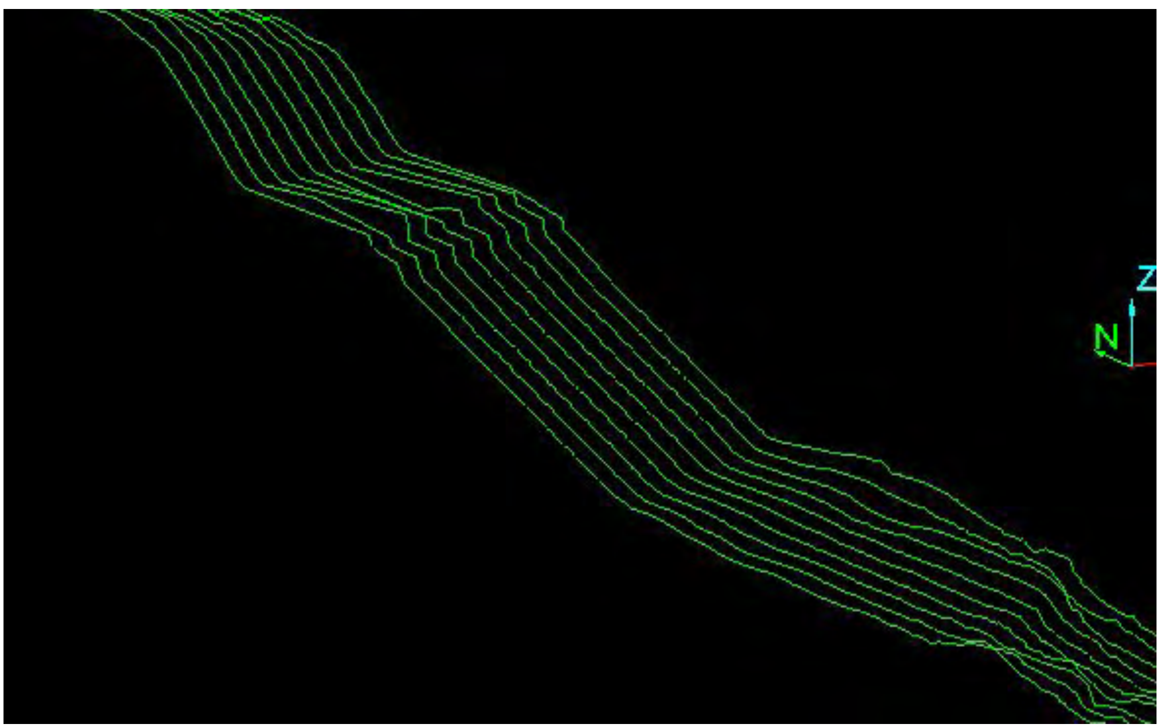


Figure QR6-96: Oblique view of cross-sections of the intact left slope adjacent to the auxiliary dam.

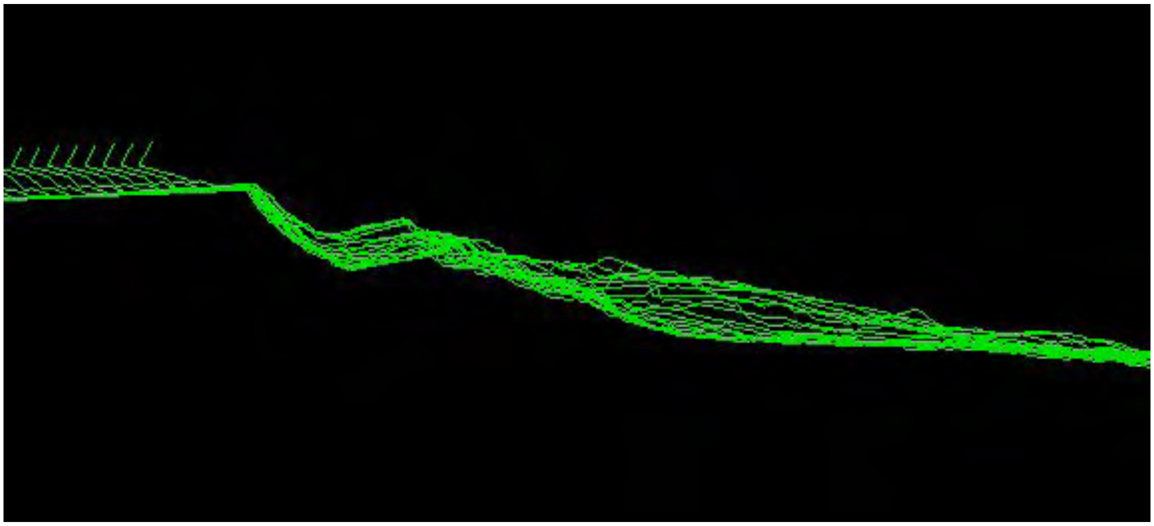


Figure QR6-97: Cross-sections through the failed portion of the auxiliary dam.

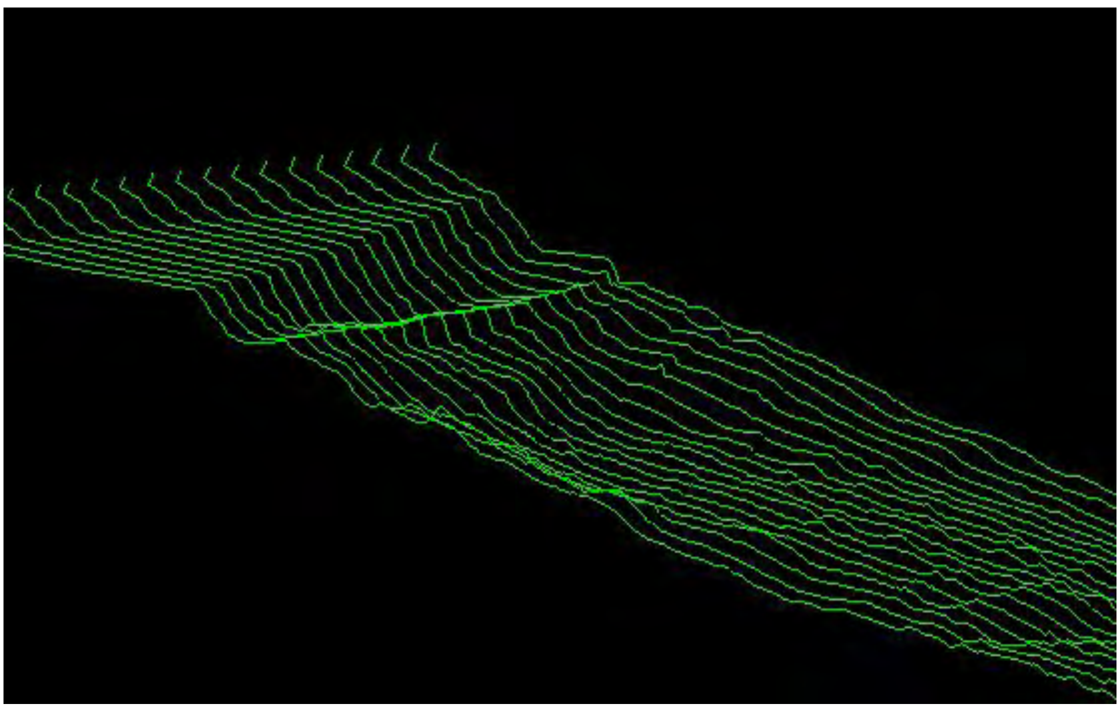


Figure QR6-98: Oblique view of cross-sections through the failed portion of the auxiliary dam.

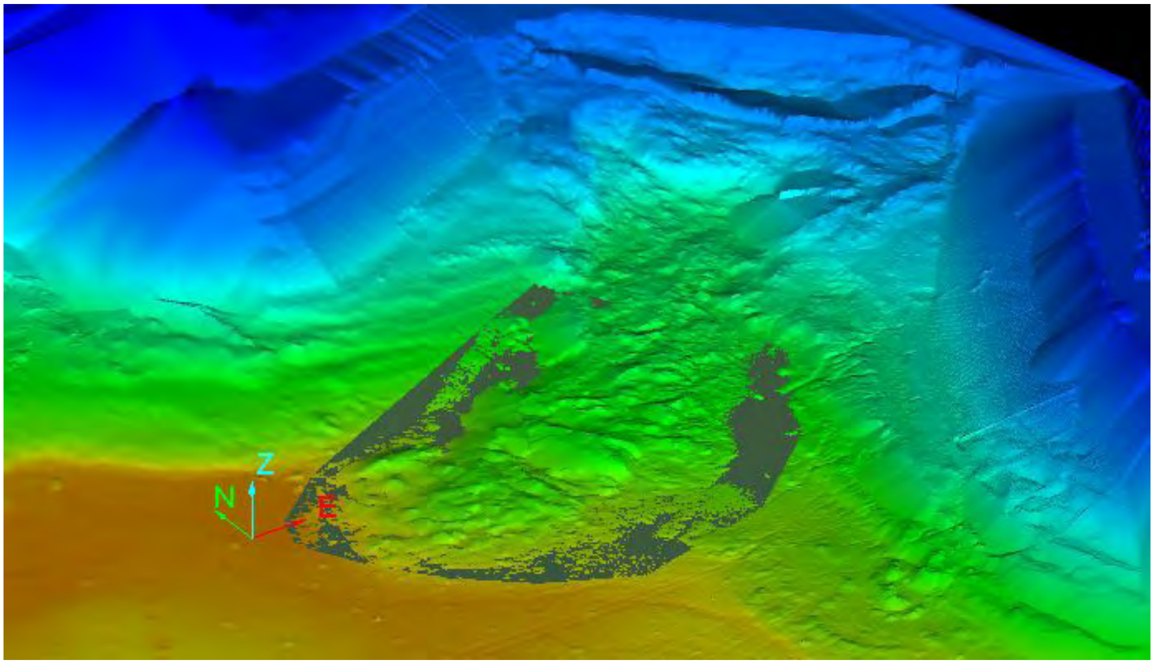


Figure QR6-99: Two model surfaces were constructed for the landslide debris and the headscarf of the auxiliary dam failure. Both volumes balanced to approximately 11,000 m of debris.

Embankments along the reservoir face at the Fujinuma park.

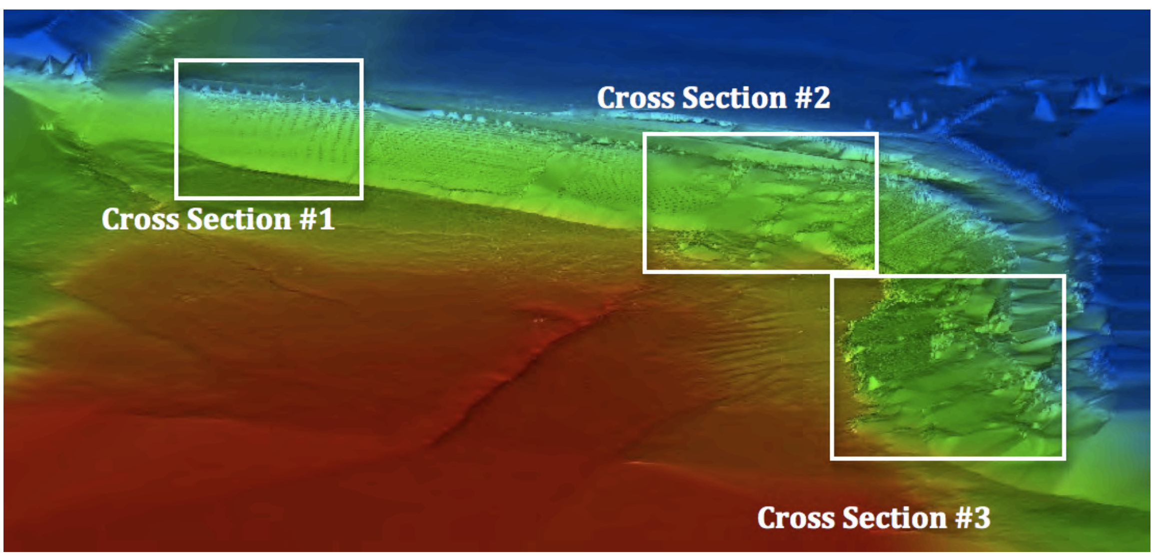


Figure QR6-100: Cross-sections were developed across three areas of the western part along the reservoir perimeter. Section one is an un-failed slope. Sections two and three are deformed sections of the reservoir embankment.

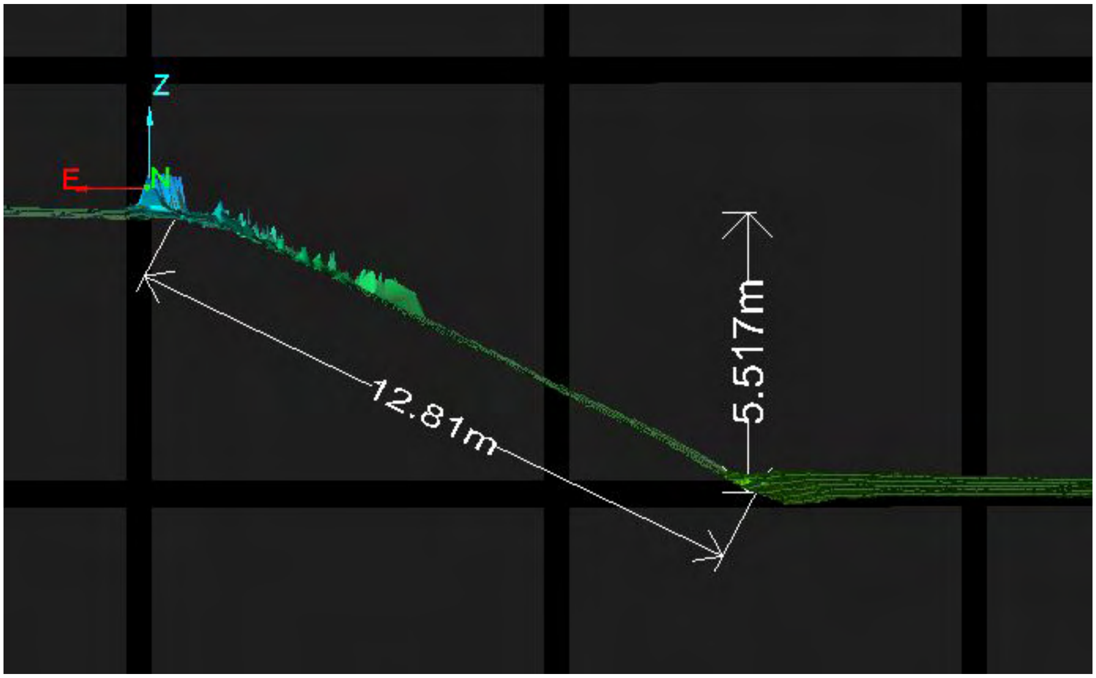


Figure QR6-101: Cross Section 1 (Unfailed). The slope has a height of 5.5 m and a grade of 1:2.0. Cross-sections from areas 2 and 3 have similar geometries prior to the earthquake.

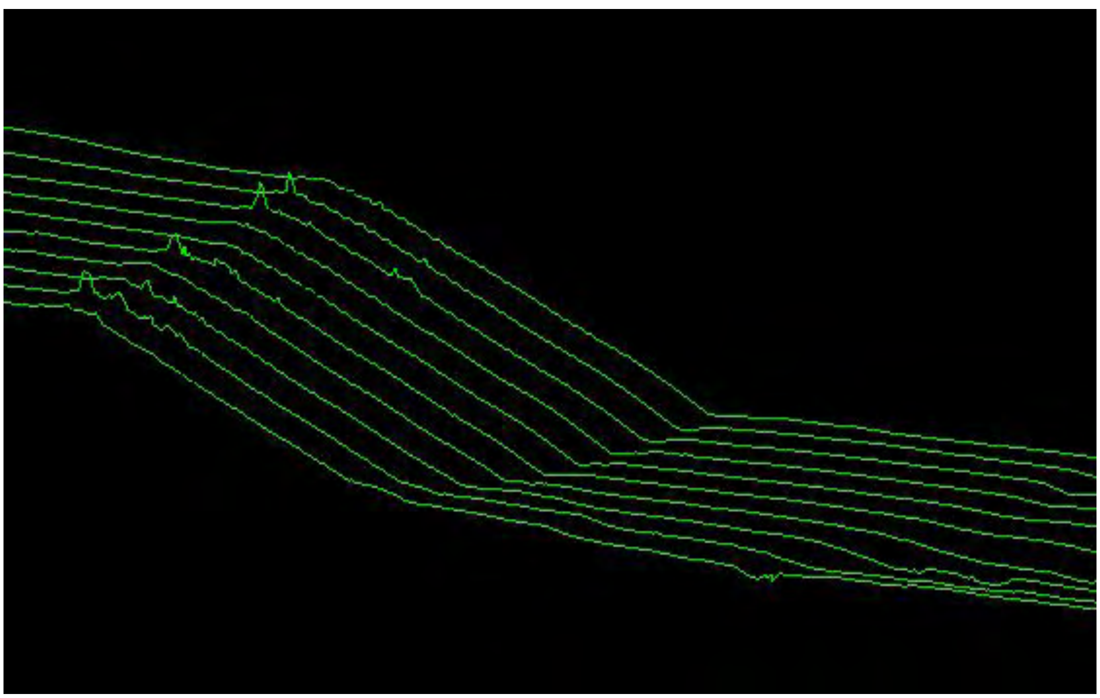


Figure QR6-102: Oblique view of cross-sections from area one in the unfailed portion of the reservoir slope.

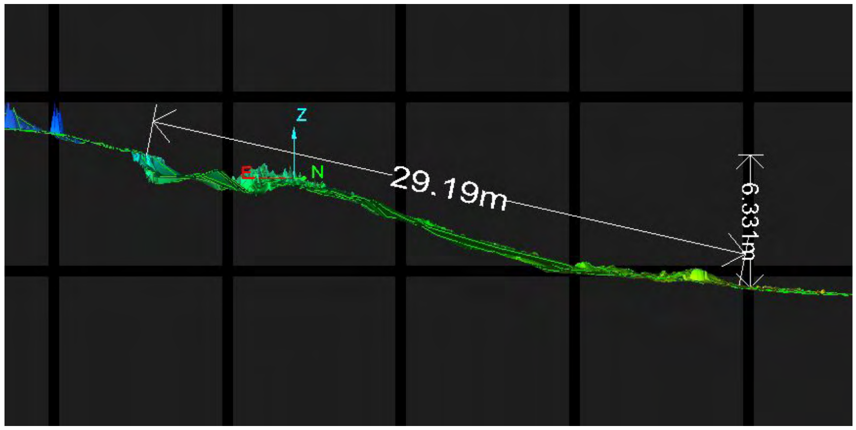


Figure QR6-103: Cross sections of area 2. Slope failure has pushed out the toe of the slope approximately 15 m in this area and reduced the slope inclination to 1:4.5.

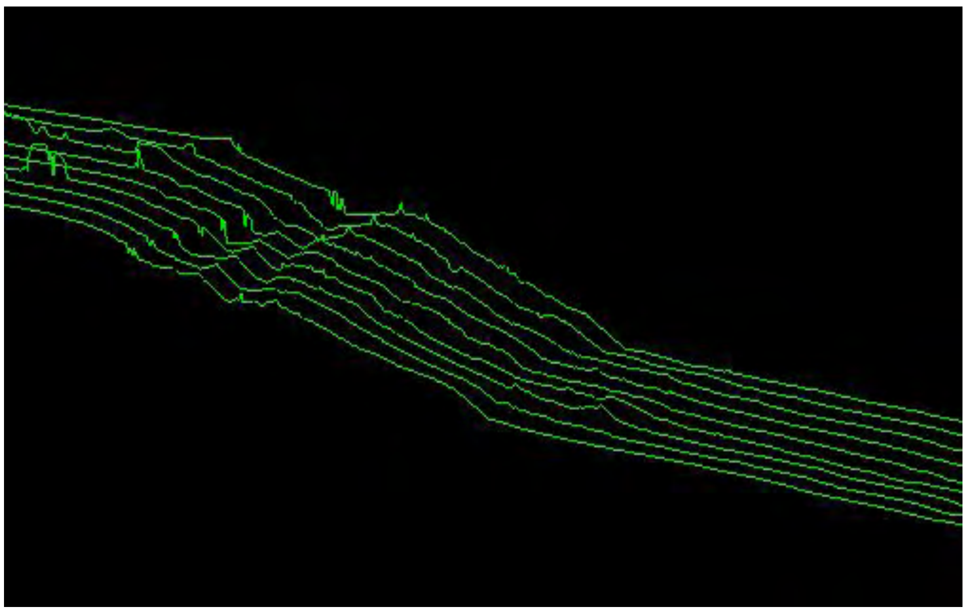


Figure QR6-104. Oblique cross-sections of the failure zone in section 2.

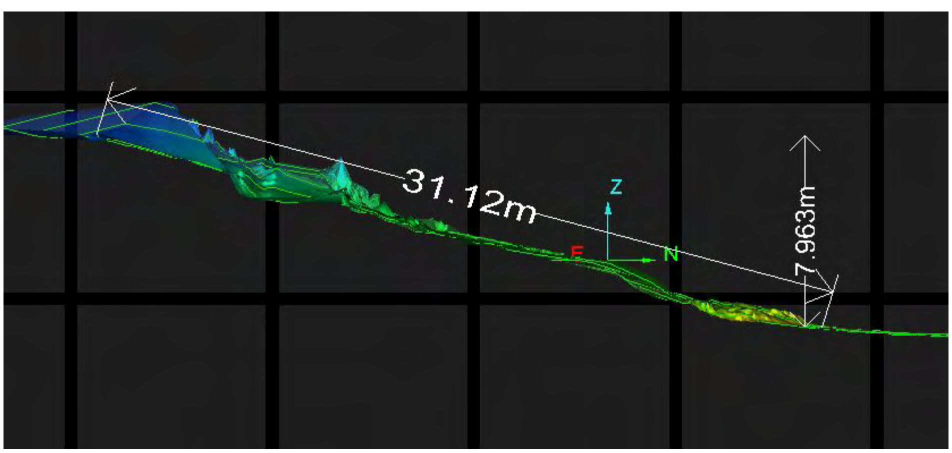


Figure QR6-105. Cross sections of area 2. Slope failure has pushed out the toe of the slope approximately 13m in this area and reduced the slope inclination to 1:3.8.

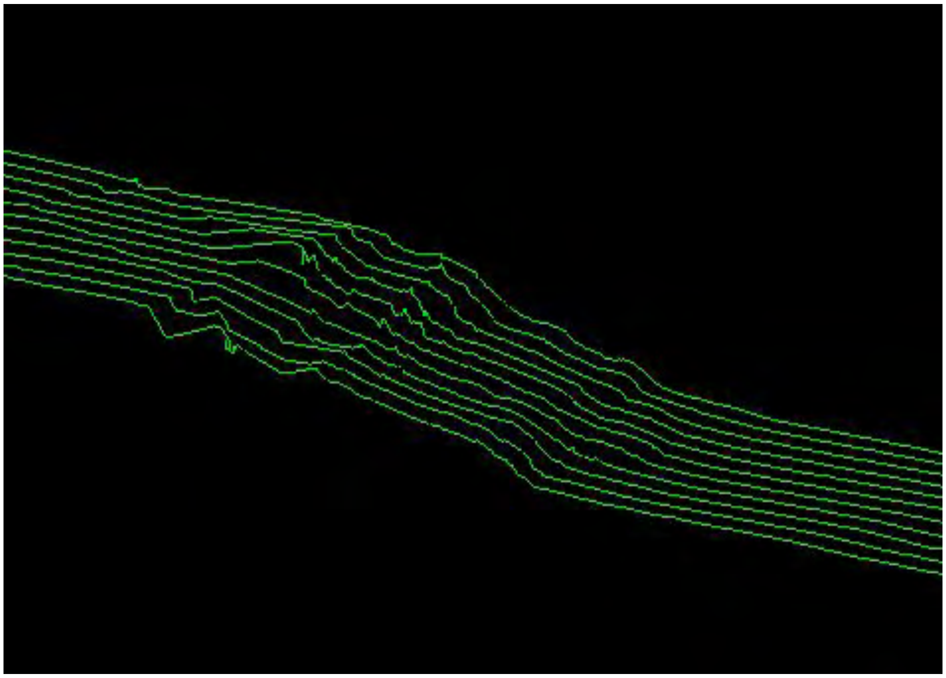


Figure QR6-106: Oblique view of cross sections from failed section 3.

Sites PARI16/PARI17

April 6:

On April 6-7, Japanese participants of the reconnaissance team visited two ports in Fukushima Prefecture. Soma port is located on the northeastern coast of Fukushima Prefecture near the border of Miyagi Prefecture. All now, port is located in the South East coastal area of Fukushima Prefecture near the border of Ibaraki Prefecture.

The following observations were made by Takahiro SUGANO, PARI and Hajime TANAKA (Tokyo U).

Soma Port, Fukushima

1) The PARI office at SOMA was destroyed by the tsunami. In general, the tsunami damage overprints or obliterates everything else one might observe at the waterfront.

2) Port 1 is now partly recovered and operational. Typical pre-earthquake water depths at the fishing port were -5.5 to -7.5 m based on briefing.

3) Estimated height of the tsunami at Soma was 10-15 m along the waterfront. The seawall is heavily damaged by the tsunami along its entire length of 2700m. The fourth block from the south end is visible but tilted and rotated, blocks 1-3 sank below the water surface. Tsunami erosion of the sub-caisson gravel pad appears to have created voids for the caissons to fall into.

All caisson tilting is towards the coastline, indicating the inside of the harbor entrance was eroded. Caissons are $15m^2$ area blocks recently placed at a cost of 3M ¥ per block for 2.7 km

4) Erosion at the north end inside breakwater is ~3 -4 meters (From -14-15m before tsunami, to -18 meters after tsunami). Apparently, Hachinohe Port, Aomori Pref. has similar erosion at base of caisson causing.. Erosion seems to happen during initial flooding and also during drawdown.

5) Along the port wharves, corner areas had severe or amplified damage. At corners, and other areas the seawall, openings in the caissons or sheet pile towards the sea eroded the soil behind the wall and beneath the pavement resulting in a collapse of the deck. Several quay wall blocks, ~$5m^2$ area and ~3m tall were flipped over by the incoming tsunami and landed upside down on the wharf deck.

6) A general mode of failure at the Port seems to be incoming wave create openings in the seawall by shifting pavement, lifting pavement panels, or moving quay wall blocks. Outgoing water excavates subgrade soil resulting in wharf collapse.

Figure QR6-107: Damage near the PARI headquarters at Soma. The headquarters building is missing, but the foundation is preserved. This view is towards land from the PARI office floor slab.

Figure QR6-108: Failure of a sheet pile wall and evacuation of soil.

Figure QR6-109: Failure of a sheet pile wall at a corner area and evacuation of soil.

Figure QR6-110: Tsunami damage to a port warehouse at Soma.

Figure QR6-111: Upside-down quay wall blocks on a wharf deck flipped over by the tsunami.

Figure QR6-112: Tsunami damage to a Soma Port warehouse.

April 7, 2011

SITES PARI 18; PARI19; PARI20 20 Port of Onahama

Takahiro SUGANO, PARI; Yasuyuki NISHIO, Director General of Onahama Port Office.

Aire RK18) Ports 1-2 are Fishing Ports; Ports 3-7 are for marine container wharves and docks. Estimated tsunami height ranges from 0.4-3.0m, typically 1.5-2.9m. There was only slight damage to the breakwater. Harbor floor erosion occurred along the area south of Wharf 1 where erosion steeped in the harbor from -6 to -14m.

Site RK19) Major tanker terminals remain closed through this region including the Kashima Denkai, Kashima Oil and Mitsubishi Chemical (MC) ports in the east coast city of Kashima, Cosmo Oil's main terminal in Chiba, the Onahama port operated by Onahama Petroleum and the JX Nippon Oil and Energy (JXNOE) port in Sendai. It is unclear when they will be able to restart operations. Berthing and port facilities at Kashima and Onahama have been destroyed.

Site RK20: Fujiwara wharf, Onahama

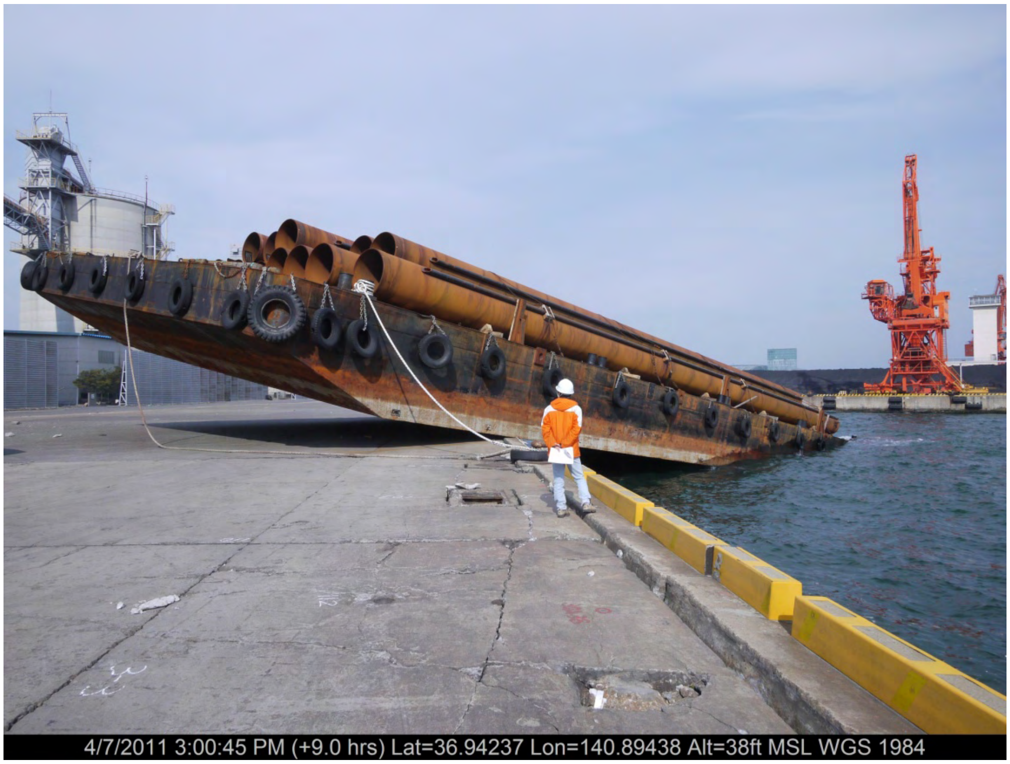


Figure QR6-113: Intact wharf with barge floated onto the deck.

Figure QR6-114: Intact wharf at Onahama with the fishing vessels loaded onto the deck.

Observations in Miyagi Prefecture

April 8, 2011
Site RK21 Abukuma Edgetsu –
South side community, along the banks of the Abukuma River tsunami damage was observed several miles inland of the Coast.

Figure QR6-115: Tsunami damage at Abukuma Edgetsu

Figure QR6-116: Tsunami damage at Abukuma Edgetsu

Site RK22: Watari District, Arahama Waste Water Plant, Miyagi Pref.

Liquefied 4.7. Reduced gray sand boils.

During the night of April 7, 2011, a large aftershock occurred off the shore of Miyagi Prefecture. The Japan meteorological agency measured the aftershock as magnitude 7.4, whereas the USGS estimate was 7.1. The PGA at nearby KiK-net station MYGH10 was 0.2 g. The Arahama waste water treatment plant was tested using SASW prior to the main earthquake event of March 11, 2011. On September 4, 2001 the site was tested using SASW and the continuous harmonic wave method and recorded as site 74ARA. This site had previously liquefied during the Miyagi Ken Oki earthquakes of 1973 and 1978. On the morning of April 8, 2011 we observed fresh evidence of liquefaction, lateral spreading, sand boils, and fissures that occurred the previous night.

Site 74ARAH is located at the Arahama Sewage Plant, Arahama, Miyagi, Japan. The site location is at 38.04198°E, 140.91947°N.

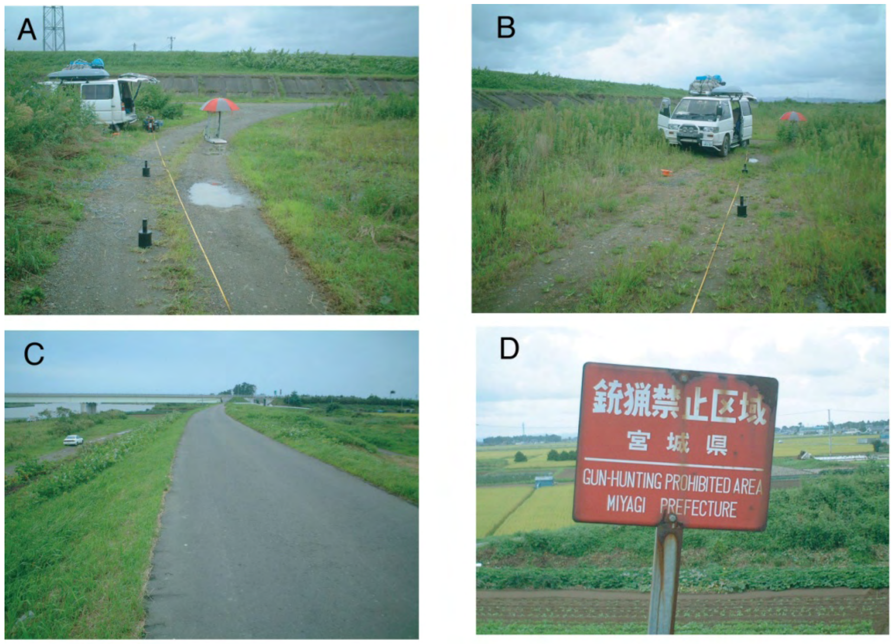
Figure QR6-117: Site RK22 one decade before the earthquake of March 11, 2011 During SASW testing. The two-story large concrete structure is the Arahama wastewater treatment plant.

Figure QR6-118: Liquefaction damage east of the wastewater treatment plant. Liquefaction is associated with the April 7, 2011 aftershock. This site is located in the tsunami inundation zone and direct evidence of liquefaction from the main event of March 11, 2001 is masked by debris, hydraulic re-working, and tsunami soil deposits.

Figure QR6-119: Liquefaction damage and fissures south of the wastewater treatment plant.

Site RK23: This site is located in the district of Yuriage, along the banks of the Natori River near the western Yuriage Bridge.

This site liquefied on the night of April 7. On the surface of the riverbank are sand boils of reduced gray sand. This site is located in the tsunami inundation zone and direct evidence of liquefaction from the main event of March 11, 2001 is masked by debris, hydraulic re-working, and tsunami soil deposits. On September 4, 2001, this site was tested by the SASW method.



Site 75YURI is located at Yuriage Kami, Watari, Miyagi, Japan. The site location is at 38.19003°E, 140.93494°N.

Figure QR6-120: Site RK23 prior to the earthquake of March 11, 2011. This site is SASW test number 75 YUR (2001) and the testing occurred west of the western Yuriage bridge.

a  .

Figure QR6-121: South bank of the Natori river west of the western Yuriage Bridge on April 8, 2001. This perspective is similar to photo C.

Figure QR6-122. Liquefaction evidence on the south bank of the Natori River west of the western Yuriage Bridge at RK23 and previous SASW test site 75YUR. In this perspective is similar to photo A

Figure QR6-123: Liquefaction evidence on the south bank of the Natori River west of the western Yuriage bridge at RK23 and previous SASW test site 75YUR. In this perspective is similar to photo A

Site RK24: Natori Town, Miyagi. Also, SASW site 76YUR.

This site is located in the district of Yuriage, along the banks of the Natori Rive at the Yuriage Bridge. This site liquefied on the night of April 7. On the surface of the riverbank are sand boils of reduced gray sand. This site is located in the tsunami inundation zone and direct evidence of liquefaction from the main event of March 11, 2001 is masked by debris, hydraulic re-working, and tsunami soil deposits. However, fissures are evident and indicate liquefaction from the main event because the soil is oxidized. Significant current scour in soil was observed along the piers supporting the bridge on the south side of the river

Figure QR6-124: Liquefaction and bridge scour was observed at RK24 along the eastern Yuriage Bridge.

Figure QR6-125: Site RK24 detail of bridge scour up soil surrounding a bridge pier on the south bank of the Natori River at the eastern Yuriage Bridge.

Figure QR6-126: RK24 detail of bridge scour up soil surrounding a bridge pier on the south bank of the Natori River at the eastern Yuriage Bridge.

Figure QR6-127: Site RK24 detail of liquefaction features from the April 7, 2011 aftershock on the south bank of the Natori River at the eastern Yuriage Bridge.

Site RK25: This site is also SASW test site77SEN (SENDAI), tested on September 4, 2001.

This site liquefied during the 1973 Miyagi Ken Oki earthquake and was originally reported by Iwasaki. The site is on the north bank of the Natori River, on the Sendai side at a location called Nakamura Dike. The site reliquefied the night of 4/7. The soil sand boils were up and oxidized can brown sand.

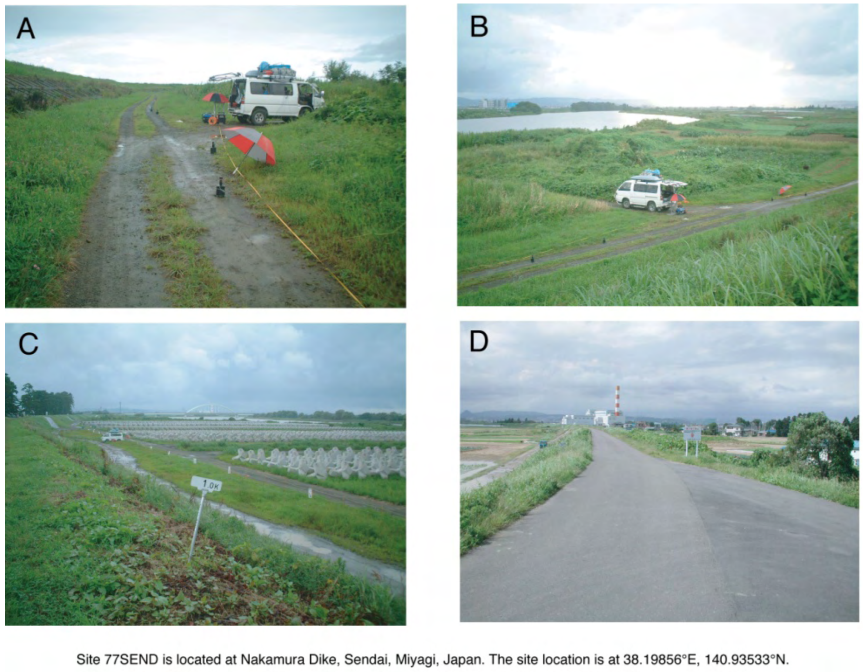


Figure QR6-128: Site RK25 before the earthquake of March 11, 2011. SASW testing was performed on the north bank of the river at a site called Nakamura Dike in Sendai city On September 4, 2001.

Figure QR6-129: This site is also SASW test site77SEN (SENDAI), tested on September 4, 2001. This site liquefied during the 1973 Miyagi Ken Oki earthquake and was originally reported by Iwasaki. The site is on the north bank of the Natori River, on the Sendai side at a location called Nakamura Dike. The site re-liquefied the night of April 7. The sand boils were oxidized brown sand. The bridge at site RK 23 is visible in the distance at the top right of the photograph.

Figure QR6-130: This site is also SASW test site77SEN (SENDAI), tested on September 4, 2001. This site liquefied during the 1973 Miyagi Ken Oki earthquake and was originally reported by Iwasaki. The site is on the north bank of the Natori River, on the Sendai side at a location called Nakamura Dike. The site reliquefied the night of 4/7. The sand boils were up and oxidized sand.

Site RK27, Nakajima Wharf at SASW site also liquefaction test site 79ISHI.

This site is adjacent to a large refinery and oil storage facility. The site liquefied during the aftershock of April 7. Site RK27 was hit by the tsunami and evidence of liquefaction from the main event are completely obscured by the tsunami damage. We also walked through the Ishinomaki of oil refinery and tank storage facility adjacent to SASW site 79ISHI. The site had interesting geotechnical damage of scoured soil beneath the pile supported foundation base of tanks exposing the piles. A buoyant tank floated off one base pad and out of the storage yard. At this site, there is evidence of significant scour of soil from piers supporting the port structures.

Site 79ISHI is located at Nakajima Wharf, Ishinomaki, Miyagi, Japan. The site location is at 38.41493°E,141.26612°N.

Figure QR6-131: Site RK27 one decade before the earthquake. This site was tested by SASW on September 5, 2001.

Figure QR6-132: Site RK27, also liquefaction test site 79ISHI. This site is called Nakajima Wharf and is adjacent to the Ishinomaki oil refinery and oil storage facility. This photograph has the same perspective as photo A.

Figure QR6-133: Site RK27, also liquefaction test site 79ISHI. This site is called Nakajima Wharf and is adjacent to the Ishinomaki oil refinery and oil storage facility. This photograph has the same perspective as photo B and D.

Figure QR6-134: Site RK27, also liquefaction test site 79ISHI. This site is called Nakajima Wharf and is adjacent to the Ishinomaki oil refinery and oil storage facility. This photograph shows tsunami damage but also likely liquefaction damage from the Main event that led to settlements along the wharf front. This photograph has the same perspective as photo C

Site RK28: Also liquefaction SASW test site 84HIYO on the Hiyori wharf, Port of Ishinomaki .

Figure QR6-135: Site RK28 Liquefaction. SASW test site 84HIYO on the Hiyori wharf, Port of Ishinomaki.

Figure QR6-136: Site RK28 Liquefaction SASW test site 84HIYO on the Hiyori wharf, Port of Ishinomaki .

Figure QR6-137: Site RK29 liquefaction at Shiomi wharf. This site is also SASW test site 78ISHS tested on September 5, 2001. Liquefaction occurred during the aftershock of April 7, 2011.

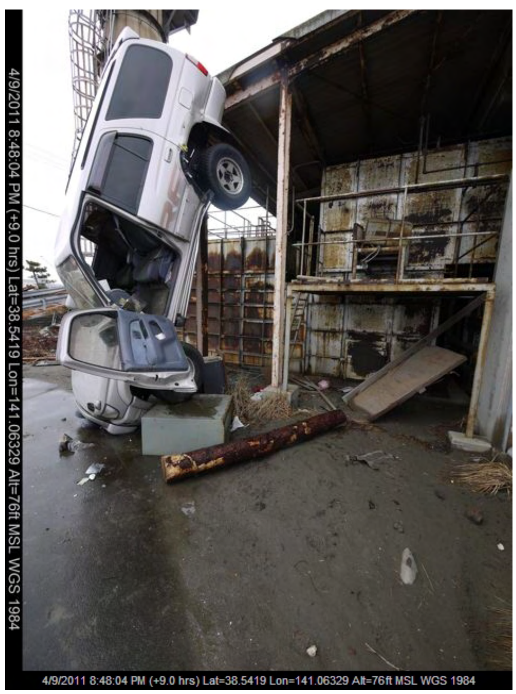


Figure QR6-138: Site RK30 Non-liquefaction site 83SHIOMI. No evidence of liquefaction from the aftershock of April 7, 2001.

Figure QR6-139: Site RK31 is a Tohoku electric company electrical substation along the frontage road of the port. Flow direction and intensity indicate direct impact of the wave on the structural support frames. Structures are bent towards the land and residential community behind substation. Much of the substation equipment has been removed by the wave from the foundation blocks. Significant scour is evident around the foundations of the substation.

Figure QR6-140: Site RK31 is a Tohoku electric company electrical substation along the frontage road of the port. Flow direction and intensity indicate direct impact of the wave on the structural support frames. Structures are bent towards the land and residential community behind substation. Much of the substation equipment has been removed by the wave from the foundation blocks. Significant scour is evident around the foundations of the substation.

Site RK32: Emabnkment Highway 257 at Koguchi, Miyagi Prefecture. [LiDAR Site]

Figure QR6-141: Partial road closure embankment highway 257 at Koguchi, Miyagi Prefecture, looking north

Figure QR6-142: Blue tarp draped over fissures on the west side of embankment highway 257 at Koguchi, Miyagi Prefecture looking north

Site RK33 Koguchi Prefecture highway 257 embankment settlement.

Figure QR6-143: Blue tarp draped over fissures on the east side of embankment highway 257 at Koguchi, Miyagi Prefecture facing the Eai River looking north.

Figure QR6-144: Blue tarp draped over fissures on the west side of embankment highway 257 at Koguchi, Miyagi Prefecture looking south.

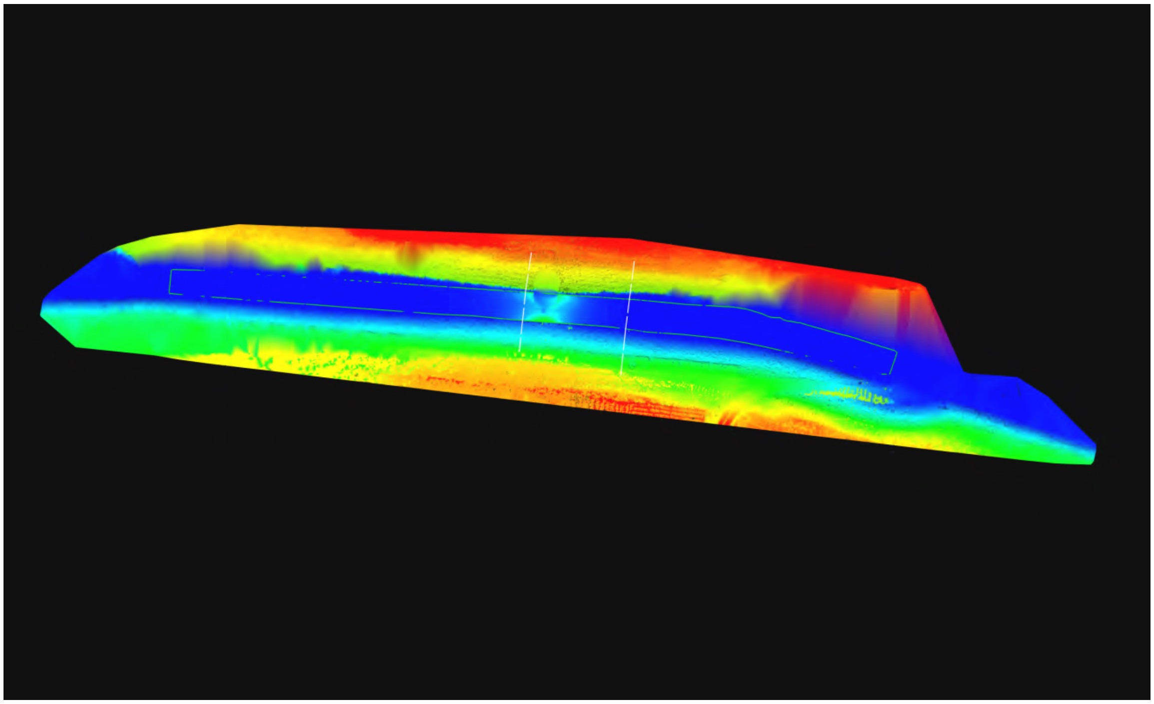


Figure QR6-145: LiDAR imagery of embankment highway 257 at Koguchi, Miyagi. The light blue segment along the road crest is an area of settlement.

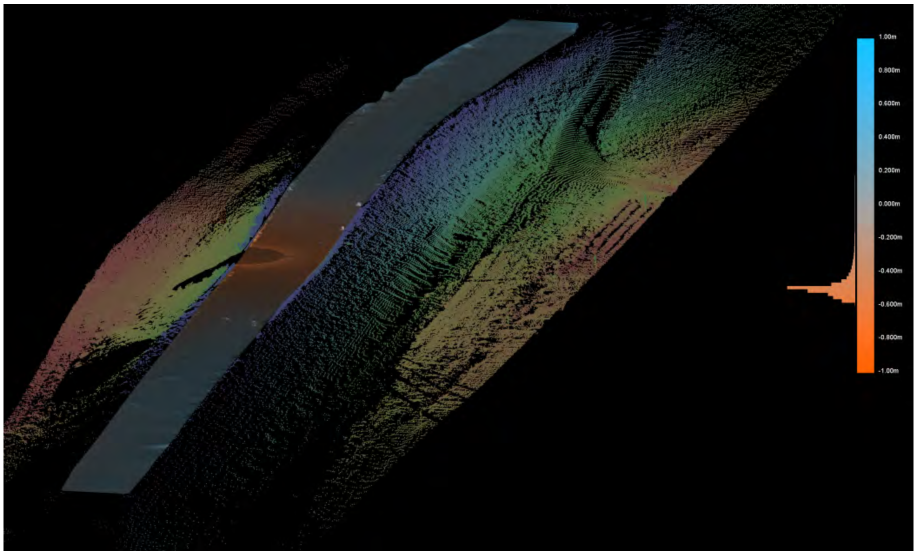


Figure QR6-146: Oblique LiDAR imagery and histogram of settlement along the road crest based on a model of the pre-earthquake geometry of the road.

Site RK33 and RK34 sites correspond with SASW test sites from September 12, 2001, 82KITA and 81KITA, respectively.

Both sites liquefied during aftershock event of April 7, 2011. At the siteRK33, there is overlapping evidence of liquefaction from aftershock of April 7 and the main shock as well. The main shock sand boils of are degraded and show evidence of pockmarks from rain fall. The main shock sand boils are oxidized whereas the sand boils of the April 7, 2011 aftershock are gray, still wet, and typically finer grained at the surface than the older liquefaction features.

Figure QR6-147. Site RK33 correspond with 82KITA. At the siteRK33, there is overlapping evidence of liquefaction from aftershock of April 7 and the main shock of March 11, 2011.

Figure QR6-148:. Signed post of the EAI River, and evidence of liquefaction at RK 33.

Figure QR6-149: Site RK33 correspond with 82KITA. At the siteRK33, there is overlapping evidence of liquefaction from aftershock of April 7 and the main shock of March 11, 2011. Here, sand boils surround residential and out structures.

Figure QR6-150: Site RK33 correspond with 82KITA. At the siteRK33, there is overlapping evidence of liquefaction from aftershock of April 7 and the main shock of March 11, 2011.

Figure QR6-151: Site RK34, SASW site from 2001 81KITA. This site liquefied during the April 7, 2011 aftershock but it is unclear if the site liquefied during the Main shock.

Site RK33, corresponds with 82KITA.

Two sets of fissures and sand boils can be seen in this photograph. The main shock sent oil to the right with a large fissure and oxidized soil. The liquefaction feature from April 7, 2011 is on the left. The aftershock liquefaction feature has a narrow fissure and sand with a reduced gray color.

Site RK35: Matsushima .

This site is a famous tourist town on the north side of Sendai. The tsunami was significantly lower in amplitude here than at Ishinomaki . A park at the waterfront has tsunami deposits of sand as irregular patches on pavement and grass. There is no apparent geotechnical damage anywhere that we traveled.

Figure QR6-152: Tsunami deposits of bay sediment in park at Matsushima.

Site RK36: Shiogama City

The eastern Harbor of the city was less impacted by the tsunami and largely cleaned up by April 9. It appears that the tsunami affected the lower portions of the first floor of structures and had no more than 1 to 2m wave heights. The western part of the city was more severely impacted by the tsunami.

Figure QR6-153: (RK38) Small country highway road embankment failure due to liquefaction. Blue tarps cover fissures on the embankment slopes at Shakushi, Miyagi.

Figure QR6-154: (RK 39) Minor liquefaction features along the country highway at Kubota, Miyagi.

Figure QR6-155: (RK 39) Bridge and settlement of soil approach fill along the country highway at Kubota, Miyagi.

Figure QR6-156: (RK 39) Bridge and settlement of soil approach fill along the country highway at Kubota, Miyagi.

Figure QR6-157: (Site RK41/42) Minamisanriku in some cases 15 m high tsunami debris can be seen on the fourth floor level and rooftops of buildings. No landslides or other geotechnical aspects other than tsunami damage.

Observations in Iwate Prefecture

Figure QR6-158: (Site RK43) Three story tsunami damage (~10+m) on structure in Rikuzentakada, Iwate.

Figure QR6-159: (Site RK43) Rikuzentakada bridge-deck closest to harbor was swept off the piers and scattered several hundred of meters inland. Soil supporting piers are scoured but in place. The bridge was built in 1932. No landslides or other geotechnical aspects other than tsunami damage. The railroad bridge on the north end of Rikuzentakada was also swept off piers with significant scour at the pier base. The bridge through-truss was thrown inland from the bridge piers, and several piers are overturned.

Figure QR6-160: (Site RK44) Rikuzentakada railroad yard overpass northeastern part of town. Wave heights exceeded the overpass height and folded the guard rail over onto the road deck (~10m).

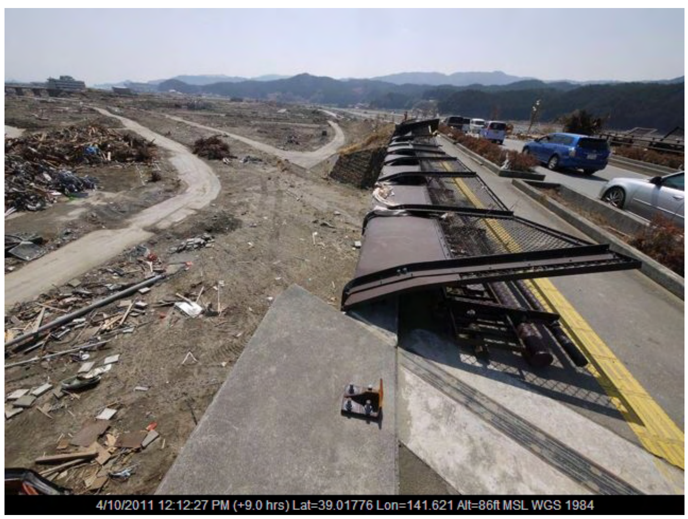


Figure QR6-161: (Site RK44) Rikuzentakada railroad yard overpass northeastern part of town. Wave heights exceeded the overpass height and folded the guard-rail over onto the road deck (~10m+ wave height).

Site RK45: Ofunato Town

The northern section that we drove through was largely unscathed by the tsunami. The port district has significant damage but most of the northern residential and commercial districts we drove through were normal with undamaged housing. Aside from the tsunami damage so far from the border of Miyagi to the north coast of Iwate there appears to be almost no road damage, landslide, liquefaction, or noteworthy structural problems other than those directly related to, or impacted by, the tsunami.

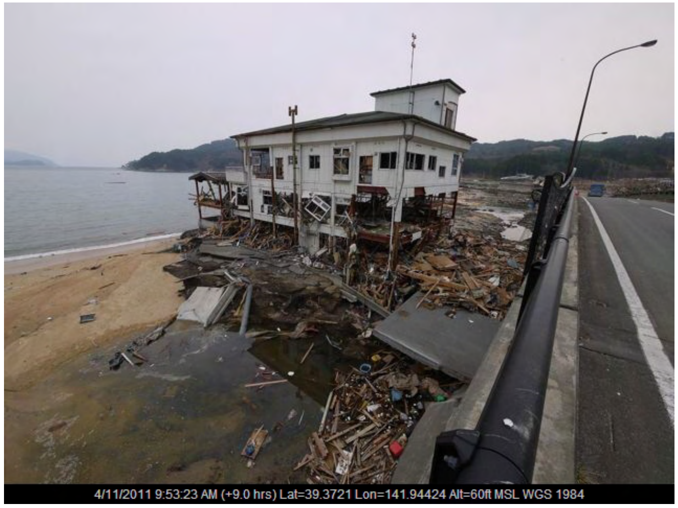


Figure QR6-162: Harbor damage from tsunami damage at Otsuchi (~15m wave height).

Figure QR6-163: (Site RK46) Otsuchi town very badly impacted by the tsunami waves but no landslides or other factors or shaking-related structural damage.

Figure QR6-164: (Site RK47) Yamada-machi - Miyako Town, Iwate Prefecture. Photograph of overturned tsunami seawall with meter stick from tsunami research team. In the central part of the city there was a fire after the tsunami and an unknown number of blocks of buildings were burnt.

Figure QR6-165: (Site RK47) Yamada-machi - Miyako Town, Iwate Prefecture. Photograph of overturned tsunami seawall with meter stick from tsunami research team. In the central part of the city there was a fire after the tsunami and an unknown number of blocks of buildings were burnt.

Figure QR6-166: (RK48) - Ferry boat floated far into Miyako town, Iwate.

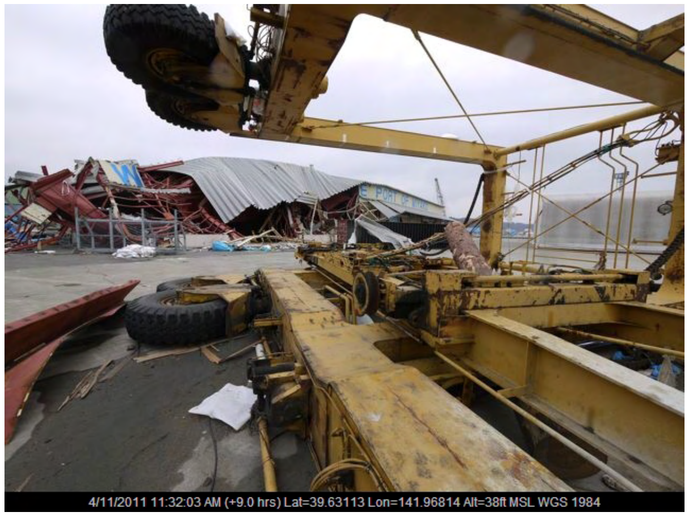


Figure QR6-167: (RK48) - Damage at Port of Miyako, Iwate. Overturned marine container carrier.

Figure QR6-168: (RK48) Tsunami damage and fire of structures in central Miyako.

Site RK49/50, NODA Town

() Noda Town suffered tsunami damage but no apparent geotechnical damage. On April 11 in the town of Noda, Iwate we had an opportunity to meet and speak with recent Prime Minister of Japan Yukio Hatoyama. Hatoyama has a Ph.D. in Industrial Engineering from Stanford. His visit coincided with the 1 month anniversary of the earthquake and tsunami. We viewed damage and talked about the earthquake effects and impacts. He was informed of our GEER activities in an epi-central region and the collaborations between GEER, the US Geological Survey, and our Japanese collaborators at the University of Tokyo, Kobe University, and the Port and Airport Research Institute. In the photo below, Hatoyama is holding a USGS hat.

Figure QR6-169: Prime Minister Yukio Hatoyama and GEER Team leader Dr. Robert Kayen USGS/UCLA visit damage at Noda, Iwate Prefecture.

Figure QR6-170: Memorabilia center at Noda, Iwate where possessions are found, cleaned, and saved for residence to recover.

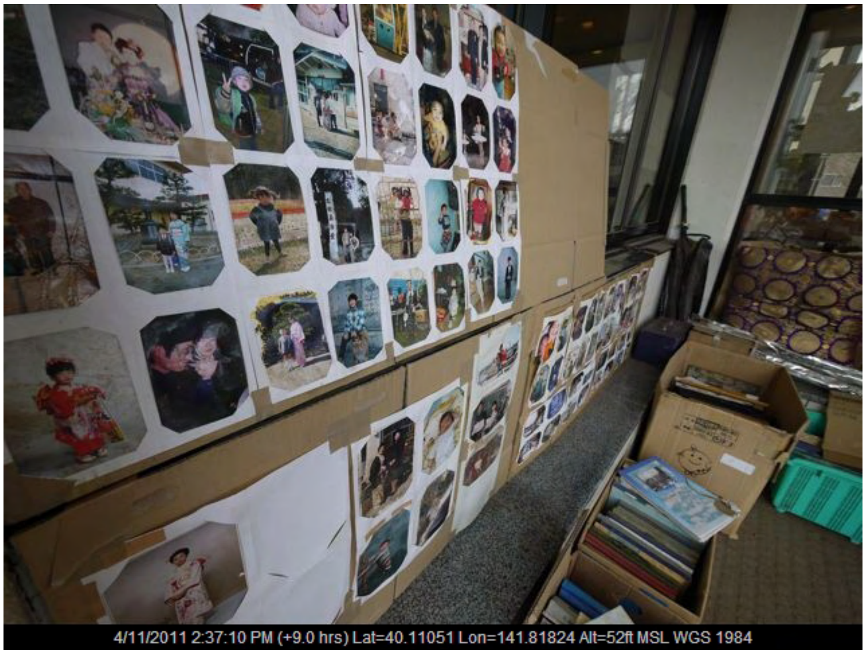


Figure QR6-171: Memorabilia center at Noda, Iwate where possessions are found, cleaned, and saved for residence to recover.

Observations in Aomori Prefecture

Figure QR6-172: (Site RK51) Tsunami deposits and debris scattered in a field adjacent to beach north of Hachinohe near Misawa air base on the Oma peninsula coast.

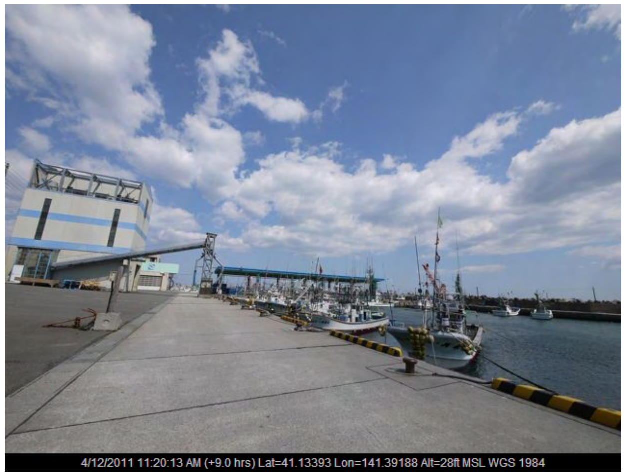


Figure QR6-173: (Site RK52) Mukainagare on the Oma Peninsula no evidence of tsunami damage at the port or any other geotechnical or structural problems. It is the first port without any damage in 670km

Figure QR6-174: (Site RK53) Oma Point on the Oma Peninsula had no evidence of tsunami damage or any other geotechnical or structural problems.

Figure QR6-175: (Site RK54) Old Aomori Train station, Aomori City. No liquefaction. This site liquefied numerous times in the past and is an old-fill at the north end of the Aomori train station. There is no evidence of liquefaction at the site.