HOKKAIDO, JAPAN, M_w 6.7 EARTHQUAKE OF SEPTEMBER 6, 2018 LIFELINE PERFORMANCE

By

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 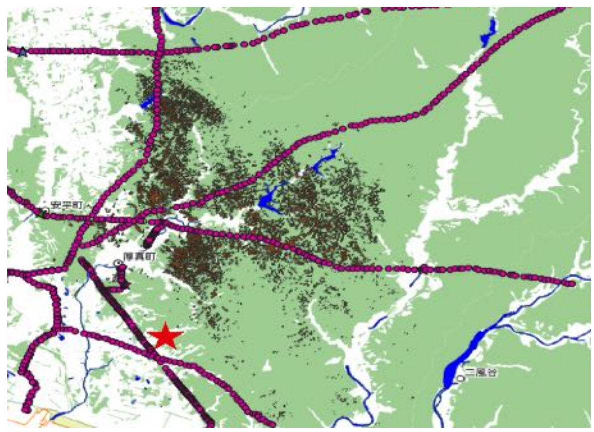

 

The Council of Lifeline Earthquake Engineering

TCLEE No. 4

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THE COUNCIL OF LIFELINE EARTHQUAKE ENGINEERING

TCLEE

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ABSTRACT

A strong earthquake occurred at 3:08 am, September 6 2018 local time. The moment magnitude of the main shock was $M_w = 6.7$. The epicenter was located at 42.671° N, 131.933° E at a depth of 31 km.

In Japan, this earthquake is sometimes referred to as the "Hokkaido Ballistic Earthquake of Heisei 30", or sometimes the "Hokkaido Eastern Iburi Earthquake". In this report, we call it the Hokkaido Earthquake.

The main shock produced several recorded motions with very high motions:

- In the North-South direction there were 7 free field instruments that recorded PGA ~0.5 to 0.6g, and one instrument that recorded ~1.35g. Peak recorded NS velocity was ~135 cm/sec.

- In the East-West direction there were 8 free field instruments that recorded PGA ~0.5 to 0.75g, and one instrument that recorded ~0.95g. Peak recorded EW velocity was ~150 cm/sec.

- In the Vertical direction there were 7 free field instruments that recorded PGA ~0.3 to 0.45g, and one instrument that recorded ~1.08g. Peak recorded Vertical velocity was ~30 cm/sec.

The earthquake triggered many landslides (widespread), as well as permanent ground deformations (PGDs) due to liquefaction (less common). This earthquake probably produced the greatest number of landslides with significant PGDs in Japan in the past 100 years or more. In the mountainous areas exposed to strong shaking (commonly PGA in the range of 0.4g to 0.6g), there were thousands of landslides, and about 10% to 20% of these slide-susceptible areas had deep-seated slides with PGDs commonly over a meter; in some cases, 10s of meters; and in a few cases, 100s of meters.

Where exposed to the landslides, infrastructure suffered heavy damage. The infrastructure included two destroyed high voltage transmission towers, and over a hundred destroyed low voltage distribution poles. In a few cases, landslides impinged on dwellings (commonly single family wood buildings), resulting in their destruction, often with loss of life. There were 41 fatalities were caused by the earthquake, most of which caused by landslides.

The strong shaking also exposed some electric substations and power plants to PGA > 0.3g. The strong shaking damaged these facilities, resulting in an island-wide power outage. The outage affected all 2,950,000 electric customers in Hokkaido Island, with cumulative power outages about 6 Billion customer-minutes. The cascading effects of the power outage resulted in telecommunication service outages, as there was insufficient battery / emergency generator backups at multiple sites; power outages also temporarily

shut down all the toll expressway roads out of Sapporo, in part because toll barriers could not be operated without power.

There was also damage to water pipes, water treatment plants, dams, telecommunications, gas systems, and roads.

In areas exposed to moderate levels of shaking (PGA of 0.1g to 0.2g), the exposed population was over 2 million people, including the major city of Sapporo. There was very limited damage in these areas. This reflects the good seismic practices that have been implemented in Japan over the past few decades. Still, there was some localized liquefaction along old stream beds, causing localized damage within Kiyota Ward located in the southeast portion of Sapporo. In this earthquake, Sapporo was Resilient.

In the areas exposed to very high shaking and many landslides, there were very high losses. The damage to farms and farm product is estimated at about $12 Billion. It will take a year, possibly more, to substantially restore farming in these areas to close to pre-earthquake levels. In this earthquake, these areas were not Resilient.

Total losses from this earthquake are estimated to be about $15 Billion (throughout this report, we use 110 Yen = $1 US dollar). About 80% of this loss was in Agriculture.

PREFACE

This report has been prepared by John Eidinger and Alex Tang (collectively, "we"). For decades, we have worked with our colleagues from around the world to examine the seismic performance of lifelines and the general topic of resilience. We continue in this effort as The Council on Lifeline Earthquake Engineering (*TCLEE*) to maintain a sharp focus on the performance of lifelines in earthquakes. In 2015, we documented the performance of lifelines of the 2014 Napa earthquake (TCLEE No. 1). In 2016, we documented the performance of lifelines in the Kumamoto, Kyushu earthquake (TCLEE No. 2). In 2017, we documented the performance of lifelines in the Puebla / Mexico City earthquake (TCLEE No. 3).

In this report (TCLEE No. 4), we document the performance of lifelines in the 2018 Hokkaido earthquake. Our colleagues and friends and practitioners of lifeline earthquake engineering in Japan have supported this investigation with tremendous support. Two of the largest electric utilities in the United States, namely Pacific Gas and Electric and Southern California Edison, have also contributed greatly to this effort. This is a solid testament of this important task for the industry and government owning and providing lifelines services.

We are sure that our friends and colleagues from New Zealand, Italy, Chile, Peru, Indonesia, China, Turkey, Algeria, Portugal and other earthquake-prone areas around the world will provide us with a continuing high level of support. We acknowledge the fact that all incur a cost in the effort to document the performance of lifelines in earthquakes, with the hope that all will recognize this as an investment for resilient lifelines and our intent to achieve a long term gain in increasing our understanding of the issues.

Mr. Eidinger and Mr. Tang have worked together to undertake dozens of field trips of post-earthquake lifelines investigation. While working together in the field, we may not agree with each other all the time, but our discussions and arguments are always good.

Respectfully submitted,

John M. Eidinger and Alex K. Tang, December 31 2018

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This findings in this report are primarily based on the observations and data collected by two investigation teams:

- Team 1 (Geohazards). A team of geologists and geotechnical engineers did the initial reconnaissance of the area. Collectively, this investigation team is called Team 1. Team 1 included: Jeff BACHHUBER (PG&E), Chris MADUGO (PG&E), Joseph SUN (PG&E), Mathew MUTO (SCE), Esam ABRAHAM (SCE), Chris HITCHCOCK (Infraterra), Koji OKUMURA (Univ. Hiroshima).

- Team 2. (Lifelines, the focus of this report). Kazuo KONAGAI, Alessandra Mayumi NAKATA, Masataka SHIGA, John EIDINGER, Alex TANG, Brian LOW, Nozar JAHANGIR, Bronson INGEMANNSON, Roderick dela CRUZ, John DAI, Okochi YASUA, Jirou NAKAMURA, Satoshi SUENAGA. Collectively, this investigation team is called Team 2.

Other investigation teams also assisted. Notably, Robert KAYEN (U.C. Berkeley) and Brad WHAM (Univ. Colorado) were both members of the GEER team. Both Robert and Brad shared their early observations with Team 1 and Team 2, and provided comments. Their assistance is much appreciated.

Revision History.

Original Release: December 31 2018.

Revision 1: March 18 2019. Added discussion of 1968 and 2003 Offshore Tokachi earthquakes with respect to landslides. Added discussion of M 5.7 aftershock of February 21 2019 near Atsuma Town. Clarified Team 1 and Team 2 efforts. Added acknowledgement of PG&E support. Added reference to GEER report. Various typographical and grammatical updates.

ACKNOWLEDGEMENTS

The authors would like to acknowledge that Pacific Gas and Electric (PG&E) helped to support and lead this reconnaissance effort. Mr. Jeff Bachhuber of PG&E's Geosciences Department was the Project Manager. PG&E supported two teams to investigate this earthquake, which was also supported by Southern California Edison (SCE):

- Team 1. Jeff Bachhuber (Team Leader, PG&E). Chris Madugo (PG&E). Matthew Muto (SCE). Joseph Sun (PG&E). Esam Abraham (SCE). Patrick Le (PG&E). Chris Hitchcock (Infraterra). Investigation time in Japan: October 16-23 2018. Team 1 concentrated on field investigation of geologic hazards.

- Team 2. John Eidinger (Team Leader, G&E). Alex Tang (L&T). Nozar Jahangir (PG&E). Brian Low (PG&E). Bronson Ingemansson (PG&E). John Dai (SCE). Roderick dela Cruz (SCE). Investigation time in Japan: November 10-18 2018. Team 2 concentrated on the performance of electric, gas, water, communications and other.

The authors performed the post-earthquake lifelines performance investigation and writing this report. For lifelines investigations, it takes a team with diverse knowledge and access to do such an effort. We have been very fortunate to have Professor Konagai of the University or Tokyo providing us with the needed logistics support. Many people of the Kubota Corporation provided us with tremendous support and information. Professor Maruyama of Chiba University was in the field for two separate trips and graciously described his findings to the investigation team. Geologists and geotechnical engineers from the Pacific Gas and Electric Company and Southern California Edison provided valuable insight and reconnaissance of the geologic hazards. These Professors and organizations provided valuable information and perishable data for this report, and we are indebted to their valuable insights and assistance in every manner. Their permission for us to use their photos and information in this report is extremely valuable.

As is not uncommon in post-earthquake reconnaissance, incomplete information in the weeks and months after the event can lead to omissions and misunderstandings. We apologize if the findings in this report are incomplete, and the reader is cautioned that it may take months to years of post-earthquake evaluations before a comprehensive understanding of lifeline impacts is available. Should readers uncover new information, which would improve the findings in this report, we request that they forward that information to the authors, and we will then update this report as suitable.

The findings and photos presented in this report reflect the collected input from many people and sources; all of them are credited wherever the information or the photo appears in this document. We are very thankful to them providing us with permission to use the information and photos given to us.

The following is a list of individuals and their organizations helping us to collect relevant information (surnames in CAPITALS):

- Prof. Emeritus Kazuo KONAGAI, University of Tokyo
- Prof. Yoshohisa MARUYAMA, Chiba University
- Prof. Nobuoto NOJIMA, Gifu University
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- Hisashi IYOU, Agriculture Division
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- Naoyuki KAZAMA, General Manager
- Takuo NAKAMURA, Manager (presenter)
- Kunihiko HASEGAWA, Manager
- Yasushi YAMAGISHI, General Manager
- Naoki SHIRAI, R&D Manager

NTT

- Dr. Keiichi HIROSE, Tokyo Head Office NTT
- Mr. Naruki FUKUDA, Department Manager, NTT Facilities Inc., Hokkaido
- Mr. Kazuzuki SEKIYA, Business Manager, NTT Facilities Inc., Hokkaido

In addition, special thanks go to Prof. Konagai's PhD former student and current researcher Mr. Masataka SHIGA and Dr. Ms. Mayumi Alessandra NAKATA who helped us overcoming the language barriers and provided us with insight to all matters Japanese. They also assisted us in the field to find locations, operating UAV drones, and allowing us to perform our tasks on site.

Place Names. This report refers to many place names. Cities like Sapporo are easily recognized in both Japanese and English. Small towns and other less common place names have been converted from Japanese to English phonetically, and the spelling may not be consistent between different translations. We apologize for any confusion this may introduce.

To all these lifeline specialists, and the next generation of earthquake engineering practitioners around the world, we hope this report helps you to better understand the world around us, and then take the needed actions to render lifelines resiliency to the next level. The following group photos include the Team 2 members and many of our colleagues from Japan who assisted the investigation.

Team 2 at the debriefing session at JSCE Headquarters, Tokyo, Japan. (Left to right: Brian Low, Nozar Jahangir, Roderick dela Cruz, John Eidinger, John Dai, Bronson Ingemansson)

Second from the right is Director General of MLIT, Hokkaido Mr. Mizhushima. (Left to right: Prof Konagai, Bronson Ingemansson, Alex Tang, Mr. Mizhushima, and John Eidinger) (Credit: Mr. Shiga)

Hokkaido MLIT Officials from all Divisions provided us with damage and recovery information

Group photo at Hokkaido MLIT meeting
Top Row (L to R): John Eidinger, Kaz Konagai, Alex Tang, Nozar Jahangir, Roderick dela Cruz, Jirou Nakamura, Mayumi Nakata. Bottom Row (L to R): Okochi Yasuo, Satoshi Suenaga, Brian Low, John Dai, Bronson Ingemansson (Credit: Mr. Shiga)

Address by Mr. Kazama, the Chief of Hokkaido Kita Gas at Sapporo. Apparently, Mr. Naoyuki, John Eidinger, and Alex Tang have a common friend Prof Kuwata of Kobe University.

Mr. Nakamura, Manager of Pipeline Division was presenting the performance of the Kita gas system in this earthquake.

Group photo at Hokkaido Gas. (Front row, L to R: Mr. dela Cruz, Mr. Tang, and Prof Konagai. Top row, L to R: Mr. Nakamura, Mr. Yasuo, Mr. Dai, Mr. Eidinger, Mr. Kazawa General Manager of Hokkaido Gas, Mr. Jahangir, Mr. Bronson, Mr. Nakamura, Ms. Nakata, Mr. Low, Mr. Suenaga). (Credit: Mr. Shiga)

Prof Konagai (Left) and Alex Tang (Right) in front of the destroyed stair column of the Water Treatment Plant (see Chapter 5). The piles were pulled out by the landslide. (Credit: Mr. Ingemansson)

REPORT COVER PHOTOS

The top left photo is an aerial view on one of the many landslides in that occurred in this earthquake. The landslide scar is indicated by the sloped area without trees; the debris form the landslide extended through farmland. This photo was taken in November 2018, after the roadway had been cleared of debris. More details about landslides are [provided in Chapter 2. (Credit: M. Shiga).

The top right photo shows a map with all the mapped landslides in the strong shaking area (red zones) and dots at the locations of more than 1,000 high voltage transmission towers that traverse that area. The epicenter is indicated by the red star. More details about landslides are in Chapter 2.

The bottom left photo is an aerial view of a collapsed transmission tower caused by a landslide that moved downslope about 1,000 feet (350 meters). The tower is part of HEPCO's electric transmission system. More details about this tower are in Chapter 3. (Credit: HEPCO).

The bottom right photo is the destroyed Water Treatment Plant that had been just been put into service in August 2018. This facility was destroyed by a landslide. The water treatment plant belongs to the town of Atsuma (more details about this water treatment plant in Chapter 5).

Credits. Several photos / maps in this report list the credit to the source author / agency, in the photo title. Photos or maps that do not have source author / agency in the titles are attributed to the chapter authors.

ENDORSEMENTS

Nothing in this report should be considered as an endorsement of any particular product or company.

While we believe the information contained in this report reasonably reflects what occurred (or did not occur) in the September 6 2018 earthquake that affected Hokkaido Prefecture, there is no doubt that this report does not contain all possible information, and it may contain inaccuracies.

This report makes mention of major Japan corporate and local government entities; some are listed on stock exchanges. While these entities shared information with us, the readers should know that none of these entities have endorsed the facts, conclusions or recommendations in this report.

1.0 Introduction

A strong earthquake occurred at 3:08 am, September 6 2018 local time. The moment magnitude of the earthquake was $M_w = 6.7$. Except where noted, we use M to mean Moment Magnitude throughout this report.

The epicenter of this earthquake is shown in Figure 1-1. Also shown in Figure 1-1 are 15 other $M \geq 6.0$ earthquakes that have affected Hokkaido since 1970. Given the location and shallow depth of the September 6 2018 event, the September 6 2018 earthquake resulted in higher level of shaking near the epicentral locations (near the red star) than any of the prior events since 1970. The M 8.3 earthquake of Sept 25 2003 did trigger some liquefaction in Sapporo, but not as severe or extensive as in the September 6 2018 earthquake. The 2003 and 1968 Off-Tokachi earthquakes both triggered landslides in the area affected by many landslides in the September 6 2018 earthquake.

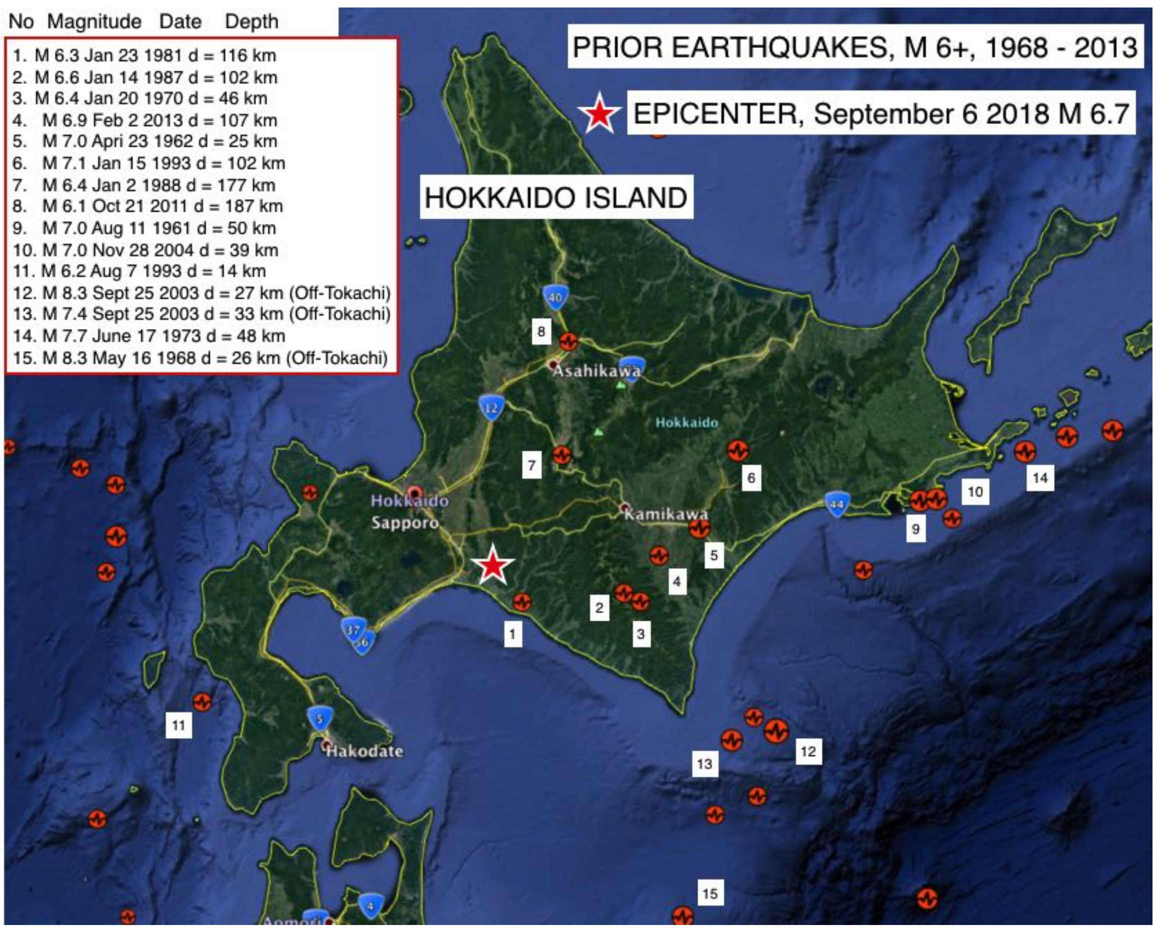

Figure 1-1. Epicenter of M= 6.7 Hokkaido Earthquake, 6 September 2018, and Prior Earthquakes with M ≥ 6.0 since 1970.

Chapter 2. Hazards

The epicenter of the earthquake was located at 42.671° N, 141.933° E, with a focal depth of 33 km. GEER (2019) locates the epicenter at 42.686° N 141.929° E with hypocentral depth of 35 to 37 km. The epicenter is just about 70 km southeast of Sapporo, Figure 1-1. It appears the earthquake occurred along a crustal fault, with reverse thrust motion, with strike along a north-south axis. The uplifted side is to the east (hanging wall), which is largely mountainous and with very low population. The footwall side is to the west, including the new Chitose airport (CTS) and the major urban areas of Sapporo.

The earthquake was recorded by 30 strong motion sensors within about a horizontal distance of about 30 km of the epicenter. About a dozen instruments recorded ground motions with PGA in excess of 0.5g; all but one of the sensors that recorded PGA > 0.5g were located east of the epicenter (on the presumed hanging wall). The highest recorded horizontal PGV was 153 cm/sec (east-west direction). The highest recorded horizontal PGA was 1.34 g (north-south direction). Recorded vertical motions were considerably lower than horizontal motions.

The earthquake triggered a large number of shallow- and deep-seated landslides in areas with PGA > 0.5g, over the hanging wall. Aftershocks in the range of M 4.8 to M 5.0 that occurred in October and November, as felt by the reconnaissance teams, appeared to result in renewed roadway damage (cracks, differential settlement), but no new large scale landslides. The depth of the moving landslide masses from the mainshock was commonly over 2 meters deep (in some cases, over 10 meters deep), and the downslope movement of these slides was commonly more than 5 meters (in many cases, the downslope movement exceeded 20 meters with horizontal run-out of debris extending another 50 meters, in some cases, the horizontal movement exceeded 350 meters).

Many of these slides were on moderately steep slopes (20° to 30°); a few were on very shallow slopes (under 5°). The common surface geologic unit in the landslide area was volcanic ash and pumice deposited by volcanic activity in several episodes over the past 40,000 years or so. Field inspection showed that in some areas there were clay layers embedded or below the volcanic tuff. Many of the landslides may have been triggered inertial overload of the slope as well as by liquefaction at the toe of the landslide zone adjacent to creeks.

The earthquake also triggered liquefaction. In southwest Sapporo, Kiyota-ward, an area covering a few city blocks, with very high ground water level, had severe liquefaction, with settlements (some over 1 meter) and some lateral spread (commonly under 1 meter). A widespread zone of liquefaction occurred just south of a large coal-fired power plant, adjacent to a sea wall; in this area, the effects of liquefaction extended inland from the sea wall about 200 meters, resulting in differential settlements between pile-supported structures and adjacent lands.

The earthquake did not result in surface faulting.

At the time of writing this report, the fault plane solution remains uncertain. Some data suggests a relatively steep (75° dip) reverse thrust mechanism. Ground motion instruments suggest a thrust, possibly with a relatively shallow dip, with horizontal east-west-direction projection of about 20 km and north-south horizontal projection of about 20 km.

Two separate landslides destroyed two steel lattice towers supporting a 66 kV line (towers "71" and "130" along the Ishiwashimi line). These were tangent (suspension) steel lattice four-legged towers. One landslide moved several 10s of feet, and the other moved many 100s of feet. The displaced towers moved so much that the deflected conductors exerted very high tension forces, resulting in buckling of the tower. As a short term measure for tower 130, a steel pole-type structure was erected to restore the transmission line, located within the displaced landslide mass. The adjacent towers immediately outside these slides were nearly undermined by ground cracking. As a moderate term solution, the adjacent towers will possibly be removed, new much-taller towers will be erected, and a new longer span over the displaced landslide might be installed. While this repair strategy might be suitable for the moderate term, it appears that the adjacent (and to-be erected tall towers) might also be located in landslide susceptible zones; LiDAR imagery clearly shows that the areas near the adjacent towers that did not slide in this earthquake, have had massive slides in the past.

One landslide had its head-scarp going through two of the four legs of a 275 kV double-circuit tower (tower "52"). This tower remained in service. However, major efforts to stabilize the slope under and downslope of the tower were implemented in the immediate weeks after the earthquake.

One landslide had its head-scarp going through three of the four legs of a 66 kV single-circuit tower. This tower remained in service with no supplementary stabilization effort done by mid-November 2018.

One landslide inundated a small water treatment plant serving the town of Atsuma. This facility had been placed in service in August 2018, just a month before the earthquake. The damage included toppling of one structure, destruction of another structure. It is likely this water treatment plant will be abandoned.

Landslides also damaged roads.

Several landslides also deposited debris into streams. A large effort was done soon after the earthquake to remove this debris, so as to avoid potential failure of these artificial "dams" along these waterways, which pose severe risk to downstream people and facilities.

One landslide deposited debris into the concrete-lined spillway of a medium-large reservoir that is impounded by an earthen dam. At the time of the earthquake, the reservoir was about 98% full. A large effort was done soon after the earthquake to remove this debris, so as to avoid overtopping and potential failure of the earthen dam should a torrential rainfall require operation of the clogged spillway.

Landslides also inundated a few reservoirs. We did not observe evidence that the debris inundations resulted in overtopping of any of the dams at these reservoirs. The debris materials will increase water turbidity. These reservoirs are primarily used for flood control and for farming irrigation, so the effects of the turbidity might be relatively modest. It is uncertain if the turbidity had effects on water treatment plants, as these reservoirs are not direct raw water supplies for surface water treatment plants.

Landslides also resulted in heavy debris that inundated many occupied houses. The earthquake occurred at 3:08 am, so these houses were occupied, people were asleep, and there was little opportunity to escape the landslide. About 41 fatalities were reported in this earthquake. The bulk of the fatalities were due to these landslide impacts. We need to recognize that one death is one too many.

The lesson here is that the potential impacts on the built environment, including housing stock and lifelines, due to landslides, surface faulting and liquefaction often remains largely overlooked.

Chapter 3. Electric Power

Nearly the entire electric power system for the entire area affected by the earthquake is operated by Hokkaido Electric Power Company (HEPCO). The system normally operates at 50 Hz. At the time of the earthquake (3:08 am local time), island-wide power demand was about 3,087 MW. There was damage to three coal-fired power plants resulting in a loss of generation of about 1,650 MW. Landslides resulted in the collapse of two transmission towers on a 66 kV line. Strong shaking resulting in phase-to-ground faults at a few locations on 275 kV lines. These transmission line faults resulted in dropping of about 600 MW of imported power. A DC link to Honshu ramped up from 50 MW to nearly 600 MW to make up for some of the lost supply, but the loss of AC power to the inverter stations resulted in dropping of the DC link. There was some damage in high voltage substations.

The electric system underwent load shedding, to attempt to keep demand and supply in balance. However, with the widespread impacts and with the sudden loss of more than half of island-wide generation, system frequency dropped from the normal steady 50 Hz to a range between 47 to nearly 50 Hz for the first 17 minutes after the earthquake.

The combination of all these effects was that the residual power grid was sustaining voltage and frequency imbalances. Protective equipment activated to protect other undamaged equipment and generation sources. The net result was that the entire Island of Hokkaido suffered a blackout, at 3:25 am on September 6 2018, or about 17 minutes after the earthquake. All 2.95 million HEPCO customers then lost power.

There were hundreds of locations where landslides damaged low voltage distribution feeders.

Within a day, about 1.3 million customers had their power restored, and within a week, essentially all customers had their power restored. Work-arounds for the damaged transmission lines were in place within a week, and portable generators hooked into low voltage feeders provided power where transmission was cut-off or where extra redundancy was useful.

In the city of Sapporo, the power outages commonly lasted about 5 hours on the south side of the city, and up to 2 days on the north side of the city. The power outages in Sapporo were almost entirely due to load shedding.

The damage to three coal-fired power plants resulted in a loss of sufficient generation capacity to ensure that peak power demand could be reliably supplied during the first 2 weeks post-earthquake. The power utility requested customers to conserve 10% to 20% power during the peak hours between 8:30 am to 8:30 pm on weekdays. The City of Sapporo government buildings voluntarily stopped elevators and shut off air conditioning to set an example of power conservation.

The peak power demand in Hokkaido occurs in the winter time, when peak demand can reach about 5,500 MW. After the earthquake, HEPCO was working to repair a sufficient number of the damaged power plants, put into service a new gas-fired power plant, and the restore the residual damage in the electric system, prior to the winter time peak demand.

HEPCO owns 3 nuclear power plants, all located at one site, with total generation capacity of 2,100 MW. These three plants are reported to have had no damage in this earthquake, with PGA at the plant site under 0.05g. However, since the 2011 Fukushima nuclear power plant disaster, it had been decided to keep these 3 HEPCO nuclear power plants out-of-service; they were not operational at the time of the September 6 2018 earthquake.

Possibly, had HEPCO been operating one or two nuclear and one or two coal power at the time of the earthquake, then while the damage at the coal plants might still have occurred, the loss of generation supply would have not been so severe, and thus much of the power outages and the entire Island-wide power outage might not have occurred.

The main observations from this earthquake with respect to power supply are as follows:

- At the time of the earthquake, more than half of total generation supply was concentrated at three coal-fired power plants at one site.

- Coal fired power plants were susceptible to earthquake-caused damage due to relative motions of pipe systems to/from the boilers; as well as turbine shaft vibration imbalances damage. The level of shaking at the coal fire power plants was moderately strong, about PGA = 0.3g to 0.5g range.

- Strong shaking (PGA > 0.5g) resulted in large displacements of conductor jumpers at strain towers, resulting in phase-to-ground faults on two 275 kV transmission lines, resulting in loss of power to the major Sapporo load center imported from distant sources.

- Landslides destroyed two towers on one 66 kV transmission line.

- The net effect was a "N-5" condition (sudden load of 3 power plants and 2 major transmission lines). Common transmission system design commonly addresses "N-1" events, and in some important areas, "N-2" events. However, common system design does not consider "N-5" events. So, this earthquake was a "beyond design basis event". The nearly simultaneous loss of these 5 important power sources resulted in system frequency imbalances, leading to the island-wide power blackout.

- A night-time earthquake might be more severe with respect to reliability than a day-time earthquake. At night time, there is less power demand, and the system operator might elect to have more than half of generation supplied from one co-located power plant site. In the day time, with higher demands, likely more geographically-distributed power plants would be operating, and the loss of one (or a few) power plants might not have nearly as much impact to the grid as a whole.

- For day-to-day emergencies, most system operators design the system to have no interruptions under "N-1" contingencies. In this earthquake, there was "N-5", an unplanned contingency.

Chapter 4. Gas

In the area affected by strong ground shaking, most of the urbanized areas are supplied with natural gas by a piped system. There was some minor damage to low pressure gas mains and service laterals, but most of the gas mains were constructed with seismic-resistant pipes and these had little or no damage. Most of the gas system repair effort occurred to service laterals and meters, as well as work within customer's houses. No automatic shut-off valves in the gas systems were activated in this earthquake, as ground motions at recording stations for this system were all under the triggering SI level of 60 cm/sec. Since the gas system was not shutdown, and gas shut off valves at meters were not activated, there was little effort needed for gas re-lights. There was only one fire ignition reported, and it was quickly controlled. There were no fire conflagrations in this earthquake.

Chapter 5. Water

The largest water system in the area affected by the earthquake is the waterworks of the City of Sapporo. This water system sustained a modest amount of damage to pipe mains, pipe appurtenances and service laterals. This relatively modest level of damage can be attributed to the relatively moderate levels of shaking for most of Sapporo (PGA commonly < 0.15g), just a few locations with significant PGDs (some PGDs were due to liquefaction and landslide, some PGDs were due to compaction); and the significant efforts in the past two decades to seismically upgrade the Sapporo water system, including replacement of older pipes with newer seismically-designed pipes for more than 20% of the entire pipeline network of nearly 6,000 km.

The water system for the town of Atsuma sustained heavy damage. A brand new water treatment plant was destroyed by a landslide. A new irrigation pipeline system for Atsuma and nearby regions sustained heavy damage due to strong ground shaking and liquefaction; these pipes were not constructed with any special seismic detailing.

There were no reported fire ignitions in the City of Sapporo.

Chapter 6. Telecommunication

Landslides caused damage to telecommunication cables and cell sites. The prolonged electric power outage resulted in short duration service interruptions before mobile power generators were brought in to various cell sites. The most significant damage was one remote office that was destroyed by landslide. Overhead aerial cable network within the landslide zones sustained extensive destruction. We did not observe damage due to strong ground shaking.

A record of 111 Cell Sites (called Base Stations[1] in Japan) were out of electric power for more than 6 hours. In Mukawa the antenna pole of a Base Station, which was not in operation at the time, was slanting about 10° from vertical but did not collapse; this Base Station was removed the day after.

Twenty-eight mobile power generators were shipped in from NTT, Honshu to provide power to Base Stations in Hokkaido due to the Island-wide power blackout. A total of more than sixty units were deployed in Hokkaido to power the Base Stations for more than 2 days.

Central Offices (Exchange Offices[2] in Japan) did not experience any set back. One Exchange Office had superficial surface cracks on walls and panel joints.

Chapter 7. Transportation

The road system performed reasonably well. All the high speed toll roads were operated by NEXCO[3], which is a private company. Due to the power outage to the toll booths, coupled with the interest of doing safety inspections, these toll roads were closed for about one day.

[1] Base Station will be used in this report.

[2] Exchange Office will be used in this report.

[3] NEXCO = Nippon Expressway Company (established in 2005)

Damage to bridges was mainly due to abutment settlement caused by permanent ground deformation.

Several secondary roads within the massive landslide areas were either covered by debris or, in some cases, the entire road slid down the slope. There were many locations where the road surfaces were cracked or subsided. By mid-November 2018, all of the more heavily travelled secondary roads had debris removed and resurfaced as needed; nearly all of the low volume roads to very small communities were re-opened, sometimes just re-graded as detours, (no paving, no guard rails) and requiring very slow speeds for vehicle access.

The JR railway, Sapporo local subway and Sapporo tram system services were closed during the power outage black out period. They returned to operation after the power was restored. There was no report of damage caused by the earthquake.

Chapters 8. Airport and Sea Ports

The New Chitose Airport was the only airport that was exposed to ground motions with PGA > 0.2g. It is about 25 km northwest of the epicenter. The Domestic Passenger Terminal sustained some non-structural damage, such as fallen ceiling tiles, broken water pipes, merchandise fallen on the floor, etc. The airport was closed (or with limited operation) from September 6 to September 8 2018. All flights in and out of the airport were cancelled during the closure, except domestic cargo flights for relief supply. Luckily, the earthquake occurred not during the high season for tourist visits to Hokkaido.

There was no report of significant Ports damage. The largest port that is closest to the epicenter is Tomakomai-Atsuma East Port, about 15 km south-west of the epicenter (PGA ~ 0.25g); there was no sign of quay damage (Figure 8-9) and it was in full operation by mid-November. The Tomakomai-Atsuma West Port (PGA ~ 0.25g) did not sustain structural damage from this earthquake; there were two places at the Container Ports that had liquefaction in the container storage areas. The sea wall to the south-east of the Tomatoh-Atsuma power plant (Figure 2-18) sustained significant damage due to liquefaction (PGA ~ 0.35g). A pier serving the Tomatoh-Atsuma power plant (PGA ~ 0.35g) sustained some damage (Figure 8-12), as evidenced by some lateral offset of the pier; as of the time of writing this report, under-pier investigations had not be performed to ascertain the cause(s) of this damage. The Ishikari and Otaru ports west of Sapporo (PGA < 0.05g) suffered no damage.

Chapter 9. Economic Impacts and Resiliency

For Hokkaido as a whole, this earthquake is estimated to have caused about $15 Billion in direct short term damage, representing about a -4.9% reduction in reduced gross domestic product (annual basis) for Hokkaido Island. About 80% of this loss was in the Agriculture sector.

There were about 6 Billion customer-minutes of power outages. The average outage was about 2,000 minutes (34 hours) for the average customer in Hokkaido. The last customer (able of receiving power), had power restored 29 days after the earthquake. The damage to major generation power plants led to requests to reduce power demand by 10% to 20% in first week after the earthquake. Until damaged power plants are repaired, and / or more power plants brought online, the reserve margin to supply peak winter time power demands will be less than normal, so further unplanned outages could result in further power blackouts.

Sapporo was Resilient.

The smaller rural / farming communities in the epicentral area were not Resilient.

Chapter 9. Social Economic Impact

One of the main industries in Hokkaido prefecture is agriculture. Farms occupy a large portion of the island. The basic products are dairy and rice. This earthquake occurred close to one of the major the farming industry areas. A major irrigation system had been recently constructed to deliver irrigation water to farms near Atsuma and Mukawa; this system sustained heavy damage. Luckily the rice crops were harvested before the earthquake; but the damage to fields and forests due to landslides and damage to irrigation was major, and will have ongoing significant impacts lasting a year or more.

Temporary housings (Figure 9-6) were constructed in Tomakomai to provide shelters for the victims. Additional units were constructed during our visit in November.

Aftershock of February 21 2019

On February 21 2019 at 21:22 local time, a M 5.7 aftershock occurred near Atsuma, with epicenter at 42.765° N 142.00° E. Using the JMA scale, the intensity of shaking was about 6- at Atsuma Cho, 5+ at Abira Cho and Mukawa Cho, and 5- at Sapporo Shi Kita Ku, Sapporo Shi Teine Ku, Chitose Shi Cho, Naganuma Cho, and Biratori Cho.

The lifeline impacts from this aftershock were as follows:

- Electric power. No outages.
- Gas. No pipe damage.
- Water. There were damaged pipes and water outages in the Toyosawa area of Atsuma Cho.
- Telecommunications. No damage or service disruptions.
- Highway (NEXCO). No damage.

- Hidaka Expressway. 28 km closed for inspection are re-opened on February 22 2019 at 1:10.

- Railway. Six lines suspended for inspections within the Atsuma area; all re-opened about 12 hours later. The airport train from CTS to Sapporo was suspended for inspection and returned to normal on February 22 2019.

- CTS Airport (JMA Intensity 4). No damage. 1 departure and arrival delay. Passengers were stranded due to suspended trains.

- Sea Ports. No reported damage.

- Liquid Fuels. Oil facilities in Tomakomai City and Ishikari City reported no damage.

- Landslide and avalanche risks reported at 255 locations: Atsuma 111, Abira 26, Mukawa 118. Two snow avalanches were reported, one in the Korimachi Horoi District. No avalanches reported at the Niseko ski area (level of shaking there very low, with PGA < 0.01g).

1.1 Limitations

The findings in this reconnaissance report for the mainshock were developed during the first two to three months after the September 6 2018 earthquake. All findings must be considered accordingly. The data in this report may be incomplete, and the interpretations may be incorrect. The authors and contributors of this report make no warranty of any kind.

1.2 TCLEE

This report has been prepared by a number of researchers in lifeline earthquake engineering. Collectively, this group is called The Council of Lifeline Earthquake Engineering, *TCLEE*.

THE COUNCIL OF LIFELINE EARTHQUAKE ENGINEERING

TCLEE

To date, *TCLEE* has published four reports. These reports are available for free at http://www.geEngineeringSystems.com.

- *TCLEE No. 1*. Napa, California earthquake, August 2014.

- *TCLEE No. 2.* Kumamoto, Japan earthquakes, April 2016.
- *TCLEE No. 3.* Mexico City and Chiapas, Mexico earthquakes, September 2017.
- *TCLEE No. 4*. Hokkaido, Japan earthquake, September 2018.

1.3 Abbreviations

AC	Alternating Current
ACP	Asbestos Cement Pipe
ALA	American Lifelines Alliance
cm	centimeter
CSZ	Cascadia Subduction Zone
CTS	Chitose Airport
DC	Direct Current
DIP	Ductile Iron Pipe
ER-DIP	Earthquake Resistant Ductile Iron Pipe
g	acceleration of gravity (= 32.2 feet / second / second = 981 gal)
GIP	Galvanized Iron Pipe
GRP	Fiberglass Pipe
GWh	Gigawatt-hour
HEPCO	Hokkaido Electric Power Company
Hz	Hertz (1 Hz = 1 cycle per second)
JMA	Japan Meteorological Agency
km	kilometer
kV	kilovolts
Ky	Yield acceleration of a slope (in g)
LNG	Liquefied Natural Gas
M	Magnitude (moment magnitude unless otherwise noted)
MILT	Ministry of Land, Infrastructure and Transportation / Tourism
MW	Megawatt
MGD	Million Gallons per Day (US fluid measure)
MVA	Million Volt Amp
mm	millimeter
NEXCO	Nippon Expressway Company
PG&E	Pacific Gas and Electric
PGA	Peak Ground Acceleration, g
PGD	Permanent Ground Displacement, (cm)
PGV	Peak Ground Velocity (cm/sec)
PVC	Polyvinyl Chloride Pipe
RR	Repair Rate (damage per km)
USGS	United States Geological Survey
WTP	Water Treatment Plant

1.4 Units

This report makes use of both common English and SI units of measure.

Common Conversions

1 kip = 1,000 pounds
1 foot = 12 inches
1 inch = 25.4 mm = 2.54 cm
1 mile = 1.609347 kilometers
1 m^3 = 264.17 gallons (US measure, fluid)
1 acre-foot = 325,851 galloons (US fluid measure)
1 pound-force = 4.448 newtons
1 pound = 0.453592 kilogram
1 psi = 6.894757 kiloPascal (kPa)
1 kPa = 0.145038 psi
1 g = 981 gal (cm/sec/sec)
1 cm/sec = 1 kine
1 m = 1,000 mm = 100 cm

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1.6 Acknowledgements

Some maps in this report use base maps derived from Google; we thank Google for their use. In each chapter, some photos were taken by the authors; and some were provided by various agencies; we thank the agencies for their use.

2.0 Seismic Hazards

Section 2 describes the seismic hazards in this earthquake.

- Section 2.1 provides maps showing the location of the epicenter, locations of past significant earthquakes, the major population centers, regional geologic conditions, and locations of the major landslide zones.

- Section 2.2 provides data describing PGA, PGV, and Spectra Accelerations in the area.

- Section 2.3 describes some of the landslides in the areas with strong ground shaking. There are more examples of landslides described in Sections 3, 5 and 6.

- Section 2.4 examines the observed liquefaction phenomena. There are more examples of liquefaction described in Sections 3, 5 and 6.

- Section 2.5 discusses surface faulting.

- Section 2.6 provides references.

2.1 Location of the Earthquake

Figure 2-1 shows the country of Japan, highlighting the island of Hokkaido, and the largest city, Sapporo, on the island, and locations of a few other large cities in Japan. Major destructive earthquakes have hit Japan over the past two decades: Kobe (1995, Hanshin), Niigata (2003, 2007), Sendai (2011, Tohoku), and Kumamoto (2016).

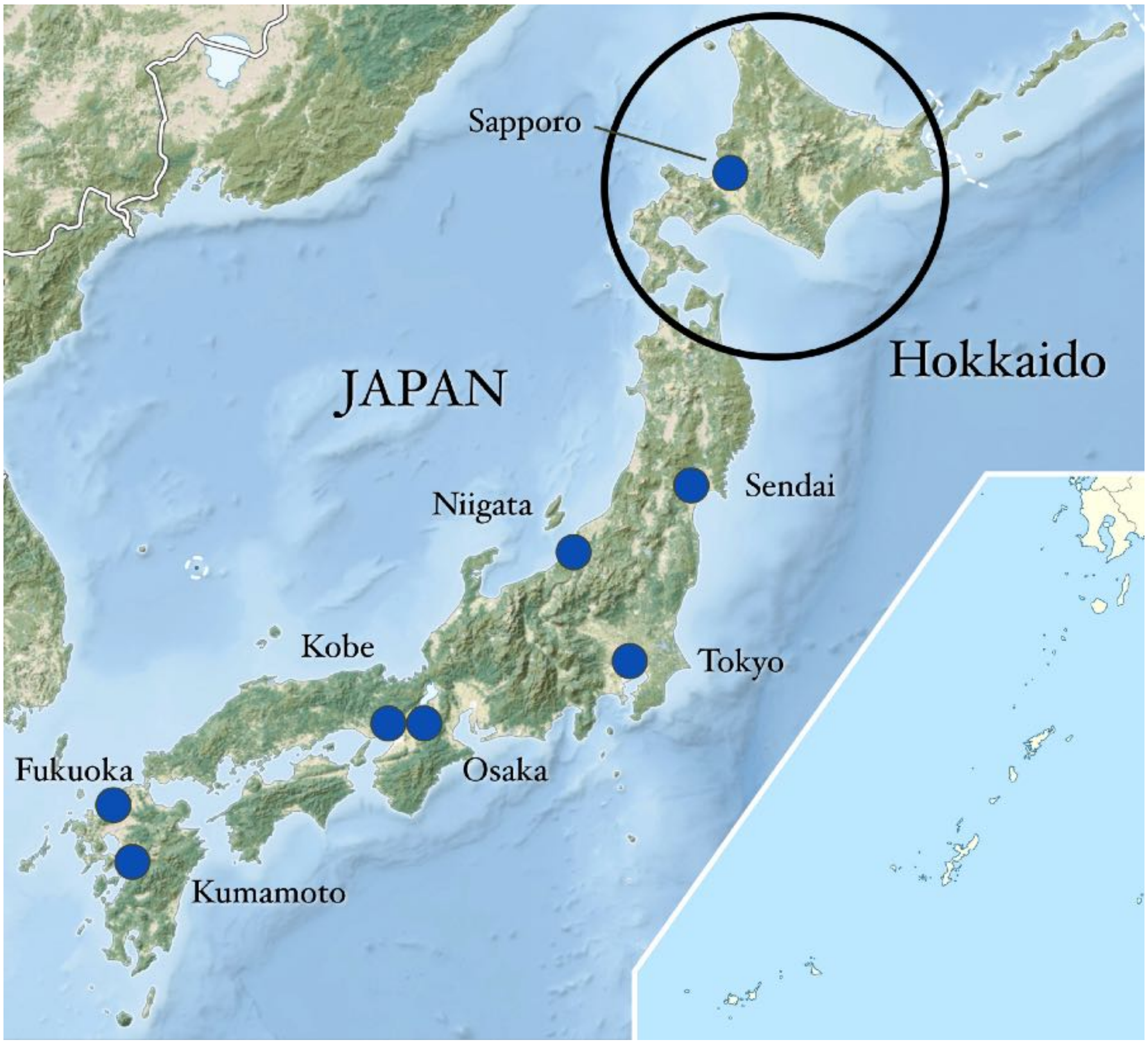


Figure 2-1. Place Names

The Island of Hokkaido has also experienced many earthquakes over the past several decades, including the 1968 offshore Tokachi M 8.3 earthquake (number 15 in Figure 2-1) and the 2003 offshore Tokachi earthquakes (numbers 12, 13 in Figure 2-1). These offshore earthquakes were located where the North American Plate is overriding the Pacific Plate; The Pacific Plate is moving west-northwest at a rate of about 8.2 cm per year relative to the North American Plate.

The 1968 offshore M 8.3 earthquake was an interplate (interface) event. Heavy rain occurred days before the 1968 earthquake. In Aomori Prefecture (the northernmost area of Honshu), there was damage to railroads and highways in more than 200 places caused by collapses of artificial embankments. In Hachinohe, there was damage to buildings, water pipes and gas pipes. Communications between Honshu and Hokkaido were cut off. Damage was estimated at $25 million ($1968). Casualties: 48 killed. Reference: USGS Preliminary Earthquake Report, EQ_030925, last update October 3 2003.

The 2003 offshore M 8.3 earthquake was an interplate (interface) event. This earthquake triggered extensive landslides. The earthquake also caused power outages. As the epicenter was nearly 100 km offshore, structural damage was relatively light, with the bulk of the damage resulting from coastal flooding due to a tsunami. Soil liquefaction was observed, almost exclusively occurring in man-made embankments. Damage to buildings was mostly in Kushiro City. Strong shaking affected many bridges. Several sea ports in the areas suffered moderate damage due to lateral ground spreading caused by liquefaction. Damage was estimated at $1.9 Billion ($2003). Reference: USGS Preliminary Earthquake Report, EQ_030925, last update October 3 2003. This earthquake appears to have ruptured of the same section of the plate interface that ruptured with M 8.1 in 1952. An estimated M 9 earthquake affected the region in 1667.

Figure 2-2 shows a satellite image that highlights Hokkaido Island. Much of the island is mountainous and forested, denoted by the dark green areas. The heavily populated area is the city of Sapporo (metro population near 2 million people). The epicenter of this earthquake was located about 70 km southeast of Sapporo. The strongest shaking areas were generally east of the epicenter, a mountainous area with very low population.

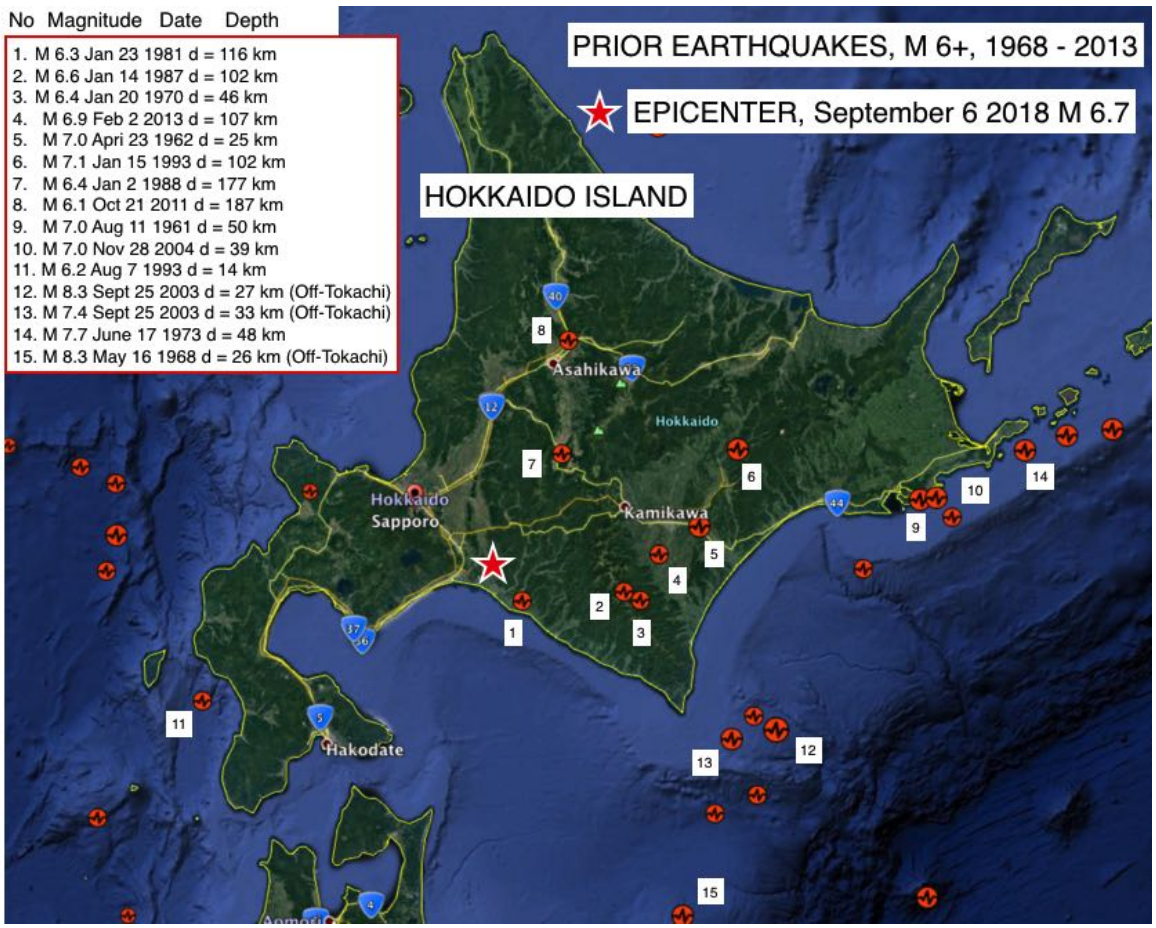


Figure 2-2. Hokkaido Island

Figure 2-3 shows a map of the region near Sapporo and near the epicenter. The areas in green are generally mountainous and forested. The areas in white are either urbanized (such as Sapporo) or narrow valley areas dominated by farming activities.

The location of the 3-unit Tomatoh-Atsuma power plant is highlighted as a red box. The Minawi-Hayakita 275-kV substation is highlighted by an orange box. The yellow boxes show locations of selected facilities and places described in this report.

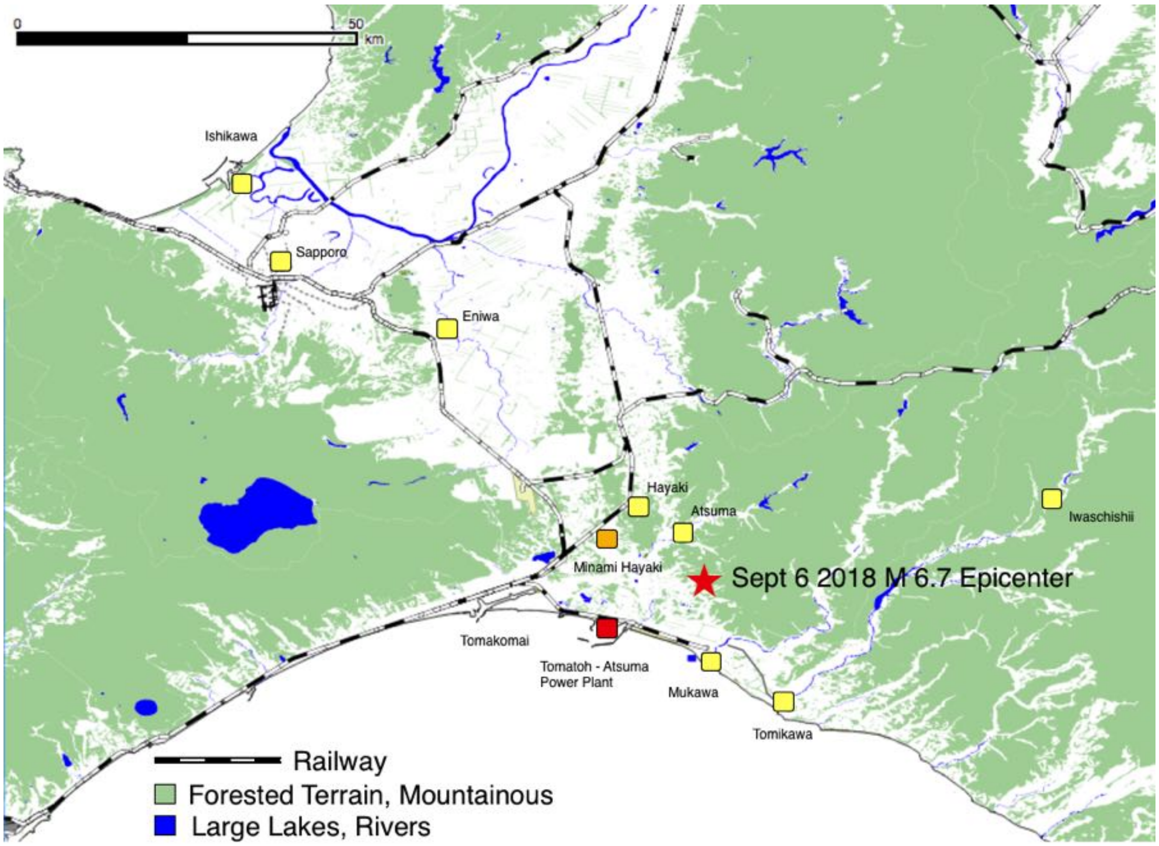


Figure 2-3. Location of Cities and Towns and Selected Facilities

Figure 2-4 shows an initial understanding of the fault mechanism. The earthquake appears to be a reverse thrust event. Slip was about 1.3 meters. The rupture did not extend to the surface. The depth of the epicenter was 35 km. The fault rupture length was 14 km. The fault rupture width was 15.9 km. The depth to the top of the fault rupture was 16.2 km.

Kayen et al (2019) alternatively reports the strike of the fault to be 333° with northeast dip of 61° or strike of 358° with easterly dip of 74°.

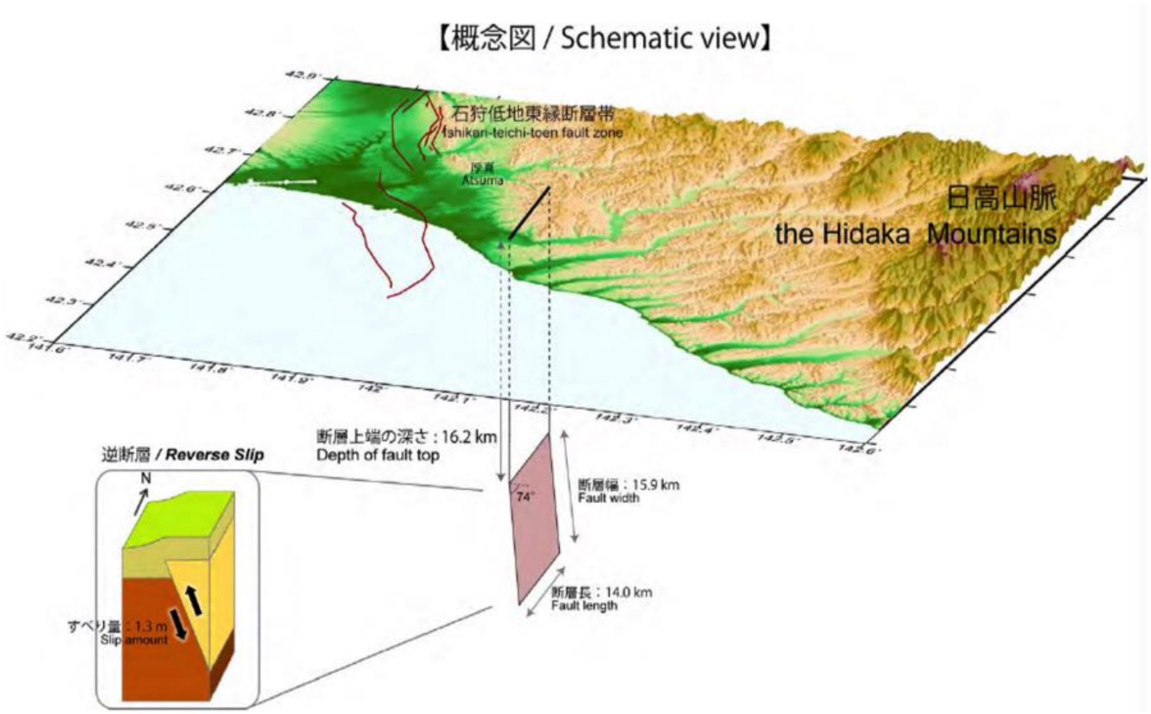


Figure 2-4. Initial Interpretation of Fault Mechanism (credit: Japan Geographical Survey Institute)

2.2 Ground Shaking

Tables 2-1 (north-south), 2-2 (east-west) and 2-3 (vertical) list the recorded motions at 30 instruments close to the epicenter.

Station Code	Latitude	Longitude	PGV (cm/sec)	PGA (%g)	PSA03 (%g)	PSA10 (%g)	PSA30 (%g)
BO.HKD126	42.5750	141.9279	49.98	39.57	77.40	65.69	-1.00
BO.HKD128	42.7655	141.8221	85.38	56.71	108.15	-1.00	10.73
BO.HKD104	42.5886	142.1310	26.01	28.18	60.97	25.79	2.86
BO.HKD125	42.7608	142.1346	52.03	61.16	162.24	59.31	7.28
BO.HDKH04	42.5126	142.0381	48.53	36.59	78.43	94.05	6.35
BO.HKD105	42.4825	142.0543	22.70	25.71	69.25	24.57	3.49
BO.IBUH01	42.8739	141.8191	-1.00	134.44	349.70	62.94	5.89
BO.HDKH01	42.7031	142.2296	26.70	54.91	172.22	18.65	3.98
BO.HKD129	42.6344	141.6057	14.58	37.65	113.97	11.40	2.95
BO.IBUH02	42.8714	142.1285	22.28	35.45	87.18	19.57	4.11
BO.HKD184	42.7900	141.6010	30.93	32.64	126.58	15.83	4.40
BO.HKD103	42.7275	142.2973	37.63	57.69	-1.00	22.12	6.15
BO.IKRH03	42.8880	141.6399	26.29	17.58	44.54	18.09	6.90
BO.SRCH10	42.9930	142.0085	8.41	11.23	30.31	10.82	2.75
BO.HKD123	42.9933	142.0085	8.66	10.93	29.65	10.97	2.54
BO.HKD124	42.9986	141.7904	19.31	57.09	63.67	7.06	3.63
BO.SRCH09	43.0587	141.8063	24.35	54.39	120.20	14.16	3.80
BO.HKD185	42.7755	141.4021	16.81	39.16	82.16	11.38	1.30
BO.HKD182	42.9925	141.5524	20.32	20.30	44.36	10.98	3.23
BO.HKD102	42.8775	142.4484	10.41	8.34	28.46	10.04	2.26
BO.HKD130	42.5627	141.3499	9.64	15.84	45.79	6.36	0.99
BO.IBUH05	42.5629	141.3497	10.72	18.85	51.22	6.80	1.10
BO.HDKH06	42.3498	142.3572	17.11	18.08	48.16	40.00	2.06
BO.HDKH05	42.5977	142.5446	4.38	6.14	19.29	6.25	0.90
BO.HKD106	42.3414	142.3688	12.83	14.04	31.25	16.01	1.63
BO.HKD040	42.9805	142.3995	4.84	9.23	26.28	7.20	1.44
BO.HKD107	42.4194	142.4992	6.12	4.88	10.80	6.17	1.82
BO.HKD181	43.1161	141.5462	18.34	25.24	63.98	16.64	3.69
BO.HKD122	43.1968	141.7754	7.38	9.62	21.92	15.52	3.53
BO.SRCH07	43.2300	141.8978	5.95	10.59	41.69	6.29	2.12

Table 2-1. North-South Instrumental Motions

In these tables, the Spectral accelerations are listed at T=0.3, 1.0 and 3.0 seconds at 5% damping. "-1.00" means no data.

Station Code	Latitude	Longitude	PGV (cm/sec)	PGA (%g)	PSA03 (%g)	PSA10 (%g)	PSA30 (%g)	Inst #
BO.HKD126	42.5750	141.9279	153.37	67.48	75.22	141.08	-1.00	1
BO.HKD128	42.7655	141.8221	113.43	68.30	124.73	-1.00	12.26	2
BO.HKD104	42.5886	142.1310	17.38	35.55	64.99	15.82	1.58	3
BO.HKD125	42.7608	142.1346	55.23	75.62	184.46	50.60	5.96	4
BO.HDKH04	42.5126	142.0381	45.21	43.01	122.37	53.50	11.73	5
BO.HKD105	42.4825	142.0543	55.14	37.89	102.76	70.61	9.44	6
BO.IBUH01	42.8739	141.8191	-1.00	94.74	284.40	58.89	6.52	7
BO.HDKH01	42.7031	142.2296	51.37	64.51	214.53	30.45	5.10	8
BO.HKD129	42.6344	141.6057	25.62	33.23	106.84	28.78	6.04	9
BO.IBUH02	42.8714	142.1285	31.26	69.24	112.87	28.87	2.51	10
BO.HKD184	42.7900	141.6010	21.60	36.08	108.74	17.35	3.12	11
BO.HKD103	42.7275	142.2973	37.19	68.68	-1.00	45.73	13.72	12
BO.IKRH03	42.8880	141.6399	17.47	19.29	51.15	14.69	3.63	13
BO.SRCH10	42.9930	142.0085	4.92	12.81	27.70	6.53	1.52	14
BO.HKD123	42.9933	142.0085	6.57	11.85	32.34	7.14	1.82	15
BO.HKD124	42.9986	141.7904	11.10	36.25	35.02	10.12	1.66	16
BO.SRCH09	43.0587	141.8063	22.51	50.74	120.42	19.37	1.91	17
BO.HKD185	42.7755	141.4021	21.95	57.04	70.97	17.90	1.55	18
BO.HKD182	42.9925	141.5524	10.40	18.02	35.86	6.83	2.03	19
BO.HKD102	42.8775	142.4484	10.88	9.37	27.73	9.45	2.64	20
BO.HKD130	42.5627	141.3499	11.18	17.18	38.15	8.92	3.14	21
BO.IBUH05	42.5629	141.3497	11.38	23.72	42.67	8.92	3.20	22
BO.HDKH06	42.3498	142.3572	18.52	15.29	54.30	25.15	5.13	23
BO.HDKH05	42.5977	142.5446	3.79	5.82	16.77	3.55	0.91	24
BO.HKD106	42.3414	142.3688	21.67	18.32	37.17	20.08	5.52	25
BO.HKD040	42.9805	142.3995	6.04	5.77	23.83	6.95	1.90	26
BO.HKD107	42.4194	142.4992	9.17	5.95	16.92	9.39	2.02	27
BO.HKD181	43.1161	141.5462	13.93	24.27	72.87	13.26	1.66	28
BO.HKD122	43.1968	141.7754	6.97	8.42	15.33	9.92	2.61	29
BO.SRCH07	43.2300	141.8978	4.59	8.32	29.26	7.27	0.91	30

Table 2-2. East-West Instrumental Motions (Instrument #)

Station Code	Latitude	Longitude	PGV (cm/sec)	PGA (%g)	PSA03 (%g)	PSA10 (%g)	PSA30 (%g)
BO.HKD126	42.575	141.9279	14.44	34.16	32.47	16.05	-1.00
BO.HKD128	42.7655	141.8221	27.25	40.42	82.16	-1.00	3.17
BO.HKD104	42.5886	142.131	7.84	11.56	31.32	6.74	0.94
BO.HKD125	42.7608	142.1346	14.75	20.74	70.71	17.16	2.28
BO.HDKH04	42.5126	142.0381	10.14	20.05	35.56	16.41	2.41
BO.HKD105	42.4825	142.0543	18.04	32.66	48.05	16.19	2.76
BO.IBUH01	42.8739	141.8191	-1.00	108.17	320.02	12.60	2.36
BO.HDKH01	42.7031	142.2296	15.26	32.27	65.42	16.37	4.36
BO.HKD129	42.6344	141.6057	7.08	12.84	21.08	7.34	1.92
BO.IBUH02	42.8714	142.1285	6.17	14.19	21.38	8.63	1.08
BO.HKD184	42.79	141.601	10.56	45.74	37.50	6.53	2.20
BO.HKD103	42.7275	142.2973	16.37	35.07	-1.00	19.30	3.84
BO.IKRH03	42.888	141.6399	4.46	10.40	14.11	4.62	2.95
BO.SRCH10	42.993	142.0085	3.46	4.47	7.97	3.49	0.91
BO.HKD123	42.9933	142.0085	3.68	4.40	11.79	3.46	0.98
BO.HKD124	42.9986	141.7904	5.22	12.24	9.67	5.23	2.44
BO.SRCH09	43.0587	141.8063	10.03	25.28	32.73	8.35	2.11
BO.HKD185	42.7755	141.4021	6.19	33.17	46.59	3.44	0.68
BO.HKD182	42.9925	141.5524	3.10	10.95	16.98	4.37	1.35
BO.HKD102	42.8775	142.4484	5.79	4.32	8.71	7.50	1.40
BO.HKD130	42.5627	141.3499	4.57	13.00	16.95	4.24	1.21
BO.IBUH05	42.5629	141.3497	4.52	13.20	15.32	4.41	1.23
BO.HDKH06	42.3498	142.3572	7.36	10.91	18.18	11.78	2.03
BO.HDKH05	42.5977	142.5446	2.51	2.84	7.57	2.33	0.39
BO.HKD106	42.3414	142.3688	4.89	4.21	9.41	9.77	1.50
BO.HKD040	42.9805	142.3995	3.35	2.87	10.71	5.84	0.86
BO.HKD107	42.4194	142.4992	3.27	2.30	4.69	5.15	1.67
BO.HKD181	43.1161	141.5462	6.93	11.97	35.45	5.22	0.90
BO.HKD122	43.1968	141.7754	3.97	5.01	9.46	6.31	1.14
BO.SRCH07	43.23	141.8978	2.90	5.14	16.73	3.75	0.72

Table 2-3. Vertical Instrumental Motions

Figure 2-5 shows the acceleration time histories for instrument HDK126 (instrument HKD126 in Tables 2-1, 2-2, 2-3). The peaks in Figure 2-4 vary slightly from those listed in the tables due to different processing techniques. The time histories show about 15 to 20 seconds of strong shaking (PGA > 0.05g), typical for a M 6.7 event.

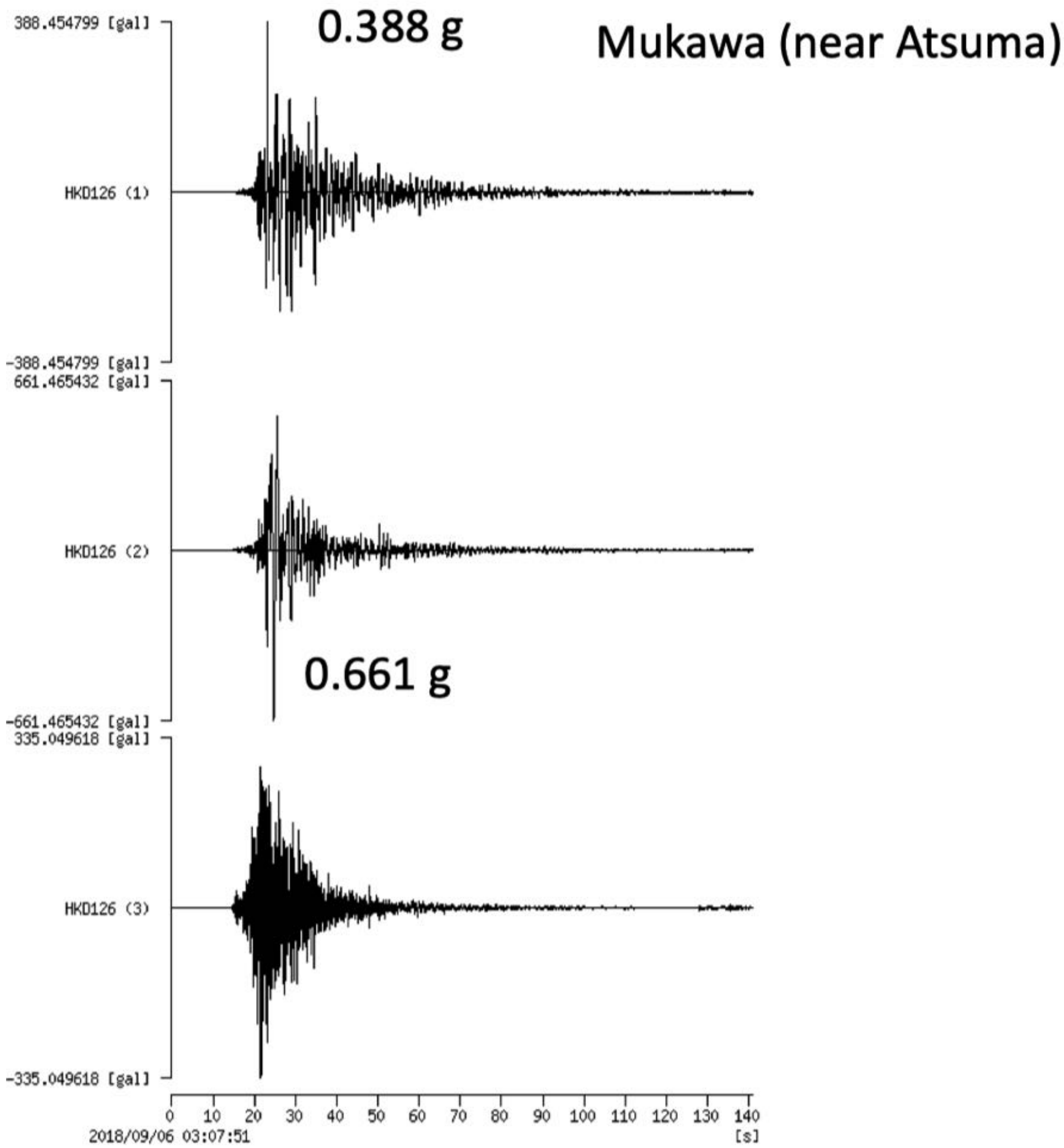


Figure 2-5. Time History Motions (HKD126) (NS, EW, Vertical) (after Kayen et al)

Using the instrumental motions, "ShakeMaps" of peak horizontal motions is created and then converted into contours of equal motions. Figure 2-6 shows these motions with respect to horizontal PGA. The listed values represent the contour intervals at selected locations. For example:

- Mountainous zones north, northeast, east of the epicenter, Atsuma: Motions are commonly PGA > 0.50g.

- Tomatoh-Atsuma: PGA ~ 0.36g.

- Murotran: PGA ~ 0.20g.
- Sapporo: PGA values are about 0.08g (west side) to 0.16g (east side).
- Port of Ishikawa: PGA ~ 0.08g.
- Port of Otaru: PGA ~ 0.04g.

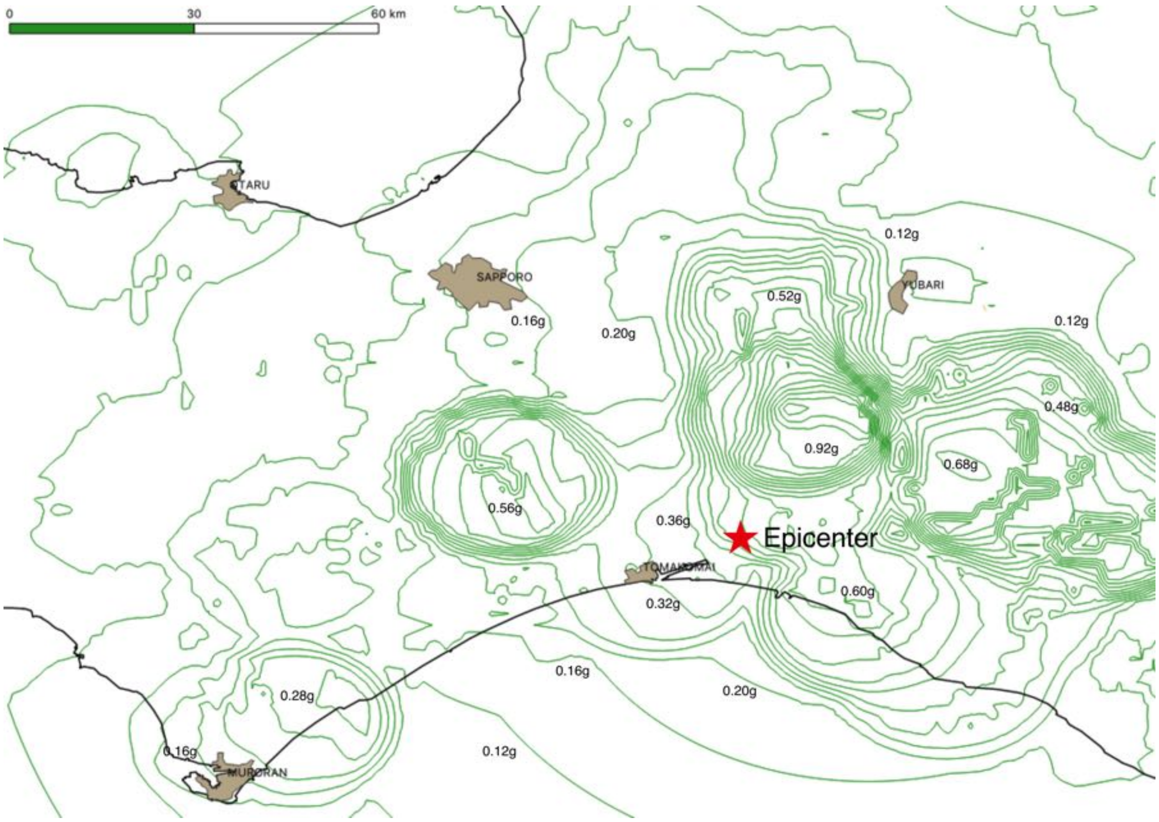


Figure 2-6. ShakeMap – Horizontal PGA (g) (full scale 60 km)

Figure 2-7 shows the recorded PGA values at selected instruments. Instrument numbers are listed in Table 2-2. Figure 2-7 shows a possible "foot wall / hanging wall" arrangement that is possibly consistent with the initial understanding of the strike mechanism.

It should be recognized that there is considerable variation of ground motions that are not reflected in Figures 2-6 and 2-7.

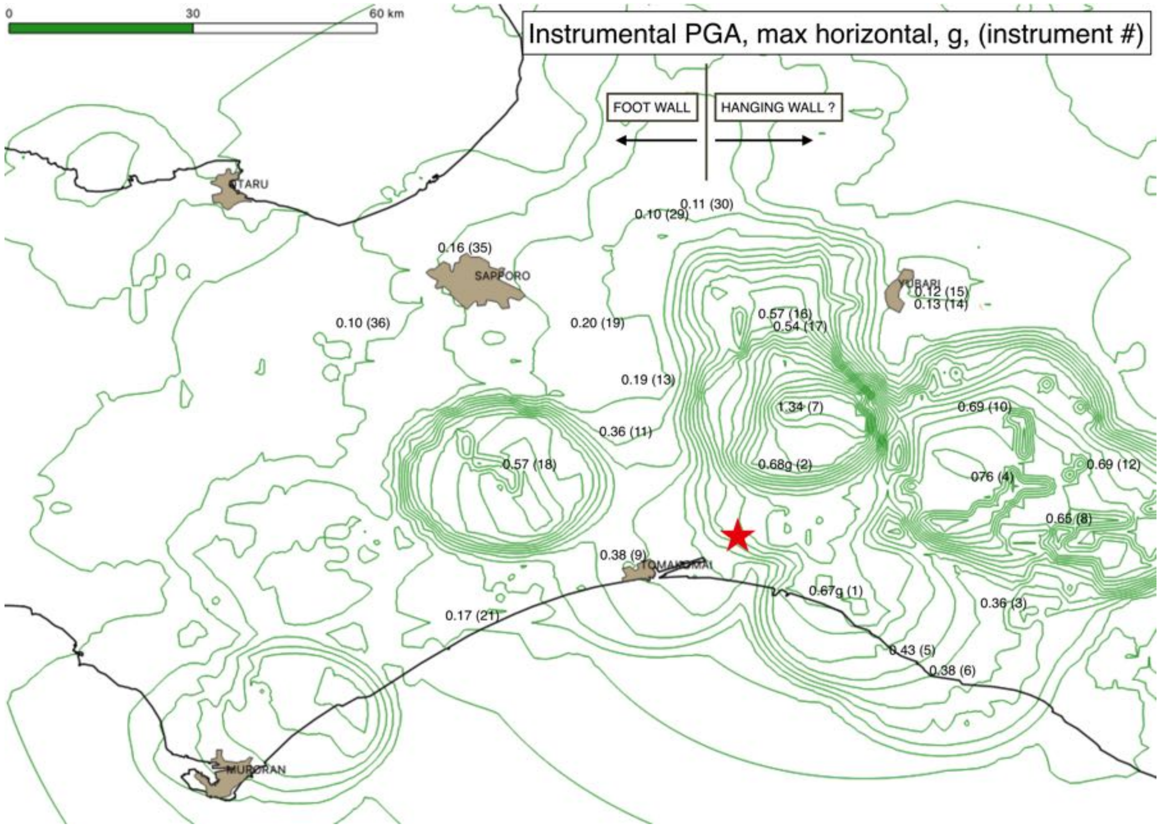


Figure 2-7. Instrumental Motions – Horizontal max |NS, EW| PGA (g) (full scale 60 km)

2.3 Landslides

Figure 2-8 shows a map of large landslides (red zones) that were triggered by this earthquake.

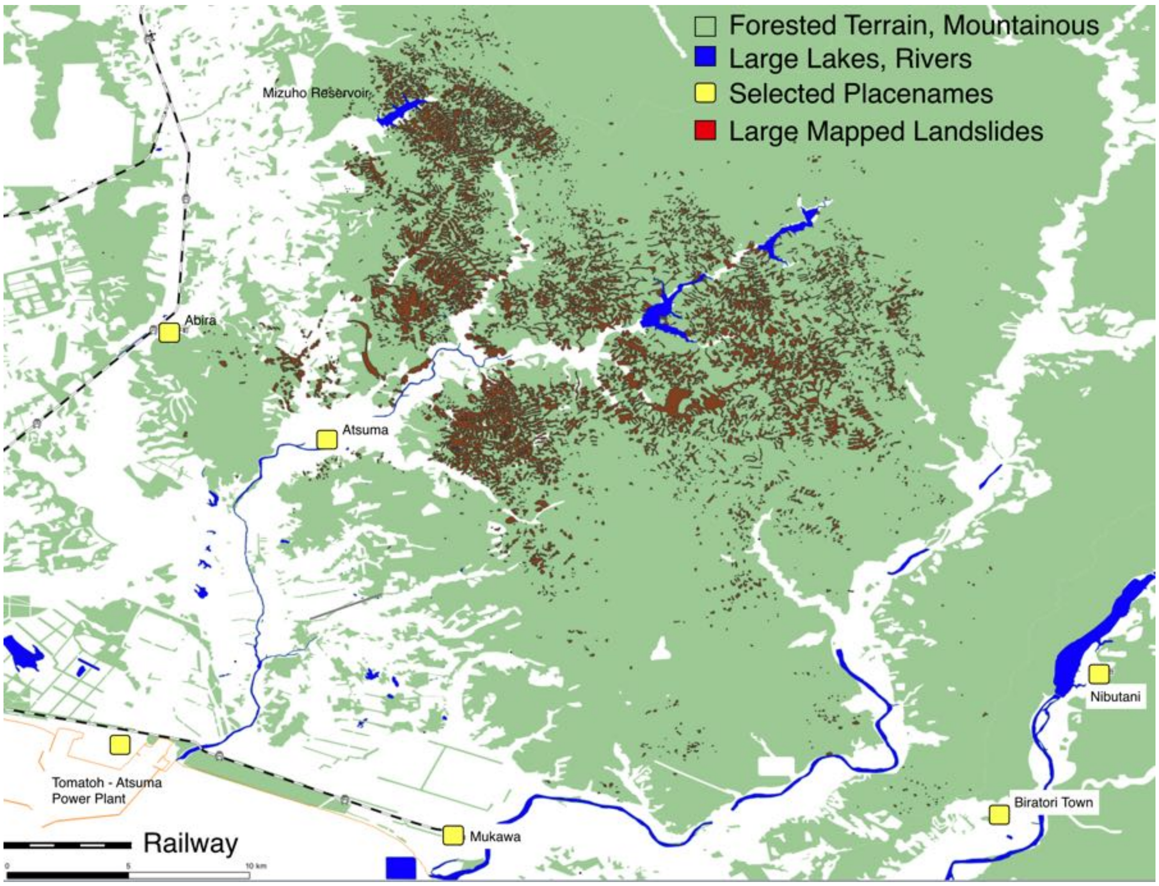


Figure 2-8. Mapped Landslides (full scale = 10 km)

In the area of very strong shaking (generally PGA > 0.5g), underlain by adverse geologic units (volcanic tuff), on the order of 30% to 50% of the sloped landmass slid.

To help understand the prevalence of landslides in this earthquake, one has to examine the degree of saturation of the ground. It is well established that under dry conditions, most soil slopes are stronger than under wet conditions.

While Sapporo was located north and west of the epicenter, the weather recorded at CTS, Sapporo's main airport, is a good indicator of the state of weather (rainfall) in the area near the epicenter.

The annual rainfall within the City of Sapporo averages about 43.5 inches per year. This puts it about on par with cities like New York, Boston and Montreal, all with average rainfalls on the order of 40 inches per year. In comparison, the Pacific coastal areas of

California get about 20 inches of rainfall per year (San Francisco), decreasing as one goes southerly to about 10 inches per year (San Diego).

In Sapporo, it is not uncommon for typhoons (same as hurricanes in the western hemisphere) to show up in mid to late August. September is the rainiest month of the year. Long term average rainfall in Sapporo is 4.9 inches (August), 5.3 inches (September). For the days leading up to the earthquake, the actual cumulative rainfall, as recorded at CTS, was 25.69 inches, see Figure 2-9.

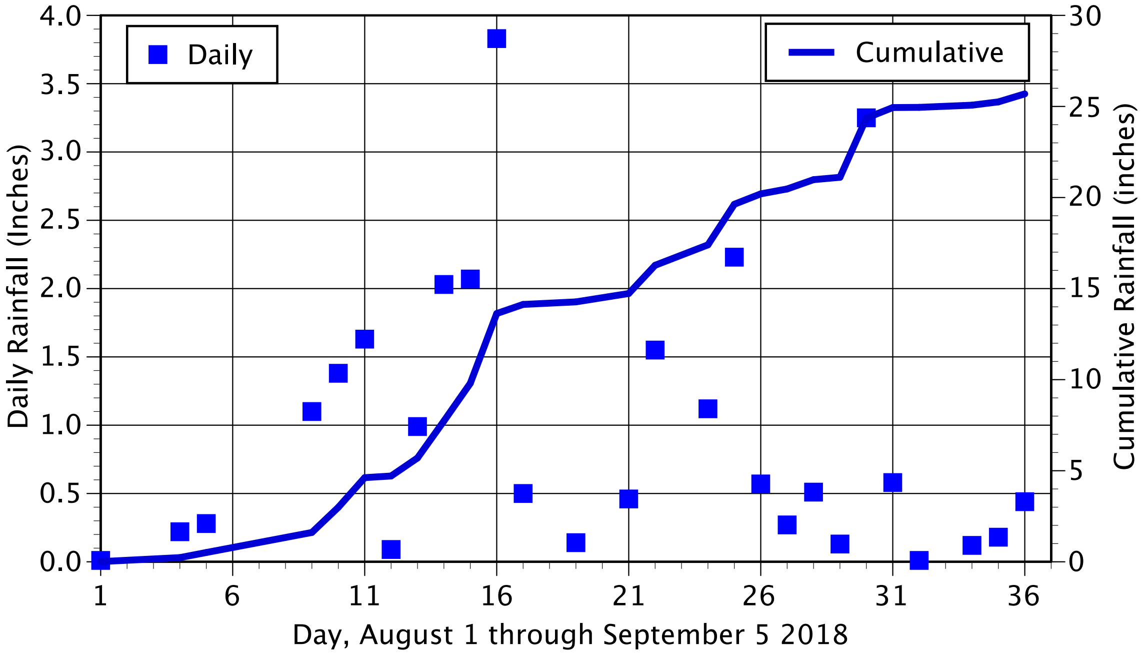


Figure 2-9. Rainfall as Measured at CTS, August 1 through September 5 2018

On September 5 2018, the day before the earthquake, a typhoon passed over Hokkaido. Within Sapporo, recorded rainfall was 46.5 mm.

Therefore, we can state that at the time of the earthquake, the hill terrain in the epicentral area had been exposed to about 15 to 35 inches of rainfall over the prior month or so. The hilly terrain near-surface soils were saturated. The water table at creeks was at or near their historical highs.

These conditions would lead to a higher susceptibility for liquefaction in low-lying areas near rivers and streams; and a higher susceptibility for landslides in hilly-terrain.

At the various agencies that we met in Japan, we asked if the observed number of landslides had been expected. Uniformly, the answer we received was "no, we did not expect earthquake triggered landslides".

The typical landslide moved 5 to 10 of meters downslope, and some landslides moved over 10s of meters downslope and then some flowed horizontally over 100 meters (some up to 350 meters) laterally into flat terrain.

There were very few structures within the moving mass of along the landslide slope; exceptions included two transmission towers that were both destroyed.

Most of the landslide-caused damaged structures were located within the nearly horizontal debris path of the landslide debris at the base of the slopes.

Some transmission towers were located at the head scarps of landslides. In one case, the head scarp traversed the four legs of a tower, but the depth of the scarp was shallow enough such that the deeper foundations remained on stable soil. All of these towers were at risk from further undermining at the head scarp; at one location, the power company made significant repairs; at another location, tarps were installed to try to limit ongoing erosion; at another location, no repair was made.

Where light-weight manmade structures were in the path of these landslides, including residential houses, barns, transmission towers, distribution poles, the destruction was almost always 100%. At a water treatment plant, a heavy concrete reservoir and one reinforced concrete building reasonably resisted the landslide mass debris impact (both were non-functional post-earthquake in part due to other landslide failures at the site); but a lighter-weight pile-supported stair structure was entirely uprooted and entirely destroyed by the debris impact.

Figures 2-10 and 2-11 show a landslide zone located east of Atsuma. Several slides initiated on this hill slope. Debris run out was commonly about 100 meters from the base of the slopes. These slopes had been clear cut of trees prior to the earthquake. These photos were taken in mid-November 2018. In the distance of Figure 2-10 are a number of landslides (areas without forest) in the hills.

Figure 2-10. Landslides east of Atsuma
(latitude 42.7596, long 141.9292) (credit: Shiga)

Figure 2-11. Landslides east of Atsuma
(latitude 42.7596, longitude 141.9292) (credit: Shiga)

Figures 2-12 and 2-13 show a landslide zone located east of Atsuma. Several slides initiated on this hill slope. Debris run out was commonly about 100 meters from the base of the slopes. These slopes were entirely forested prior to the earthquake. These photos were taken in mid-November 2018, by which time the road had been cleared of debris.

The slides in Figure 2-13 are a close-up view on the left-most (western-most) slides in Figure 2-12.

Figure 2-12. Landslides east of Atsuma (latitude 42.7510, longitude 141.9856) (Credit: Shiga)

Figure 2-13. Landslides east of Atsuma (latitude 42.7510, longitude 141.9856) (Credit: Shiga)

The slide in Figure 2-14 is located just east of Atsuma. The inset shows 7 geologists and geotechnical engineers examining the soil layering at the edge of the slide. Four layers of volcanic tuff (also called Tephra, unit Ta) are exposed, labeled Ta-a, Ta-b, Ta-c, Ta-d, with estimated ages of 9000 years ago (Ta-d), ~2000 years ago (Ta-c); 1667 AD (Ta-b) and 1739 AD (Ta-a). Tephra is a material that falls out of the air during a volcanic eruption. The term "Lapilli" is used to describe the size of the particles, from 2 mm to 64 mm in diameter. The term "ash" is used to describe particles that are smaller than 2 mm in diameter.

The Lapilli ash fall from the Shikotsu-Ko volcano was laid here by eruptions of these ages; but possibly the higher layers reflect prior landslides at this location, and not independent volcanic eruptions. Lake Shikotsu is the large caldera lake in the southwest portion of Figure 2-3. This caldera was formed 40 to 50 thousand years ago, and the present-day caldera was formed some 31 to 34 thousand years ago by one of Hokkaido's largest quaternary eruptions. The present-day volcanoes Mount Tarumae, Mount Eniwa and Mount Fuppushi are located on this rim of this caldera.

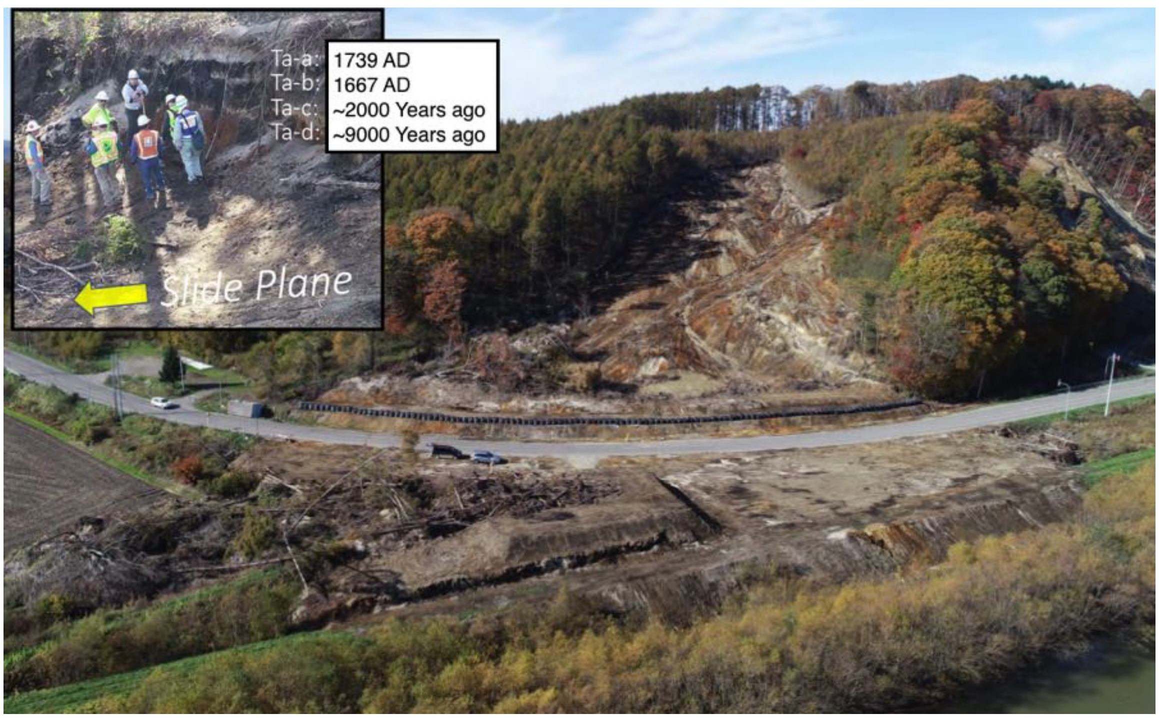


Figure 2-14. Landslide zone east of Atsuma latitude 42.7371, longitude 141.9016) (Credit: Madugo)

While most of the landslides in the mapped area in Figure 2-8 occurred on moderately steep slopes (30° to 40° slopes common), some of the landslides occurred on very shallow slopes. Figure 2-15 shows a digital elevation model created by a drove over flight, using photogrammetric methods. The developed cross section shows the head scarp at about 40 feet higher elevation than the near-toe of the slide, with a horizontal distance of about 640 feet, or an average 4° slope.

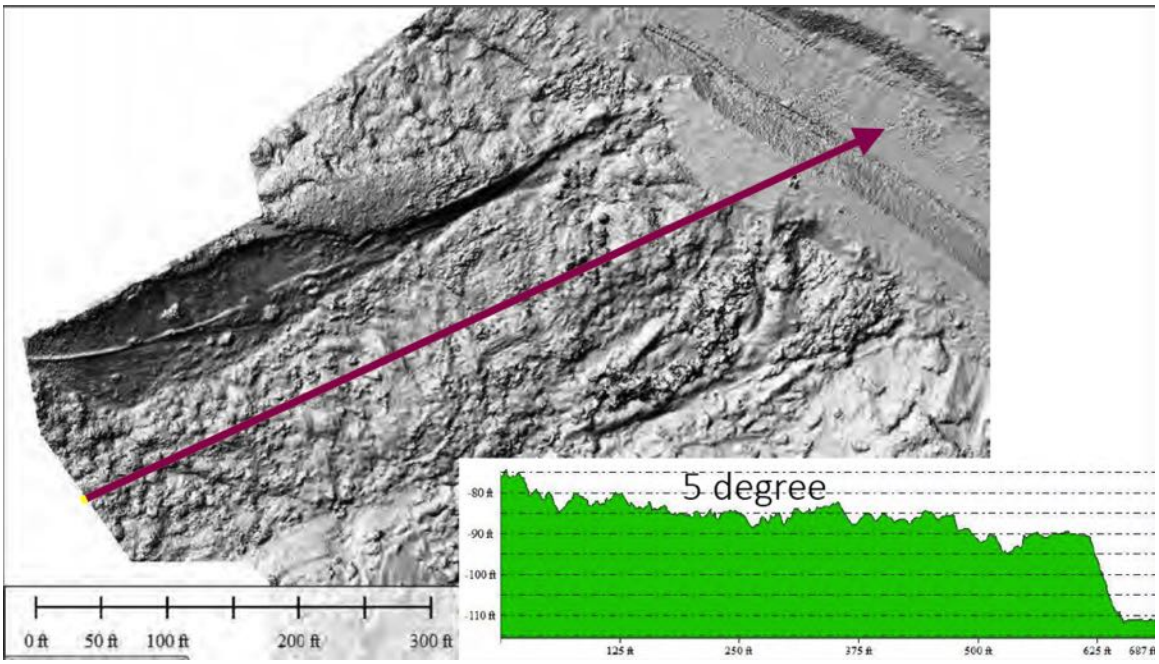


Figure 2-15. Landslide zone east of Atsuma
(latitude 42.7549, longitude 141.8636) (Credit: Madugo)

There were many other landslides in the area.

- Some of these landslides had debris that impacted residential houses, resulting in fatalities. We do not show these landslides anywhere in this report; they have been reported in various other publications. We are very sorry for the loss of life in those landslides; even one life lost is too many.

- Some of these landslides undermined or impacted transmission towers. Several of these are further described in Section 3 on the Electric system.

- Some of these landslides deposited debris into reservoirs, and in one case, into a spillway at a dam. These are further described in Section 5 on the Water system.

- A landslide undermined several houses in Sapporo (it is understood there was no loss of life; just economic loss of the undermined structures). This is described in Section 10.

- Many landslides undermined roads. Some of these are shown in Section 3. A great number of access roads (possibly 100s of locations) to transmission towers were impacted by landslides, which will make future access for inspection or maintenance of these towers more problematic.

Figure 2-16 shows the effects of landslide / embankment failure along the street highlighted in yellow. Several of these houses moved sideways and downslope by a meter or more; several buildings were "red-tagged".

Figure 2-16. Landslide zone in Kita (near Southeast Sapporo)

Figure 2-17 shows an aerial photograph of landslides triggered by the 1968 Offshore Tokachi M 8.3 earthquake. This area was also draped in wet pumice-rich volcanic materials. The level of ground shaking at this location is uncertain, but thought to be in the PGA = 0.10g to 0.20g range. The general trend of these slide masses is very similar to those that occurred in 2018:

- Slide zone is 10s of meters wide; slope is moderately steep (20° to 30°); depth of slide mass is ~5 to 10 meters; slide mass moves downwards and then horizontally into adjacent agriculture fields.

Figure 2-17. Triggered Landslides due to the 1968 M 8.3 Offshore Earthquake (credit: Konagai)

The underlying mechanisms of the slide mass motions appears to following the following trends:

- The "yield" acceleration (Ky) needed to initiate the slide in saturated pumice-rich areas is variable. In areas with PGA > 0.5g, about 50% of the slopes initiated slides. As PGA reduces, the chance that a slide is triggered is much reduced.

- Once the slide is triggered, the slide plane is commonly 5 to 10 meters deep. While the term "shallow" slide or "deep slide" is sometimes defined as shallow (< 10 m) or deep (> 10 m), for engineering purposes, the depth of slide is deep enough to affect most common infrastructure (like buried pipes) and foundations of nearly all structures.

- The movement of the slide mass is not principally controlled by the duration of shaking that exceeds the yield acceleration. In the Newmark Sliding Block analogy, the PGD is estimated by double integrating the acceleration time history over the Ky value. But in these slides (as commonly observed in the 2018 earthquake and as observed in the longer duration 1968 earthquake), the amount of PGD appears to be (at least partially) controlled as a debris flow that continues downhill, and then continues laterally as a debris flow into adjacent flat lands, behaving somewhat as a viscous-type mass.

2.4 Liquefaction

There was considerable liquefaction in the Kiyota-Ward of Sapporo. The effects of the liquefaction on the water system are described in Section 5.4.

Figure 2-18 shows as aerial view taken two years prior to the earthquake. The three yellow stars show the locations of broken water pipes (see also Figure 5-7).

Figure 2-18. Liquefaction zone in Kiyota-Ward (latitude 42.9888 long 141.4564)

Figure 2-19 shows the locations of 26 power poles (yellow dots) that were subjected to PGDs in excess of 0.5 meters in the liquefaction PGD zone. None of these poles collapsed, but several were tilted and one sunk downwards as much as a meter. Maximum PGD was on the order of 2 meters. From a functionality point of view, these poles might all have to be reset to be vertical once this community is re-built.

Figure 2-19. Location of Concrete Power Poles in Liquefaction zone in Kiyota-Ward (latitude 42.9888 long 141.4564)

Figure 2-20 shows the sea wall near the Tomatoh-Atsuma power plant. Figure 2-21 shows the ejected sand along line A-A'. Figure 2-22 shows the effects of liquefaction along the sea wall along line B-B'. Figure 2-23 highlights the scale of PGDs.

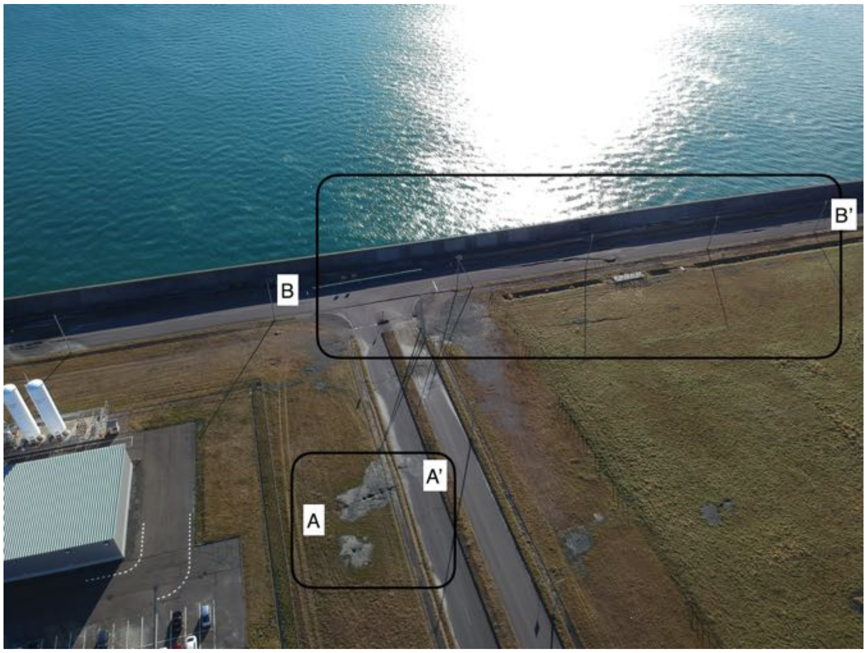


Figure 2-20. Liquefaction at Sea Wall (looking south) (lat 42.6042, long 141.7969)

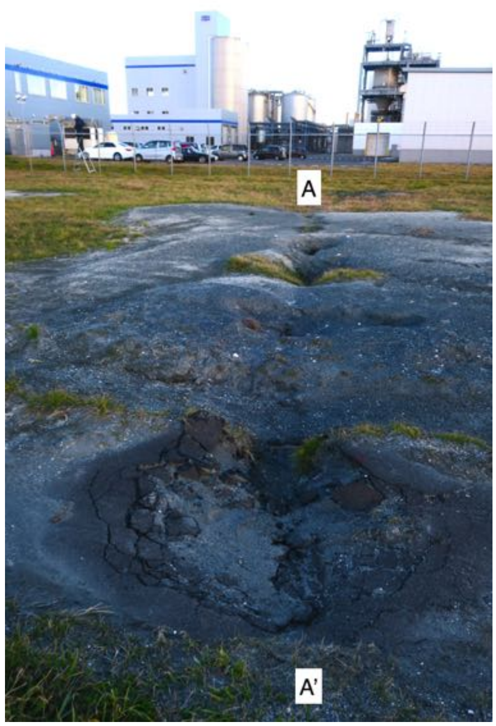


Figure 2-21. Ejected Sand, Line A-A'

Figure 2-22. Road Failure, Line B-B'

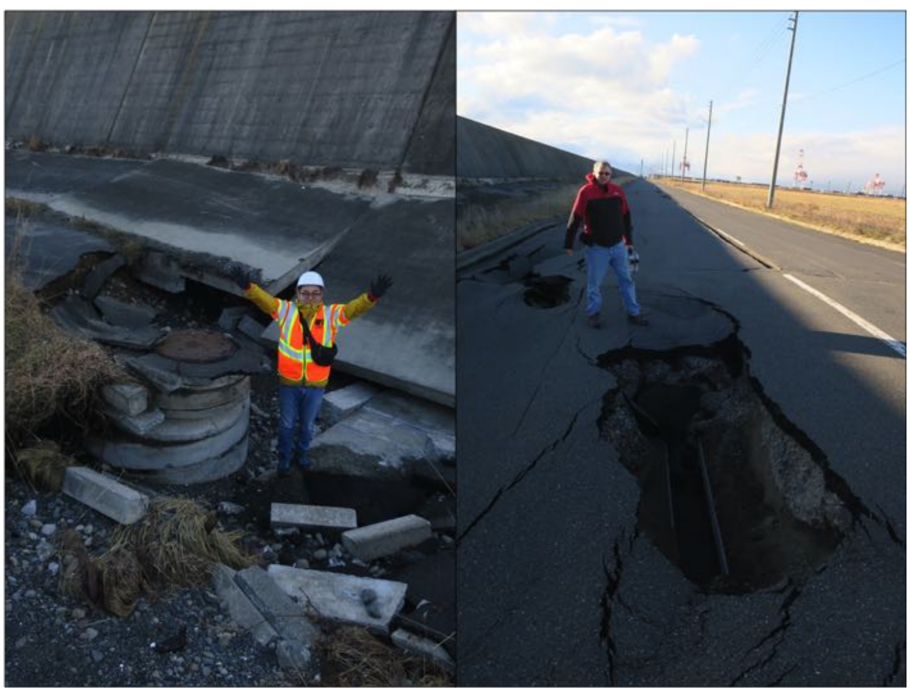


Figure 2-23. Left: Settlement at Storm Drain (Shiga). Right: Road failure (Eidinger)

2.5 Surface Faulting

There was no surface faulting in this earthquake.

2.6 Aftershocks

There were many small aftershocks in the days after the September 6 2018 mainshock. The impacts to the lifelines described in this report include the effects by these aftershocks.

On February 21 2019 (21:22 pm local time), about 5.5 months after the mainshock, a M 5.7 crustal earthquake occurred with epicenter near Atsuma. Some of the effects of this earthquake include:

- Travelers were stranded at the JR Sapporo train station and at the CTS New Chitose airport. JR Hokkaido canceled a total of 58 trains while safety checks were carried out. About 680 people were stranded in trains and 170 people were forced to spend the night at CTS.

- Two snow avalanches were reported, one in the Korimachi Horoi district

- 111 customers lost water supply at Horonai and Toyosawa areas of Atsuma, due to damage to water pipes. Water supply was restored by 18:00 pm February 23 2019; customers were warned that if colored water came out of faucets, that they should let the water drain a while before use.

2.7 References

Kayen, R., Wham, B., Grant, A., Atsushi M., Anderson D., Zimmaro Z., Wang P., Tsai Y T., Bachhuber J., Madugo C., Sun, J., Hitchcock H., Motto M., Seismological, Geological, and Geotechnical Engineering Aspects of the 2018 Mw 6.6 Hokkaido Eastern Iburi Earthquake, Version 1.0, February 2019 (available at www.geerassociation.org).

Rainfall data: weather instrument at New Chitose Airport (CTS), accessed from weather.com (November 2018).

3.0 Electric Power System

Section 3 describes the performance of the electric power system.

- Section 3.1 provides an overview of the electric system.
- Section 3.2 provides an overview of the power outage.
- Section 3.3 describes the damage to high voltage substations.
- Section 3.4 describes the damage to transmission towers.
- Section 3.5 describes the damage to power plants.
- Section 3.6 examines the damage to low voltage distribution.
- Section 3.7 describes various stages of the power restoration.
- Section 3.8 describes issues related to the Tomari nuclear power plant.

3.1 Overview

Figure 3-1 shows an overview of the electric grid of Japan. All of the nine major power companies of Japan are shown. The Hokkaido Electric Power Company (HEPCO) system serves the Island of Hokkaido. The typical annual maximum power demand for each power company is also shown: for HEPCO, is about 5.1 GW.

Also highlighted in Figure 3-1 is that the eastern part of Japan (Tokyo and eastwards) is operated at 50 Hz, while western Japan is operated at 60 Hz. Japan's bifurcated power system started in the 19th century, namely, when early power ventures were small in scale and highly localized. Tokyo, Eastern Japan bought electric equipment from Germany (50 Hz), while Osaka, western Japan, bought electric equipment from the USA (60 Hz).

Also shown is the Kita-hon DC power link between the Island of Honshu and Hokkaido. This DC link has a rated capacity of about 600 MW. The Kita-hon DC link is owned and operated by a separate company, called J-Power. Currently, a second DC link to Hokkaido is being constructed, to provide an additional 300 MW capacity. Normally, the DC link is operated with power flows in the southbound direction, and the additional link is being built to reflect that there is a growing amount of wind and solar power being generated in Hokkaido, which can be transmitted southbound to Honshu.

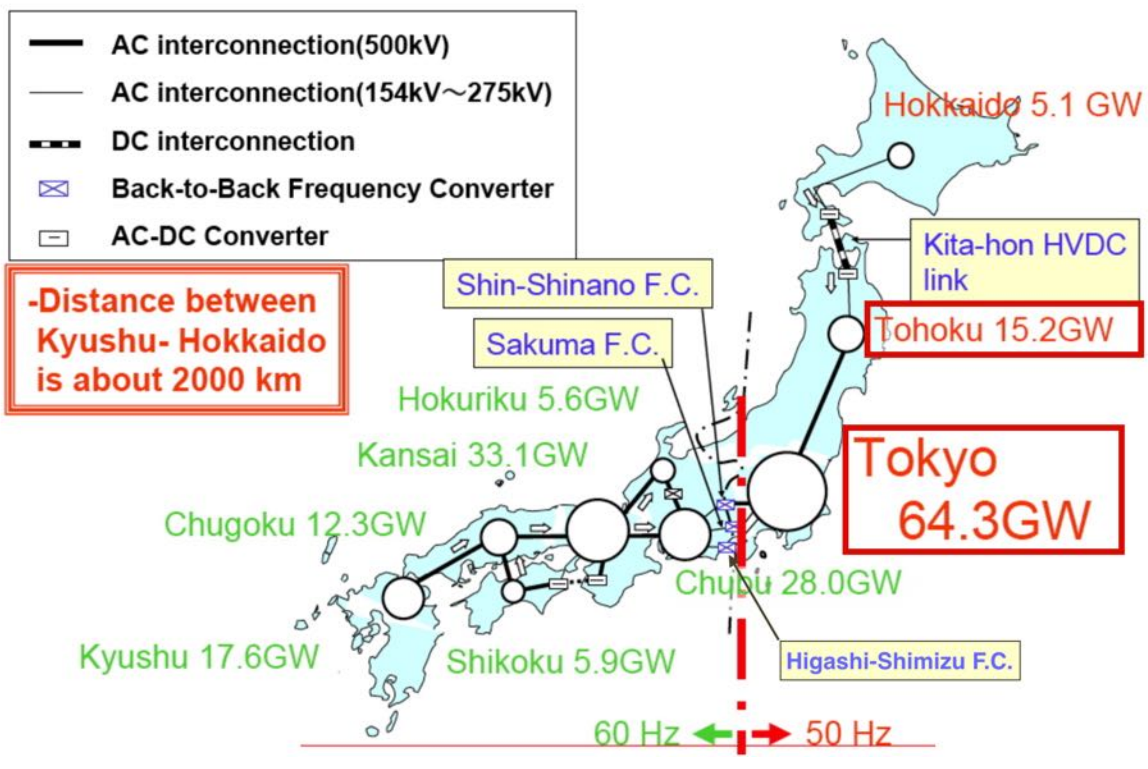


Figure 3-1. Electric Grid of Japan

Figure 3-2 shows an overview map of major elements of the HEPCO electric system.

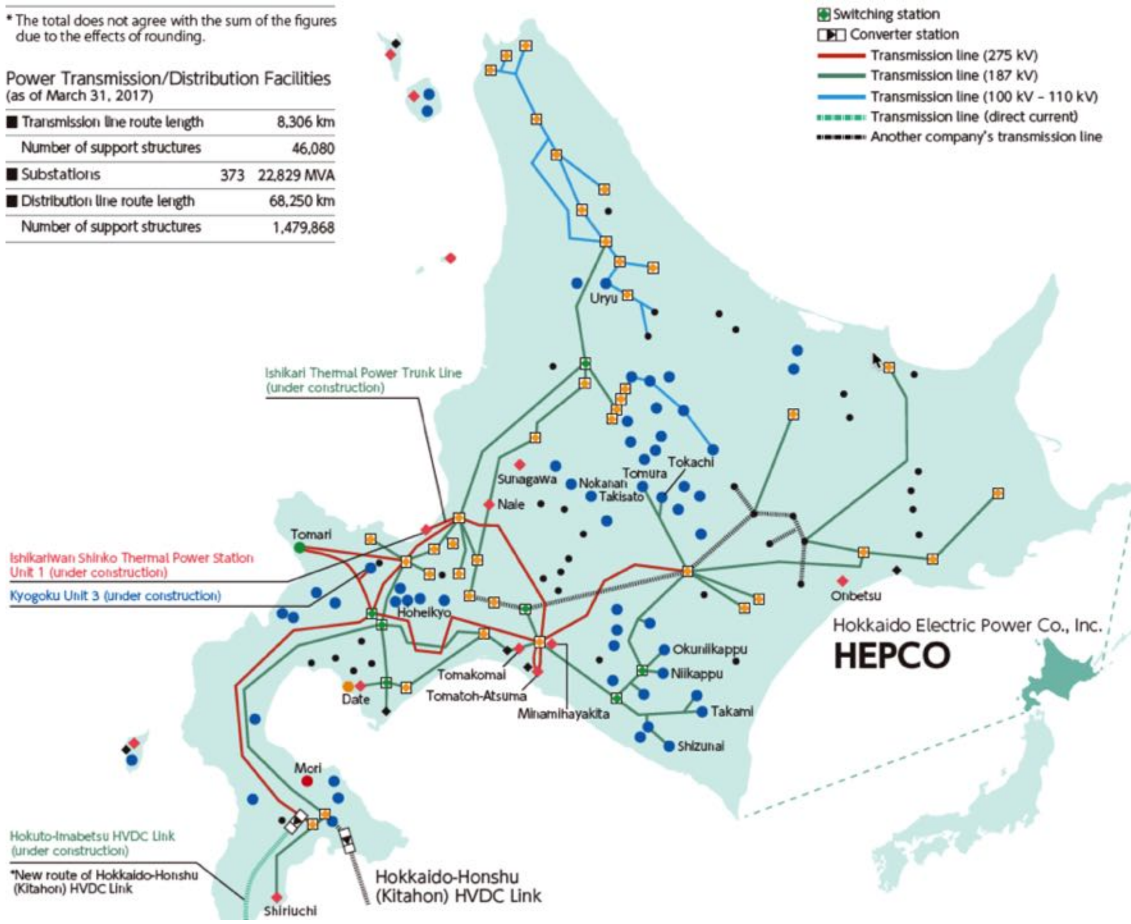


Figure 3-2. HEPCO Transmission System (as of March 2017)

The system includes 8,306 km of transmission lines, 46,080 transmission towers and poles, 373 substations, 22,829 MVA of transformer capacity, 68,250 km of distribution feeders, and 1,479,868 distribution poles. The historic highest peak hourly power demand reached about 5,500 MW during the winter of 2017. More common peak power demands are about 5,000 MW in the winter time and 4,000 MW in the summer time. At the time of the earthquake (3:08 am September 6 2018), power demand was 3,087 MW, representing common over-night demand during the late summer.

Table 3-1 lists the power generating stations serving Hokkaido Island. Table 3-1 includes power plants owned by others (mostly wind, solar and hydro), as well as the existing DC link (owned by J Power) between Honshu and Hokkaido. Not included in Table 3-1 are several new power plants under recent construction, including Ishikari (3 unit gas-fired, 3 x 570 MW), Kyogoku Unit 3 pump storage, (200 MW) and the second DC link to Honshu (300 MW), all slated to come on line by the year 2025.

Power Plant	Type	Rated Capacity MW	Power Plant	Type	Rated Capacity MW
Sunagawa 3	Coal	125	Kyogoku 1	Hydro PS	200
Sunagawa 4	Coal	125	Kyogoku 2	Hydro PS	200
Naie 1	Coal	175	Takami 1	Hydro	200
Naie 2	Coal	175	Takami 2	Hydro	
Date 1	Oil heavy	350	Nukabira 1	Hydro	100
Date 2	Oil	350	Nukabira 2	Hydro	
Onbetsu 1 + 2	Oil light	280	Hoheikyo	Hydro	50
Tomatoh-Atsuma 1	Coal	350	Kamilwamatsu	Hydro	30.4
Tomatoh-Atsuma 2	Coal	600	Nokanan	Hydro	30
Tomatoh-Atsuma 4	Coal	700	Okuniikappu	Hydro	44
Shiriuchi 1	Oil heavy	350	Shizunai	Hydro	48
Shiriuchi 2	Oil heavy	350	Takisato	Hydro	57
Niikappu 1	Hydro PS	200	Tokachi	Hydro	40
Niikappu 2	Hydro PS		Tomura	Hydro	40
DC Link	DC	578	Uryu	Hydro	51
Tomakomai 1	Oil heavy	250	Hydro (by Others)	Hydro	344
Tomakomai Kyodo 3	Oil heavy	250	Wind (by Others)	Wind	319
Mori	Geothermal	25	Solar (by Others)	Solar	1,151
Tomari 1, 2, 3	Nuclear	2,070			
				Total	10,207

Table 3-1. Power Generation (as of March 31 2017)

Since the 2011 Tohoku M 9 earthquake, all nuclear power plants in Japan have underwent increased efforts to establish seismic and tsunami security. The 3-unit Tomari nuclear power plant has been shut down for the past few years while various seismic upgrades have been implemented there, including: a base-isolated administration building, a 16.5 meter tall levee (tsunami protection), new emergency generators located on high ground, new gravity-fed water tanks for emergency cooling, and sea-water cannons. With regards to the September 6 2018 earthquake, the level of shaking at Tomari nuclear power plant was very low (PGA < 0.05g), and there was no damage at the plant; due to the island-wide blackout, all six emergency generators were started up to provide plant power, which lasted a few hours until offset power was restored to the power plant.

Table 3-2 lists some key financial data for HEPCO. The data in Table 3-2 was derived from public annual filings. Financial data converted to $USD at 110 Yen = $1 USD.

Fiscal Year	Annual Revenue	Net Income (Loss)	Electric Sales (GWh / Year)
2012	$5.58 Billion	($0.66 Billion)	32,145
2013	$5.07 Billion	($1.21 Billion)	31,184
2014	$5.48 Billion	($0.57 Billion)	30,636
2015	$6.02 Billion	$0.003 Billion	29,810
2016	$6.31 Billion	$0.19 Billion	28,592
2017	$6.39 Billion	$0.008 Billion	26,806
2018	$6.66 Billion	$0.18 Billion	24,806
2019	$6.86 Billion (est.)		23,300 (est.)

Table 3-2. Financial Data for HEPCO (Source: HEPCO annual reports)

With the shutdown of Tomari, HEPCO had to operate replacement power plants, including coal and oil. This resulted in increased operating costs to buy coal and oil fossil fuels, while at the same time maintaining and upgrading the Tomari nuclear power plant. Annual electric sales (in terms of Gigawatt-hours of electric sold) has been steadily decreasing, reflecting both a slow decline in the population of Hokkaido Island, as well as increasing competition from independently-owned wind and solar generators. The construction of the new 3-unit Ishikari gas-fired power plant represents a major capital project, including large gas holders at a LNG terminal, a pipeline to connect the gas holders with the power plant, and new 275 kV transmission line to add the power plant to the grid.

In the past few years, there has been a large increase in the amount of solar and wind power generation capacity on Hokkaido Island. Most of this is not owned by HEPCO.

- As of March 31 2014. Solar: installed 354 MW. Wind: installed 316 MW.
- As of March 31 2015. Solar: installed 612 MW. Wind: installed 318 MW.
- As of March 31 2017. Solar: installed 1151 MW. Wind: installed 350 MW.

3.2 Power Outage and Restoration

3.2.1 Power Outage and Restoration

The September 6 2018 earthquake resulted in an island-wide power outage. All of HEPCO's 2.95 million customers (1 customer = 1 billing account) temporarily lost power.

The core reasons for the island-wide power outage are as follows:

- At the time of the earthquake, September 6, 2018 3:08 am (local time), power demand was about 3,087 MW.

- Just before the earthquake, the three Tomatoh-Atsuma coal-fired power plants were generating about 1,650 MW. All three plants suffered damage due to strong ground shaking. Two units went offline immediately at 3:08 am, and the third unit went offline at 3:25 am.

- Five large hydroelectric power plants were operating at the time of the earthquake. These units were generating about 500 MW. All these plants were tripped offline. Transmission lines failed due to collapse of two towers due to landslide, and phase-to-ground faults due to dynamic oscillation of jumpers at a few locations, further isolating these power supplies from the major load center (Sapporo area).

- Wind farms were operating at the time of the earthquake. All these wind farms were tripped offline due to system frequency imbalances.

By the evening of September 6 2018, operations at five hydroelectric power plants had been resumed. Power from these hydroelectric power plants was sent to the undamaged thermal power plants to black-start them on a step-by-step basis.

Figure 3-3 shows a time line of the electric system frequency from just before 3:08 am (the time of the earthquake) to 3:25 am (the time of the Island-wide power outage). See Section 9.3.6 for a more detailed description of power restoration over the days and weeks post-earthquake.

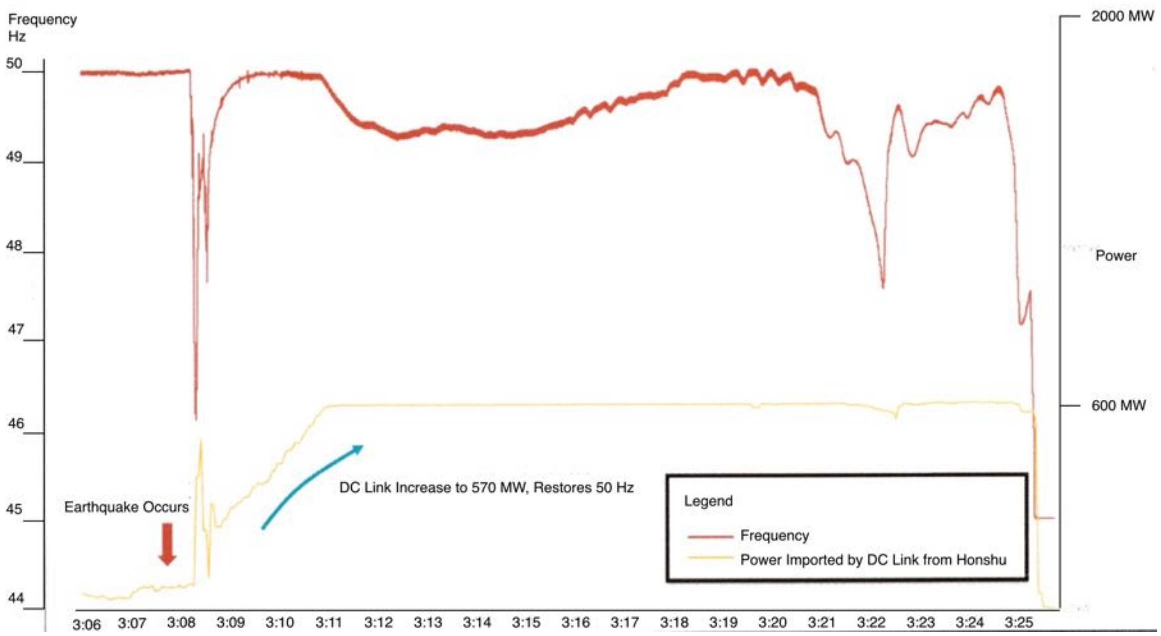


Figure 3-3. System Frequency and DC Link Power Flow

The data in Figure 3-3 is derived from system frequency data recorded by HEPCO every 0.02 seconds and power flow measured every 3 seconds.

The normal operating frequency of the HEPCO system is 50 Hz. For the 17 minutes from the time of the earthquake (3:08 am) until the time of the island-wide blackout (3:25 am), there were a number of disturbances to the electric grid, including loss of generating power plants, loss of transmission lines, operating of the DC link, and various load shedding actions. In the remainder of this section, we will describe these items in more detail. In later Sections, we will describe the actual damage to various components in the electric system.

Figure 3-4 shows a simplified diagram showing the core components of the transmission system on Hokkaido.

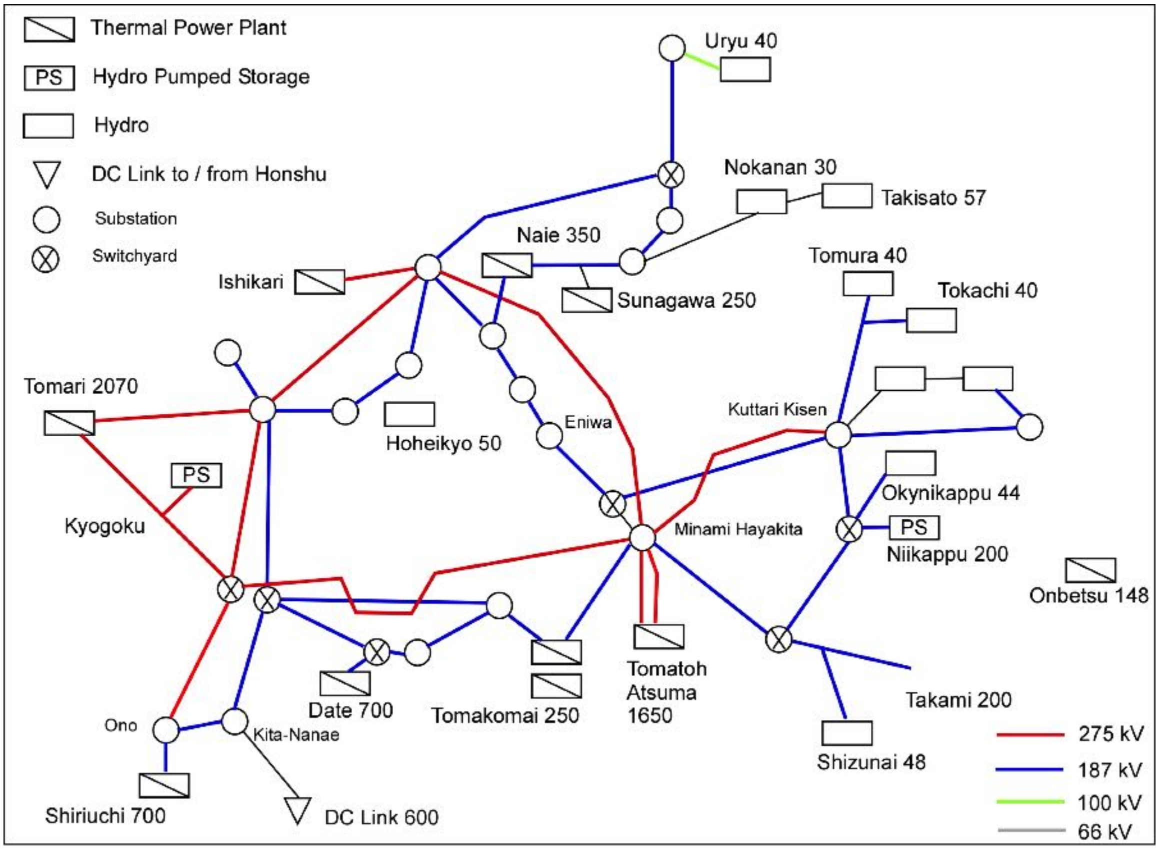


Figure 3-4. Transmission System Schematic Diagram

The red lines in Figure 3-4 show the 275 kV transmission network. Each red line represents double 275 kV circuits.

The blue lines in Figure 3-4 show the 187 kV transmission network. Most blue lines represents double 187 kV circuits.

Figure 3-4 also shows all the major thermal (coal, oil, gas, nuclear) power plants on the Island as well as the larger hydroelectric power plants. The rated output (MW) for all units is listed after the power plant name.

Not shown in Figure 3-4 are several 187 kV circuits to remote power plants in the east end of the Island; nor the 100 kV circuits to the far north of the Island; nor the 66 kV sub-transmission network. Landslides took out two towers on a single circuit 66 kV line.

Not shown in Figure 3-4 are the dozens of wind and solar generating units. Many of the wind and solar units are located in the far east or north of the Island. There was no known damage to these generating units.

Just before the earthquake, night-time island-wide power demand was about 3,087 MW. To meet night-time demand, the power plants in Table 3-3 were operating. Several power plants were in spinning reserve, namely:

<table>
<tr><th>Power Plant</th><th>Status</th><th>Type</th><th>Rated Capacity MW</th><th>Operating MW</th></tr>
<tr><td>Sunagawa 3</td><td>Reserve</td><td>Coal</td><td>125</td><td></td></tr>
<tr><td>Sunagawa 4</td><td>Reserve</td><td>Coal</td><td>125</td><td></td></tr>
<tr><td>Naie 1</td><td>On line</td><td>Coal</td><td>175</td><td>61</td></tr>
<tr><td>Naie 2</td><td>Reserve</td><td>Coal</td><td>175</td><td></td></tr>
<tr><td>Date 2</td><td>On line</td><td>Oil heavy</td><td>350</td><td>76</td></tr>
<tr><td>Tomatoh-Atsuma 1</td><td>On line</td><td>Coal</td><td>350</td><td>338</td></tr>
<tr><td>Tomatoh-Atsuma 2</td><td>On line</td><td>Coal</td><td>600</td><td>556</td></tr>
<tr><td>Tomatoh-Atsuma 4</td><td>On line</td><td>Coal</td><td>700</td><td>598</td></tr>
<tr><td>Shiriuchi 1</td><td>On line</td><td>Oil heavy</td><td>350</td><td>96</td></tr>
<tr><td>Niikappu 1</td><td>On line</td><td>Hydro</td><td rowspan="2">200</td><td rowspan="4">69</td></tr>
<tr><td>Niikappu 2</td><td>On line</td><td>Hydro</td></tr>
<tr><td>Takami 1</td><td>On line</td><td>Hydro</td><td rowspan="2">161</td></tr>
<tr><td>Nukabira 1</td><td>On line</td><td>Hydro</td></tr>
<tr><td>Other Hydro</td><td>On line</td><td>Hydro</td><td>711</td><td>711</td></tr>
<tr><td>Wind</td><td>On line</td><td>Wind</td><td>319</td><td>166</td></tr>
<tr><td>DC Link</td><td>On line</td><td>DC</td><td>578</td><td>72</td></tr>
<tr><td>Others</td><td>On line</td><td></td><td>344</td><td>344</td></tr>
<tr><td>Total</td><td></td><td></td><td>5263</td><td>3087</td></tr>
</table>

Table 3-3. Power Plants Operating at 3:07 am

Figure 3-5 shows the approximate level of shaking (with regards to horizontal PGA) throughout the power grid.

- In the area highlighted in red, including the epicenter, the ground shaking was commonly over 0.5g. In this area, there were hundreds to thousands of landslides. There were no high voltage (187 kV or higher) substations exposed in this area. There were some 66 kV substations exposed, generally without damage.

- In the area highlighted in orange, the ground shaking was commonly in the range of 0.30g to 0.40g. This included the Tomatoh-Atsuma coal fired plant, and the Minami-Hayaki 275 – 187 – 66 kV substation.

- In the areas highlighted in yellow, the ground shaking was commonly in the range of 0.10g to 0.15g. This includes most of the City of Sapporo, the Date power plant, and various hydroelectric stations to the east.

- In the area highlighted in green (Otaru and Ishikari port areas), the ground shaking was commonly 0.03g to 0.05g.

- In the areas without color boxes, the ground shaking was commonly 0.01g to 0.03g.

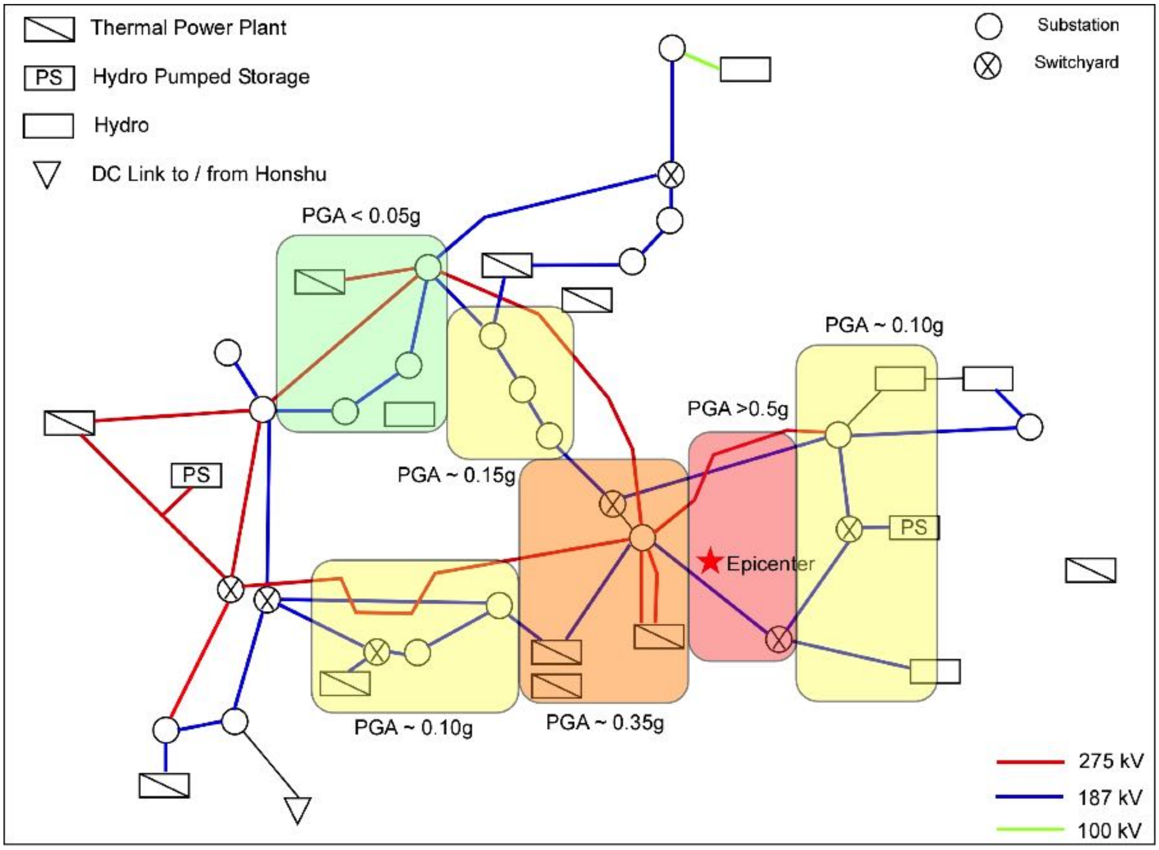


Figure 3-5. Shaking Levels in the Transmission Grid

The bulk of the physical damage to the power grid occurred in the red and orange areas. This includes damage to the Tomatoh-Atsuma power plants, collapsed transmission towers, faulted transmission lines due to the "galloping" of jumpers that resulted in phase-to-ground faults, some damage to equipment within substations, and many collapsed distribution poles due to landslides. There was also some damage in the yellow zones due to landslide and liquefaction effects on distribution lines. Sections 3.3 to 3.7 will explain the physical damage.

Figure 3-6 highlights the system response from 3:08 am (a few seconds before the earthquake) until 3:10 am. Figure 3-6 shows the same data as Figure 3-3, using an expanded scale just for the two minutes following the earthquake.

- Immediately after the earthquake, Tomatoh-Atsuma Units 2 and 4 tripped offline. This was caused by various damage to the boilers, detection of excessive vibration in the turbines, and a fire. This dropped 1,160 MW of generation supply. Two 275 kV transmission lines from the east also faulted (landslide and line faults), dropping another 600 MW of supply from remote hydro and wind power plants.

- System frequency immediately began to drop. When the frequency reached 48.5 Hz, under-frequency relays shed l,300 MW of load. The eastern part of Hokkaido Island underwent a blackout, probably due to the rapid drop of the transmission lines that led to local frequency / voltage imbalances in that area.

- The Kita-Hon DC link was triggered when frequency dropped to 49.62 Hz. Over the course of a few seconds, the DC link ramped up to over 500 MW from south to north, and with the drop of load, system frequency began to recover towards 49 Hz.

- The DC link dropped load at about 3:08 am + 30 seconds, leading to a second drop in system frequency. The DC link quickly recovered in a few seconds, and system frequency increased, reaching 50 Hz by 3:10 am.

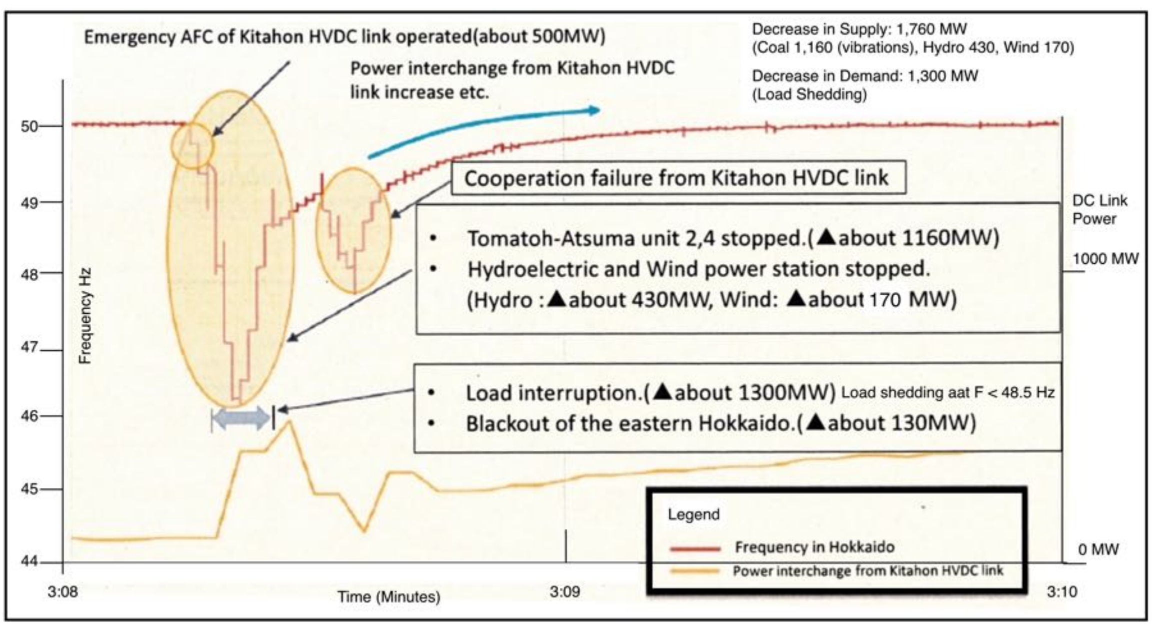


Figure 3-6. System Response, 3:08 am to 3:10 am

By 3:10 am, about 1,760 MW of supply had been lost, of which about 500 MW had been "made up" by the ramp-up of the DC link from 72 MW to nearly 570 MW. At the same time, about 1,300 MW of demand had been shed. Therefore, by 3:10 am, the system was "more-or-less" in balance, and system frequency was restored to 50 Hz. Up to this point, the system had sustained about a "N-4" event (loss of two large generators and loss of two large transmission lines). The loss of the transmission lines due to "phase-to-ground" faults should have been only for a short amount of time, allowing time inspect the cause(s) of the fault and then clear the fault.

After 3:11 am, power demand increased (in the portion of the grid that was not already cut-off), as people had been awoken by the earthquake and were then turning on lights, etc. This lasted a few minutes, during which time the power output from Naie 1 was ramped up (62 MW ramping up to 175 MW) and Date 2 was increased (76 MW ramping up to 350 MW). Both Naie 1 and Date 2 power plants were not damaged, and the transmission lines linking those plants to the main load center of Sapporo were undamaged. Between 3:11 am and 3:14 am, this demand load increase resulted in system frequency dropping from nearly 50 Hz to about 49.2 Hz, but as the two power plants ramped up, system frequency again increased to about 50 Hz by 3:20 am.

At around 3:21 am, damage at Unit 1 of Tomatoh-Atsuma did not allow for a stable power output. At 3:21 am, output from this power plant was decreased by about 200 MW. System frequency then dropped to about 48 Hz.

At around 3:22 am, an additional 160 MW of load was shed, and the system frequency quickly increased to about 49.5 Hz.

Between 3:24 am and 3:25 am, the damage at Tomatoh-Atsuma unit 1 resulted in the entire unit tripping off line, a drop of another 138 MW in supply. System frequency declined rapidly to about 47.8 Hz. Another 60 MW of load was then shed, and system frequency briefly increased to about 48 Hz for a few seconds. Then, Shiriuchi 1, Date 2 and Naie 1 all stopped, resulting in a further loss of 340 MW in supply. System frequency rapidly dropped to about 45 Hz.

At about 3:24 + 40 seconds, due to the drop to 45 Hz, the DC – AC inverter station on the DC link relayed out, and the 570 MW supply was immediately lost.

At this point, at about 3:25 am + 10 seconds, an Island-wide outage occurred.

3.2.2 Power Restoration on September 6

By 6 am September 6 2018, HEPCO began the process of restoring power to Hokkaido.

To restore the system requires re-start of larger thermal power plants from smaller hydroelectric power plants with black start capability. This process was done manually, taking about 45 hours to complete.

Within 45 hours, the system was able to operate with enough undamaged generators to supply demand of about 3,000 MW. (The 3 unit 1,650 MW Tomatoh-Atsuma coal plant was damaged to the point that it several days / weeks to restore power at these units). The transmission lines that had faulted due to phase-to-ground faults were quickly restored. The single 66 kV transmission line that sustained loss of two towers due to landslide would remain out of service for some time. There was one 275 kV tower that had a head scarp slide through its legs, but was still operable; HEPCO rapidly did emergency repairs for this tower (No. 52) as those two 275 kV circuits were vital to import hydropower from the east part of the Island to the Sapporo load center in the west.

During the power outage that began at September 6 3:25 am, offsite power was lost to the Tomari nuclear power plant. Six emergency generators at the nuclear power plant all turned on, as planned, and these generators provided the needed power for cooling water systems for the fuel pools. One of the early priorities for HEPCO was to restore offsite power to Tomari. Essentially, the plan was to restart the Takami hydroelectric plant (200 MW) located about 150 km east of Sapporo; have that power supplied to the Kuttari-Kisen and Minami-Hayakita substations via 187 kV transmission lines; and have that power transmitted via 275 kV lines westward to the Tomari 275 kV yard. It appears that the initial plan was to energize the low voltage busses at the nuclear power plant, running power backwards through the main 275 kV step-up transformers. An alternate method would have been to energize the low voltage busses via the auxiliary transformers, operating at 66 kV.

During the first black start restoration effort on September 6 2018 at about 6:19 am, a shunt reactor at Tomari substation tripped due to a large current that was generated when power was supplied to the main step-up 275 kV power transformer at Tomari Unit 3 at 6:19 am. Voltage increased and a ground fault accident occurred at 6:21 am on a 275 kV transmission line, after which two 275 kV shunt reactors were switched off, one each at the 275 kV Minami-Hayakita and the 275 kV Kuttari-Kisen yards. At the same time, the Takami hydroelectric power plant (providing black start power via 187 kV transmission lines) and others were stopped at 6:21 am because of the accident current.

During the second black start restoration effort, the main step-up 275 kV transformer at Tomari 3 was not used to energize the low voltage busses within the power plant. Instead, the 66 kV auxiliary transformer was used to energize the low voltage busses within the power plant. This was successful.

After that, the remaining parts of the transmission system were re-energized appropriately. On the south side of the City of Sapporo, power was restored to customers by about 9 am September 6, 2018. On the north side of the City of Sapporo, power outages extended about 2 days. Restoration of power to customers that were cut-off due to infrastructure damage (due to liquefaction, landslides, etc.) took a longer time. See Section 9.3.6 for further information about power restoration.

3.2.3 Analysis

The proximate cause(s) of the island-wide power outage were as follows:

- Immediate loss of 2 large thermal power plants, supplying 1,154 MW of total 3,087 MW of demand.
- Loss of about 600 MW of power from remote power plants due to transmission line faults.
- As power supply was lost, load shedding to match the loss of supply did occur.
- As power supply was lost, additional power was supplied from the DC link and ramp up to three thermal power plants to their full capacity. The system was more-or-less in balance for a few minutes.
- The loss of one more power plant (338 MW) at 3:25 am led to un-recoverable drop in frequency (load shedding was not fast enough), which led to an under frequency at the DC inverter station, which dropped another 578 MW.
- This caused the island-wide outage.

After the outage, analyses were performed to see "what the outage would have been" had different actions been taken. The analyses suggest:

- Had the two unit Kyogoku hydro-electric plants been quickly put into operation at about 3:24 am, thereby adding 400 MW in supply, there is a high chance the island-wide blackout could have been averted. However, at the time of the earthquake, both these units were offline for maintenance purposes.
- Changing the automatic-load shedding to reflect under-frequencies should be re-considered, at least under earthquakes. Earthquakes can sometimes lead to multiple outages all over the system, not all of which can be expected or mitigated. More pro-active load shedding might be warranted in a post-earthquake situation, reflecting that additional failures might occur within a few minutes (or due to aftershocks), while at the same time guarding against over frequency situations.
- The sensitivity of wind- and solar- generators to under-frequency events was not tested in this event, as nearly all of these were offline or tripped due to transmission line failures in the first seconds after the earthquake. However, it is thought that wind- and solar-generators might be very sensitive to frequency variations. If a high percentage of system-wide power is being generated by wind- and solar at the time of the earthquake, the system might become quickly

imbalanced leading to blackouts. A review of emergency operations of these systems is warranted.

- The construction of a second DC link (300 MW) to Honshu is nearly completed and is expected to be on line in 2019. This would provide more margin to accommodate sudden large losses.

- A review should be made as to the merits of changing the DC-AC inverter stations to "self-excited" type, and possibly not prone to outage due to loss of AC power.

Other approaches might also reduce the chance of an island-wide outage in a future crustal earthquake:

- The construction of the 3 Unit Ishikari (3 x 570 MW) will provide a substantial increase in generation supply margin. These units will use natural gas as their supply. The Tomatoh-Atsuma plants have been repaired and use coal as their supply. While a common strategy is to schedule the use power plants based on their marginal operating costs, a different strategy might be invoked whereby the spatial nature of earthquakes is considered. While gas-fired power plants are often designed to be seismically-robust, turbine generator sets may still be vulnerable at PGA > 0.5g (excessive vibration); and there could be damage to gas pipelines, etc. Given the nature of crustal earthquakes in Hokkaido, no single crustal earthquake is likely to produce high shaking at both Ishikari and Tomatoh-Atsuma at the same time. Therefore, during periods of low demand (early morning hours), it might be prudent to always keep at least one large unit Tomatoh-Atsuma on line, and one large unit at Ishikari on line.

- This earthquake showed that phase-to-ground faults do occur due to excessive galloping of transmission lines. The damage is concentrated at strain towers, where jumpers can easily move enough to substantially reduce the phase-to-ground (or perhaps even phase-to-phase) clearances. Recent shake table tests have shown this to occur as a function of long period (T > 1 second) ground motions, possibly aggravated when longitudinal tower frequencies are in the same range of the long period motions form the earthquake. More study of these phenomena is warranted. In the interim, approaches to mitigate this risk include:

    - Network spatial redundancy. Keep transmission lines separate by 10s of meters (might be enough to avoid co-located hazards) or several km (certainly enough to avoid co-located hazards) is a good thing.

    - Double circuit towers (or in Japan, even 4-circuit or sometimes 6-circuit) towers do not provide network spatial redundancy.

- Adding underhung porcelain post-insulators to limit jumped deflections will introduce the potential failure of these underhung post insulators due to cable impact forces. Some such porcelain insulators have been broken in past earthquakes. An approach that uses composite insulators to control cable deflections may be an acceptable approach to prevent these faults.

3.3 Substations

Figure 3-7 shows an aerial view of the 275 kV – 187 kV – 66 kV Minami-Hayakita substation. There are 10 275 kV circuits at this yard, two 275 kV – 187 kV transformers, a 187 kV – 66 kV transformer (second one being constructed in November 2018). A battery storage facility was recently constructed, to address the recent large increase in wind and solar generation.

The level of shaking at this yard was about horizontal PGA = 0.35g. No liquefaction, landslide or surface faulting is known to have occurred within the yard.

Figure 3-7. Minami-Hayakita 275 kV Substation (Latitude 42.7140 Longitude 141.7815)

The 275 kV yard uses gas-insulated switchgear. The 66 kV and 187 kV yards use flexible bus.

In November 2018, CCVTs in the 187 kV yard were being modified by a field crew, see Figure 3-8. Piles for a new 187 kV – 66 kV transformer bank were being driven. No other earthquake-related damage is known to have occurred at this yard; detailed documentation is suggested. It is recommended that a seismic inspection of this yard be conducted, and the inventory and style of equipment catalogued to identify what is apparently good seismic design detailing and good seismic performance at PGA ~ 0.35g.

Figure 3-8. Minami 187 kV CCVTs

Figure 3-9 shows an aerial view of the 187 kV Eniwa yard. There are four 187 kV circuits at this yard, and two 187 kV – 66 kV voltage transformers. The 187 kV yard used rigid bus. Most disconnect switches are pantograph-type. When visited, about half the 187 kV switches were open, reflecting the usual operating practice to only keep the main 187 kV bus energized.

The level of shaking at this yard was about horizontal PGA = 0.20g. No liquefaction, landslide or surface faulting is known to have occurred within the yard.

Figure 3-9. Eniwa 187 kV Substation (Latitude 42.9315 Longitude 141.6018)

This yard uses dead-end type SF6 Circuit Breakers, attached to adjacent equipment using both rigid bus and flexible bus with limited slack, see Figure 3-10.

Most disconnect switches are panto-graph type (scissor-type), connected to the primary and secondary 187 kV busses, see Figure 3-11. None of these switches are known to have been damaged. Given the different relative stiffness of the rigid busses and the switches, one would expect that earthquakes that generate high motions would result in a significant and un-planned force at the connecting bus bar: this was the case in the Kumamoto 2016 earthquakes, where many high voltage switches in a similar arrangement collapsed, (ref. TCLEE No. 2). The fact that none of the switches collapsed in this earthquake is possibly mostly due to the relatively modest level of shaking at this yard (perhaps PGA ~ 0.20g), rather than specific aseismic detailing.

Figure 3-10. Eniwa 187 kV Substation. 187 kV Circuit Breakers

Figure 3-11. Eniwa 187 kV Substation. 187 kV Pantograph Switches

Figure 3-12a,b shows the position where one of the 187 kV lighting arrestors collapsed. This surge arrestor in one of three serving the right-most transformer in Figure 3-9. Inspection of the attached conductors suggests that the failure was not due to the conductors having insufficient slack; rather, it was an inertial overload. During the earthquake, the surge arrestor broke at its base, and swung sideways (towards the right in this photo, see Figure 3-12b). Fortunately, the arrestor did not impact anything (it was more than 10 meters away from the 187 kV transformer bushings), so the net result was at most a temporary line fault that could be cleared once repair men could de-energize and safely cut away the broken surge arrestor. The photo in Figure 3-12a was taken on November 14 2018, more than 2 months after the earthquake, and a replacement surge arrestor has not yet been installed.

Figure 3-12a. Eniwa 187 kV Substation. Location of Damaged Surge Arrestor

Figure 3-12b. Eniwa 187 kV Substation. Damaged Surge Arrestor (credit: HEPCO)

Figure 3-13 shows an aerial view of the 66 kV Hayakita yard.

The level of shaking at this yard was about horizontal PGA = 0.50g; possibly higher. No liquefaction, landslide or surface faulting is known to have occurred within the yard.

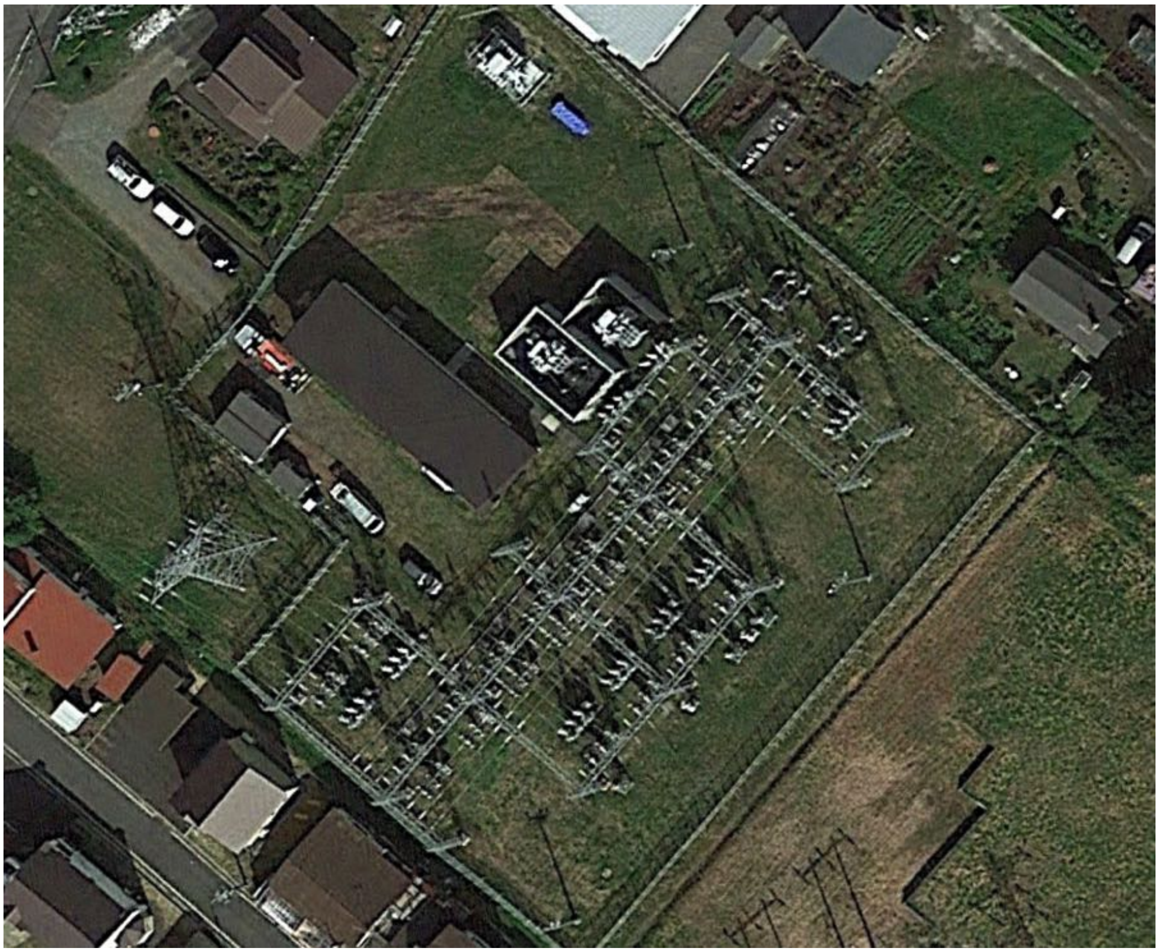


Figure 3-13. Hayakita 66 kV Switchyard (Latitude 41.7612 Longitude 141.8125)

Figure 3-14 shows one of the many similar circuit breakers at this yard. All breakers were SF6-type, and all had suitable flexible loops to adjacent equipment positions. This demonstrates that HEPCO has implemented good seismic detailing.

Figure 3-14. Hayakita 66 kV SF6 Circuit Breaker

Figure 3-15 shows a wave trap atop a CCVT for one of the 66 kV lines at this yard. This type of detail would not normally be found at substations in the west coast of the USA; wave traps are heavy, and in this configuration, apply extra weight and extra bending moment to the CCVT below. Nevertheless, the equipment did not fail in this earthquake, suggesting that at 66 kV, this CCVT (as well as the electrical standoffs under the Wave Trap) were suitably strong.

Figure 3-15. Hayakita 66 kV SF6 Wave Trap

Figure 3-16 shows the electrical standoffs under the wave trap.

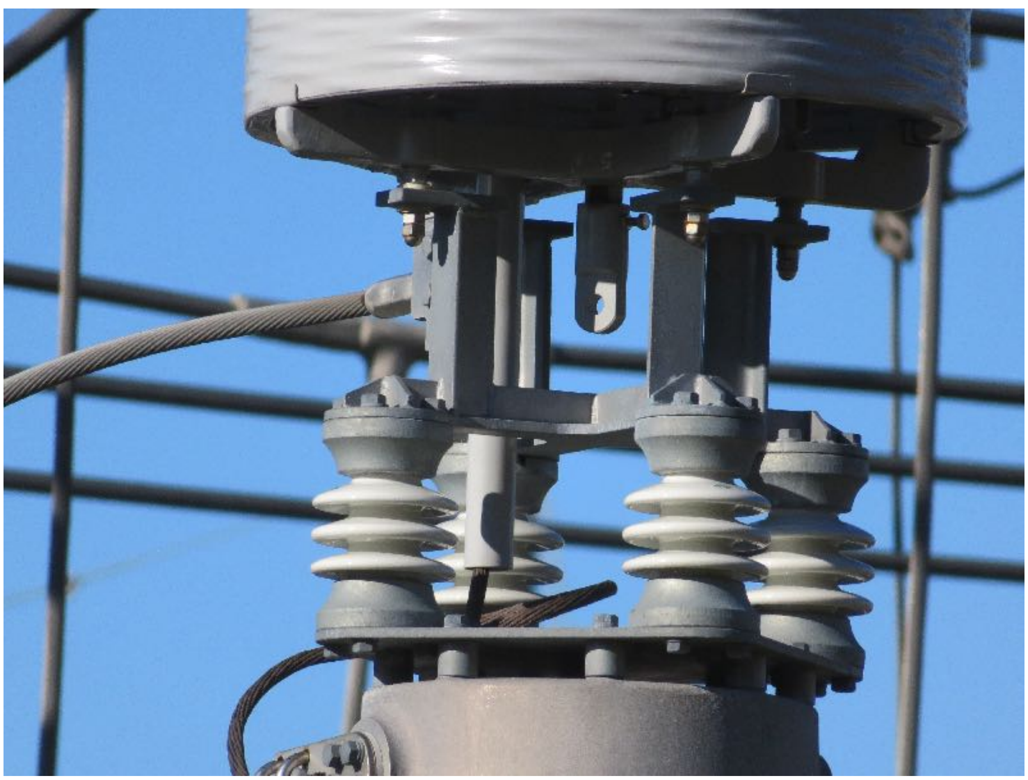


Figure 3-16. Hayakita 66 kV SF6 Wave Trap Electrical Standoffs

There was also other damage at high voltage substation yards; the most important was the failure of a high voltage conductor-to-transformer bushing connection. It is recommended that once the electric system is restored to normal service, that HEPCO document all the substation component damage (and non-damage) for all substation / switchyards that sustained PGA > 0.2g. This will help document the seismic withstand capacity and seismic limits of a range of equipment.

3.4 Transmission Lines and Towers

Figure 3-17 shows the locations where transmission lines were damaged. The 2-digit or 3-digit number refers to HEPCO's tower numbering system, usually beginning with "1" at the substation and incrementing higher for each tower along the transmission line. Figure 3-17 shows locations of damage at 8 transmission towers; 2 other transmission lines were faulted due to damage of equipment at substations. A portion of the single circuit 66 kV Iwashimishi line is shown, to highlight the relative locations of collapsed towers due to landslides. At least one other tower was exposed to landslide movements; but not so severe as to fault the line or warrant immediate repair.

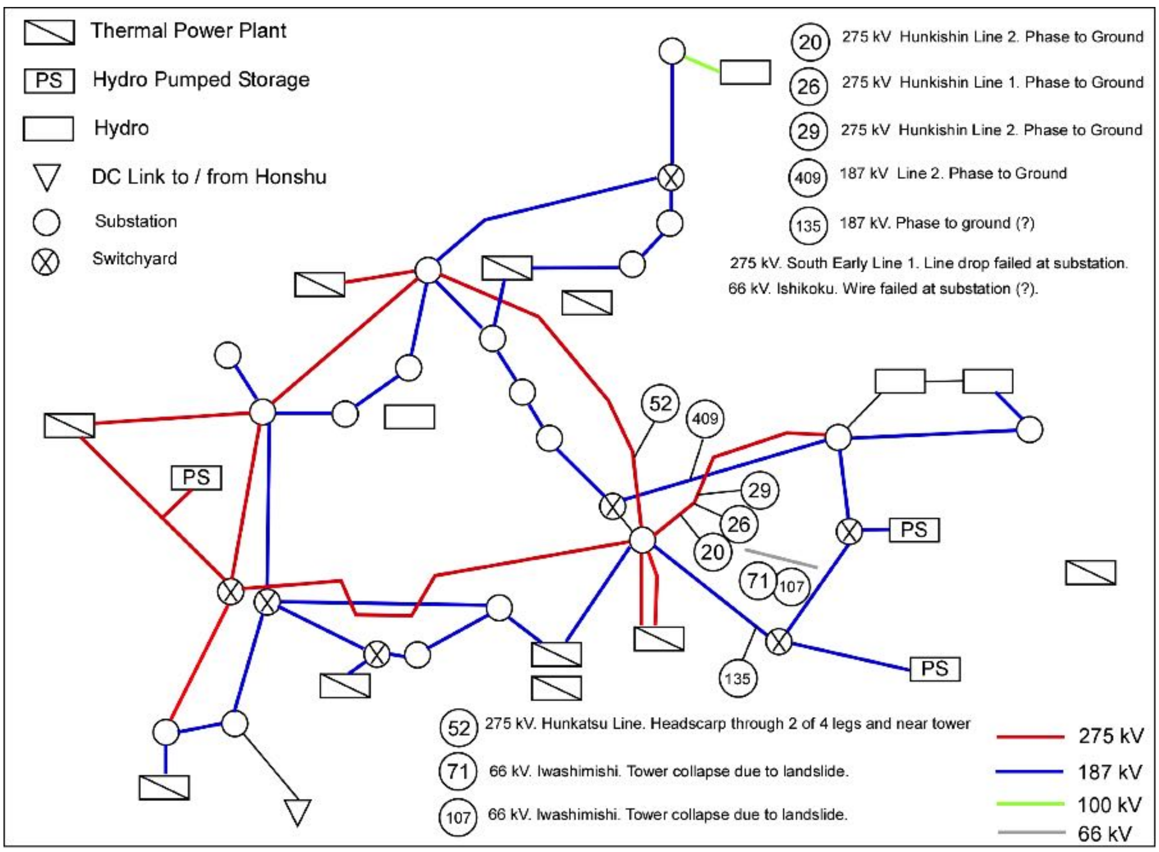


Figure 3-17. Locations of Transmission Tower Damage

Other damaged transmission lines included:

- 66 kV Ishikoku line. Damage due to broken wire / equipment at a substation.

- 275 kV South Early Line 1. Damage due to a broken wire / equipment at a substation.

Figure 3-18 shows a 275 kV double circuit transmission tower with overhead ground wires, tangent suspension-type.

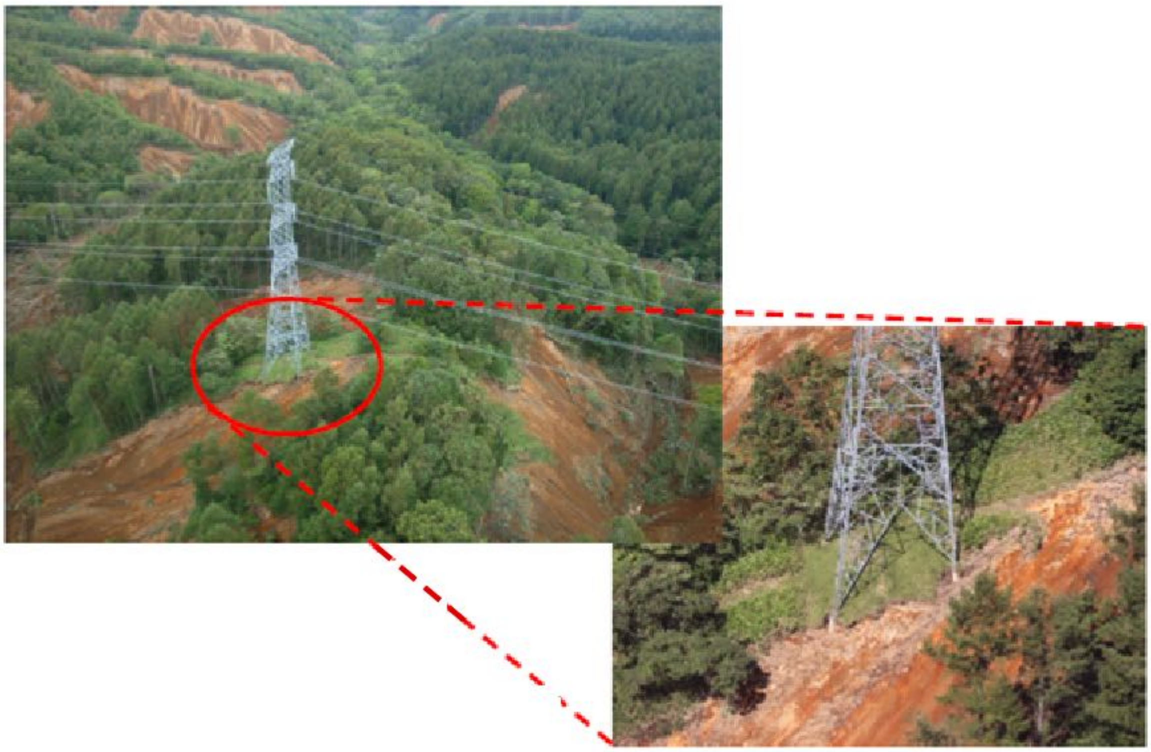


Figure 3-18. Landslide at 275 kV Tower (Photos taken Sept 11 2018, Courtesy HEPCO) (latitude 42.7804, longitude 141.9745)

This tower is located in a remote area, located about 1.5 km from the nearest paved vehicle road. There were many landslides that can be seen in Figures 3-18. Figure 3-19 shows the many landslides mapped in the vicinity of this tower (red polygons) and the Apporo reservoir (blue lake, see also Figure 5-22). The head scarp of the landslide extended through the two southern legs of the four legs of this 4-legged lattice structure.

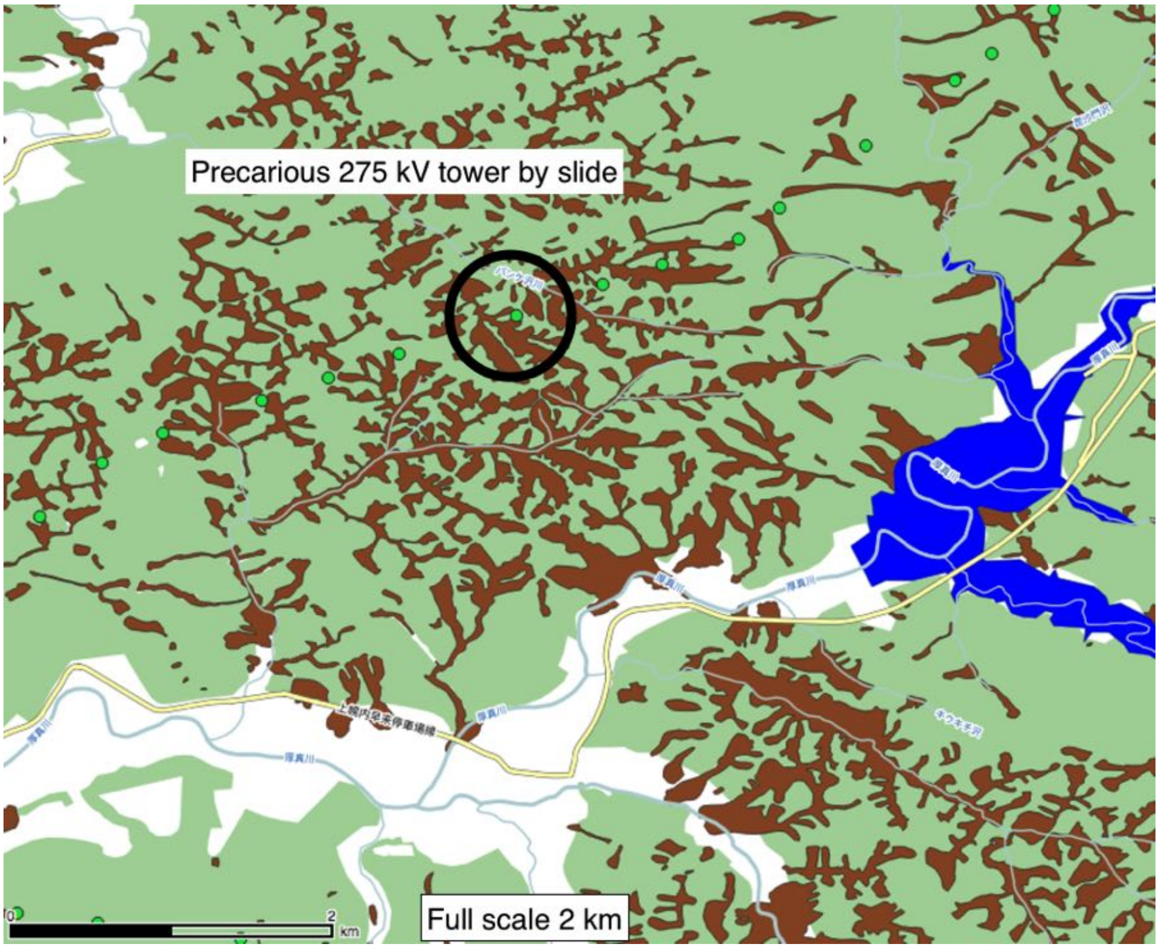


Figure 3-19. Landslides in the vicinity of 275 kV Tower
(latitude 42.7804, longitude 141.9745)

Due to the precarious condition of the ground condition at the base of the tower, importance of this two-circuit transmission line, HEPCO decided to prioritize repairs for this tower. The repairs consisted of stabilizing the ground conditions under and downslope of the tower; the repairs are described below. The level of effort to make these repairs included construction of a temporary access route by ground and helicopter support.

Figures 3-20 through 3-25 are photos that were taken on November 14 2018, after HEPCO had completed some landslide mitigations. At the time of this inspection, we did not observe any damage to the tower: no primary of secondary member appeared to be buckled or otherwise distorted.

Figure 3-20. Repaired 275 kV Tower (Latitude 42.7804, Longitude 141.9745)

Figures 3-21 and 3-22 show aerial views of the repaired tower and surrounding landslides. The denuded slopes are all areas that had landslides that were commonly 2 to 3 meters deep and with downslope movements as much as 50 meters or more.

The slope immediately surrounding and downslope of the tower was stabilized with stepped retaining walls constructed of steel wide flange soldier piles with precast concrete lagging, see Figure 3-23. The shoulders of the soldier pile wall were supplemented with wood logs. Figure 3-24 shows that the repairs to this area included re-grading the area. Figure 3-25 shows locally reinforcement with sandbags around all four of the existing tower foundations. All areas of the repairs were covered in straw mat.

Figure 3-21. Aerial View looking Southwest (credit: Shiga)

Figure 3-22. Aerial View looking Southeast (credit: Shiga)

Figure 3-23. Benched Retaining Wall

Figure 3-24. Legs and Foundation of Tower

Figure 3-25. Typical Repair at Tower Foundation within Landslide

Figure 3-26 shows the collapsed 66 kV tower on the Iwashimishi sub-transmission line.

Figure 3-26. Collapsed 66 kV Tower 107 on Iwashimishi Line (credit: HEPCO)

Figure 3-27 shows this collapsed tower in context of the landslide it was located in. The collapsed tower is on the ground in the red circle. A replacement bypass tower is located just downhill of the collapsed tower, also in the red circle. The head scarp of the landslide is in the top right of the photo. The general sense of direction of the landslide is indicated by the large yellow arrow, with PGDs well over 50 feet. Water was observed coming out of the exposed slope materials (tan color) on the right side of this photo. At the bottom of this photo, there is evidence of a previous repair of a landslide. The level of shaking at this side is estimated to have been in excess of PGA > 0.5g, based on interpolation from other instrumented recordings.

Figure 3-28 shows two geoscientists examining the strata within the head scarp in Figure 3-27. This photo shows size of the head scarp and massive nature of the layered strata.

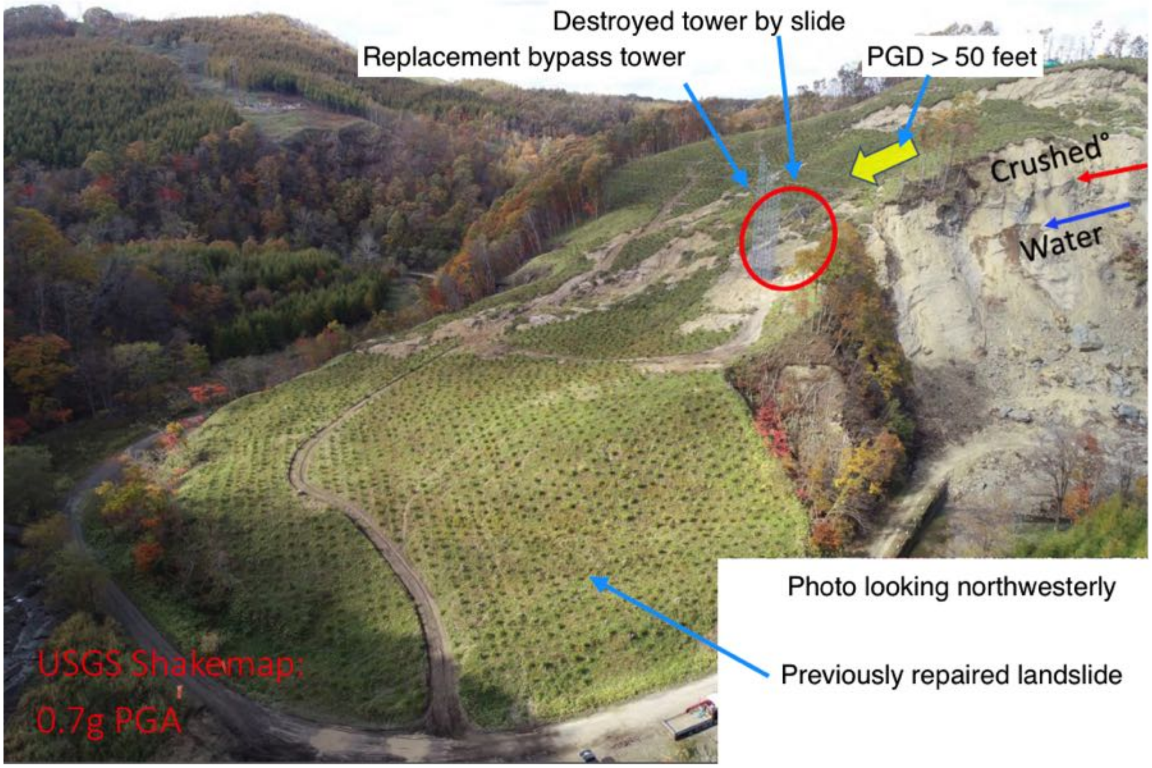


Figure 3-27. Collapsed 66 kV Tower (107) on Iwashimishi Line (lat 42.7188 long 142.1512)

Figure 3-28. Size of blocks in the head scarp of the landslide at Tower 107

Figure 3-29 shows the collapsed tower (107, in red circle) and the replacement pole structure (blue circle).

Figure 3-29. Collapsed Tower 107 (Red Circle) and Replacement Tower (Blue Circle) (photo: HEPCO)

Figure 3-30 shows another collapsed landslide along this same 66 kV Iwashimishi circuit (tower 71). In this location, the landslide has moved as much as 350 meters downslope, entirely destroying the four-leg lattice tower. The two adjacent towers outside the slide were undamaged and it is understood that the long term fix is to move those towers back, raise them, and span over the landslide zone.

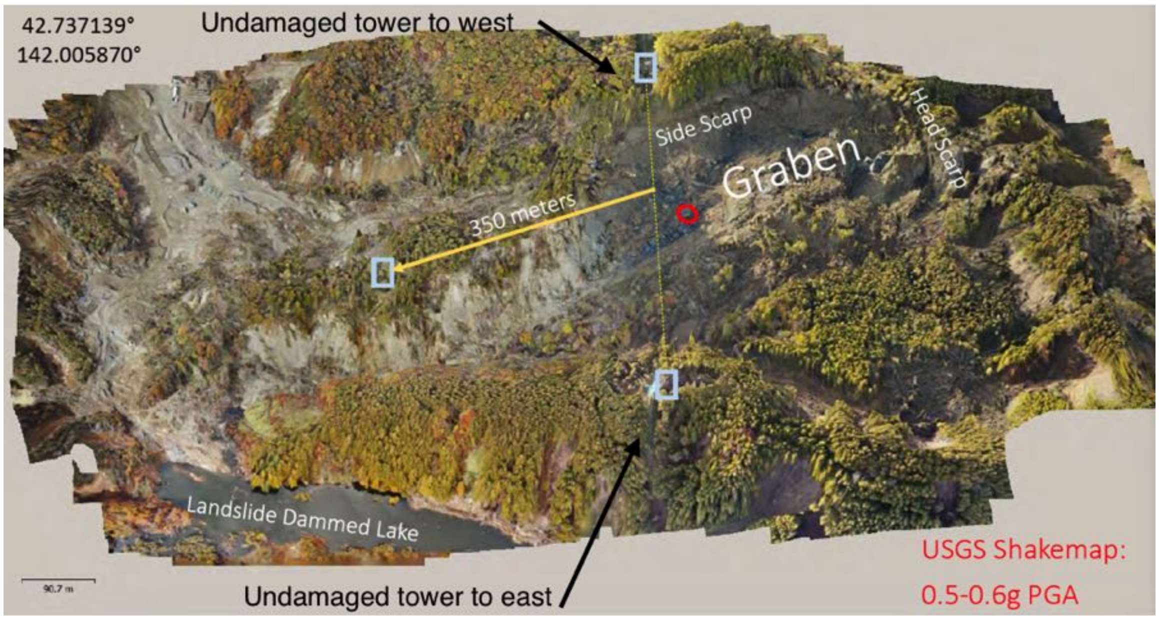


Figure 3-30. Collapsed 66 kV Tower (71) on Iwashimishi Line (latitude 42.7371 longitude 142.0058)

Figure 3-31 shows a digital elevation map produced by LiDAR survey completed after the earthquake. The major slide in this earthquake is indicated by the red ovals, with the location of the tower in the larger red circle. To the top (west), labeled Previously mapped (Pre-historic slide) one can see morphology that suggests another massive landslide had previously occurred in the adjacent valley, possibly triggered by another prior earthquake. This suggests that if the slopes and geology are similar, that terrain that has not shown evidence of recent prior landslides can still undergo massive landslide movements in future earthquakes.

Figure 3-31. Post-earthquake LiDAR-based digital elevation map, Tower 71

Figure 3-32 shows a landslide that occurred beneath a 66 kV suspension tower. The slide has moved a few meters downslope. The base of the tower is about 55 meters above sea level; the toe of the slide is about 30 meters above sea level. The distance from the tower (point C3 in Figure 3-34) to the toe (point C4 in Figure 3-34) is about 130 meters. The average angle of the slope is about 10.6° (= ATAN (25 / 130). At the crest of the hill, the head scarp of the slide has gone between three of the four legs of this tower, exposing the concrete piers, Figure 3-33. This tower was visited twice, on October 10 2018 and November 14 2018; and could observe no discernable ongoing movement of the four legs of the tower. We inspected the braces and found no visible distortions of either the primary or secondary braces. We concluded that the bottom depth of the landslide is above the base of the concrete piers. A long term effort to repair the landslide from further undermining this tower may be suitable.

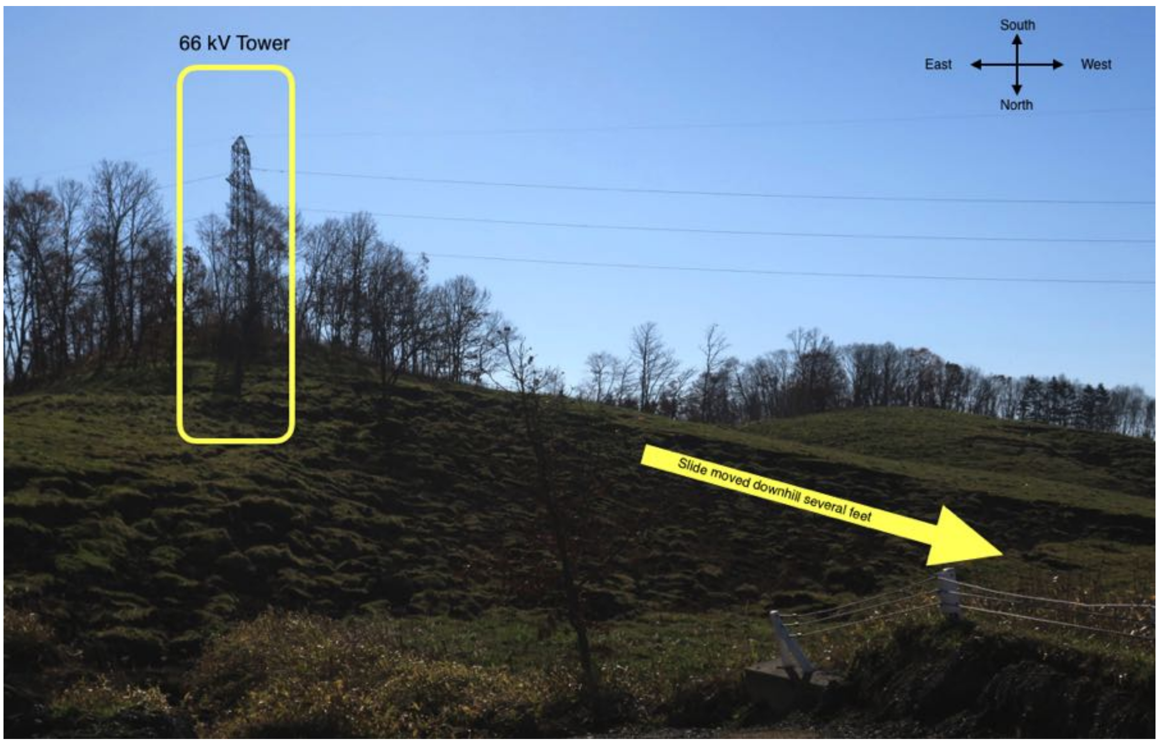
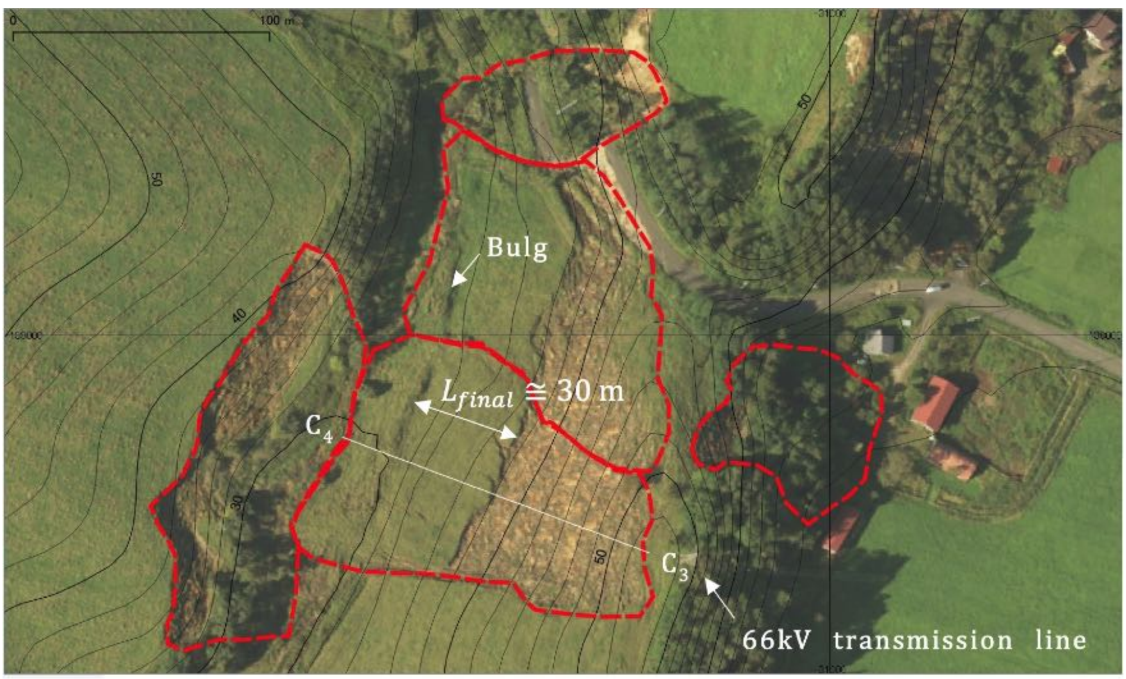


Figure 3-32. Landslide beneath 66 kV Suspension Tower (Lat 42.7560, long 141.8695)

Figure 3-33. Head scarp beneath the tower in Figure 3-32 has exposed three of the four concrete piers



Coherent landslide mass compressed against the other side wall of valley[1)]

Figure 3-34. Map of Landslide Area. The location of the tower in Figures 3-32 and 3-33 is indicated by the white arrow. (Ref: Konagai et al, 2018).

Figures 3-35 and 3-36 show Towers 26 and 29 on the 275 kV Karikatsu lines (see Figure 3-17 for location). The line jumpers and string insulators in the black circles moved during sufficiently during the earthquake to cause phase-to-ground faults.

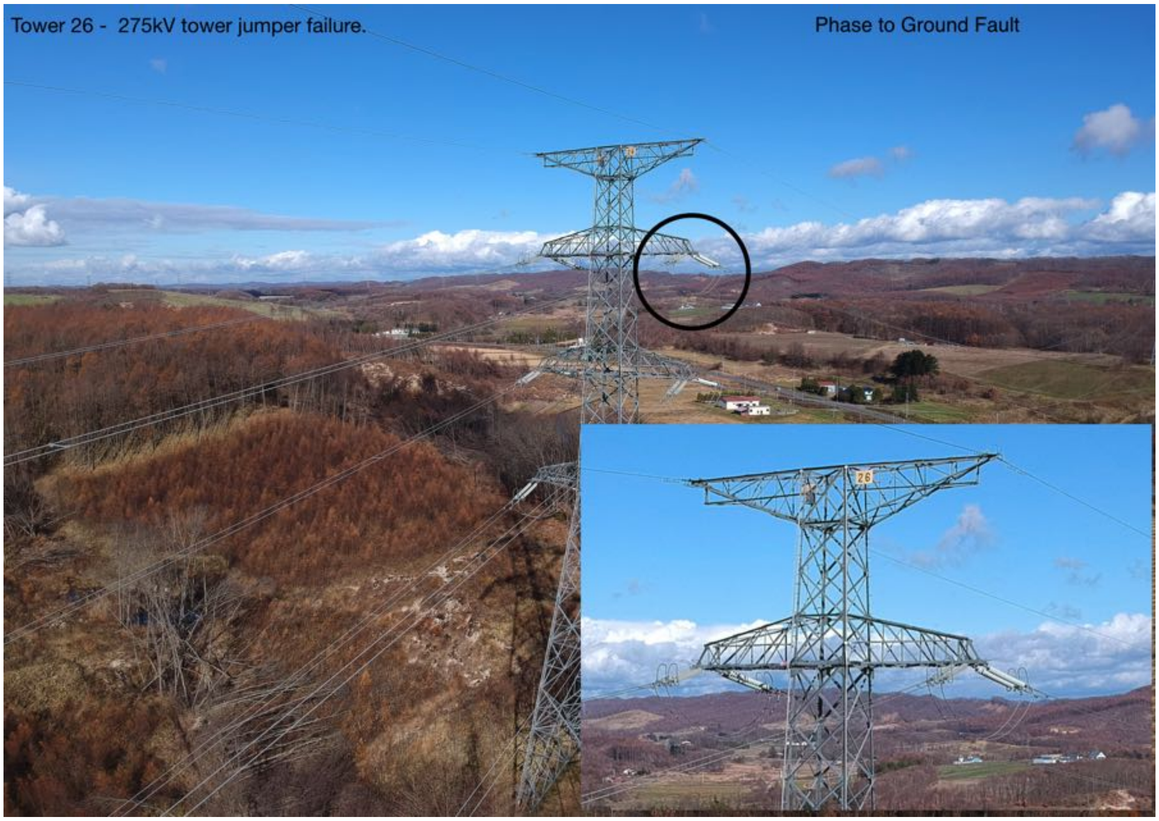


Figure 3-35. Tower 26, Line Fault

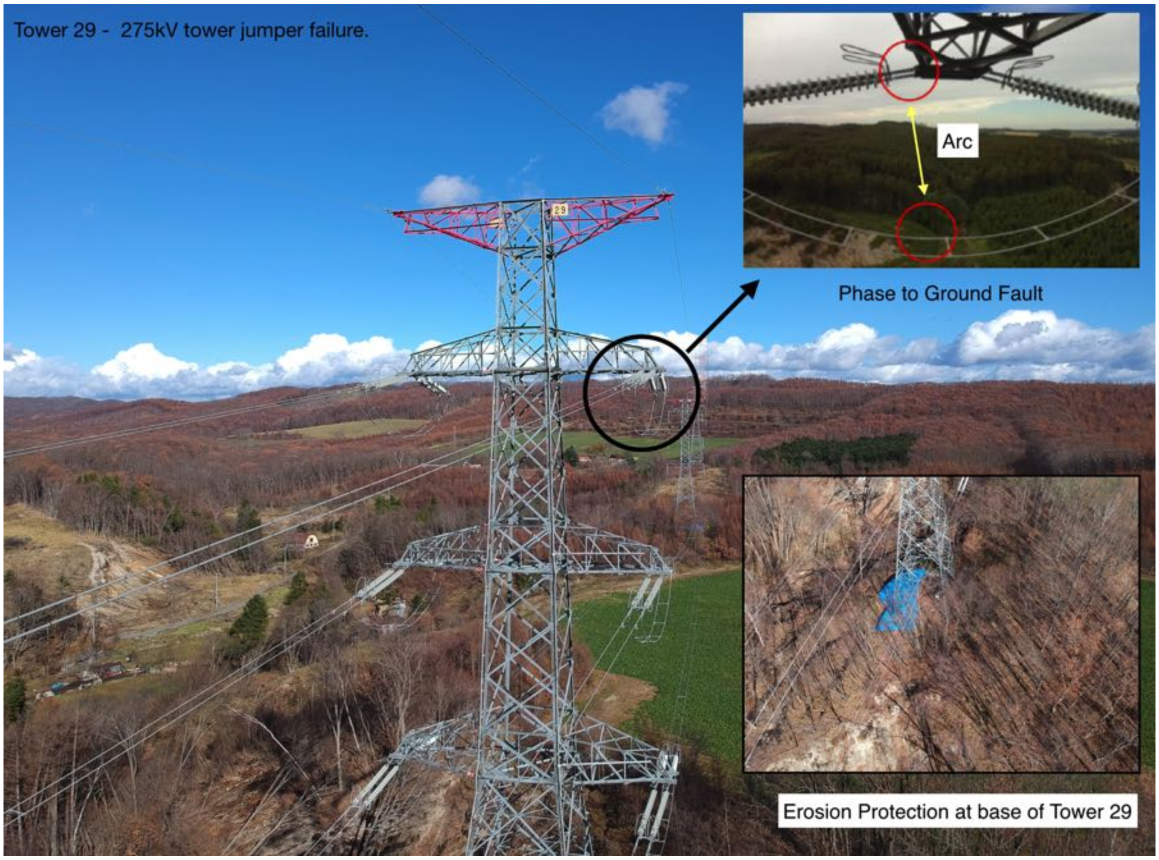


Figure 3-36. Tower 29, Line Fault

3.5 Power Plants

Figure 3-37 shows the three unit Tomatoh-Atsuma power plants. Coal for the power plant is shown in the foreground. The power plants are in the large buildings in the background.

Figure 3-37. Tomatoh-Atsuma Power Plant (looking north)

Figure 3-38 shows a schematic of the damage for Tomatoh-Atsuma Units 1, 2 and 4.

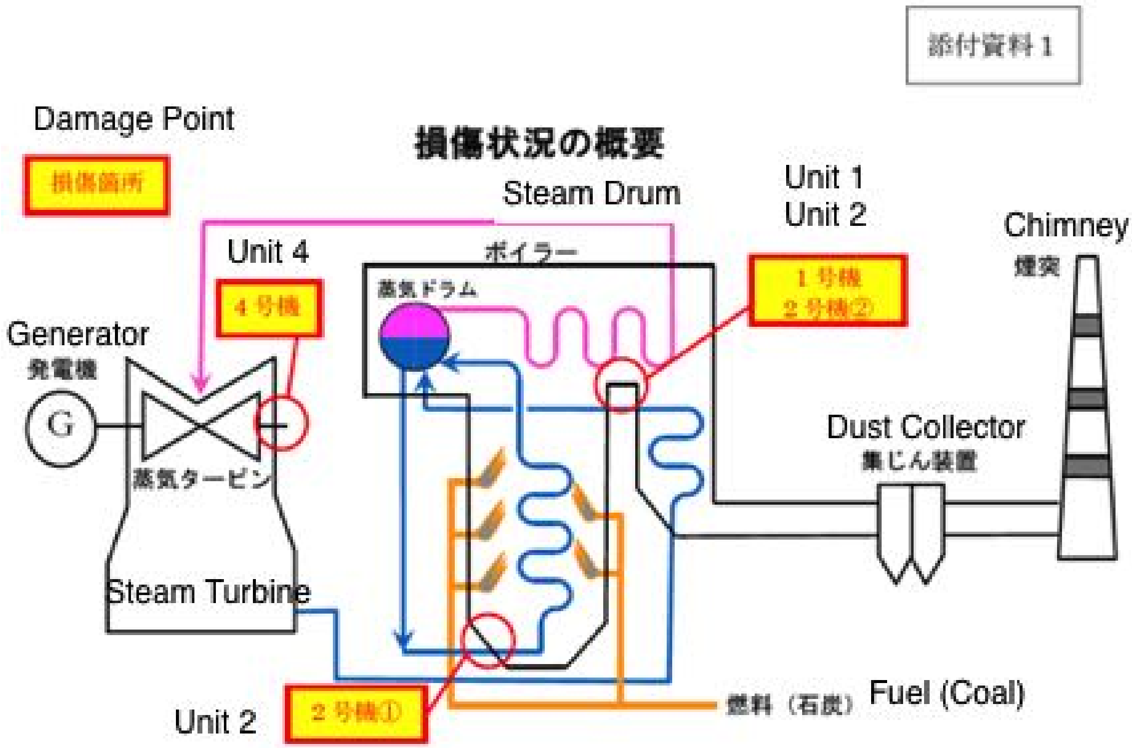


Figure 3-38. Outline of Damage at Tomatoh-Atsuma Units 1, 2, 4 (photo: HEPCO)

Figure 3-39 shows damage to the boiler tubes for Tomatoh Atsuma Units 1 and 2.

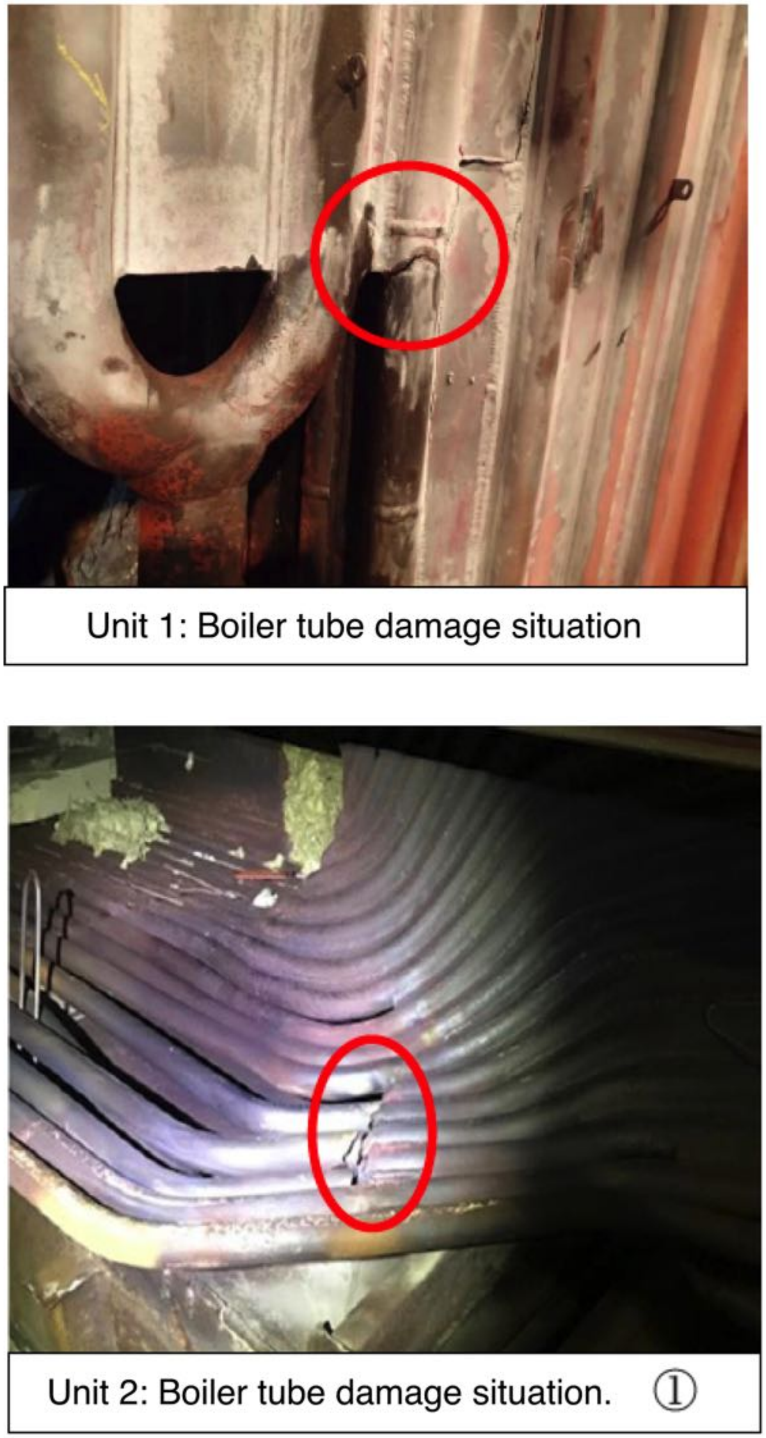


Figure 3-39. Damage of Boiler Tubes Tomatoh-Atsuma Units 1, 2 (photos: HEPCO)

Figure 3-40 shows damage to the boiler tubes for Tomatoh Atsuma Units 2 and 4.

Figure 3-40. Damage of Boiler Tubes Tomatoh-Atsuma Units 1, 2 (photos: HEPCO)

Kushiro City is located about 150 km east of the epicenter, along the southern coast of Hokkaido Island. HEPCO operates two oil power plants, called Onbetsu, located a few km west of the city. The 74 MW oil-burned power plant (Unit 2) was activated on September 11 2018, after the earthquake, to help with the island-wide supply of power. Upon start-up, excessive vibration was noted at a bearing on the gas turbine (Figure 3-41).

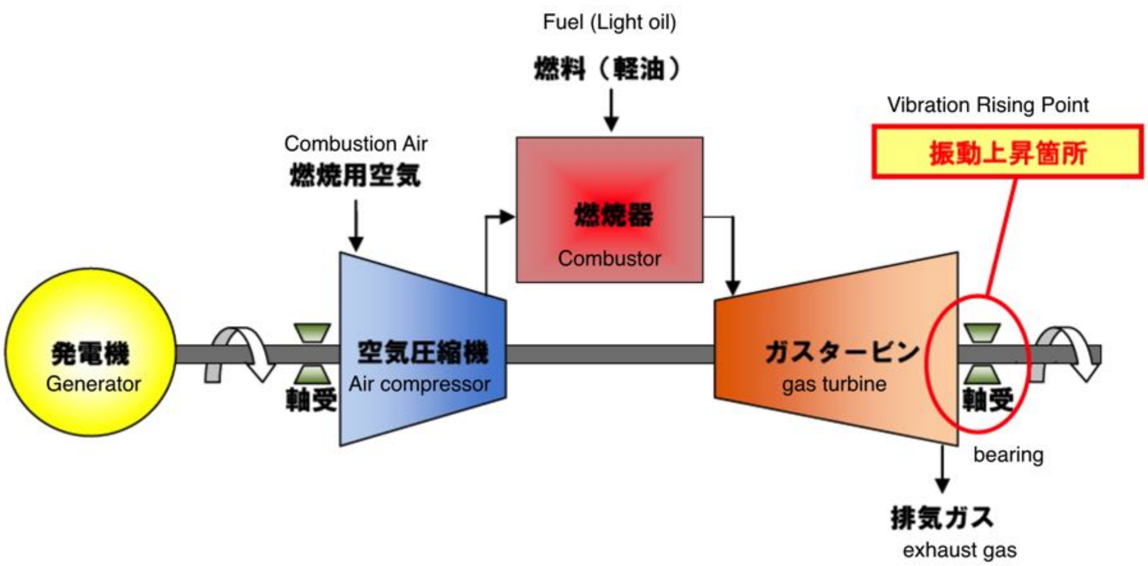


Figure 3-41. Excessive Vibration, Unit 2 (photos: HEPCO)

By September 11 2018, HEPCO had the following repair plans and forecasts for the three unit Tomatoh-Atsuma coal power plant:

- The repair of Tomatoh-Atsuma Unit 1 boiler would consist of the following steps. Internal inspection of the boiler confirmed the damage to two boiler pipes. The plan was to replace the damaged pipes, conduct hydraulic tests for the replaced pipes, and then put Unit 1 back into service during the week of September 16 2018. By September 12 2018, that recovery date had been pushed back until after the end of September. Unit 1 was ultimately reactivated on September 17 at 9:00 am.

- The repair of Tomatoh-Atsuma Unit 2 boiler would consist of the following steps. Internal inspection of the boiler confirmed the damage to eleven boiler pipes. The plan was to replace the damaged pipes, conduct hydraulic tests for the replaced pipes, and put the Unit 2 back into service during the week of September 16 2018. By September 12 2018, that recovery date had been pushed back until after the end of October. Unit 2 was ultimately reactivated on October 10 at 6:00 am.

- The repair of Tomatoh-Atsuma Unit 4 would consist of the following steps. Internal inspection of the boiler had not yet confirmed the damage effects. Initial observations suggested that external inspection of the unit 4 turbine could not isolate the cause(s) of damage; and internal inspection of the Unit 4 turbine would take considerable time, and that repairs for the turbine may take a long time to complete. By September 12, the plan was to have Unit 4 restored after mid-November 2018. Unit 4 was ultimately reactivated on September 25 at 3:00 pm.

Given the damage to difficulty in making a firm prediction of when the thee units would be restored to service, there was concern that peak demand power supply might be difficult to provide. Therefore, HEPCO asked its customers on September 11 2018 to conserve power by everyone in Hokkaido, namely to reduce peak power demand by 20% during weekdays from 8:30 am to 8:30 pm.

In parallel, HEPCO was attempting to expedite restoration Kyogoku Hydro Unit 1 (200 MW) to service. That unit had been taken off line on September 2 2018 due to a malfunction of its turbine (not earthquake related). With post-earthquake efforts, Unit 1 was to be restored to service by September 13 2018. Unit 2 was restored to service on September 14 2018. Once both of these power plants were put back on-line, HEPCO announced that they did not require possible "planned blackouts" in the forthcoming days.

On September 14 2018, HEPCO requested its customers continue to conserve power, but by 10% (Monday-Friday, 830 am – 830 pm) rather than by 20%. HEPCO noted that this situation could still change, as any further difficulties with the aging thermal power plants could still put the demand-to-supply ratio out of balance.

On September 13 2018, Tower 107 on the 66 kV Iwachisi transmission line had been bypassed with a temporary steel tower.

On September 16 2018, Tower 71 on the 66 kV Iwachisi transmission line had been bypassed with a temporary steel tower.

By November 2018, repairs to the landslide at the base of a 275 kV double circuit tower would be completed.

3.6 Distribution System

The distribution system in Hokkaido is operated by HEPCO. It consists of about 50,000 km of low voltage distribution feeders. Most of these feeders use overhead lines, with about 148,000 concrete poles. The use of underground feeders is relatively limited, such as in downtown Sapporo.

Damage to the distribution system (known as of September 18 2018) included the following:

- Broken concrete poles: 35 (almost all due to massive landslide)

- Tilted concrete poles: 156 (some due to minor landslide, some due to embankment slides, some due to liquefaction). By September 16, this total was increased to 166

- Poles with other base-level damage: 5

- Other pole damage: 121

- Total poles to be replaced: 317

- Distribution feeders (faulted, disconnected, wire damage): 283

- Distribution transformers damaged: 32

- Distribution transformers tilted: 382

The damage to the distribution system was due to three primary reasons:

- Landslides. In areas where overhead concrete poles were located in landslides, the poles were often destroyed (the usual case when PGDs exceeded tends of meters; or when the concrete pole was impacted by debris run outs from landslides). Where landslides had smaller PGDs (on the order of a meter or two), the poles were usually still standing (and usually still operable), but tilted.

- Liquefaction. In the Kitayama ward, there was considerable liquefaction over about a ten block area. Common PGDs were 0.5 to 2 meters. Within this zone were about 30 concrete poles. None of these poles collapsed. About half these poles were tilted, commonly 5 to 10 degrees out of plumb. One pole dropped about a meter. The feeder conductor sag in some areas became excessive (inadequate phase-to-ground clearance), and in other areas the conductors had much reduced slack. Nearby houses had secondaries drop from the transformers mounted atop the poles. We observed no transformers in this area that collapsed to the ground; but possibly some were functionally damaged. No pole toppled or was outright destroyed in this liquefaction PGD zone.

- Shaking. In areas subject to very strong ground shaking (PGA > 0.5g or so), we observed wire entanglement in one span. Figures 3-42 and 3-43 show this span, located in the town of Abira. The higher voltage distribution line is at the top level. At the second-to-top level is a three-phase-plus-neutral lower voltage secondary feeder, which has been entangled twice over the course of a single span (once in each of the black boxes in Figure 3-42, and once in a close-up of the more distant entanglement in Figure 3-43). These photos were taken on November 15 2018, and it appeared that the feeder was then-in-service. In this area, all the feeder conductors are insulated, reflecting the severe winter weather that sometimes produces icing and snow build up on the wires; hence the entanglement does not result in a line fault. The example entanglement[4] was observed at only one span, out of more than a hundred spans in this general area. It might have been that more such entanglements occurred, and that these had already been repaired; or possibly this entanglement was unique.

Figure 3-42. Wire Entanglement

[4] It has been speculated that the observed entanglement of these insulated wires possibly reflects a "design feature" by HEPCO; this is thought unlikely and remains an open question.

Figure 3-43. Wire Entanglement

Wire entanglements of this sort have been observed in past earthquakes around the world. It is the authors observations that this has occurred in areas where there is either very strong shaking (PGA > 0.5g or so) or strong influence of long period motions (locations underlain by deep soft sediments).

Other types of wire-line failures may have occurred. It is understood that there was an area-wide blackout within about 20 seconds of the earthquake, throughout the high shaking area (PGA > 0.5g, area in red block in Figure 3-5). Also, many distribution feeders used insulated wires. For these two reasons, the incidence of wire-slapping phase-to-phase faults (and wire burns) might have been much lower than otherwise had the power stayed on and had the wires been bare (uninsulated).

Figure 3-44 shows a toppled distribution pole due to major PGDs along a road.

Figure 3-44. Toppled Distribution Pole due to PGDs along a Road (Atsuma-Cho) (Credit: HEPCO)

Figure 3-45 shows a toppled distribution pole with "tilted" transformers. The underlying cause is PGDs due to a landslide that also destroyed a house. Figure 3-46 shows two other toppled / tilted poles.

Figure 3-45. Toppled Distribution Pole due to PGDs (Atsuma-Cho) (Credit: HEPCO)

Figure 3-46. Toppled and Tilted Distribution Poles (Credit: HEPCO)

Figure 3-47 shows two distribution power poles. A landslide moved about 40 feet to the left (direction of large arrows in this photo), and destroyed both the road and the pole that was at the "replacement pole" location. This photo was taken November 14 2018, and by that time, the road had been partially rebuilt, and the destroyed pole has been replaced. Of interest is that while the destroyed pole moved some 40+ feet to the left, there was no damage to the adjacent non-replaced poles. The feeder circuit at the top of the poles was repaired. The communication cables at mid-height of these poles had not yet been repaired as of November 14 2018.

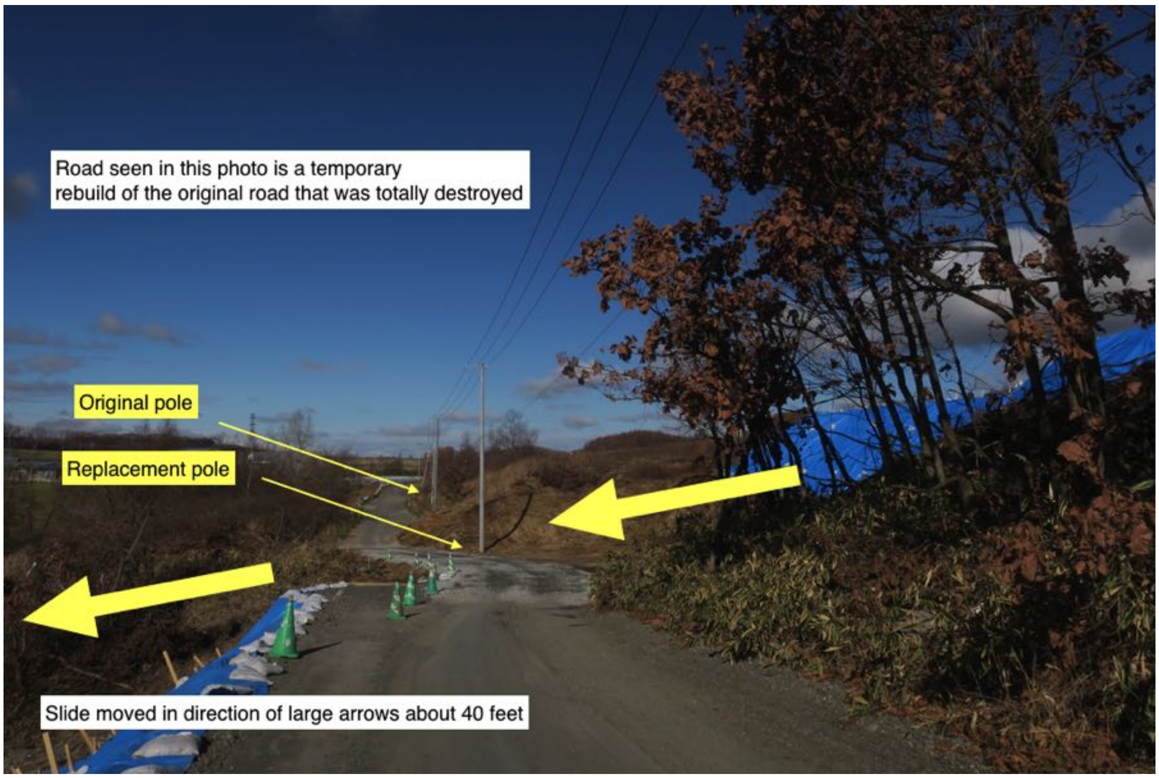


Figure 3-47. Original and Replaced Power Distribution Poles

3.7 Power Restoration

HEPCO has a total of 25 emergency generator trucks, of the type seen in Figure 3-48. By September 7, Tokyo Electric Power had provided an additional 10 such trucks, and Tohoku Electric Power had supplied another 6 such trucks. By September 9, a total of 115 such trucks were deployed from other power utilities throughout Japan. These trucks include a diesel-powered generator that outputs power at the line voltage of typical distribution feeders. In Figure 3-48, the three vertical conductors provide power from the generator set directly into the overhead distribution feeder.

Figure 3-48. Hooking up an Emergency Generator to a Distribution Primary

The function of these trucks is to restore power to distribution feeders that have been directly cut-off from the transmission lines. In this earthquake, loss of transmission lines did not directly cut-off any feeders; instead these trucks were used to power portions of feeders that were cut-off from other parts of the same feeder due to landslides; or to provide redundant power supply to critical facilities like hospitals that were cut-off due to the Island-wide power outage.

Once the initial Island-wide power outage was resolved, HEPCO faced a pressing issue as follows:

- The peak power demand for September 2017 was 3.83 GW. With the damaged Tomatoh-Atsuma coal fired power plant, there as little reserve generation capacity.

- The peak power demand for October, November and December 2017 was 4.23 GW 4.67 GW and 5.25 GW, respectively. Unless more generation could be brought on line before winter-time demands were needed, the remaining undamaged generation capacity might not be sufficient for peak demands.

By September 13 2018, HEPCO had restored power to all customers except for 161 houses in Atsutamachi and Anping Town.

By September 16 2018, HEPCO had restored power to all customers except for 59 houses in Atsutaira-cho and Atsutoshimacho.

With the restart of Tomato-Atsuma Unit 1 on September 18 2018, HEPCO's request for a 10% power demand reduction was no longer necessary, subject to change if there were any unplanned power plant shutdowns.

3.8 Tomari Nuclear Power Plant

HEPCO owns and operates the three unit Tomari nuclear power plant. This plant is located about 70 km west of Sapporo. In the earthquake, the level of shaking at this power plant was well under PGA = 0.05g.

Since the 2011 Tohoku earthquake, all three units have been kept offline. Various safety upgrades to the plant have been made since 2011, to provide more resiliency for earthquakes and tsunamis. It is the long term intent of HEPCO to restore these nuclear power plants to normal operation. In the interim, the nuclear fuel in the reactors has been placed into the fuel storage pools.

Due to the Hokkaido Island-wide power outage, offsite power was lost to the plant site at about 3:28 am, lasting for a few hours. All six emergency generators came on line, providing power to keep nuclear fuel in the storage pools cool. Offsite power was eventually restored.

There was no physical damage at the nuclear power plant due to the direct impact of the earthquake at 3:08 am. During the black start operations, a shunt reactor at the switchyard was damaged due to overcurrent.

3.9 References and Acknowledgements

Chubu Electric. Chubu Electric staff provided a detailed description of the progression of the power outages.

Hokkaido Electric. HEPCO provided many press releases and updates as to the status of the electric system.

Konagai, K, Nishiyama, S., Ohishi, K., Kodama, D., Nanno, Y., Large ground deformations caused by the 2018 Hokkaido Eastern Iburi Earthquake, JSCE Journal of Disaster Fact Sheets, FS2018-E-0003, 2018.

Tang A., Eidinger J., Kumamoto, Japan Earthquakes of April 14 and April 16 2018, Lifeline Performance, TCLEE No. 2, www.geEngineeringSystems.com, May 7 2017.

4.0 Gas System

4.1 Overview of the Gas System

Figure 4-1 shows a map of the cities in Hokkaido with natural gas systems supplied by underground pipe to end-user customers.

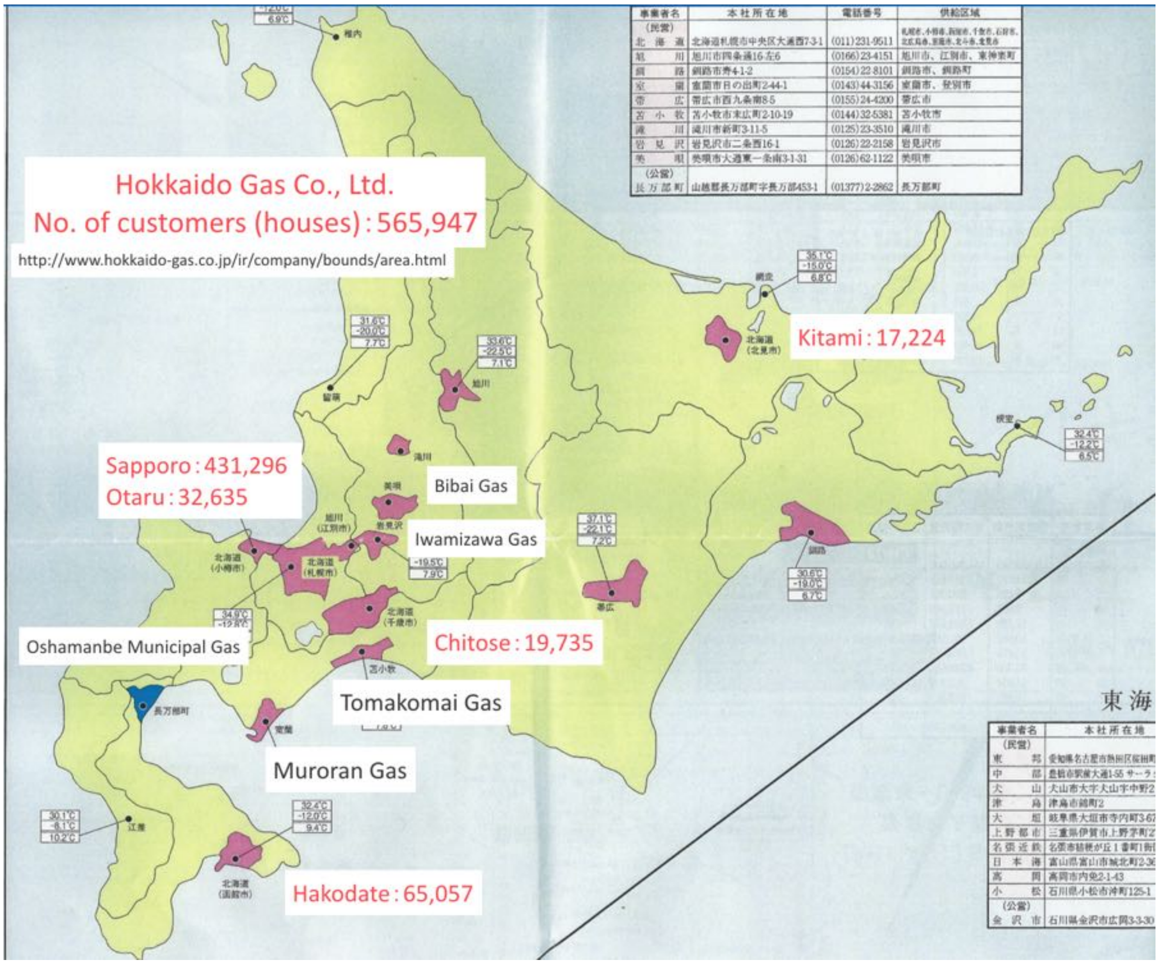


Figure 4-1. Natural Gas Systems, Hokkaido Island

The largest gas system serves the City of Sapporo, with about 431,000 customers.

In Section 4, we use "Kita Gas" and "Hokkaido Gas" interchangeably to refer to the gas system serving Sapporo.

Figure 4-2 shows a schematic that describes how the typical gas system operates and the underlying seismic design strategy. LNG gas is delivered to Hokkaido at the LNG terminal (see Figures 4-3 and 4-4) where it is off loaded into large circular concrete tanks. The tanks are designed for seismic forces.

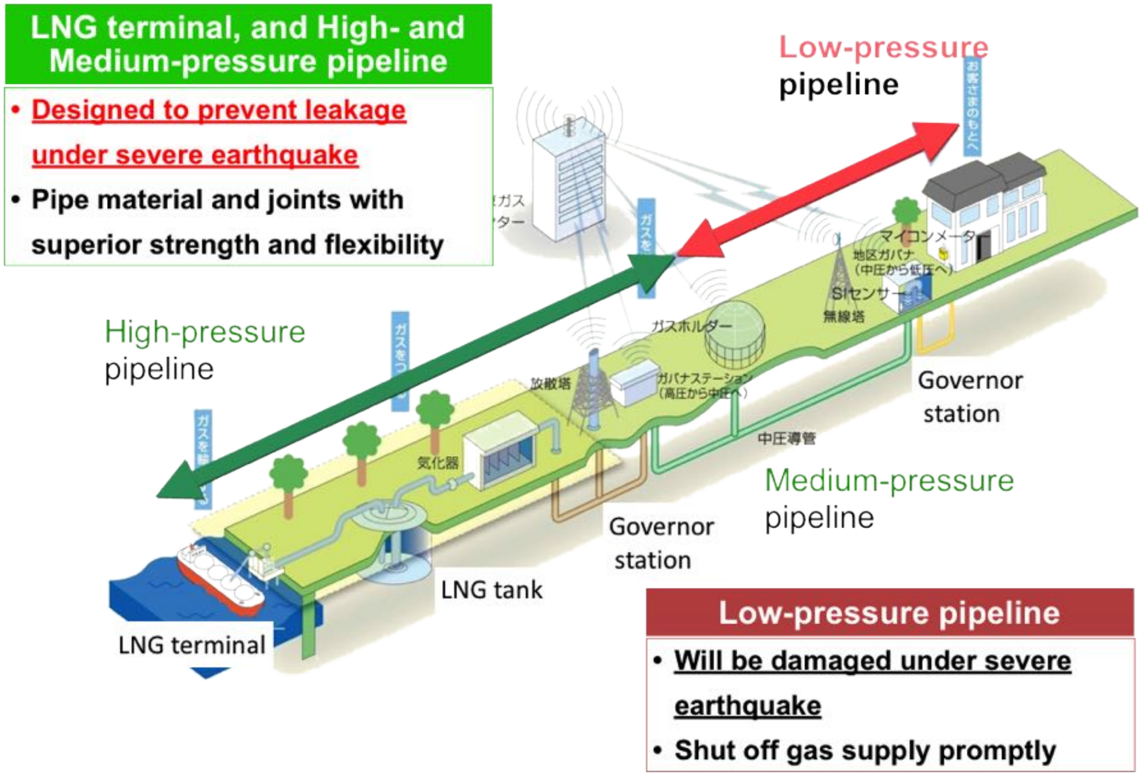


Figure 4-2. Schematic Gas System (credit: Maruyama)

Figure 4-3 shows the LNG terminal where natural gas is off loaded from Liquefied Natural Gas ships and then stored in four very large tanks at the Ishikari port. Tanks 1 and 2 store gas for the Hokkaido Gas Company and Tanks 3 and 4 store gas for the Ishikari power plant. Figure 4-4 shows Tank 1 (furthest tank on left in Figure 4-3). Figure 4-3 shows Tank 3 (front to the right) and Tank 4 (front to the left, under construction).

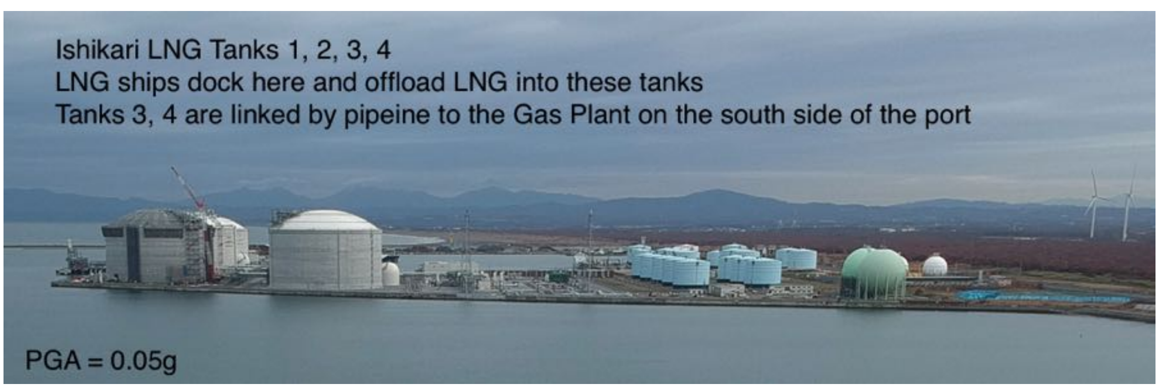


Figure 4-3. LNG Tanks 1, 2, 3, 4 at Ishikari LNG Terminal (November 2018)

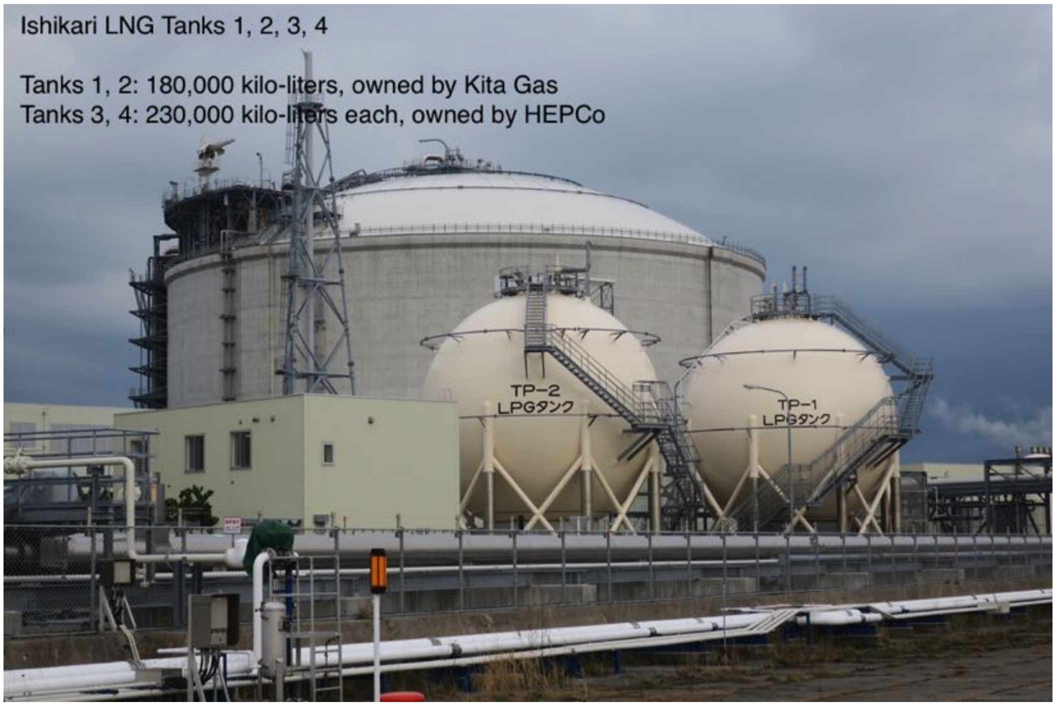


Figure 4-4. LNG Tank 1 at Ishikari Port

Figure 4-5. Ishikari Gas-Fired Power Plant

4.2 Gas Shutoff System

One of the earthquake strategies used in Japan is to automatically shut off the gas supply system to areas (also called blocks, with about 50,000 houses per block, see Figure 4-6) that have experienced ground shaking in excess of a prescribed intensity level, using the formula in equation 1. This formula integrates the Spectral Velocity response spectrum from an instrument, for 20% damping, from 0.1 to 2.5 seconds, and if the weighted average is over 60 cm/sec (a moderately high level of ground shaking), the instrument sends a signal to valves in the gas pipe system to automatically close. The concept here is to avoid new supply of natural gas into an area where high levels of ground shaking (of ground deformations) may have likely resulted in serious levels of underground gas pipe damage. This strategy is relatively easy to implement, needing only a suitable instrument and logic to convert a felt motion into an integrated spectrum, a process that can be done within a few seconds or so of the end of shaking, and then a signal to suitable valves at suitable locations to close. It might be better if this strategy relied on PGDs (rather than ground velocities), as well as actual gas pipe damage (indicated by sudden loss of pressure), but PGDs are difficult to measure within the first seconds after an earthquake, and knowing the exact pattern of gas pipe damage is similarly difficult to assess in the first seconds after an earthquake. The isolation of the gas supply pipes does little to nothing to resolve the residual amount of gas within all the downstream gas pipes, which can be a substantial source of fuel for feeding any fires, should fire ignitions occur; however it does allow for the continued gas flow to be stopped so the fire(s) are not continuously fueled. One would have to be careful in setting up this system to not unintentionally isolate critical gas customers (like gas-fired power plants).

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_v^{\xi=0.2}\left(T\right)dT \geq 60\ cm/\sec \quad [eq.1]$$

In this earthquake, the highest recorded SI was 57.7 cm/sec, recorded at Chitose. Therefore, none of the shutoff valves were actuated during this earthquake.

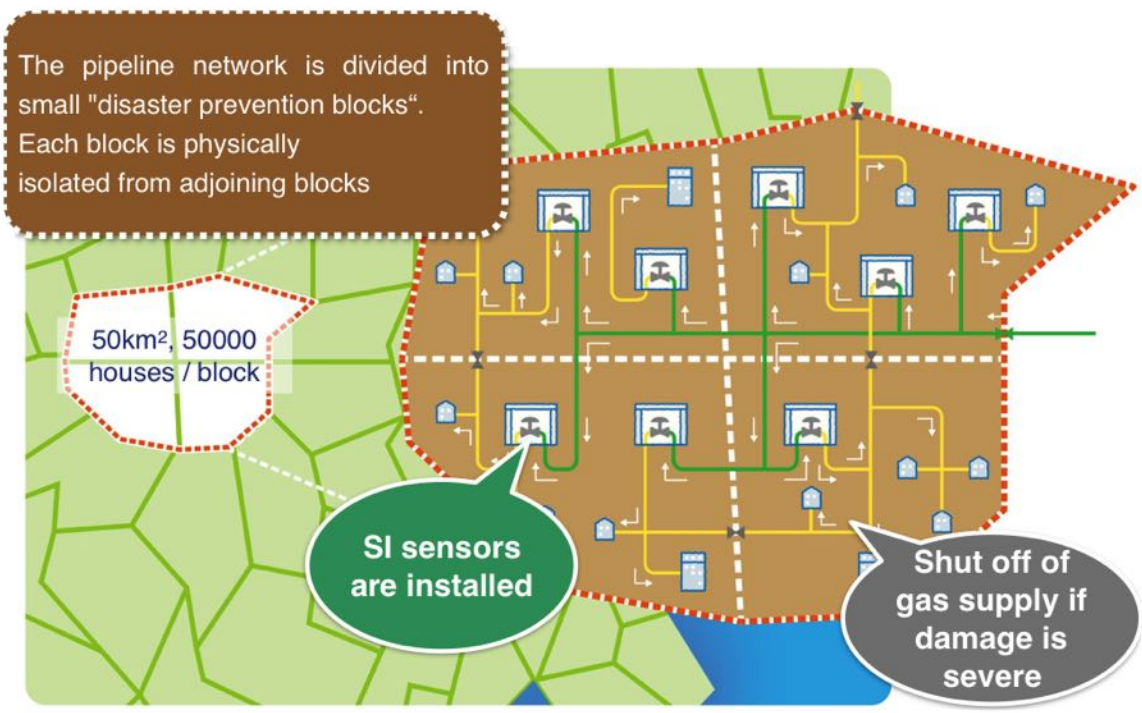


Figure 4-6. Disaster Prevention Blocks (credit: Maruyama)

For the City of Sapporo, Figure 4-7 shows the locations of the actual blocks (heavy black lines). Recorded SI in Sapporo were: 55 cm/sec (Block B3, west side of city); 43 cm/sec (Block D-1, north central part of city); 31 cm/sec (Block E-2, east side of city).

Near Chitose, recorded SI were: 26 cm/sec (north of the airport); 35 cm/sec (northeast of the airport); 57.7 cm/sec (south end of airport).

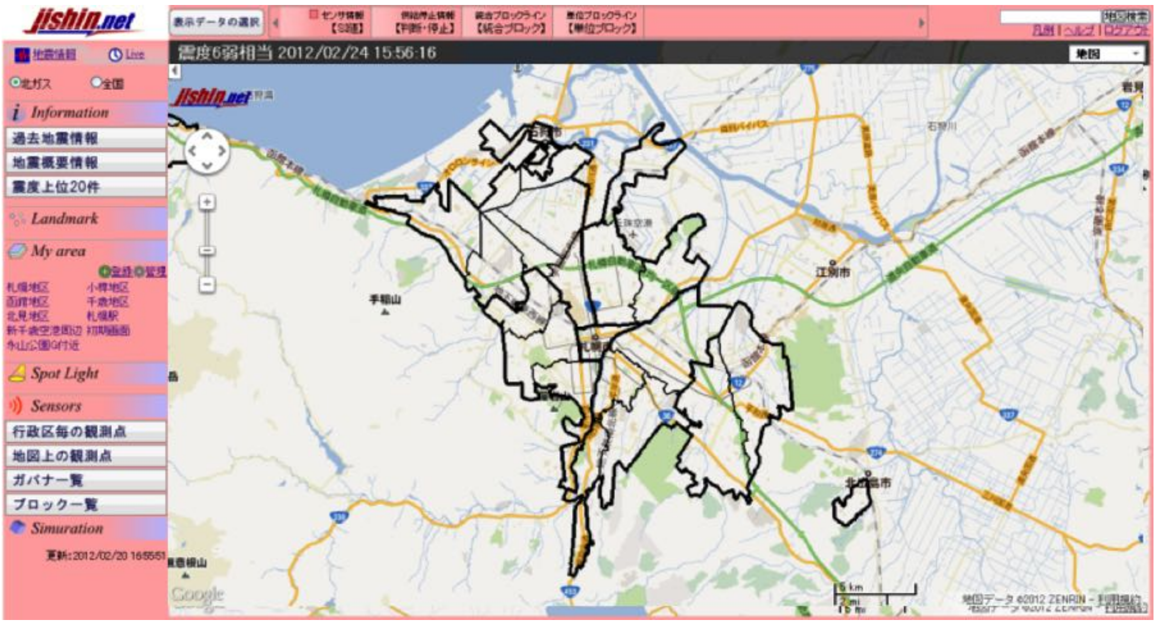


Figure 4-7. Disaster Prevention Blocks for Sapporo

The concept is that after the earthquake, the strong motion instruments record the motion. Then, software converts the motions into the equivalent SI intensity (cm/sec), using Equation 1 above. This should take place within 5 minutes of the earthquake. For any location where SI exceeds 60 cm/sec, shut-off valves are closed. Power to operate the shut-off valves is derived from differential pressure within the pipes; not from offsite power.

4.3 Earthquake Response

In this earthquake, no shut off valves closed because no recorded motions exceeded 60 cm/sec. Therefore, gas was constantly supplied to Sapporo and to Chitose. There were no fires reported in either Sapporo or Chitose.

At the LNG terminal, offsite power was immediately lost at about 3:07 am. The gas generator plant then stopped due to loss of offsite power. Operations continued using power from emergency generators. Offsite power was restored to the LNG port at 23:35 September 6 2018 (about a 20 hour outage).

By 3:14 am September 6, all the instruments reported in that SI was less than 60 cm/sec. Therefore, operations continued.

By 3:53 am, an emergency response team was formed to respond to any issue that might arise.

For the three days from September 6 to September 9, survey teams were dispatched to look for leaks. No leaks were reported. At 16:30 on September 9 2018, the survey teams were dismissed. No significant "re-light" efforts were required.

There was no damage reported to any of the gas controls in the system.

Kita Gas reported that the primary impact of the electric power outage was to cause delays in getting emergency response crews to do damage assessments; and make the repairs that were needed.

The status of buried pipes was as follows:

- High pressure pipe (~ 1 MPa, 145 psi). 40 km. No damage. Usually steel pipe.
- Medium pressure pipe "A" (~300 KPa, 45 psi). 155 km. No damage.
- Medium pressure pipe "B" (~300 KPa, 45 psi). 499 km. No damage.
- Low pressure pipe (~2.5 KPa, 0.4 psi). 4,697 km. 2 leaks. Both pipes were located in soft ground areas and reported to be on low pressure branch connections. These leaks were reported to have been not on steel-welded pipe. These leaks were in areas that experienced PGA ~0.35g (about highest levels in Sapporo).
- Service laterals to houses. 11 leaks. These appear to have been due to corrosion. These leaks were found when customers reported a smell (odor) from gas, and then called in.

There were no gas pipes in the portion of Kiyota ward where there was significant liquefaction that damaged water pipes (see Chapter 5 for maps and description of the ground failures in that area).

There was no reported damage to either the Tomakomai Gas system (PGA ~0.25g to 0.35g) or the Muroran Gas system (PGA ~ 0.10g).

We understand that all gas meters into buildings include a seismic shut-off capability. Apparently, none of these were activated in the earthquake.

4.4 Kerosene, Propane Household Tanks, Liquid Fuel Tanks

In many of the smaller communities, the majority of households use kerosene tanks. Kerosene tanks are small rectangular tanks, supported on steel braced frames. Even in areas with very strong shaking (PGA > 0.5g), we did not observe complete toppling of these tanks; but we did not inspected every building, so this failure mode cannot be ruled out. There were reports of broken lines connected to some of these tanks, and we did observe tilting of these tanks in areas subjected to liquefaction PGDs. The typical tank has a shut off valve installed. Some (but not all) tanks were observed to have a pig-tail pipe arrangement to allow for differential movements, see Figure 4-8. Figure 4-9 shows a typical installation of propane tanks for a residential building.

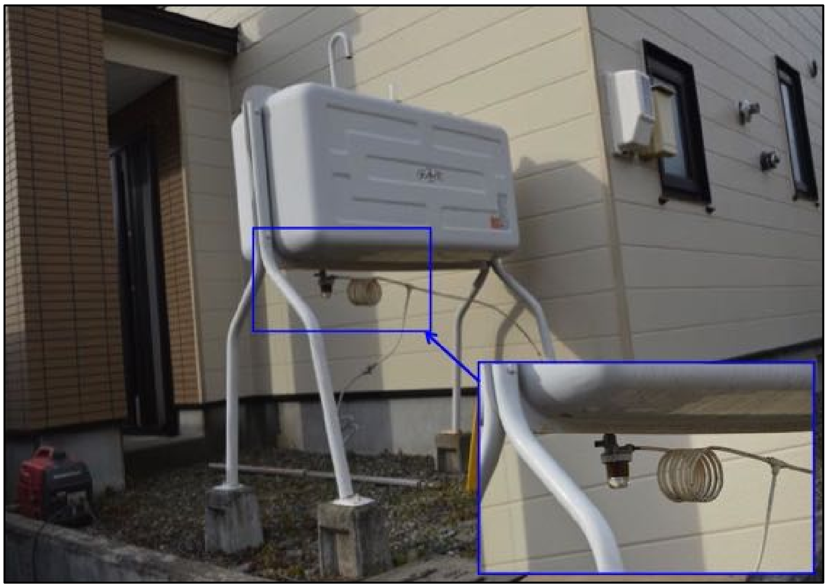


Figure 4-8. Kerosene tank outside of most residential buildings

Figure 4-9. Propane tanks strapped to wall anchors. This household uses both gas and propane

For the most part, household propane tanks are vertically-standing tanks, generally up to 1.5 meters tall by up to 0.5 meters in diameter, strapped to anchors on the adjacent building wall, see Figure 4-9. If the building remained standing, there was little damage to the propane tanks. All the tanks we observed were chained, as in Figure 4-9; we did not see instances where the tank had both top- and bottom-level chains.

Figure 4-10 shows an aerial view of a large liquid fuels tank farm. This tank farm is close to the epicenter. All 96 tanks are steel, with floating roofs. There was no report of damage to the tanks in this facility; we were unable to gain access for detailed inspection. From the exterior or the property, we observed no effects of sloshing of oil as spills on the exterior of the tanks.

Figure 4-10. Aerial view of the tank farm for oil storage. A total of 82 tanks in this facility. (Source: Google Earth)

4.5 Acknowledgements

The description of the piped natural gas system presented in Section 4 is adapted from materials developed originally by Prof. Yoshihisa Maruyama of Chiba University, information from the Japan Gas Association, and information provided by the Kita Gas Group. We especially extend our sincere appreciation to Professor Maruyama for collecting and developing much of the information presented in Chapter 4.

5.0 Water System

The earthquake cut off all water supplies completely for the towns of Abira, Atsuma and Ebetsu. Water supply was interrupted to at least some customers in Sapporo, Ebetsu, Abira, Atsuma, Mukawa, Hiratori and Hidaka. Some water outages were also reported in Kuriyama, Nanporo, Ishikari, Urausu, Uryu and Nemuro. Figure 5-1 shows a map with the number of households that had suspended water supplies for at least some time between September 6 2018 and September 14 2018 (colored areas) and the JMA intensities based on instrumental recordings (colored dots). Figure 5-2 repeats this data, but shows just the water outages (best estimate) due to the Island-wide power blackout, excluding damage due to broken pipes, etc. See Table 9-9 for a numeric breakdown of the number of households with outages.

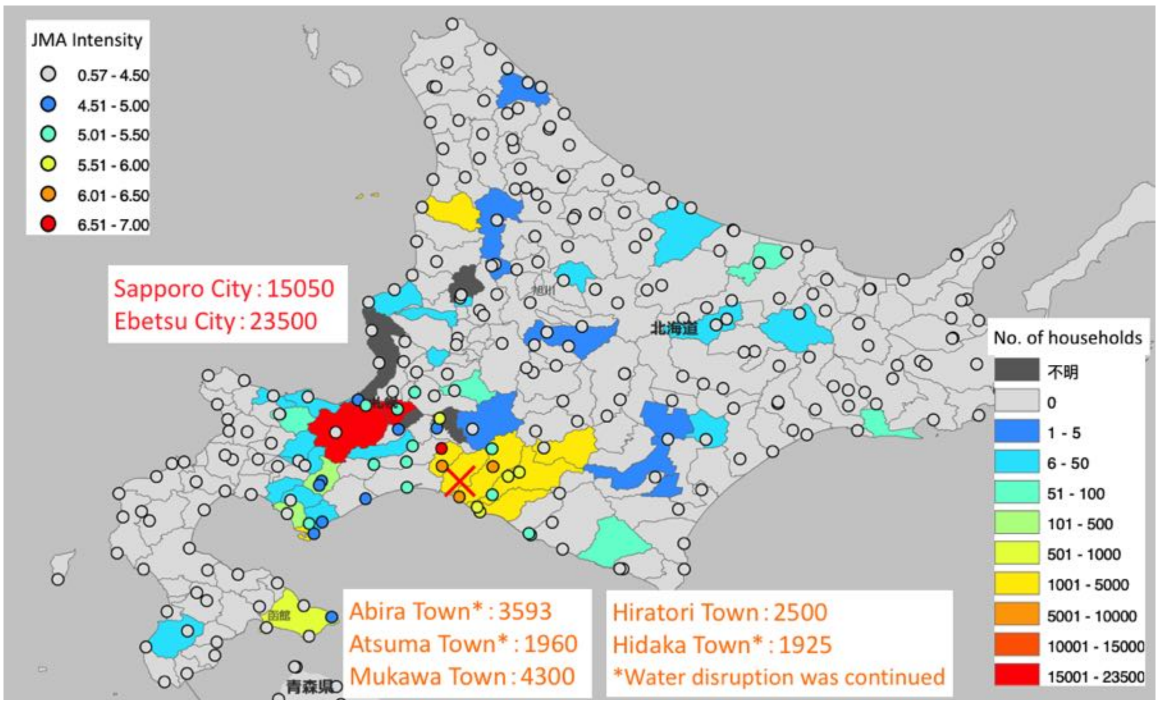


Figure 5-1. Map of Areas with Water Outages (source: Prof. Maruyama)

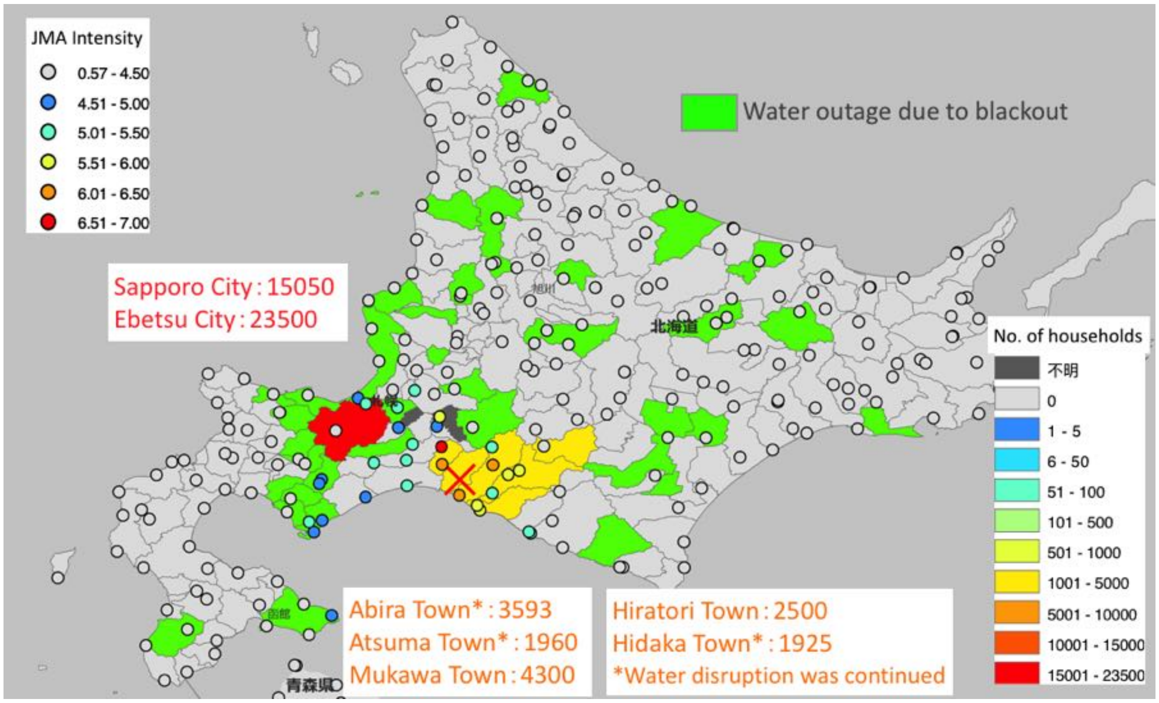


Figure 5-2. Map of Areas with Water Outages due to Blackout (source: Prof. Maruyama)

5.1 Overview of the Sapporo Waterworks System

The largest water system affected by the earthquake is the waterworks of the City of Sapporo. This system serves about 1.96 million people (2017 data). Figure 5-3 shows an overview map of the system, along with the major facilities.

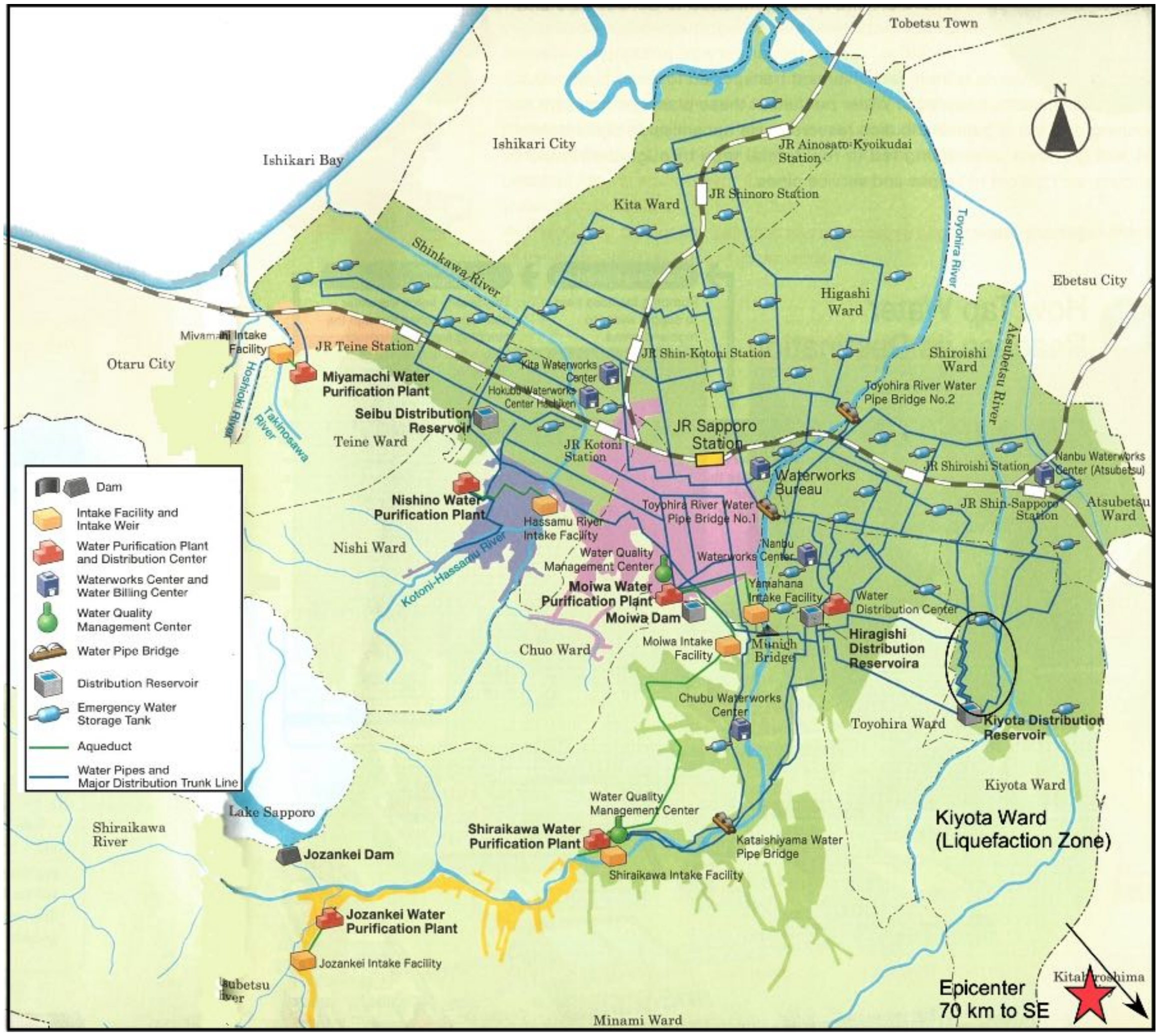


Figure 5-3. Map of Sapporo Water System

The Sapporo water system is comprised of five water treatment plants, 6,000 km of buried water pipes, 45 treated water reservoirs, and various pump stations and pressure reducing stations, and various office and maintenance facilities.

For more than 30 years, the City of Sapporo water system has been implementing various seismic and corrosion-related (aging) upgrades. These upgrades include two rounds of pipeline replacements, installation of 38 emergency water supply tanks, seismic hardening of water tanks and facilities, etc. As of 2015, the percentage of facilities that have been seismically hardened were:

- 20%. Water treatment plants
- 82%. Treated water distribution reservoirs
- 24%. Distribution pipelines.

The September 6 2018 earthquake damaged water mains (150 mm to 500 mm diameter) at about 14 locations (latest count as of mid-November 2018). The approximate locations of the pipeline and appurtenance damage is shown in Figure 5-4.

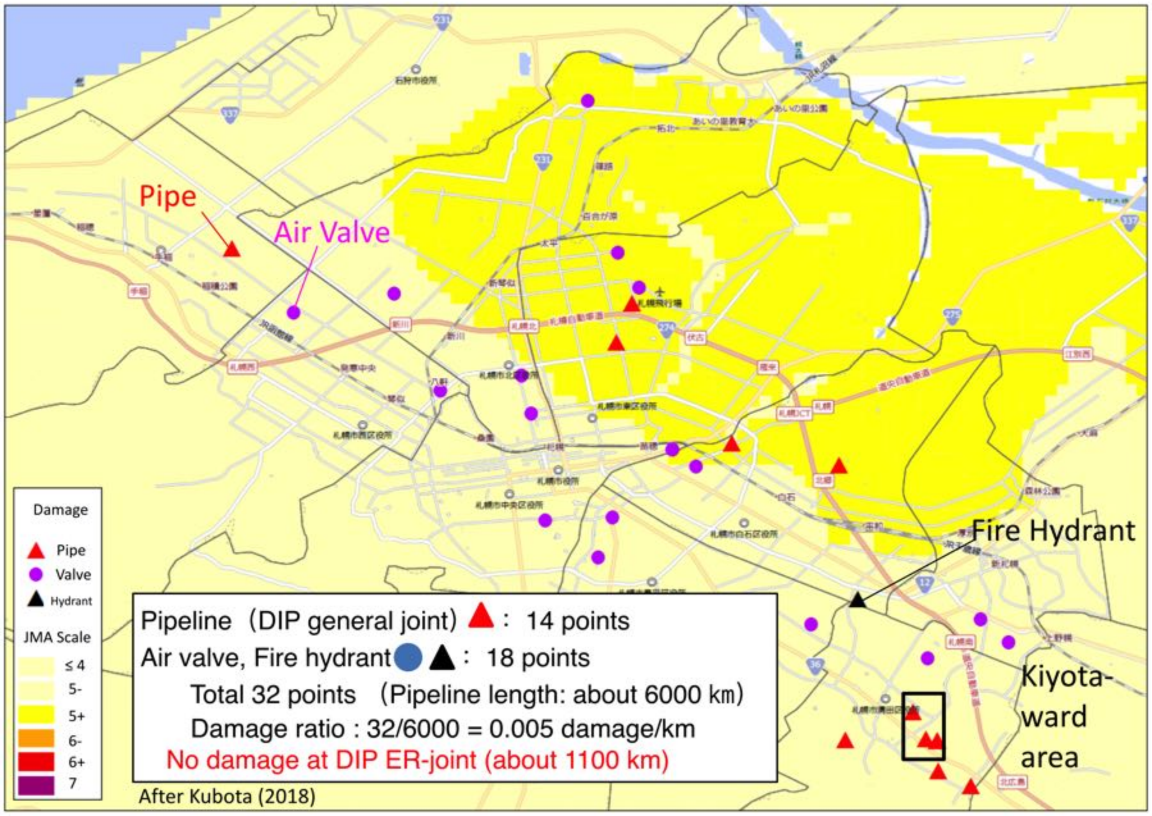


Figure 5-4. Location of Pipeline Damage

The most concentrated pipeline damage location was in the area called Kiyota Ward, where significant liquefaction resulted in 3 broken water mains. City-wide, the number of damaged appurtenances was 17 air valves and 1 fire hydrant. The exact number of damaged service laterals (commonly 25 mm or smaller) is uncertain, but were estimated to be perhaps 10 or so) by the water agency.

At 16 water distribution reservoir sites, each with two basins, one of the two basins was outfitted with "seismic shut-off valves" on inlet and outlet pipes. Most of the distribution reservoirs are buried reinforced concrete rectangular tanks. The concept here is that should strong shaking occur, that one tank (or basin) should remain in service to provide water for firefighting (or other) purposes, while the other tank (or basin) would be automatically "shut off" to retain the water supply until a manual assessment can be made as to the nature of the emergency. The "shut-off" triggers include a sensor for strong shaking (PGA = 0.2g or higher) or sudden drop in pressure. None of the sensors were triggered in this earthquake, suggesting that ground motions throughout Sapporo were typically well under PGA = 0.2g. At the reservoir (single basin) that supported the pressure zone with the concentrated pipeline damage (Kiyota Ward), there were no automated shut-off valves, and that reservoir was rapidly emptied by the broken downstream pipes. By the year 2020, it is expected that shut-off valve hardware will be installed at an additional 4 locations.

5.2 Sapporo Dams and Water Treatment Plants

There was no earthquake-related damage to any of the dams or water treatment plants in the Sapporo water system.

The City of Sapporo water system includes five water treatment plants. All five plants include coagulation, sedimentation, filtration, pH control (alum), and disinfection (sodium hypochlorite)

- Miyamachi WTP. Located in northwest Sapporo (PGA ~0.05g). Raw water source is the Takinosawa and Hoshioki rivers. Supply capacity is 1.5 Million Gallons per Day (MGD). The mountains in this area are described as "hard rock" with no observed landslides.

- Nishino WTP. Located in western Sapporo (PGA ~ 0.10g). Raw water source is the Kotoni-Hassamu river. Supply capacity is 4 MGD. The mountains in this area are described as "hard rock" with no observed landslides.

- Moiwa WTP. Located in western Sapporo (PGA ~ 0.10g). Includes a water quality lab. Raw water source is the Toyohira river. Supply capacity is 41 MGD. The mountains in this area are described as "hard rock" with no observed landslides.

- Jozankei WTP. Located southwest of Sapporo (PGA ~ 0.15g). Raw water source is the Toyohira river. Supply capacity is 2.4 MGD. The mountains in this area are described as "hard rock" with no observed landslides.

- Shirakawa WTP. Located in western Sapporo (PGA ~ 0.10g). Includes the water quality lab. Raw water source is the Toyohira river. This WTP serves the largest portion of Sapporo, with capacity 172 MGD. The mountains in this area are described as "hard rock" with no observed landslides.

- Jozankei Dam. Located west of Sapporo. Concrete gravity dam, built 1989. Impounds Lake Sapporo, fed by the Otarunai River. PGA ~ 0.10g. Can supply up to 320,000 m^3 (85 MGD) per day during the summer. Reservoir capacity is 21.7 Billion gallons (67,000 acre-feet). The mountains in this area are described as "hard rock" with no observed landslides in this earthquake.

- Hoheikyo Dam. Located southwest of Sapporo. Concrete arch dam, built 1972. Impounds Lake Jozan, fed by the Toyohira River. PGA ~ 0.15g. Can supply up to 528,000 m^3 (139 MGD) per day during the summer. Reservoir capacity is 12.4

Billion gallons (38,000 acre-feet). The mountains in this area are described as "hard rock" with no observed landslides in this earthquake.

- Under normal operations, the Toyohira River (via three WTPs) supplies about 98% of the total water used in the City of Sapporo.

The seismic design basis for the dams and water treatment plants is commonly referred to as "JMA scale 7". This translates to design for a response spectra with at least PGA ~ 0.40g or higher; newer facilities might be designed for a so-called "Level 2" earthquake, to have good performance at PGA ~ 0.75g or higher. Given the lack of damage in this particular earthquake, we did not inspect these dams or water treatment plants, and the precise nature of their design basis is somewhat speculative. However, they did perform well.

Each of the water treatment plants is outfitted with suitably-sized emergency diesel generators. Therefore, the power outage that occurred over the first hours to a day or so, did not affect any of the water treatment plant operations.

About 75% of all water is supplied by gravity. By "gravity", it is meant that water flows downslope from the WTPs to end-user customers, without any intervening pump stations. In the downtown area, gravity water supply needs to be pumped by customer-owned pumps within high-rise buildings, in order to supply the highest floors.

About 25% of the water is supplied in pumped zones. By "pumped zones", it is meant that water from the lower elevation gravity zones has to be pumped uphill to higher elevations. Most of the pumped zones are in the mountainous areas to the south, southeast and southwest of downtown Sapporo.

To the north and west of the City of Sapporo are the cities of Otaru, Ishikari and Tobetsu. These cities have an independent water supply, namely the Tobetsu river, flowing from the north of Sapporo. The water system for these three cities is operated as the Ishikari Seibu Water Supply Authority (ISWSA). The level of shaking in this area was commonly PGA ≤ 0.05g, and there was no specific damage reported the ISWSA water system, but some short-term water household outages in Otaru (48), Tobetsu (17) and Ishikari (uncertain) were reported (see Table 9-9); the cause of these short term water outages was not verified; possibly due to power outages or water main breaks.

Recognizing some of the lessons learned from the 2011 Tohoku earthquake, and recognizing that Sapporo has 98% of its supply from one source (the Toyohira River), and ISWSA has 100% of its supply from one source (the Tobetsu River), the City of Sapporo and the ISWSA decided to construct a joining pipeline to allow water to flow between the two systems, sufficient to supply up to 20 liters per person per day. This system could be used in case of single source contamination (like, from ash from a volcanic eruption), earthquake-caused damage, to more easily allow short term shutdown of portions of either system for maintenance purposes, etc. This linking pipeline is scheduled to go into operation in 2025. Due to the limited effects of the 2018 earthquake, there was no need to operate this linking pipeline; but future larger earthquakes or other events could require operation of this intertie.

5.3 Sapporo Pipe Inventory, Replacement, Damage and Fragility

The original water pipes in the Sapporo system date from 1937 and included Asbestos Cement pipe (ACP) and Galvanized Iron Pipe (GIP). Recognizing the possible health issues with ACP and long term corrosion issues with GIP, the Sapporo Water Department elected to do a wholesale pipe replacement program, replacing every pipe that was aged over 40 years old. This was a long term effort, beginning around 1971, with more than 100 km of pipe replaced every year between 1974 and 2002. All the replacement pipe was Ductile Iron Pipe (DIP), commonly with rubber gasket "push-on" joints, or rubber gasket with mechanical fittings (semi-restrained joints).

A second pipeline replacement program is now (2018) being implemented, with a target to replace about 60 km of pipe each year. The target life spans of existing pipe has been set at either 40 years, 60 years or 80 years, optimized to reflect that pipes in more corrosive soils (peats and clays in the northern part of the city) have a shorter economic lifespan than pipes in the eastern part of the city, where the soils are generally less corrosive. The current target is to replace nearly all pipe over an 80 to 100 year cycle.

As of 2018, there are about 6,000 km of pipe mains (this length does not include service laterals).

Since the 1995 Kobe earthquake, there has been keen awareness of the vulnerability of water pipelines due to strong shaking / ground movements in earthquakes. In Japan, two kinds of "seismic-designed" water pipe are commonly in current use, namely welded steel pipe (small portion) or ductile iron pipe manufactured by Kubota with special Earthquake-Resistant (ER) joints (majority portion). During the time period since 1995 to 2018, about 1,100 km of pipeline in Sapporo had been replaced with ER-DIP, manufactured by Kubota. The current target in Sapporo is to upgrade all water pipes with diameter 400 mm or larger (16-inch or larger) with ER-DIP pipe by the year 2030.

Recognizing that in larger pressure zones that pipe breaks in local area can de-pressurize widespread areas, a further upgrade strategy is to sub-divide large pressure zones into small "block" zones interconnected to main transmission pipes and adjacent blocks through only a few valves. In this way, if pipeline damage occurs in one block zone, then only a few valves need be turned to isolate that block from adjacent blocks, thus restoring water service to more customers in a shorter time.

Over time, Kubota has updated its seismically-designed pipe, with various trade names, such as S-II joints, Genex, etc.; herein, we call them uniformly "ER-DIP". In all these applications, the DI pipe is manufactured with special end conditions, allowing each segment of pipe to be installed using male / female joinery with a rubber gasket and lock ring, in such a manner that each assembled joint can take about ±2 inches of extension /

contraction (target 1% of pipe segment length of about 16 feet = 192 inches), and up to 8° or rotation, before "locking up". In ALA (2005), we call this "chained pipe". Once locked up, additional forces / movements applied to the pipe segment can get transferred to the next adjoining pipe segment joint. In this manner, a well designed and constructed pipeline can readily accommodate ground strains on the order of 1%, which is usually sufficient to withstand without leakage the effects of high shaking, or liquefaction-induced settlements, or moderate lateral spreads; or moderate movements of landslides, or moderate amounts of fault offset. Special designs can be done to accommodate near "knife edge" landslide or fault offset movements of up to 10 feet or so, by shortening the length of each pipe segment (more joints), and / or specifying suitable backfills (not very stiff). In Japan, Kubota's ER-DIP has been installed for many 1,000s of km of length, and exposed to large earthquakes in the 1995 Kobe, 2011 Tohoku, 2016 Kumamoto and now the 2018 Hokkaido earthquakes. In the high seismic regions of North America, there are now (2018) more than a dozen ER-DIP installations in California, Oregon, Washington and British Columbia, reflecting that American and Canadian water agencies now see the merit of adopting ER-DIP as part of their pipeline systems, especially in areas prone to PGDs. In all these recent earthquakes in Japan, there has been essentially no failure of these ER-DIP due to ground shaking or moderate amounts of PGDs (up to a meter or so). To date, there have been no significant earthquakes ($M \geq 6$) to test the recently (mostly post-2014) North American-installed ER-DIP. Note, the failure rate of ER-DIP is not exactly zero: there was one failure due to a mis-installed pipe in the Kumamoto 2016 earthquake, and one failure of a under-hung pipe due to a bridge failure due to tsunami in the 2011 Tohoku earthquake. For practical purposes, the observed failure rate of ER-DIP has been essentially 0.000 per km in areas exposed to PGVs up to 100 cm/sec and PGDs of up to 30 cm; for planning purposes, Kubota ER-DIP can be assumed to have a failure rate forecasted using ALA (2001) fragility models with k1 (shaking) of about 0.01, and k2 (liquefaction) of about 0.01; as long as one separately accounts for additional damage for appurtenances and service / hydrant laterals.

In the City of Sapporo in the 2018 earthquake, there were 14 observed water main failures plus 18 appurtenance failures plus about 10 service line failures. Most of these failures were for DIP (non-ER) and its appurtenances and service laterals. The city-wide failure rate for non-ER-DIP was thus 42 / (6000-1100) = 0.0086 repairs per km. Of the 14 pipeline failures, at least 3 were observed to be due to PGDs, and the remaining might have been PGD or PGV. The common level of ground velocity in the area was about 2 to 4 inches per second; most areas likely under 10 inches/second. If we exclude the known failures due to PGDs, then the failure rate of DIP (excluding appurtenances / laterals) with push on or mechanical-type joints was 11 / (6000-1100) = 0.00225 per km at an average PGV ~ 3 inches per second.

In comparison, ALA (2001) forecasts the following damage rate for DI pipe with push-on joints (inclusive of appurtenances and laterals):

RR (per 1000 feet) = 0.5 * 0.00187 * PGV (3) (inch/second) = 0.00281 / 1,000 feet (pipe main plus appurtenances plus service laterals), or 0.00927 / km. This compares reasonably closely with the corresponding observed damage rate in all of Sapporo of about 0.0086 repairs / km.

It is recommended that the Sapporo dataset set be included as part of future updates to the ALA (2001) fragility models. In so doing, there are some further refinements that might be warranted:

- The Sapporo DI pipe is very recently installed (much of it post-2000). The long term effects of corrosion in the Sapporo pipes might not yet have been impacting the DI pipe. In Sapporo, nearly all DI pipe is installed with polyethylene bags over the pipe. In Sapporo, the yearly number of repairs due to all factors (corrosion, aging, excavation, etc.) is about 24 (24 / 6000 km = 0.0040 repair / km / year, all pipe types). In comparison, EBMUD's[5] yearly repair rate is about 750 / 4,000 miles = 0.188 repairs per mile per year, = 0.117 repairs per km per year. EBMUD has a comparable inventory of pipes (about 4,000 miles), but EBMUD's pipes are much older on average (many dating to the 1920s), and still include significant mileage of relatively fragile Cast Iron Pipe and Asbestos Cement pipe (more than half of the entire pipeline inventory).

- Sapporo noted that current "lost water" in the system is about 2.6%. Lost water is water that is un-accounted for by meters, either due to leakage or from unmetered usage (like from fire hydrants). In the USA, a "tight" water system might have about 8% "lost" water (like EBMUD), and a very leaky system might have as much as 50% "lost" water (like reported for New Orleans after hurricane Katrina). Higher rates of "lost" water reflects the continuing effects of corrosion on old pipes, as well as influence of ground movements (frost heave, expansive soils, landslides, etc.) and other factors.

- There is strong evidence that a pipe replacement program will reduce the amount of "lost" water, and will reduce the annual number of pipe repairs. A "tight" water pipe system might also indicate that the pipe system has particularly good resilience against the effects of ground shaking in earthquakes.

- The ALA (2001) pipe fragility models outline an approach to address the effects of corrosion on water pipes, with a factor of up to 3 times increase in repairs for older cast iron or steel or galvanized iron pipes located in corrosive soils.

- The ALA (2001) fragility models lump damage to pipeline mains, appurtenances and service laterals all together. This approach was adopted reflecting that prior to 2001, the available empirical evidence often lumped together repairs to all these items, and provided the overall length of pipe. For ER-DIP, the practical failure rate for most levels of shaking / PGDs is nearly zero; but unless installations for appurtenances, fire hydrant laterals, and service lines are also seismically

[5] EBMUD is East Bay Municipal Utilities District, providing water for Oakland and 22 cities.

installed, then damage to those components will still occur. Clearly, a refinement in the fragility models should be taken to de-aggregate the damage for all three categories (pipe mains, appurtenances, service laterals), to reflect their individual seismic vulnerabilities.

- In past earthquakes there has been a very wide range of damage to service laterals as a ratio of damage to pipe mains. The number of repairs for laterals has sometimes greatly exceeded those to pipe mains (as was the case in the Kumamoto 2016 earthquake (Ref. TCLEE No. 2, 2017), where there were over 3000 lateral repairs and about 300 pipe main repairs), or the range of damage to laterals has been lower than that to pipe mains (Sapporo 2018) (10 lateral repairs versus 32 pipe main + appurtenance repairs). The rate of damage to service laterals will depend on the length of service lateral pipes (short pipes have less chance of damage versus long pipes); the style of construction of the service laterals (laterals with flexible joints adjacent to the pipe main will do better than those without such joints); the material of the service lateral (brittle cemented PVC pipe is more prone to damage than tougher HDPE pipe, stainless steel pipe, etc.); the influence of corrosion on the service laterals; the age of the service laterals; the extent service laterals traverse landslide, liquefaction or other PGD zones, etc.

- If we factor all these issues together, one might adjust the ALA (2001) model for nearly-new DI pipe to include a "young" corrosion factor of less than 1 (pipes under 20 years old might have about a 0.5 factor), with moderately old pipes (say 40 to 50 year old having a corrosion factor of about 1, and very old pipes in corrosive soils having a corrosion factor of 3 (or more). In areas with non-corrosive soils (say Burbank California, where depth of groundwater is commonly > 100 feet and soils are largely granular), the influence of age and corrosive effects is much lower. The effects of a "tight" water system might also be accounted for by an adjustment factor. While damage to 2-inch air valves appurtenances and < 1-inch service laterals often has less impact on pipe serviceability than pipe main failures (most of these appurtenance / lateral failures will open up leaks with equivalent cross sectional area of 1 square inch or smaller), the level of effort (manhours in the field, and related equipment) needed to make these repairs is not dissimilar to the level of effort to repair a 6-inch or 8-inch pipe main. Also, one must recognize that there are large uncertainties involved, and ALA notes that a factor of one-third to three times (lognormal beta = 1.15) is recommended for forecast of pipe damage due to shaking.

However the fragility analysis is pursued, for the case of Sapporo in 2018, the key points are as follows:

- The level of shaking in most of Sapporo was low.

- The number of pipe repairs in Sapporo outside of PGD zones (11 mains, 18 appurtenances, ~ 10 service laterals) was higher than the number of pipe repairs than a typical day (less than 1). All of this damage was repairable within 24 hours by the regular approach to repair water pipes by using outside contractors.

- There were no reported fire ignitions in Sapporo. A fire broke out at a Mitsubishi Steel manufacturing facility located within Nippon Steel and Sumitomo Metal's steel works in Muroran, according to the local fire department. This fire was quickly controlled by the fire department with no injuries reported. Muroran is a city of about 94,000 people, located about 100 km west of the epicenter.

- There were no water quality impacts.

5.4 Sapporo Kiyota-ku Pipe Damage due to PGDs

Figure 5-5 shows the Kiyota-ku area in southeast Sapporo where many structures and a few water pipes were damaged due to liquefaction.

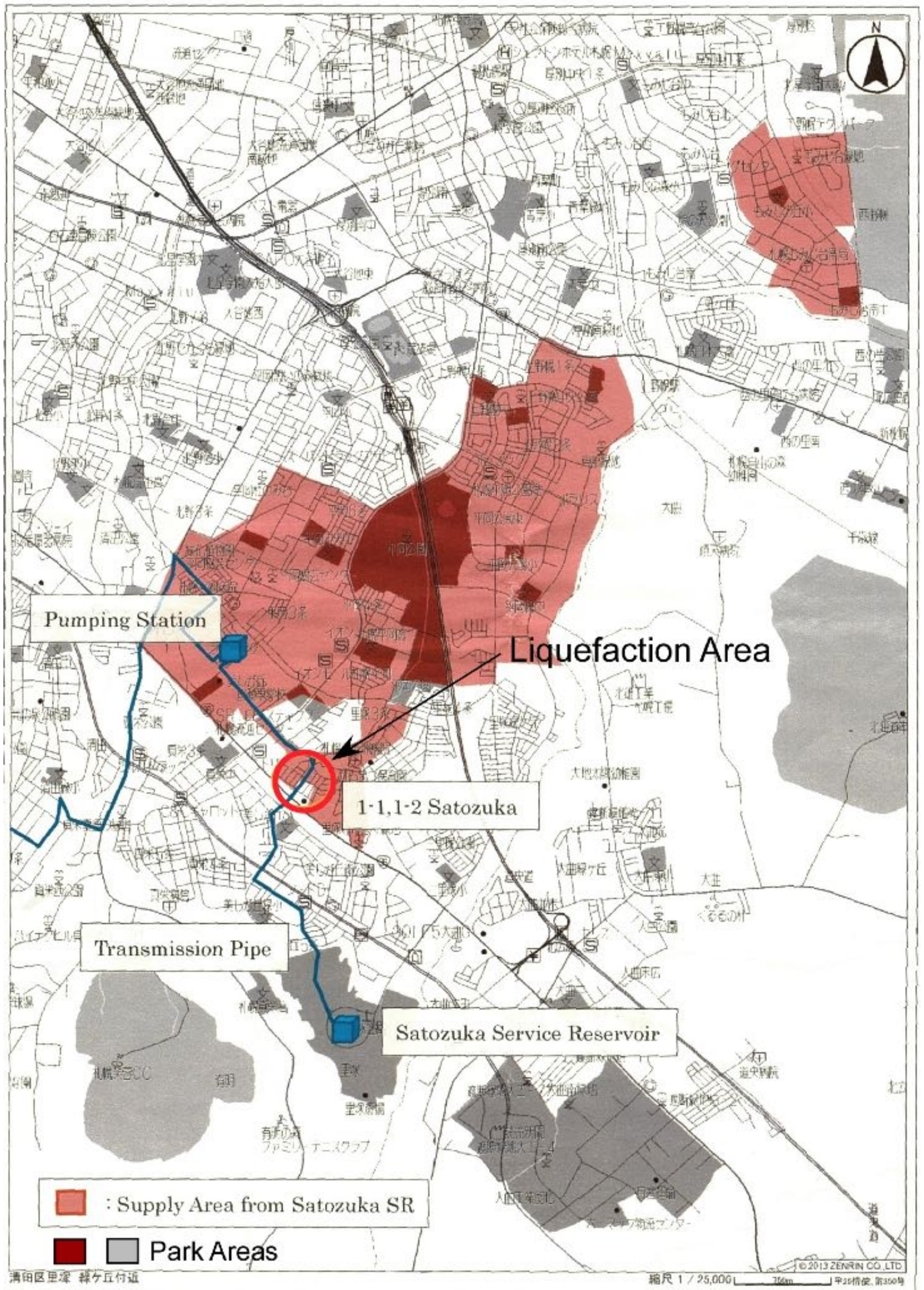


Figure 5-5. Map of Kiyota-Ward and Satozuka Pressure Zone

The light red area is the Satozuka water pressure zone, served by a single pump station and a single distribution reservoir. Within this area, a zone with severe liquefaction occurred in the so-called Kiyota Ward (highlighted by the orange circle in Figure 5-5). The heavy blue line is a 500 mm DIP transmission pipe (with K-type mechanical joints) that moves water from the pump station to the distribution reservoir; this pipe broke within the liquefaction area, resulting in emptying the Satozuka Service distribution reservoir.

Figure 5-6 shows a map of the Liquefaction Area (area highlighted in Figure 5-5).

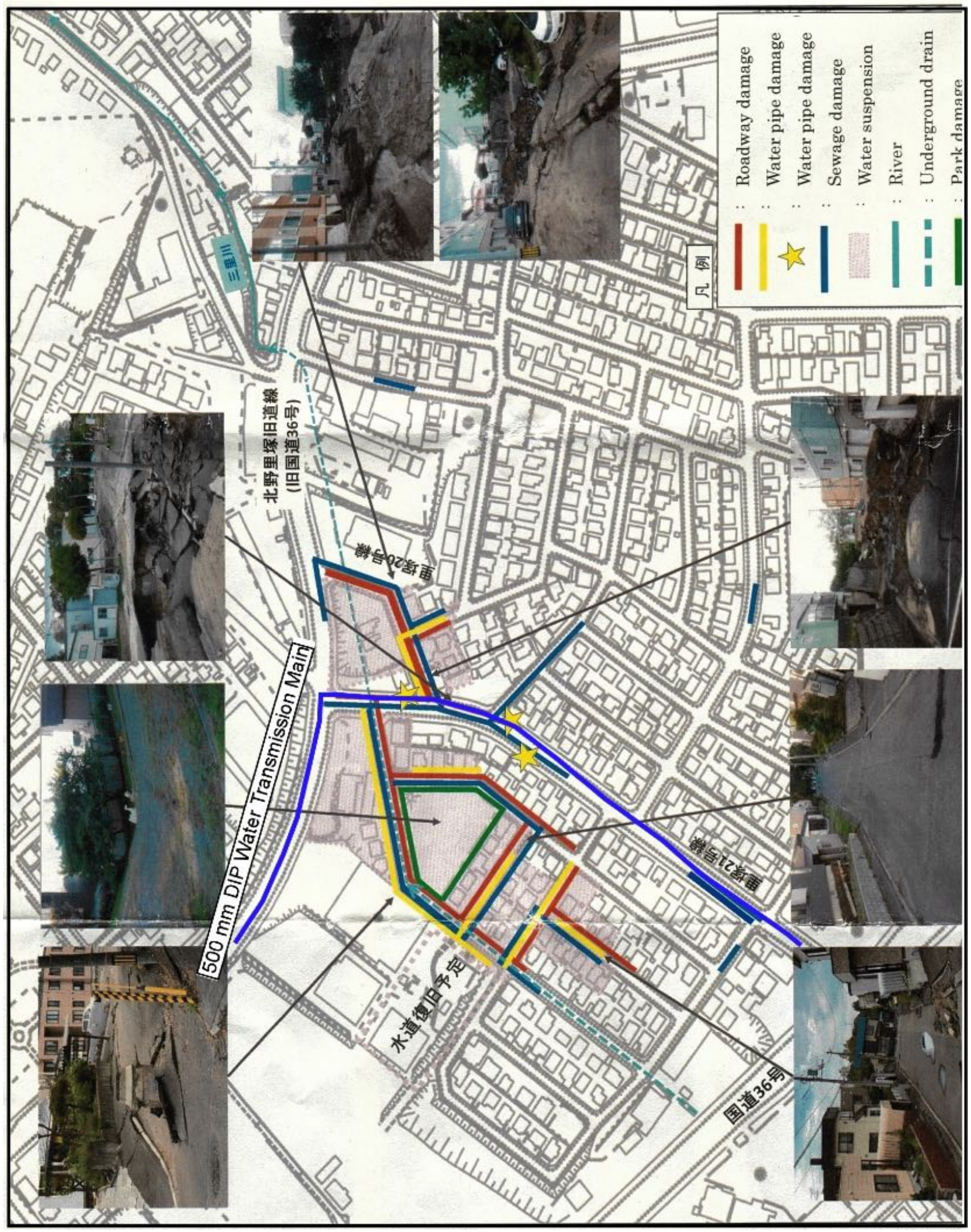


Figure 5-6. Damage in the Liquefaction Zone

The three yellow stars show the locations where the water pipes broke. The heavy blue line shows the route of the 500 mm DIP transmission water pipe through the liquefaction zone, between the pump station and distribution reservoir.

- Grey areas. These are the areas where water had to be cut-off due to damage to the water pipes.

- Building outlines. Essentially all buildings in this area are single family residential structures. Construction in this area began in 1978 – 1979. A few of these buildings were constructed on piles; these buildings suffered very little damage with the exception of damage to attached services. Most of the buildings were not built on piles; many of the buildings suffered heavy foundation damage (some tilted more than 30°). It is understood that there were no fatalities in this area. All the tilted buildings have been "red tagged", and the remaining buildings in the area have been "yellow tagged".

- Red lines. These are the roads that were damaged by liquefaction. The manifestations included subsidence (initially a few feet, increasing to several feet over the course of a month). All these roads will have to be re-built. When visited on November 15 2018, some of the roads were being rebuilt as follows: gravity retaining walls were placed adjacent to the roads; the right-of-way was built up with fill and gravel to make a level surface.

- Dark Grey Lines. These are sanitary sewers and manholes that have been heavily damaged. Inspection showed that these were filled with sand. It is likely that all these will have to be replaced.

- Yellow lines. These are water pipes that have been distorted, and will likely be replaced.

- There are no natural gas distribution pipes in the liquefaction area, but there is a 200 mm MDPE gas pipe that parallels the 500 mm water pipe (heavy blue line with text description) in the curved road. This gas pipe did not traverse the liquefaction zone and was not damaged.

- The park in the center of the area (five-sided area) suffered heavy settlement, on the order of 2.2 meters in the center of the park. A displacement meter was placed in the park after the earthquake, in order to monitor ongoing settlements or movements.

- Dashed line. This is the location of a storm drain that was installed circa late 1970s. This storm drain re-routed the original natural creek that drained the area.

Based on the observations, the likely process leading to the damage was as follows:

- In the 1970s a "cut-and-fill" process occurred to create a gently sloping area that could be developed for residential building. The original creek was diverted into a storm culvert. It is thought that the fill used to flatten out the former drainage consisted of nearby native materials, composed of volcanic ash; and the drainage was filled to a depth of about 6 meters. Sand was confirmed at the north side of the zone; but we did not do subsurface investigations to confirm the type of subsurface materials throughout.

- Houses and utilities were installed beginning in the late 1970s. With the exception of a few houses, no pile foundations were used for residential house construction. Regular style DIP water pipes (T-Type push-on joints or K-Type mechanical joints) were installed, without special seismic-resistant joints; both types of joints have limited capability to resist pipe pullout.

- For the month just prior to the September 6 2018 earthquake, there was heavy rainfall in the area, see Figure 2-9. This brought the ground water table up to near the surface.

- The level of shaking in this area might have been about PGA = 0.10g in the September 6 2018 earthquake (there are no recorded instruments within the affected area). This level of shaking was high enough to trigger liquefaction along the filled in area of the original drainage creek.

- The liquefied and-like materials were "piped away" and downhill (toward the northeast). This led to loss of support materials, and hence the observed major settlements.

Beginning in November 2018, the Sapporo Water Department took it upon itself to begin construction to re-route the 500 mm DIP transmission pipe outside of the liquefaction area. Prior to the earthquake, it is unclear if this area had previously been mapped as a "high seismic hazard zone" and this slated for prioritized installation of ER-DIP. With regards to prioritization, the water department noted that the original high priority was to replace non-seismic DIP with ER-DIP in areas north of the JR Sapporo station, considering that the corrosion hazard in the northern zones (peat soils) were more prevalent and had the original higher priority. It is unclear if the severity of this particular seismic hazard zone was well understood prior to the earthquake.

Figure 5-7 shows pictures of the damaged pipes. The location of the two southerly pipe failure pull-aparts coincided with the assumed edge of the filled in channel; in other words, the filled in channel moved downslope, and the pipe segment that transitioned from the stable materials adjacent to the filled zone simply pulled away from the pipe segment dragged down and somewhat sideways within the filled zone. The location of the third pull-apart pipe coincides with the location of the largest settlement within the center of the drainage, exceeding 1 meter; at that location, the adjacent pipe segments would have deflected in a manner so as to put great rotation demand on the adjoining joint, leading to its failure.

- Top Left, Top Right. Roadway damage observed over the damaged 500 mm K-type DIP pipe. See also Figure 5-8.

- Middle Left. Pull out of K-Type joint on 500 mm DIP. As originally installed, the male end would have been inserted all the way into the bell. As observed when the pipe was exposed, the edge of the male end was a few mm to the bottom of the restrainer flanges. The two flanges serve to form a compression joint to make a leak tight connection with some limited capacity to withstand pull out forces. See also Figure 5-8.

- Middle right. About 5 meters of 500 mm pipe were removed and replaced with a new DIP pipe. The new DIP pipe is encased in a polyethylene bag to provide corrosion resistance. Note that the original pipe (circa 1978) was not similarly encased. It is not certain that this area is particularly corrosive, but the practice to use plastic bags is now commonly used in the Sapporo water system. While the new pipe segment is a ER-type pipe, the adjacent pipes remain non-ER, so the pipeline as a whole remains vulnerable.

- Bottom left. Exposing a damaged 200 mm DI (T-type joint) pipe. See Figure 5-9 for the condition of the road above this pipe prior to its excavation.

- Bottom right. The 200 mm DI pipe make end has slipped out of the female end by about 6 inches.

Figure 5-7. Pipe Damage in the Liquefaction Zone (credit: City of Sapporo)

Figure 5-8. Damage to 500 mm DIP Pipe (credit: Kubota)

Figure 5-9. Damage to 500 mm DIP Pipe (credit: Kubota)

Figure 5-10 shows the relative vertical movements of a sewer manhole with the major settlement of the surrounding street. At depth, these relative movements will damage the sewer-to-manhole connection. In this area, inspection of the sewers showed major inundation by sand and debris.

Figure 5-10. Manhole in Liquefaction Zone (credit: Kubota)

The affected area is located near the foot of the Shika volcanic mountain. The ground elevations of the area range from 50 to 60 meters above sea level.

Figure 5-11 shows an interpretation of the situation in this area. The major settlements occurred along the red-dotted path, which is the historical location of the original drainage channel in the area. The photos on the left show the effects of settlements along the red-dashed line, often in excess of 1 to 2 feet initially post-earthquake, and increasing in time.

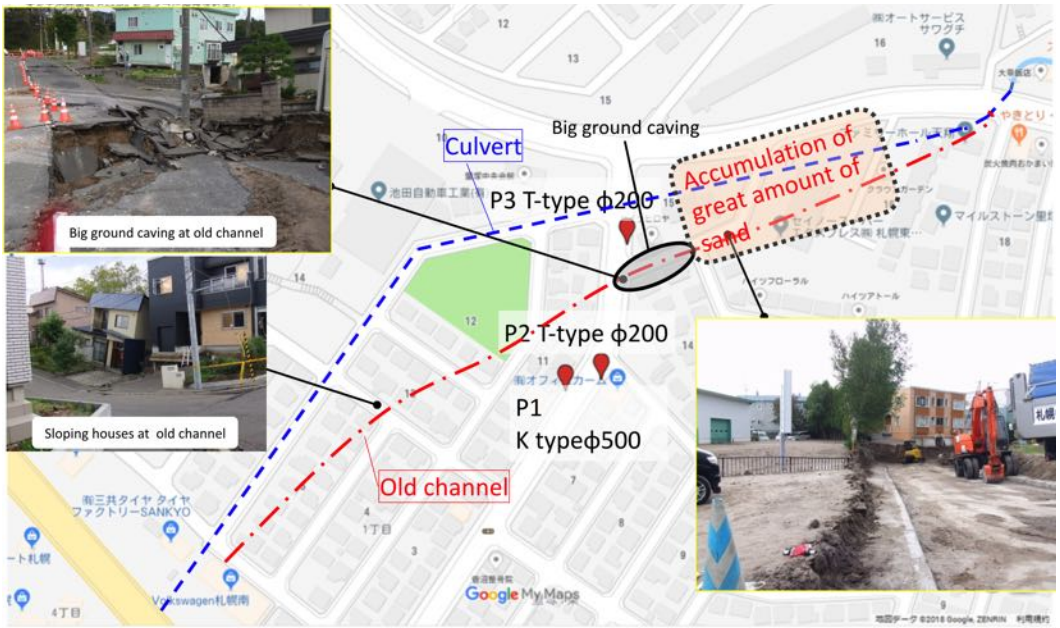


Figure 5-11. Pipeline Damage in Liquefaction Zone (credit: Kubota)

Figure 5-12 shows historical (1950) and present day (2018) topographical maps of the area. The blue dashed lines are the historical drainage channels. The small red oval is at the same location as the black oval in Figure 5-9.

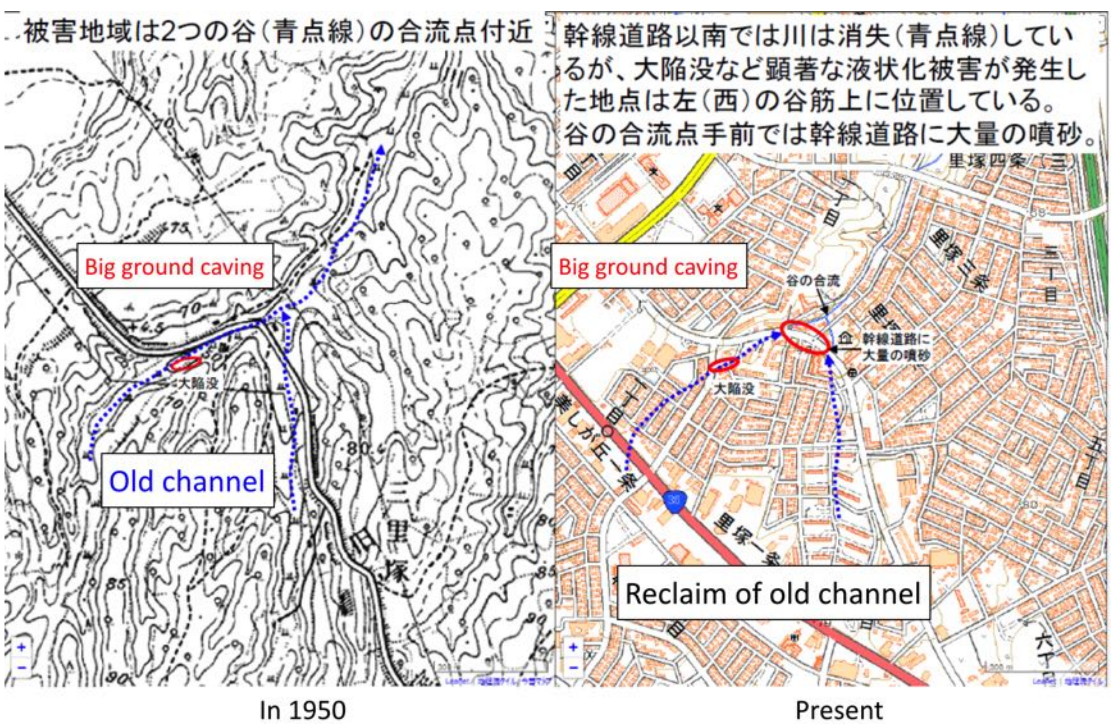


Figure 5-12. Historical Location of Drainage Channels (from [http://home.kanto-gakuin.ac.jp/~wakamatu/wakamatsu/reports/satozuka_report.pdf(2018.9.28](http://home.kanto-gakuin.ac.jp/~wakamatu/wakamatsu/reports/satozuka_report.pdf)))

A survey of this area done on September 14 2018 indicated the following statistics:

- 311 residential houses
- 62 houses: red tagged (dangerous, occupancy not allowed)
- 47 houses: yellow tagged (warning, temporary occupancy to remove items, etc. only)

Summary. In this area, the culvert placed to divert the original drainage was placed at the northern part of the area, outside of the original drainage. It is thought that this culvert was possibly not capturing carrying all the water of the original drainage; possibly it was even leaking. The original drainage likely was flowing water due to the heavy rains of the preceding 36 days (see Figure 2-9). The original drainage materials were likely volcanic ash, granular in nature, and with little post-liquefied strength. The shaking of September 6 2018 liquefied these materials. With the natural slope of the side, and with the ongoing water flowing through the original drainage, the fill materials migrated downslope, leading to major settlements in the area. The resulting settlements broke underground water pipes at three locations, destroyed underground sewers, destroyed significant parts of the surface roadways, and destroyed or heavily damaged many residential structures. More than 30 HEPCO low voltage distribution concrete poles were located within the settled area, and most of these poles were tilted some sand a few feet); none fell over.

5.5 Other Pipe Damage in Sapporo

Figure 5-13 shows repairs being made to a water service line in northern Sapporo.

Figure 5-13. Service Line Repair, North of JR Sapporo Station (credit: Kubota)

5.6 Restoration of Water Service

The City of Sapporo reported that all pipe repairs were completed within one day after the earthquake. All repairs were made by outside contractors, supervised by Sapporo staff, as is the common practice in Sapporo (the City of Sapporo does not have its own internal pipe repair crews).

Power outages in the City were typically about 5 hours in duration on the southwest part of the city (downtown core area), and about 24 hours in duration on the east side of the city (more outlying residential areas). The cause of these outages was power curtailment by HEPCO, due to the loss of generation and network issues, as outlined in Chapter 3 of this report. In nearly all locations (except locally in a severe PGD zone in Kiyota-ward), there was no damage to electric system infrastructure inside of Sapporo City. These power outages did not greatly impact the water system, in that there were emergency generators available at the water treatment plants, some emergency generators at some pump stations (but not all), and sufficient storage in elevated distribution treated water reservoirs to outlast the power outages (except for the reservoir serving the damaged area in Kiyota-ward). See Table 9-9 for a more detailed breakdown of the restoration of water supply in Sapporo and other cities and communities.

5.7 Sapporo Water System Earthquake Response Plan

The City of Sapporo has recognized that earthquakes play an important role in the design of a water system. The 2018 earthquake was a small-to-moderate earthquake within Sapporo.

The City has adopted the following earthquake targets for the "design basis" earthquake.

- Assume intensity JMA = 7 everywhere.
- Assume 2,300 pipe repairs if the entire city is exposed to JMA 7
- Target restoration times:
    - 1 to 3 days. Provide up 3 liters per person per day for drinking purposes. Accomplish this through use of 38 buried emergency water tanks, scattered throughout the city (5 more buried emergency tanks are scheduled to be built). Each of the buried emergency tanks holds about 100 m^3 (36,000 gallons).
    - 5 to 10 days. Restore 20 liter per person per day (drinking + bathing + flushing toilets).
    - 11 to 20 days. Restore 100 liters per person per day.
    - 21 to 28 days. Regular service.

5.8 Atsuma WTP and Atsuma / Biratori Pipeline Damage

The town of Atsuma recently constructed (2016) a new water treatment plant. This plant takes raw water from the nearby river and delivers potable water to the residents of Atsuma. Figure 5-14 shows a recent winter-time photo of the plant, looking to the north.

Figure 5-14. Atsuma New Water Treatment Plant (Tomisato) (photo credit: http://www.maruhiro-nozawagumi.com/sekou.html)

Figure 5-15. Landslide Impact on Atsuma WTP (credit: Google)

Figure 5-16. Landslide Impact on Atsuma WTP, Oblique View (credit: https://www.jiji.com/jc/article?k=2018091200862&g=wth)

The earthquake triggered a landslide just behind (and to the north) of the WTP. The hillside to the immediate north of the WTP ranges in elevation from about 56 to 145 meters above sea level over a horizontal distance of about 100 meters, making the average slope about 40°. The landslide debris moved nearly horizontal about 200 meters, dropping over that elevation by about 10 meters, until it inundated the river to the south of the plant.

The landslide inundated the WTP. The debris of the slide impacted each of the structures. On the west (left side of Figure 5-14), debris hit the tank, forming a high debris scar on the up-hill side; the tank stayed in place. The debris hit the "stair building" used to access the roof of the tank; the building was pushed over 50 feet to the southwest, uprooting its pile foundation. The debris hit the water treatment plant building (filters, offices, etc.), inundating the building.

We inspected the site on November 15 2018. At that time, no effort had begun to remove the landslide debris or otherwise repair the plant. It is uncertain if this plant will be ultimately repaired or abandoned. We questioned the City of Sapporo water department as to whether it was likely that the landslide risk had been factored into the original design requirements; it was suggested that up to the time of this earthquake, the potential for earthquake-induced landslides in the area was not recognized.

After the earthquake, the town of Atsuma restarted its older Shinmachi water treatment plant.

Within the town of Atsuma, there was also damage to buried water pipes. Figure 5-17 shows two removed 200 mm DIP pipe elbows (A-Type). Figures 5-18 and 5-19 show the location of a damaged 150 mm PVC pipe. The roadway failed (possibly an embankment slump), leading to the damaged pipe. Repairs were made using GX-type ER-DIP.

Figure 5-17. Removed Elbows of 200 mm DIP (credit: Kubota)

Figure 5-18. Location of damaged 150 mm PVC Pipe (credit: Kubota)

Figure 5-19. Removed 150 mm PVC Pipe (credit: Kubota)

Figures 5-20 and 5-21 show the damage to a 150 mm K-type joint DIP in the town of Biratori.

Figure 5-20. Slump of roadside embankment in Biratori-town (separation at edge of asphalt is about 5 inches) (credit: Kubota)

Figure 5-21. Pull-out of K-type joint for 150 mm DIP near road embankment slip in Figure 5-17 (credit: Kubota)

5.9 Atsuma Irrigation Project

In about 2016, a new Apporo Dam was constructed (locally called the Yuza Yutaka / National Yufutsu East Land Water Project). This new dam allowed more water to be stored. The original (top right) and new (lower top right) reservoirs are the two lakes near the top right of Figure 5-22. Water is diverted at the outlet works of the new Apporo dam into large diameter pipes (length 82.1 km) and canals (length 8.8 km) and then delivered to various downstream farms for irrigation purposes.

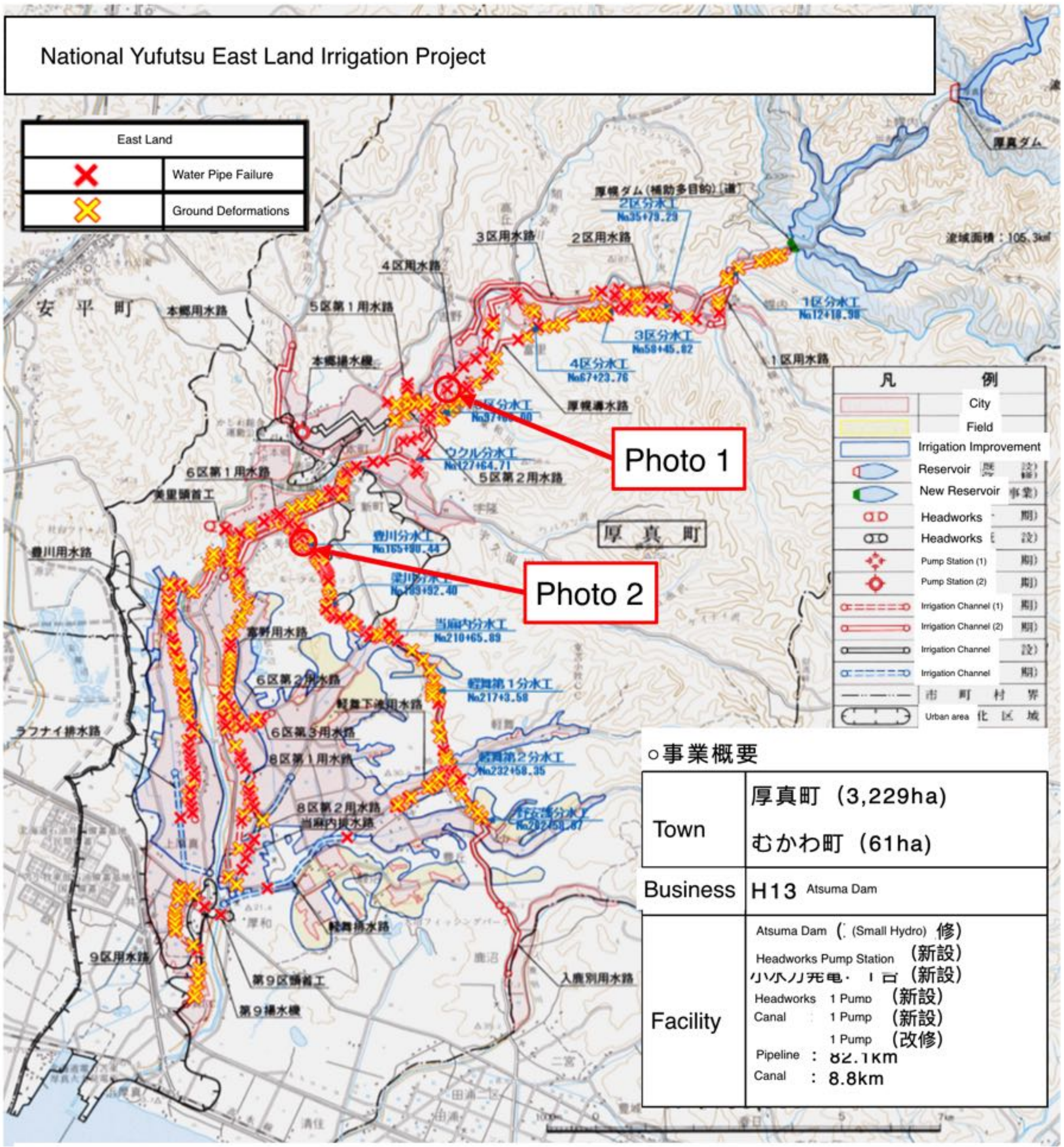


Figure 5-22. Atsuma Irrigation Project (Credit: MILT)

Figure 5-22 shows a map of the upper Atsuma and lower Apporo reservoirs (top right) and the downstream pipelines. The red "X" locations show where the pipelines were damaged. The yellow "X" locations show where there was ground deformations observed at the surface. The estimated cost to make all the repairs is about $185 million USD (20,500,000,000 Yen). Figures 5-23 and 5-24 show the ground deformations at the locations called "Photo 1" and "Photo 2) in Figure 5-22.

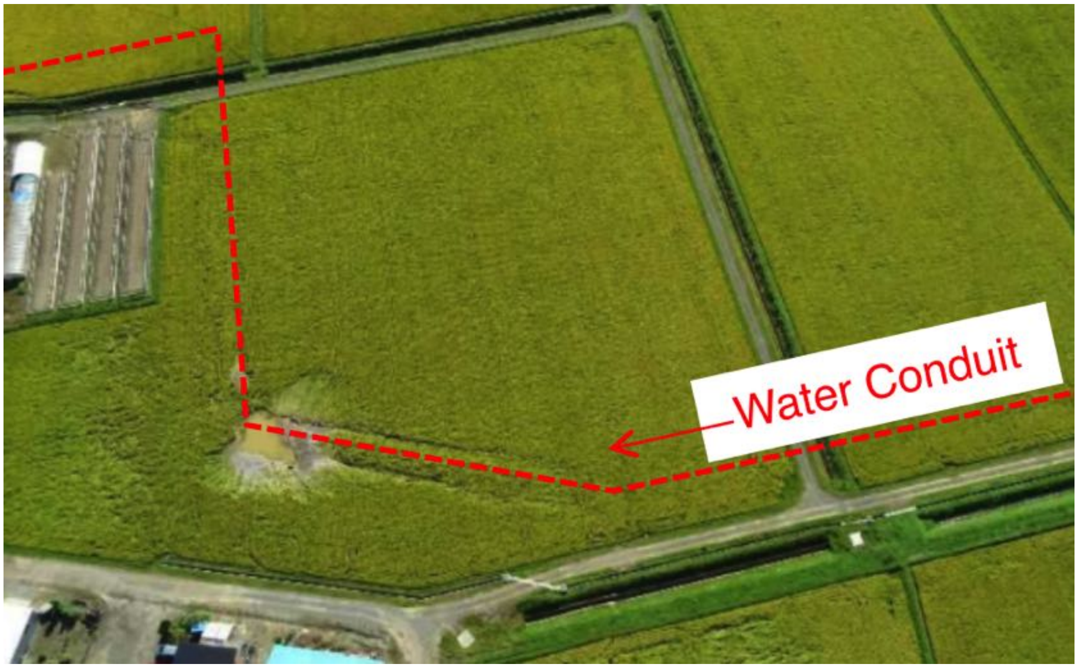


Figure 5-23. Pipe Failure (Photo 1) (Credit: MILT)

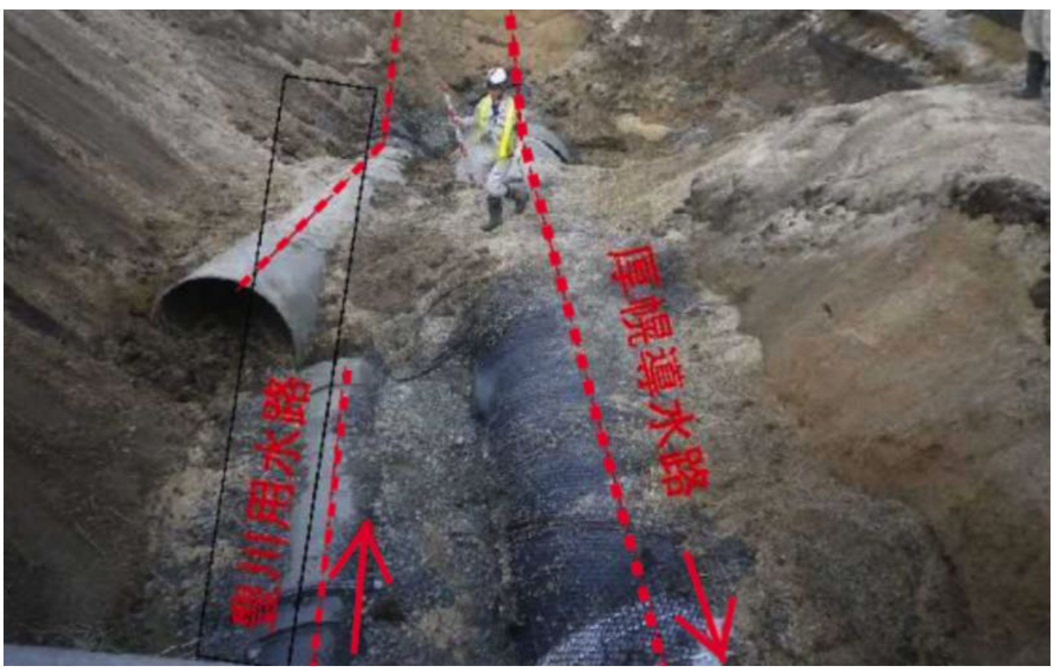


Figure 5-24. Pipe Failure (Photo 2) (Credit: MILT)

The pipes shown in Figure 5-24 are 1.5 meter diameter fiberglass pipe (GRP). These are low pressure pipe, connected using rubber "push on" joints. The ALA (2001) fragility model is RR = $k_2 * 1.06 * PGD^{0.319.}$ We did not examine the detailed engineering characteristics for these pipes, but it is thought that the irrigation water delivered by these pipes was under open channel flow.

The total number of repair locations was about 100. The repair rate is about 100 / 90.7 km = 1.1 per km. Assuming that 25% of the area underwent 2 inches of settlements, then the forecast number of repairs would be (using the backbone fragility model for rubber gasketed pipe, k_2 = 1.0): RR = 1.06 * (2)^0.319 = 1.32 repairs per 1,000 feet. This suggests that about (100 / 1.32) * 1000 = 76,000 feet (23 km of the 82.1 km) of the alignment underwent some type of ground deformation. Given the widespread observations of some surface manifestation of PGDs (large number if yellow "X"s in Figure 5-14), it might be suggested that k_2 for rubber gasketed GRP is less than 1.0. Alternatively, if the pipes were buoyant (the pipes are under gravity flow and not entirely filled with water), then the liquefaction in the area would have tried to float the pipes, which also would result in a great amount of damage, as clearly the pipe joints are unable to sustain much differential movements.

A possible repair strategy would be to excavate the damaged pipes and relay them, possibly with repaired joints. This will save cost in terms of re-using the pipe barrels; however, the pipes would remain vulnerable to repeated failure in future liquefaction events. One lesson learned is that lightweight pipes under open channel flow should not be selected in ground areas subject to liquefaction.

5.10 Landslides at Dams

Figure 5-25 shows the extent of landslides around Atsuma Upper Reservoir. Three landslides (red zones) were mapped directly adjacent to the waters of the reservoir. A large landslide at the south abutment of the earthen dam deposited a lot of debris into the concrete-lined spillway. Removal of this debris was a priority of the MILT TEC force teams in the days immediately after the earthquake, Figure 5-26.

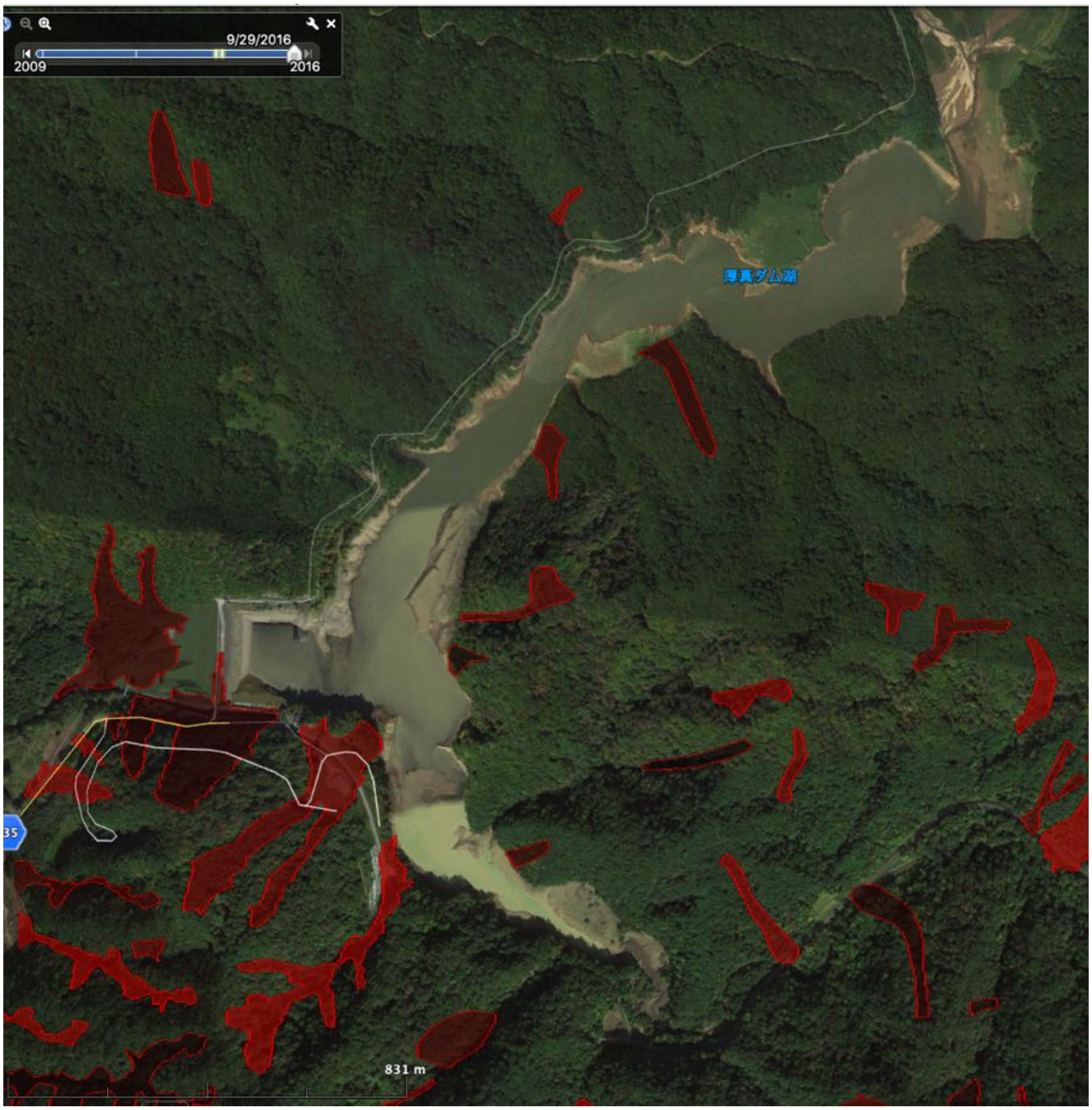


Figure 5-25. Landslides (Red highlighted areas) Near Upper Atsuma Reservoir

Figure 5-26. Repair of Spillway, Upper Atsuma Reservoir (Credit: MILT)

The following describes the damage in Figure 5-26:

- Top Left. Before the earthquake. Earthen dam. Concrete-lined spillway is at the right (south) abutment.
- Middle Left. Before the earthquake. Concrete lined spillway.
- Bottom left. This aerial photo was taken immediately after the earthquake. The arrow pointing upwards shows the location of many fallen trees into the spillway. The arrow pointing downwards shows the location of much sediment that was deposited into the spillway.
- Top Middle. View of the upper spillway with a lot of fallen trees. Photo is taken September 7 2018.
- Bottom Middle. View of the upper spillway after removing the trees. Photo is taken September 12 2018.
- Top Right. Beginning of effort to remove the debris. Note there are three large excavators working within the spillway. Photo is taken September 13.

- Bottom Right. End of effort to remove the debris. Photo is taken September 29.

Figure 5-27 shows an aerial view of the area immediately downstream of the Apporo Lower Reservoir (see Figure 3-19 shows a GIS-based map of these landslides). The light areas show the scars on the hillsides from earthquake-induced landslides. The water in the reservoir (right of the concrete gravity dam) is turbid. About 50% of the hillsides slid in this area.

Figure 5-27. Landslides (Scar Areas) Below Lower Atsuma Reservoir (Credit: GEER)

Figure 5-28 shows landslides near Mizuho Reservoir. The yellow dots are the locations of towers supporting twin 275 kV transmission lines, and the circled dot is the location of a tower that is immediately adjacent to a landslide. Red polygons show locations with major earthquake-induced landslides, of which 8 separate slides inundated the reservoir. The yellow rectangle shows the location of the bridge seen in Figure 5-29. The two yellow dots above and to the left of the rectangle are transmission towers with bases *outside* the mapped landslides, as seen in Figure 5-29.

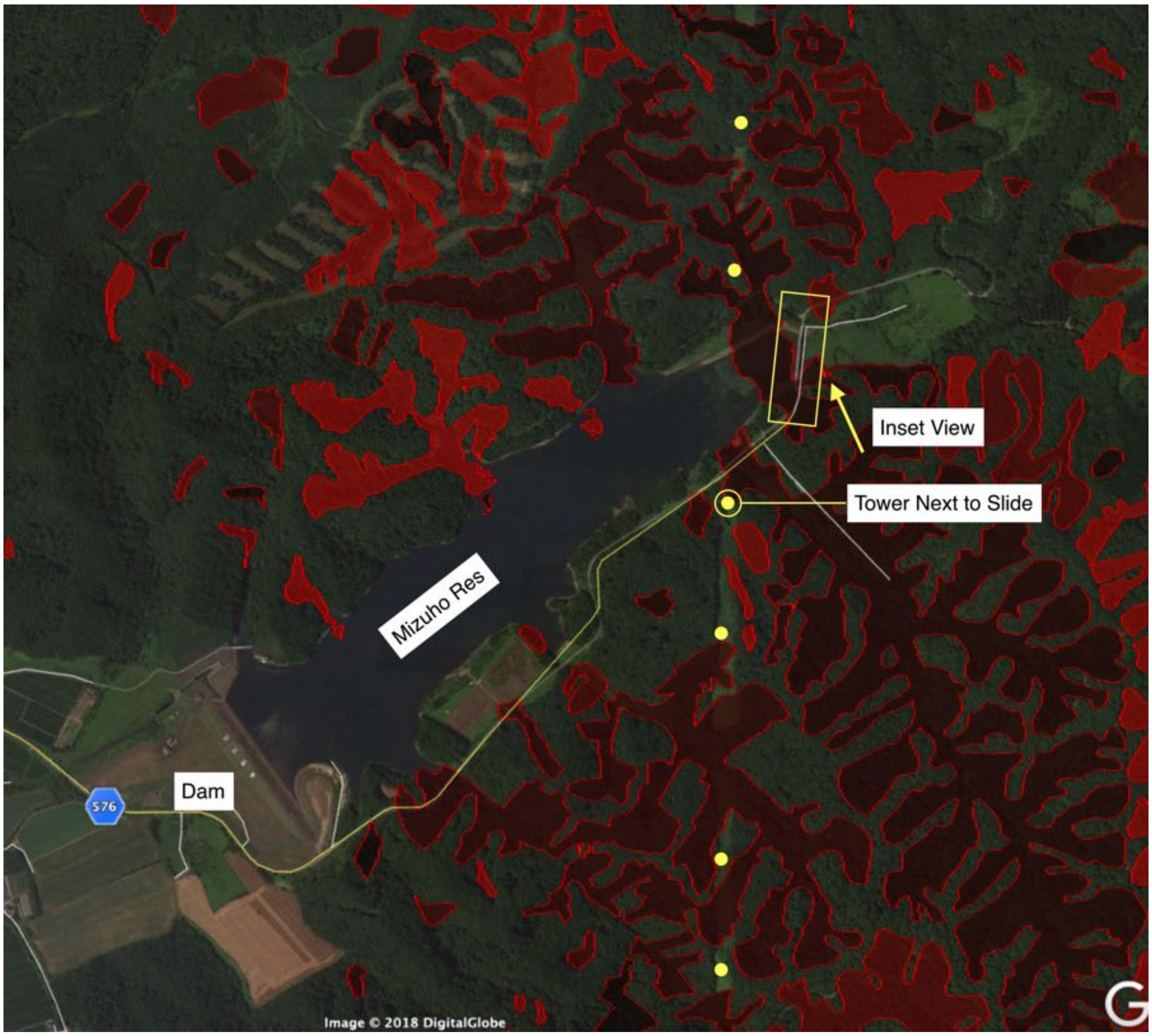


Figure 5-28. Landslides (Scar Areas) Near Mizuho Reservoir (latitude 42.8469, longitude 141.9123)

Figure 5-29 is taken from the east end of Mizuho reservoir, looking westerly towards the dam in the distance. This photo was taken in mid-October 2018, after the reservoir was drawn down. Landslide debris is seen in the foreground. The inset image shows the bridge at the east end of the dam; the landslide debris to the left (west) of the bridge is from two slides either side of the reservoir. The access road on the south (lower left) of the bridge was destroyed by the landslide. The landslide debris into the reservoir will increase turbidity of the water supply.

At the time of the earthquake, the reservoir was reported to have been nearly full. The landslide debris is not known to have caused waves that overtopped the dam.

Figure 5-29. Landslide Inundation into Mizuho Reservoir (photo: PG&E)

Figure 5-30. Access road destroyed by landslide at Mizuho Reservoir (photo: PG&E)

5.11 Pipe Replacement for US and Canadian Water Utilities

This earthquake, and many other earthquakes worldwide, exposed the primary vulnerability of water utilities: damage to buried pipes. In the US and Canada, the vast majority (>99%) of buried water pipes have been installed without any seismic requirements. This "Achilles heel" of water systems remains a serious weakness.

One brute-force way to solve this weakness is to replace these vulnerable non-seismic pipes with new, seismic-resistant pipes. In the USA, the major "code writing" organizations, namely the American Water Works Association (AWWA) and ASCE, remain nearly silent on this topic. Neither AWWA or ASCE have code-style "standards" for seismic design of water pipes; in fact, the AWWA manual for the design of steel pipes (M11 2004) ignores seismic loads; for example, the details for welding girth joints for steel pipes as outlined in AWWA M11 would result in girth joints with much less capacity that the main barrel of the steel pipe, thereby undermining much of the potential ductility of steel pipes; so the continuing use of M11 for design of steel pipes propagates the installation of more badly-designed pipe from a seismic perspective.

Reflecting these issues, a task group was organized in 2000 under the auspices of the American Lifelines Alliance (ALA). That task group developed reports covering two topics: "Water Pipelines Fragility" (ALA 2001) and subsequently the "Guidelines for Seismic design of Water Pipes" (ALA 2005). Today (2018), the 2005 Guidelines remain the only document in the USA that gives comprehensive guidance as to how to approach the design of new or replacement water pipes for seismic issues. That task group made a conscious decision to call the 2005-document "Guidelines" rather than a "Standard", meaning that the task group intended the Guidelines to be entirely voluntary. Why were they made voluntary?

The task group, being composed of engineers from water utilities, consultancies and universities, were especially worried about the cost effectiveness of pipeline replacement strictly for seismic reasons. The task group's concern was that while there are definitely newer water pipe materials and designs (for example, Kubota's seismic resistant "chained" ductile iron pipe Figure 5-31, HDPE Figure 5-32, etc.) that can be extremely reliable to accommodate high levels of ground shaking and moderate to large permanent ground deformations, the installation of these pipes will be expensive and capital intensive. The incremental benefits these seismic-resistant pipes bring derive from avoiding earthquake-induced water outages for earthquakes with rather long return intervals. For new subdivisions, the incremental cost of seismic-resistant pipes versus "standard non-seismic-resistant" pipes might be very small (or nil), and it makes good economic sense to use them in seismic prone areas. For replacement of older existing pipes, the cost of the seismic-resistant pipes might not be cost effective, when considered on a full life cycle basis, with the alternative of the "do-nothing" alternative coupled with a reasonably well thought out emergency response plan to deal with broken pipes after a rare earthquake.

It is this author's observations that essentially no US water utility serving a moderate-to-large community (say about 1,000,000 people or more) is truly prepared to ramp up to several thousand people to take care of all the pipe damage and its ancillary effects that an earthquake can cause. Most water utilities serving a population of 1,000,000 people are easily able to manage repair for one or two pipe breaks per day using its regular manpower and equipment and spare part resources; with few economic impacts and few customer complaints; but few (if any) water utility can manage a situation where several thousand pipe repairs must be dealt with simultaneously. This will lead to long restoration times for water service. Even "industry leader" water utilities like EBMUD still face, as of 2018, the potential for several thousand pipe repairs in a single future earthquake, and with manpower limitations, restoration times to reach nearly 100% restoration of water service might take many weeks (or months). For the customers without water for weeks to months, the economic impacts will be large, and customer anger at the water utility might become unbridled. If one ignores the political issues of public versus private ownership of water utilities, the public might perceive incompetence on the part of the affected water utility's management if widespread outages last much longer than a few days; worse, if unchecked fires turn into conflagrations, one could easily imagine public outcry that water utility leadership should be "hung from the yard arm" or its modern day equivalent; with corresponding lawsuits. Whether any post-disaster use of the court system will result in much good (other than filling the lawyers' pockets with gold at the expense of the public), remains a topic open to debate.

It would appear that to avoid negligence, modern-day water utility leadership should inform and quantify for themselves of their earthquake exposure, and then make informed decisions as to how to proceed. If one takes a prudent long term course of action, one could be inoculated from the charge that the modern-day investor-owned water utility has "lined its pockets" at the expense of its customers[6]. In some fashion, water utility leadership can quantify whether the "no pipe replacement / rely on post-earthquake response" approach (lower initial capital cost for customers, but larger post-earthquake economic losses) is a more cost effective long term strategy than a "do some pipe replacement / have a good emergency response plan to deal with residual weaknesses" approach.

What the public does not easily grasp is that the economics of pipeline replacement with seismic resistant pipe is a costly business. And yet it is up to today's water utility leadership to understand these economic issues, and then make an informed decision as to whether, or not, to replace old and seismically-weak pipe with new seismic-resistant pipe. This type of program, for a community of 1,000,000 people in California, could cost around \$7.6 billion dollars. For example, if the average pipe diameter is 8 inches and a community of 1,000,000 people has 3,000 miles of pipe to be replaced, and the average cost of replaced pipe is \$60 per inch-foot, then a full pipe replacement program will take about \$7.6 billion dollars (in constant 2018 dollars). This translates to a capital cost per

[6] Public-owned utilities which do not invest in pipe replacement may also be similarly guilty of failing to protect the public in a cost effective manner.

capita of about $7,600. If one amortizes this capital cost over 15 years, the capital cost per capita per month is about $42. For an average household of 2.5 people, this translates to a capital cost on the order of $100 per month. Most likely, the rate-paying public will not happily embrace a doubling of the water rates.

This suggests that a smarter approach for pipe replacement is needed than a simple "brute force, replace it all" strategy.

Excluding seismic issues, there are three other reasons for water utilities to replace pipe. These include:

- Water pipes continue to age, and with time, water pipes will deteriorate due to the effects of external and internal corrosive attack, erosion and damage to internal liners, tuberculation. When this accumulated damage becomes severe enough, resulting in a pipe repair rate much in excess of about 0.3 to 0.5 repairs per mile per year, it will clearly become cost effective to replace these old pipes. There is no single "replacement time cycle" applicable to all pipes; in passive soils, a well-constructed cast iron pipe installed in 1910 might remain economically viable for 200 years or longer, whereas the same pipe installed in aggressive soils might remain economically viable for only 30 years or less. Water utilities that replace older cast iron pipe that have been experiencing relatively low repair rates (much under 0.10 repairs per mile per year) are probably replacing pipes too quickly / in a non-cost-effective manner, if one ignores concurrent seismic issues.

- Water pipes also need to occasionally be replaced due to changes in water demand (peak demand or fire flow demands).

- When new highways are built or streets re-routed, older pipes often need to be replaced or rerouted.

It is beyond the scope of this report to examine all these pipe replacement issues. The author has written on the economics of replacing pipe due to a combination of seismic and aging-related issues, see (Eidinger 2010, 2015, 2016). Many US water utilities replace about 0.2% to 0.4% of their pipe inventory, per year, based on non-seismic issues, and the capital costs for such replacement are already "baked in" to ongoing water rates. What is often apparent in these ongoing pipe replacement programs, is that most (but not all) of water utilities continue to replace the older pipes with newer non-seismic pipes. Thus, these water utilities are making the potentially costly mistake that they are making little or no improvement for seismic issues, even if the differential capital cost is tiny or nil.

The omission by some water utilities to adopt ALA 2005 (or similar) as part of their ongoing work when pipes are being replaced for non-seismic issues is only "punting" the problem down the road, and is likely a non-cost effective strategy in seismic-prone regions. Water utilities in high seismic regions (including much of California, Oregon, Washington, Alaska, Utah, New Madrid Zone, Charleston Zone, all of Vancouver Island, the Lower Mainland of British Columbia (including communities from Vancouver to Abbottsford) should be encouraged to adopt ALA 2005 (or similar) as being an example of sound economic and management practice. If a water utility develops a capital budget to replace between 0.5% to 1% of its pipe inventory per year, then over a 30 to 75 year time frame, the majority of the seismic weaknesses of buried pipes can be eliminated, with the residual vulnerabilities addressed though an aggressive and well thought out emergency response plan.

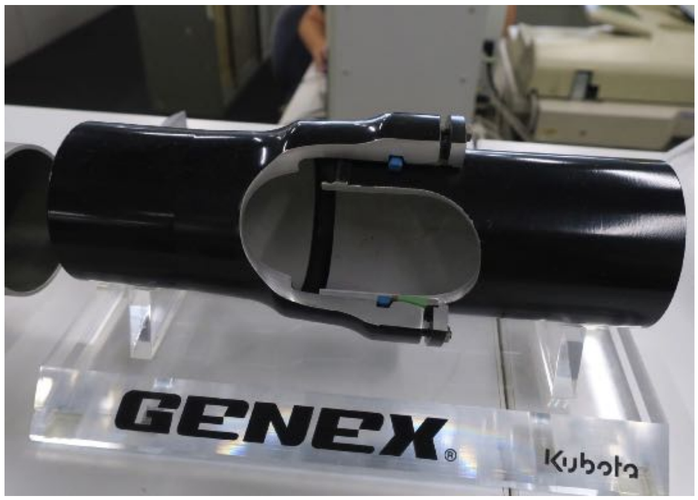


Figure 5-31. Kubota Chained Seismic Resistant Ductile Iron Pipe

Figure 5-32. Seismic Resistant High Density Polyethylene Pipe Using Electric-Fusion Joint Coupling System

5.12 References and Acknowledgements

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6.0 Telecommunications

6.1 Description of System

The three major telecommunications service providers in Hokkaido are NTT East, KDDI, and Softbank. They provide landline, wireless, and Internet services. The trade names of different services are all different from the parent company. NTT East has the biggest market shares in all sectors of the services in Hokkaido. The other service providers are UQ Communications (UQ コミュニケーションズ), and Wireless City Planning (ワイヤレスシティプランニング).

NTT network topology is the same all over Japan. With respect to NTT, the company always takes advantage of network expansion and upgrades to include adding alternative links to critical nodes to enhance network resiliency. Both mesh and loop techniques are incorporated in the additional links. That is, redundancy is created without intentionally adding links to the existing network. The proprietary system control called MaRIA is one of the key elements of reducing network congestion after a major disaster. The 171 service reduces call volume between the disaster impacted area and the external community. These system controls are reasons of good performance and quick recovery.

Under normal operations, essentially all telecommunication services rely on power supplied by the local power company. To increase system reliability, many telecommunication sites (but not all sites) therefore include on-site battery systems, usually designed to accommodate short power outages of up to a few hours or so. Even in developed countries like the USA, Canada and Japan, only a small portion (commonly on the order of 25% or so) of sites like cell phone sites have permanent on-site emergency generators, capable of providing power for longer duration outages.

It has been recorded many times in prior earthquakes around the world that telecommunication services, particularly wireless services, are often interrupted due to two major reasons:

- First, and most common, Power Outages. Concurrent power outages by the local power company. In this September 6 2018 earthquake, there were widespread power outages, and many telecommunication sites did not have sufficient backup power (or efficacy of emergency response) to keep local batteries charged during the power outage. The result was that there were communication outages.

- Second, and quite common. Call saturation. After an earthquake, there will commonly be a huge increase in calls, often far in excess of the capacity of the phone system.

- Third, Inertial failures. In this earthquake, we did not observe inertial failures. Battery racks are well braced. Telco buildings are well designed for shaking.

Communication racks and the equipment within are well braced and sometimes shake-table qualified.

- Fourth. Small PGD-type failures. Some small-PGD-type (PGDs commonly under a foot or so) failures are easily mitigated, such as providing suitable slack at bridge abutments to allow bridge-supported cables to remain undamaged when abutments settle. The best way to mitigate this vulnerability is during initial installation, by including suitable standardized details.

- Fifth. Large PGD-type failures. Some telecommunication equipment may be installed in areas prone to large PGDs, such as major landslides. It will often be outside the responsibility of the Telco to mitigate the landslide (or liquefaction zone or surface faulting zone), as the land is not owned by the Telco. In this earthquake, landslides did destroy some overhead wire systems supported on poles owned by HEPCO.

It is clear to the authors that the Power Outage issue does not yet seem to be entirely addressed. It is obvious that a good long term solution is to rapidly bring in a sufficient number of mobile power generators, along with the emergency response logistics to deploy and fuel them, in order to keep the vast majority of the telecommunication system running throughout the post-earthquake recovery process. The authors have recommended this solution in many prior TCLEE reports, and we continue to make this recommendation in this report.

In Hokkaido, NTT commonly deploys the mid-zone Base Station (with backup power) to cover the smaller Base Station (usually without backup power). This arrangement is thought to be satisfactory to address short-duration local-area power outages; while allowing that call saturation might still occur.

6.2 Overview of System Performance

The telecommunications system in general performed well in this earthquake. The quick recovery of components damaged or destroyed by landslides and permanent ground deformation was a result of lessons learned from the 2011 Great East Japan Earthquake and Tsunami. The speedy set up of mobile power generators within Sapporo and the earthquake impacted areas also contributed to the overall good performance of the telecommunications system.

Commercial electric power caused many service interruptions all over Hokkaido, Figure 6-1 provides a view of the impact power outage had on NTT services. The pockets of red and dark grey areas are the most populated areas. The grey areas are where there was no phone service on September 8. The red areas are the locations that NTT brought in mobile power generators to provide essential services. In some areas the demand of telecom services was much higher than capacity (call saturation limitations).

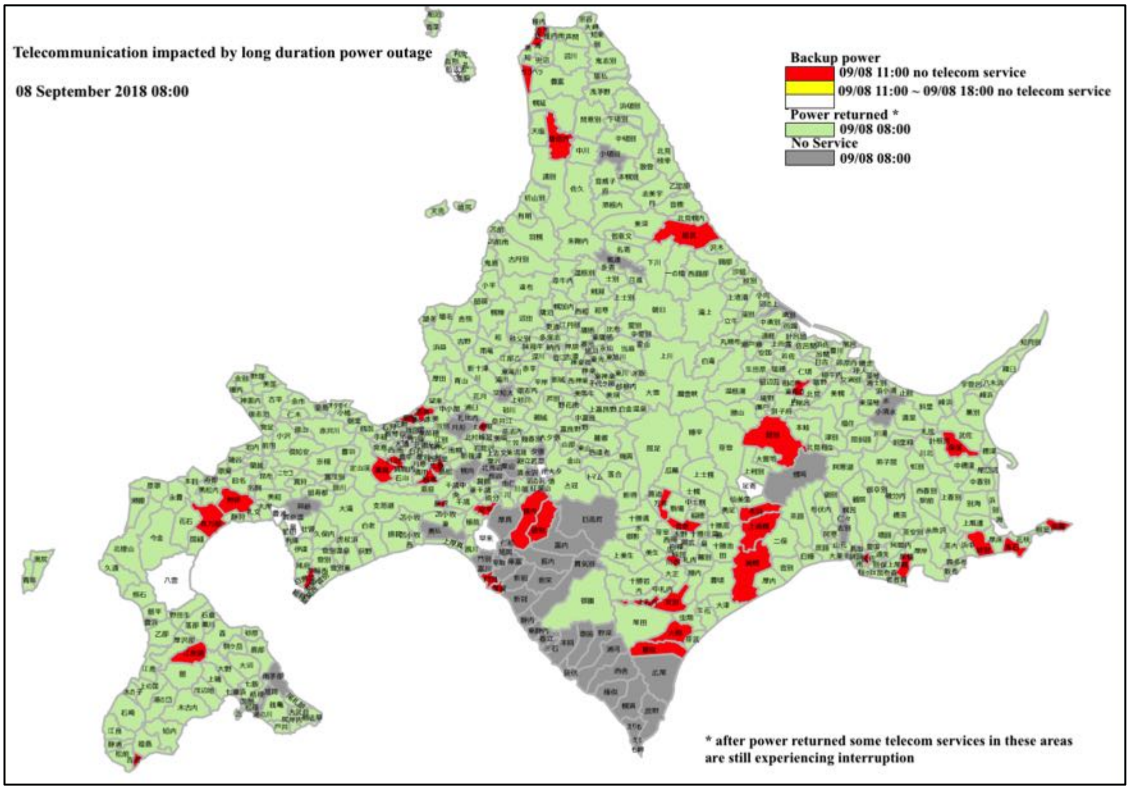

Figure 6-1 NTT electric power situations on September 8 two days after the earthquake.

6.3 Landline Network Damage

The landline network sustained significant damage in this earthquake due to the extensive landslides that destroyed the utility poles burying both copper and optical fiber cables with mud, sand and debris. Figure 6-2 shows one of the many examples of landslide that destroy the cable links.

Figure 6-2. Telecom poles and cables (metal and fiber) destroyed by debris

The landslides in the rural areas of Atsuma are the main reason of large number of landline services interruption.

Figure 6-3. The massive landslide destroyed the road and the utility poles for both power and telecom connections. (Credit: Masataka Shiga)

Figure 6-3 shows the link was discontinued by one of the large landslides. This is just one of many landslide locations in this area where there was considerable destruction of poles that carry the links needed to provide connectivity to Remote Offices and Exchange Offices, which process calls.

There was a report of an optical fiber cable damaged at the abutment of a bridge on the Hokkaido Expressway. The location of this bridge is N42.9143°, E141.9212°. The expressway was open to traffic during our visit and there was no safe place to stop for close up inspection. A photo was taken with the apparent replacement cable on the bridge. Figure 6-4 shows the cable bundle, the loop radius suggested that the cable is optical fiber. There was evidence of ground deformation at this location, Figure 6-5.

Figure 6-4. Replaced cable temporarily strapped to the guard rail of the expressway

Figure 6-5. Evidence of ground deformation at the abutment area, ~ 30 cm displacement of the drainage channel.

In addition to connection links damaged by the landslides, one of the Remote Offices that was close to the new Water Treatment Plant that was destroyed by a landslide (see

Chapter 5 for details of the water treatment plant). This is one of the key nodes that link the telecom landlines to the network. Figure 6-6 shows the original Remote Office structure prior to the earthquake. Figure 6-7 shows the office that was destroyed by the landslide.

Figure 6-6. The pre-earthquake Remote Office in Atsuma (42.7555°, 141.9403°). (Source: Google Earth)

Figure 6-7. Remote Office destroyed by landslide. (Source: Prof Suzuki of Toyo University)

As a temporary service restoration NTT East installed a DLC (Digital Loop Carrier) cabinet, which used both copper and fiber to connect the area to the network, Figures 6-8 and 6-9. This was also the approach used after the Great East Japan Earthquake and

Tsunami. It also means that NTT is improving the carrier's bandwidth and speed in the same time repairing the damage.

Figure 6-8. The new DLC cabinet, note the water tank of the WTP after the landslide (Source: Prof Suzuki of Toyo University)

Figure 6-9. View of the cabinet from the ruins of the WTP, note fence was added

The time line of NTT landline recovery is shown in Figure 6-10. The bulk of the interruption was the result of the Island-wide power blackout.

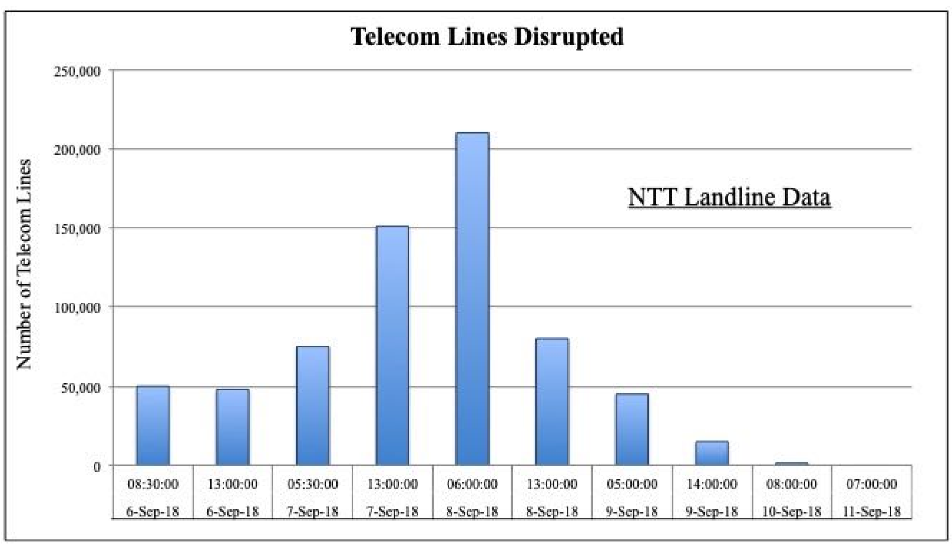

Figure 6-10. Time line of NTT landline recovery (Credit: Prof Suzuki of Toyo University)

6.4 Wireless System Damage

With the Hokkaido Island-wide black out after the earthquake, the wireless network also suffered service interruptions when the onsite backup power (usually batteries) was exhausted. The Base Stations that did not have backup power were off line immediately. Only the mid-zone Base Stations with large capacity have battery backup power; just some of those have backup generators. Under critical conditions, the mid-zone Base Stations can provide coverage to cells that are off line due to power outage.

There are 577 NTT DoCoMo Base Stations within Hokkaido Prefecture. It was reported that there were 111 Base Stations that had service interruptions due to lack of power. NTT East provided over 60 units of mobile power generators to keep the wireless network in service. The power outage to most Base Stations was estimated to be 6 hours.

NTT East has a reserve of 23,000 liters of fuel, of which 13,000 liters were used in this earthquake. There are four sizes of mobile generators; 50 kV, 150 kV, 1,000 kV and 2,000 kV.

Due to landline damage at one of the Base Stations in Atsuma, a mobile satellite unit was deployed to connect the Base Station to the network, Figure 6-11. This photo was taken after power was restored; therefore the NTT mobile generator unit was no longer on site. The DoCoMo Base Station was installed in 2010, while the KDDI Base Station was installed in 2017.

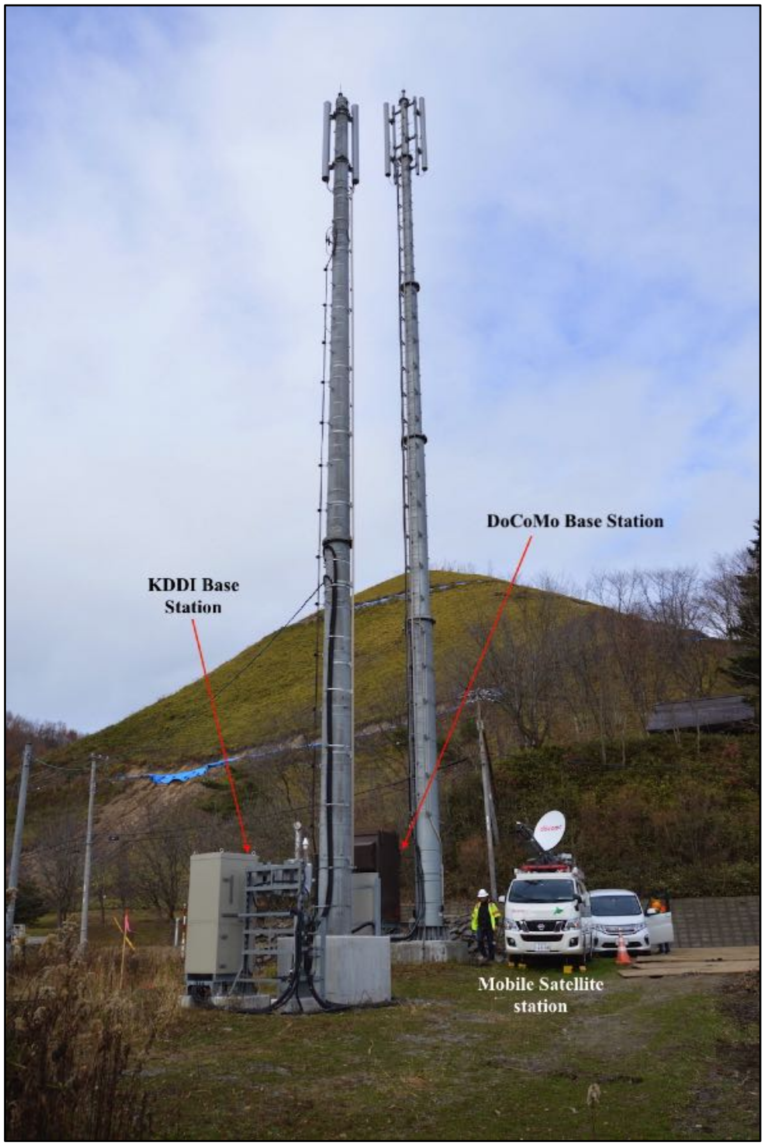

Figure 6-11. Mobile Satellite station was used to link this Base Station to the network

During our investigation in the landslide impacted areas (Hayakita and Atsuma), we observed that many Base Stations were built far from the hill sides. Figure 6-12 shows one of the many examples of Base Stations that were located well outside the landslide zones. Many of the Base Stations do not have microwave antenna to connect to Exchange Offices or Remote Offices. That means many of them are connected by cables (copper or fiber). The initial decision to place these base stations in the low-lying farming zones, rather than at higher elevation in the hillside zones, may have been made for economic reasons (easier to construct, easier to access for maintenance). Offset by somewhat less coverage areas. This strategy might also be worthwhile to consider in areas prone to landslides.

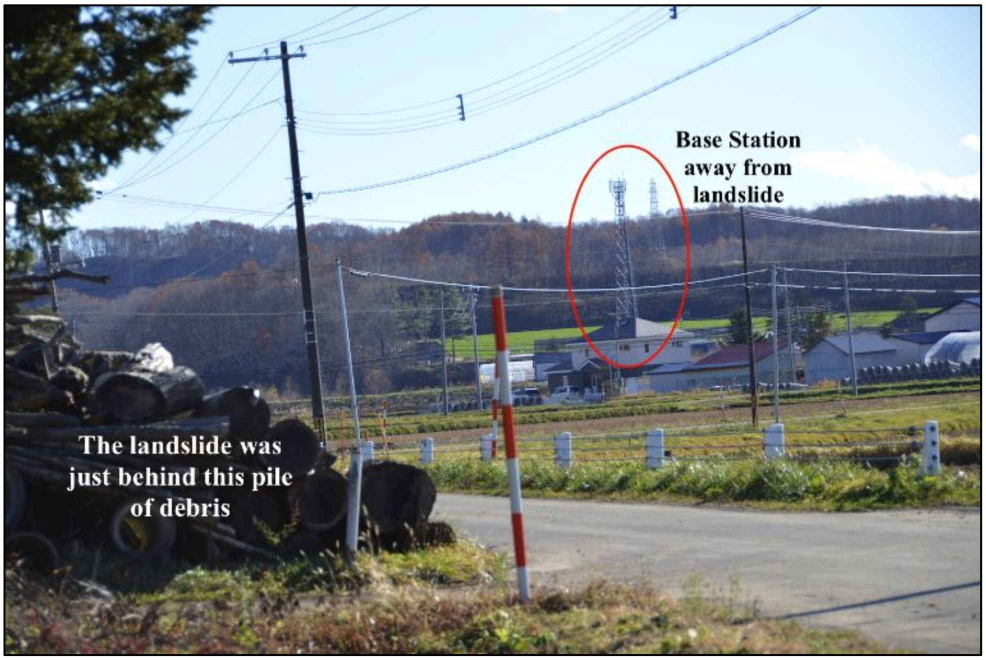

Figure 6-12. Base Station that outside the landslide area

We visited one Base Station site (Figure 6-13) in Sapporo close to Kiyota Ward, which had major liquefaction problem (see Chapter 5 for a description of the liquefaction issues in Kiyota Ward). The Base Station in Figure 6-13 belongs to DoCoMo and is on the edge of small hill. The retaining wall built around the Base Station did not have any sign of failure. The slope next to the Base Station was not protected. It showed a small amount soil spreading down at the lower edge by the parking lot. The guard rail along the top of the slope (Figure 6-14) indicated some ground movement causing the guard rail deformed and twisted with one bracket bolted to the retaining pole broken (Figures 6-15 and 6-16). The Base Station was not affected. Based on the size of the Base Station housing, batteries might have been used to power the equipment for short duration power outage.

Figure 6-13. This site shows a slight slide (1) of surface soil covering part of the parking lot. The guard rail pole (2) was rotated.

Figure 6-14. Guard Rail twisted and support poles rotated

Figure 6-15. The support pole rotated about 40^0.

Figure 6-16. Retaining bracket broken from the anchor on the pole.

6.5 Major Observations and Recommendations

The blackout is going to be a hard lesson learned by all utilities that depend on electric power to provide services to customers.

Mobile power generators (generator on a truck) can be a good investment in preparedness and recovery category. However, there are many issues that come with the investment. Periodic test runs and ongoing maintenance are just a few items that need to be managed. Fuel storage is another key element. Other indirect issues such as access to site after a disaster, available resource to execute the task are the factors that need to be considered. The sharing of emergency generators between many nearby operators, coupled with suitable mutual aid agreements, can be a part of an effective strategy; sharing of these assets (both in terms of cost and deployment) between multiple companies in competition with each other, remains an open item.

NTT East developed a test site in Sendai installing a micro-grid power network to provide power to their own Base Stations and Exchange Offices as well as the nearby hospital and school. That test was very successful during the Great Japan East Earthquake and Tsunami of 2011. There were no power outages to the sites connected to this micro-grid, while the city had power outage due to substation and cable damage. This concept was not implemented in the NTT network in Hokkaido; the reason is probably the costs of investment, in particular in areas with low population density.

The development of manhole size Base Stations, which can be installed underground, can be a good solution. The issue is the coverage. That means more manhole type of Base Stations is required to cover a large area. There are many other problems associated with underground installation. Flooding is just one of many problems. Also when underground cables are damaged it is difficult to locate the failures and the process to repair will take longer.

In fact the key question is: based on the magnitude of the disaster - what is the acceptable service interruption? This remains a most critical topic in telecom resiliency, as the world is more and more dependent on Voice and Data over Internet protocol for homes, medical services, etc.

6.6 References and Acknowledgements

The information and data shared by both Prof Nojima and Prof Suzuki are most valuable to this chapter. Dr. Hirose’s effort to set up the meeting at NTT East in Sapporo is much appreciated. Prof Konagai provided interpretation at the NTT East meeting.

Prof. Nojima, Gifu University. Presentation charts.

Prof. Suzuki, Toyo University. Written communications.

7.0 Transportation

7.1 Overview

The Hokkaido transportation system includes roads, railways, airports and ports. In Chapter 7, we examine the impacts to roads and railways. In Chapter 8, we examine the impacts to airports and sea ports.

This earthquake caused many transportation setbacks, particularly secondary roads in Atsuma Cho (厚真町), Abira Cho (安平町), Mukawa Cho (鵡川町). Chitose City (千歳市), Hidaka Cho (日高町), Biratori Cho (平取町), and Sapporo City Higashi Ku (札幌市東区). These locations are all within JMA intensity of 7 to 6 minus. This earthquake is ranked number 1 with respect to the number of triggered landslides in Japan within the Heisei calendar; the number 2 was the Heisei 16 (2004) Niigata Chuetsu earthquake. The total estimated area of landslides was 13.4 square km, which is equivalent to 440 Sapporo Domes (Figure 7-1).

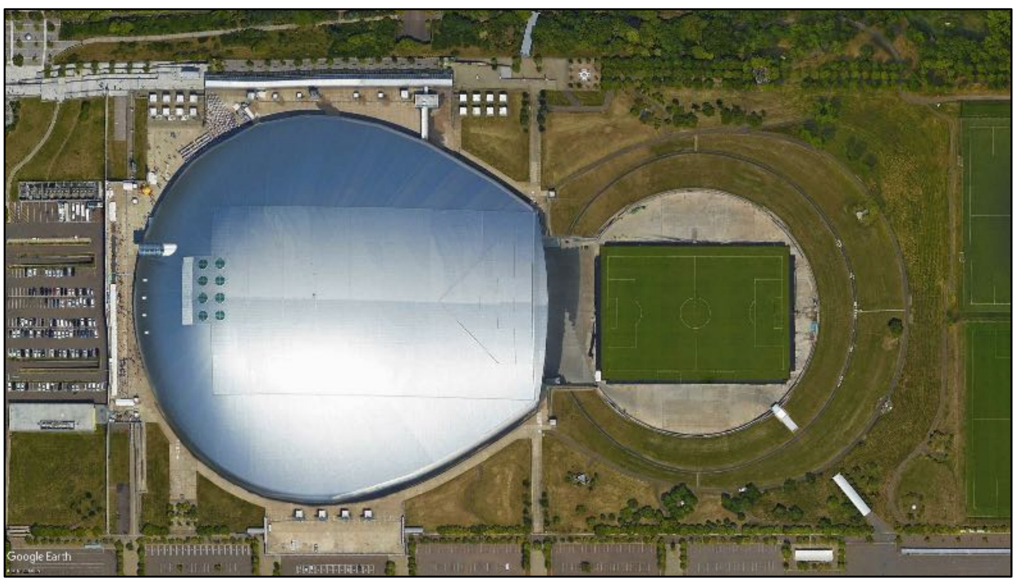

Figure 7-1 Aerial view of the Sapporo Doom, a reference of the size of landslides as a result of the Hokkaido East Iburi Earthquake (Credit: Google Earth)

Figure 7-2 shows an aerial view of the landslides of this earthquake. The left side of this photo shows the low lying flat agricultural areas, and a low-lying narrow valley extends to the east. The bulk of the area in Figure 7-2 is hilly terrain, all forested; careful examination of the photo shows hundreds of landslides in this terrain. See Chapter 2 for many examples of these landslides.

Figure 7-2. Aerial view of Landslides (Credit: Geospatial Information Authority of Japan)

Figure 7-3 shows the expressway, highway, and road network in Hokkaido. Heavy red lines show the expressway / toll roads; thinner lines show other highways (non-toll) and secondary roads.

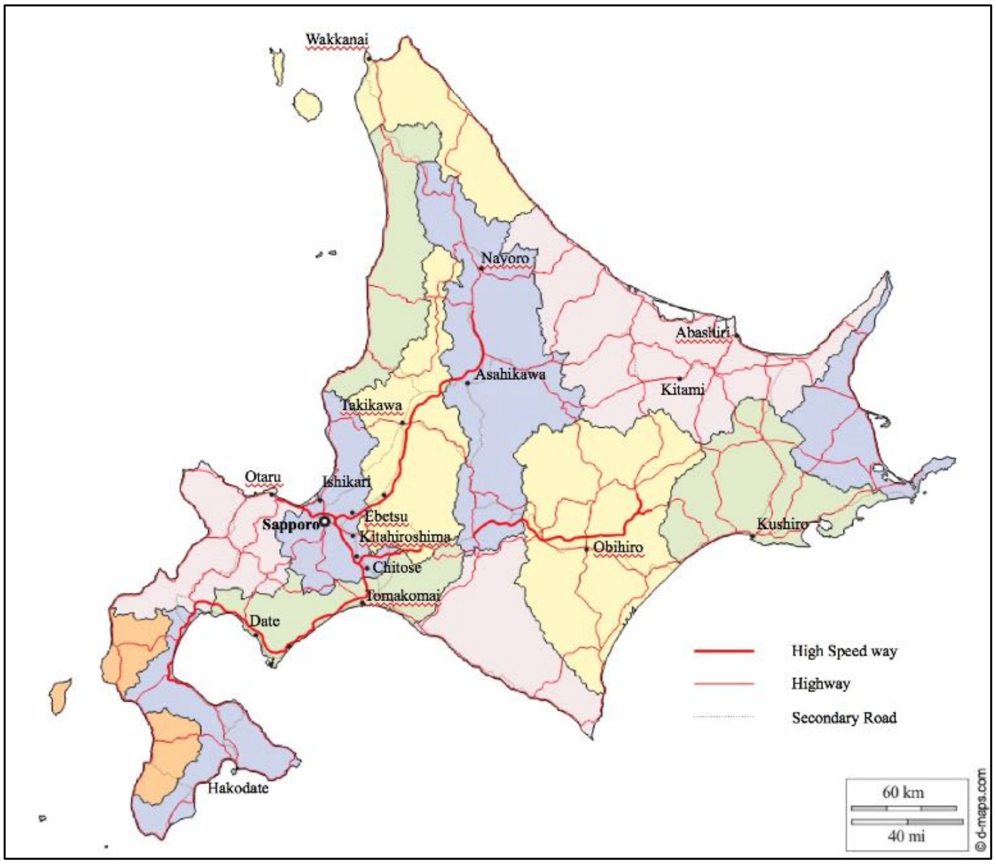

Figure 7-3. High speed way (Expressway-toll road), highway, and secondary road systems in Hokkaido. (Source: modified d-map)

The epicenter was near the town of Atsuma, about 25 km southeast of Chitose. The areas east of Atsuma sustained the worst damage. These areas include the towns of Mukawa, Hiratori, Hidaka, Shin-Hidaka, Urakawa, Samani, and Erimo. The mode of damage is basically landslide damage to roads, debris covering roads, and debris blocking rivers.

Many of the lower-volume roads in the rural areas were not completely clear for normal traffic by mid-November. Major expressways and highways were open in late September.

The Expressways are owned and operated by Nippon East Expressway Company (NEXCO). All the Expressways are toll roads and the responsibility of NEXCO East. The highways (non-toll) and secondary roads are the responsibility of the Ministry of Land, Infrastructure and Transportation / Tourism (MILT).

The railway system included the Shinkansen, regular rail (operated by Hokkaido Railway Company), subway and surface-level trams in Sapporo. Figure 7-4 shows the railway system in Hokkaido. Shinkansen provides high speed rail service up from Honshu to Shin Hakodate Hokuto Station close to Hakodate.

All these rail systems performed well, and with few exceptions there were no reported physical damage. However, there were service interruptions to all these railways due to the Island-wide black out.

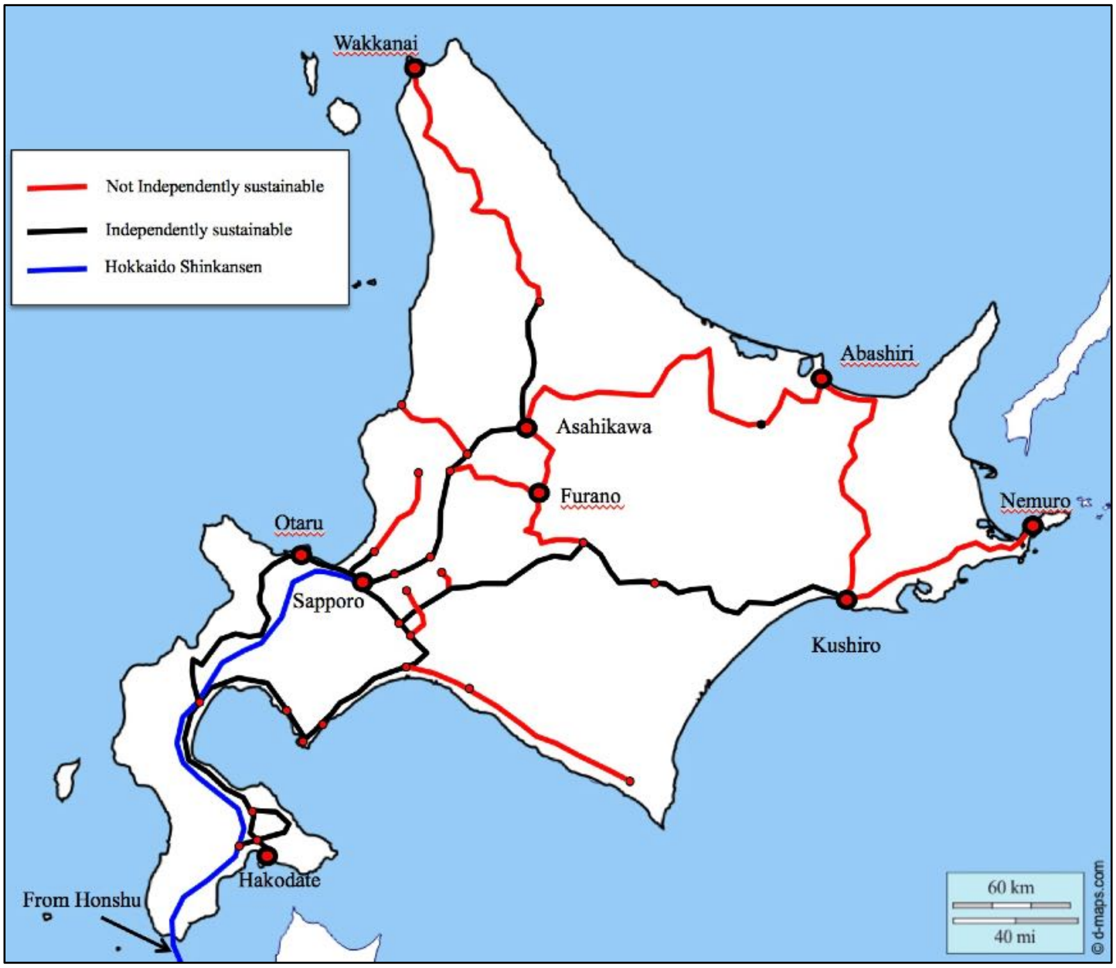

Figure 7-4. Railway system in Hokkaido. Subway and tram system in Sapporo not shown. (Source: modified d-map)

From Figure 7-4 the color red railway networks are not self-sustainable due to low ridership. These railways are supported by the local government (the sub prefectures). Many of them operate in the winter for tourists. The section of Shinkansen from Hakodate to Sapporo is not constructed yet.

7.2 Railway System Performance

The railway systems (train, subway and trams services) were not affected by this earthquake. The railway line that is in the high earthquake intensity zones is the Hidaka Main Line, which is operated by Japan Railway (JR). This line runs between Tomakomai and Samani. There was no reported damage to this line. However, the 2016 typhoon damaged part of the track by landslides and wave surge. Figures 7-5 and 7-6 show the aerial view of the damaged section. The locations are 42.4189°, 142.2246° and 42.4129°, 142.2348° respectively.

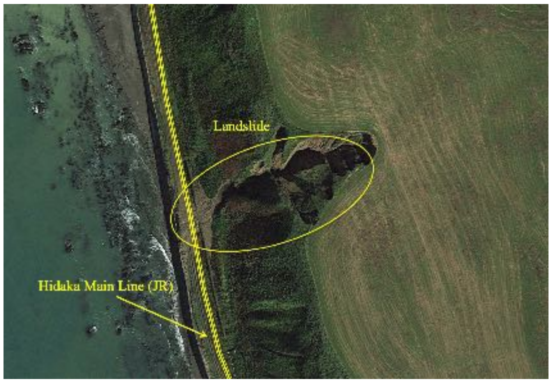

Figure 7-5. Landslide damaged the Track. (Source: Google Earth)

Figure 7-6. Wave damaged the sea wall, then the sea wall damaged the track. (Google Earth)

The tram network compliments the subway and bus routes within Sapporo. Figure 7-7 shows a Sapporo tram in operation.

The main train station (43.0686°, 141.3509°) at Sapporo is the hub for the JR trains and subway networks. Figure 7-8 shows the network of subway and street car (tram). The subway train is on rubber tires, so the noise level in subway stations is very low.

Figure 7-7. Street Car (Tram) in Sapporo

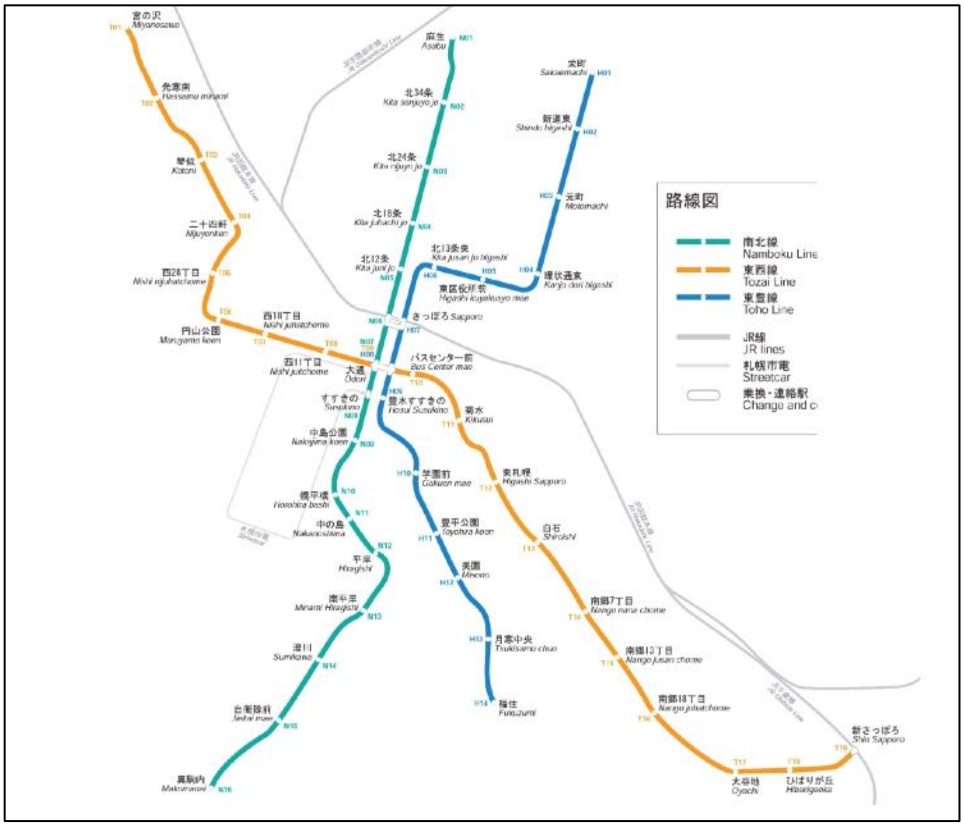

Figure 7-8. Sapporo subway, street car, and train network (Source: Sapporo Municipal Subway)

Since the subway and street car all run on electric power, the Island-wide black out caused shut down all subway and street car services.

The Shinkansen railway system was connected to Hokkaido in 2016, when a tunnel (Seikan Tunnel) connecting Hanshu and Hokkaido was constructed. The terminal station in Hokkaido is Shin-Hakodate-Hokuto Station. This station connects to Hakodate and all the major cities of Hokkaido by JR. Figure 7-9 shows the Hokkaido Shinkansen Line connecting to Tohoku Shinkansen Line at Shin-Aomori Station.

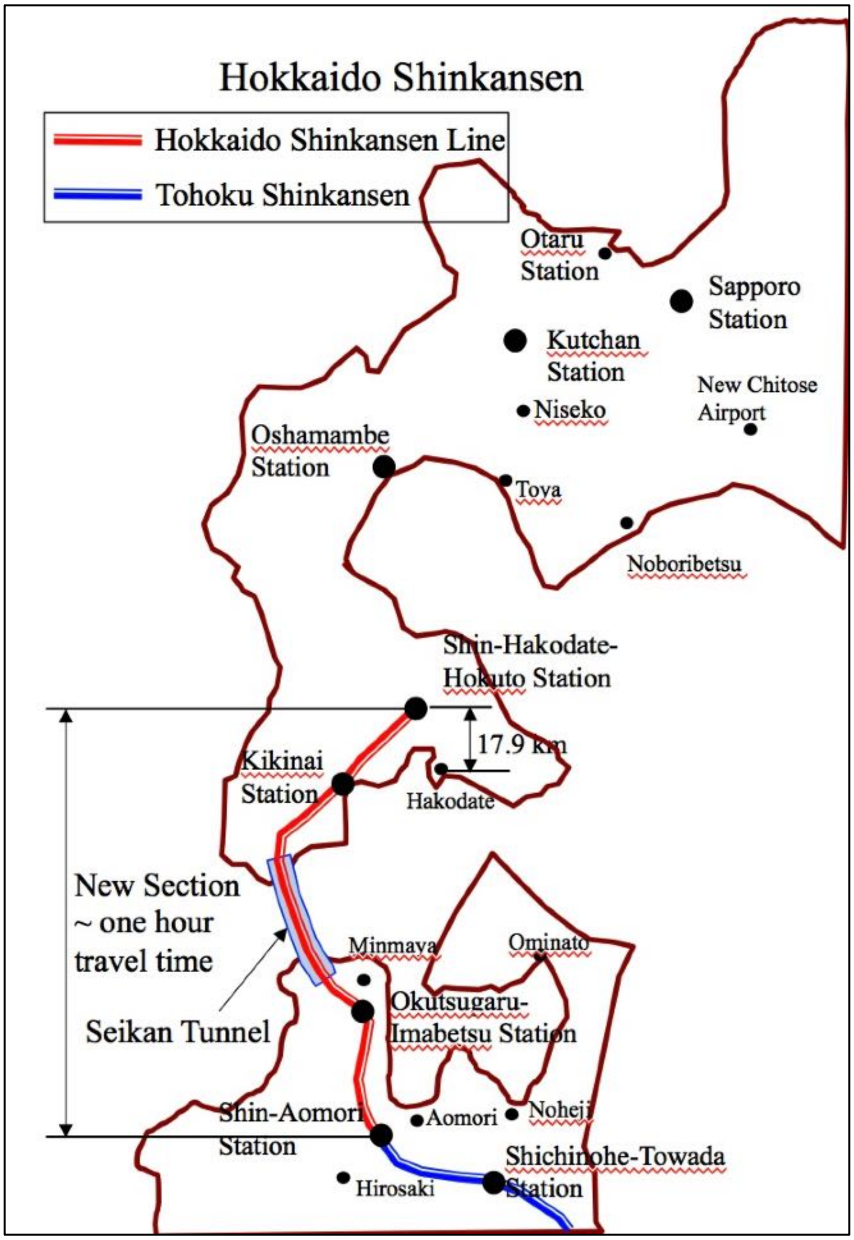

Figure 7-9. The new Shinkansen Line connecting Honshu to Hokkaido since 2016

See Section 9.3.4 for a further description of interruptions to railways.

7.3 Roads and Bridges Performance

The three classes of roadways sustained various degrees of damage. The three classes of roadways are: expressway (toll road), highway, and secondary road. All these roads are paved roads. The majority of the damage was repaired by September 10, three days after the main shock.

The reported damage to these roads is discussed in the sections below.

7.3.1 Expressway (NEXCO)

NEXCO operates and maintain the expressways. Toll Booths are set up at entrance and exit point to collect the established fees. The Toll Booths require electric power to run equipment for fee collection as well lifting the gate bars to enter and exit the expressway. All the expressways were initially closed due to power outages at the toll booth. Due to the black out, NEXCO traffic control was on backup power generator but as fuel ran out and re-supply did not arrive in time, it was not possible to monitor the traffic.

Japan has established a standard policy for expressway toll road closure based on computed Japan Meteorological Agency (JMA) intensity. The policy is that all roads in zones of JMA intensity 4.5 (soft soil zones) or JMA 5.5 (firm soil zones and bridges) and higher are to be closed until inspections are completed. Based on inspection results the agency that is responsible for the roads then decides on actions to re-open or to keep the roads closed.

Figure 7-10 shows a schematic map of all the toll-expressways in Hokkaido. The two expressways that are inside the JMA intensity 4.5 and up zones are Hokkaido and Doto expressway, Figure 7-11. So these sections within the intensity zones were immediately closed for traffic.

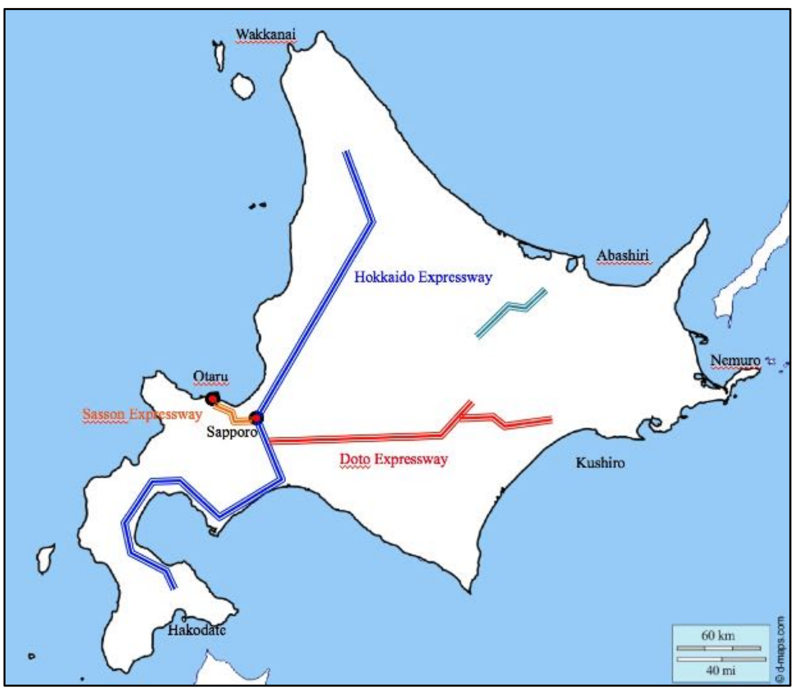

Figure 7-10. Expressways in Hokkaido. (Source: modified d-map)

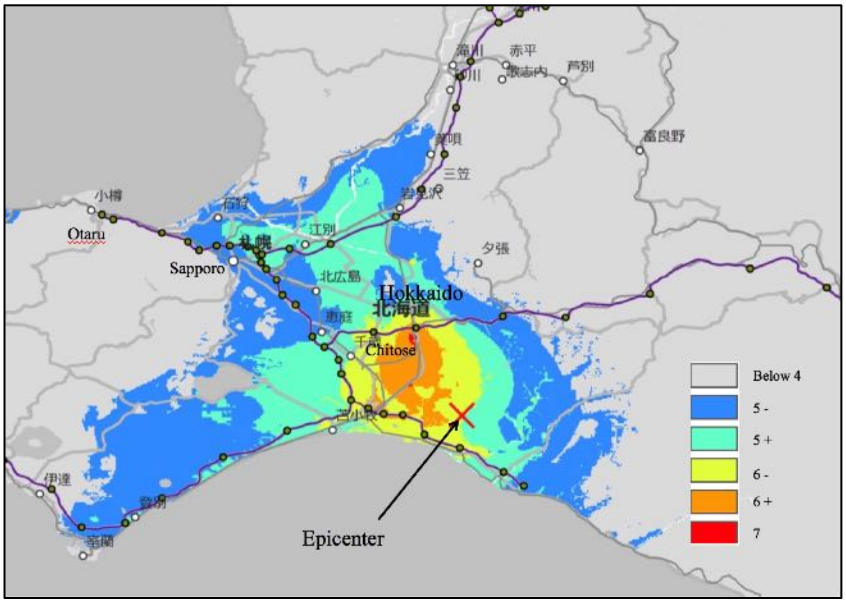

Figure 7-11. JMA intensity overlay on the expressways. (Source: Prof Maruyama)

The Figures 7-12 to 7-17 provide the sequence of expressway re-opening to traffic from right after the main shock on September 6 2018 03:08 am. Road closures are indicated by the heavy red lines. Figures 7-18 to 7-20 show the damage sustained by the expressway, which, in context of the area involved, was relatively minor.

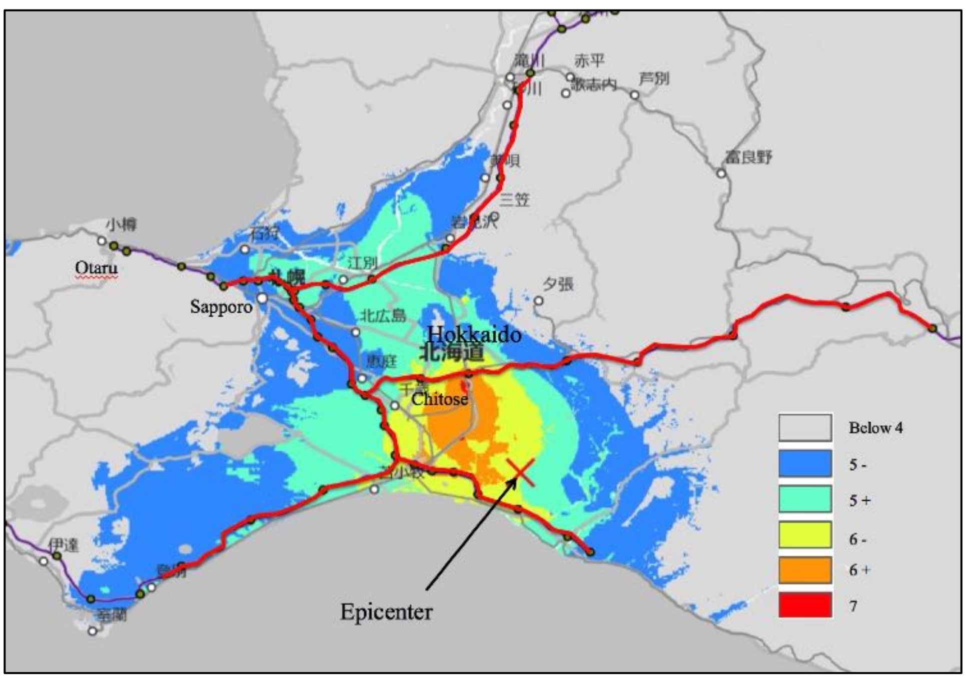

Figure 7-12. All expressways intensity 5- or higher were closed. Closures in zones with JMA intensity 4 or below were closed due to power outage. (Source: Prof Maruyama)

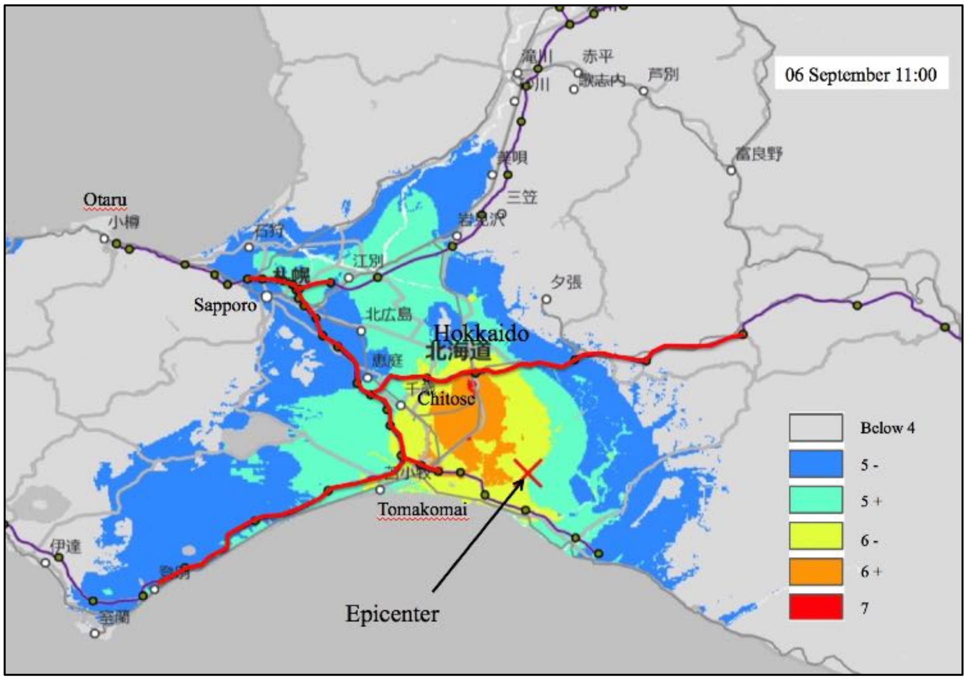

Figure 7-13. At 11:00 am on 6 September Hokkaido Expressway and a major part of Doto Expressway were closed. (Source: Prof Maruyama)

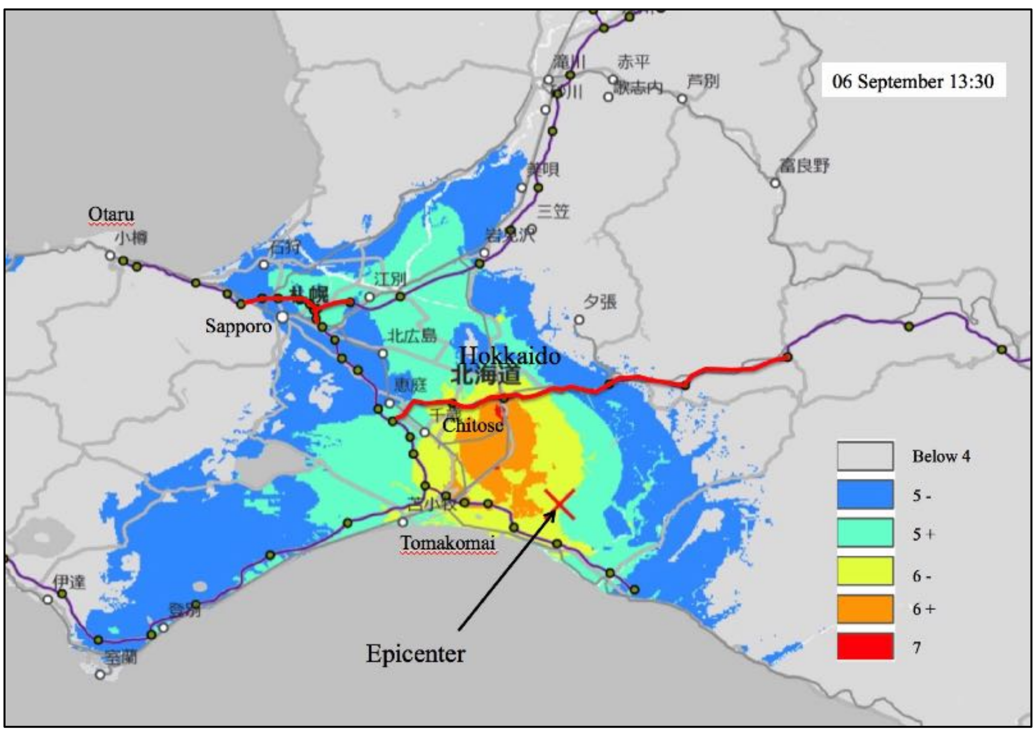

Figure 7-14. By 13:30 on 6 September only a small section of Hokkaido Expressway were closed. (Source: Prof Maruyama)

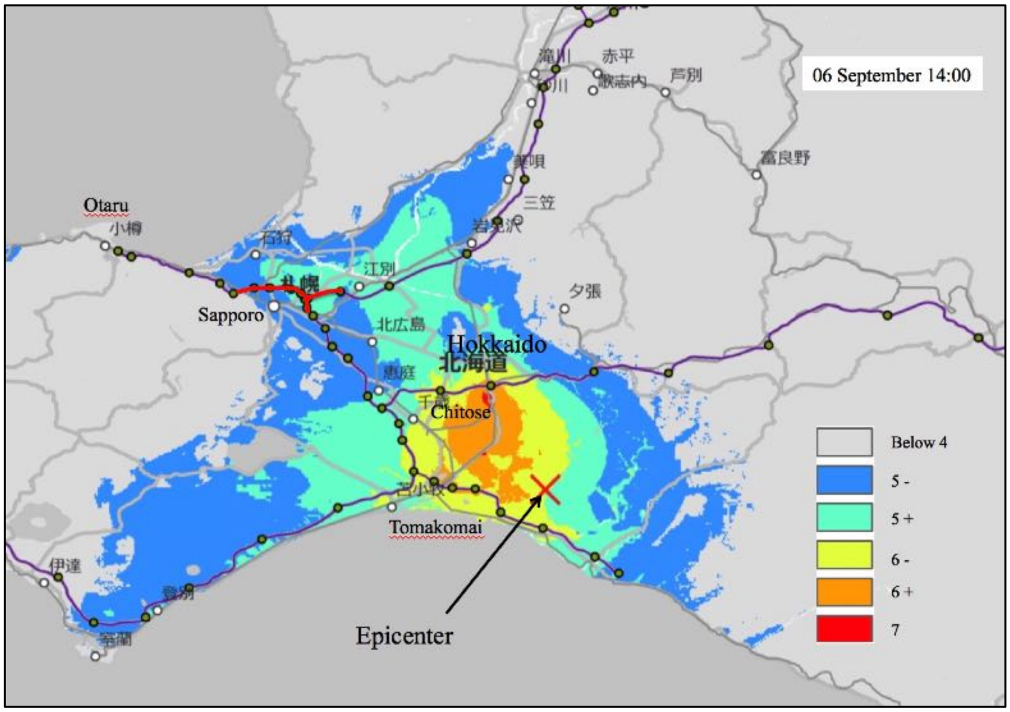

Figure 7-15. By 14:00 on 06 September only part of Hokkaido Expressway was still closed. (Source: Prof Maruyama)

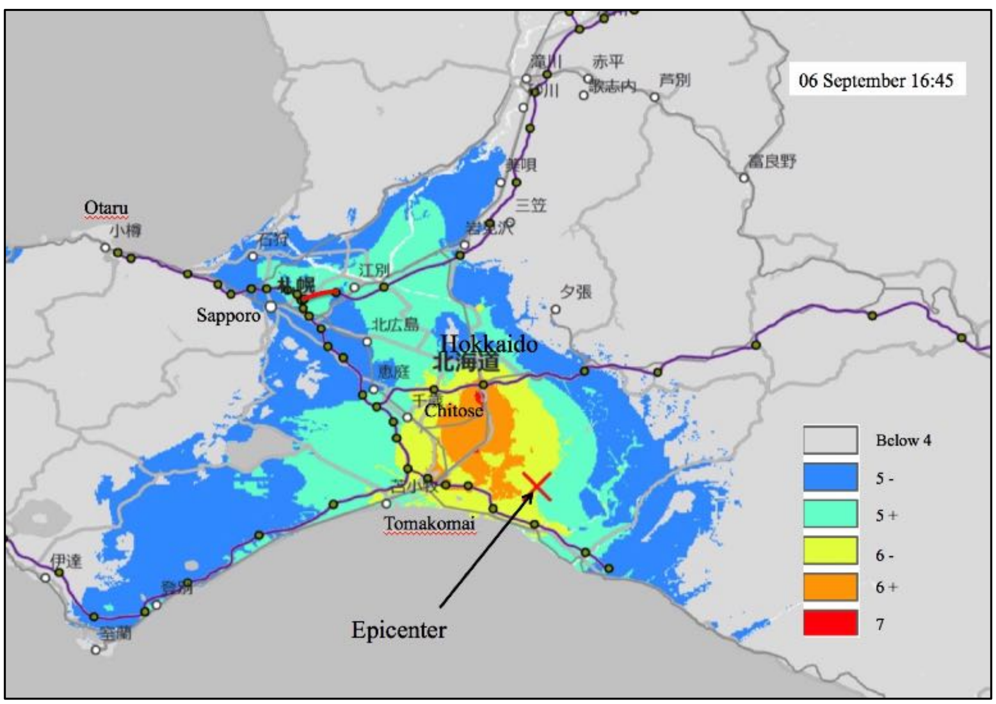

Figure 7-16. The small section between Sapporo-higashi and Ebetsu was still closed at 16:45 06 September. (Source: Prof Maruyama)

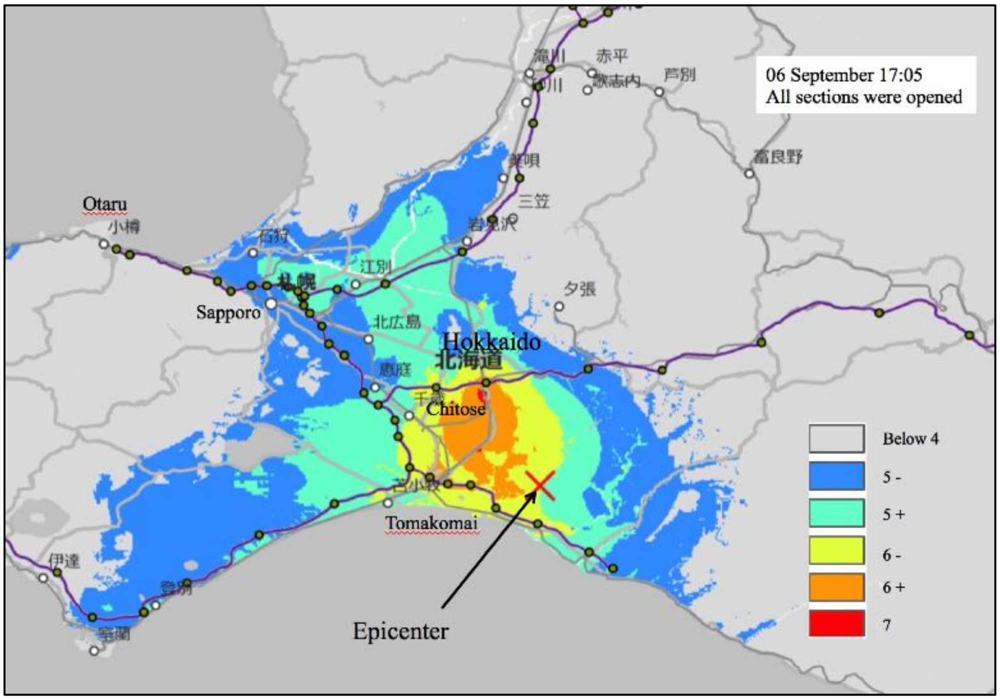

Figure 7-17. By 17:05 on 6 September all expressways in Hokkaido were open to normal traffic (Source: Prof Maruyama)

The major damage to the expressways were road surface cracks and road subsidence. One bridge was damaged where the abutment settled and the movement damaged an optical fiber cable that was co-located with the bridge deck.

Figure 7-18 shows the damage sustained by the expressway, which was quite minor. The major damage to the expressways was road surface cracks and road subsidence. The damage to bridge was confined to one bridge where the abutment settled and the movement damaged an optical fiber cable (Figure 7-19) that was co-located with the bridge deck. The location of the Kita-Hiroshima IC was 42.9885°, 141.4704°. The location of the optical fiber damage was 42.91428°, 141.9212°.

Figure 7-18. Road surface crack close to toll booth at Kita-Hiroshima Interchange. (Credit: Prof Maruyama)

Figure 7-19. The photo on the left shows the location of the optical fiber damaged on this bridge, the left photo shows the close up view the damage conduit. The location is west of Chitose-higashi. (Credit: Prof Maruyama)

7.3.2 Highway and Secondary Roads

Highway Damage

Figure 7-20 shows the location of the highway that stretches from Tomatoh-Chuo Interchange to Hidaka-Astsuko Interchange (Hidaka Highway). This is a non-toll road highway. This highway sustained multiple locations of road surface cracks and depressions. The time line of the repair to open this highway for normal traffic is shown in Figure 7-20, taking until September 9 to reopen the entire highway to Hidaka.

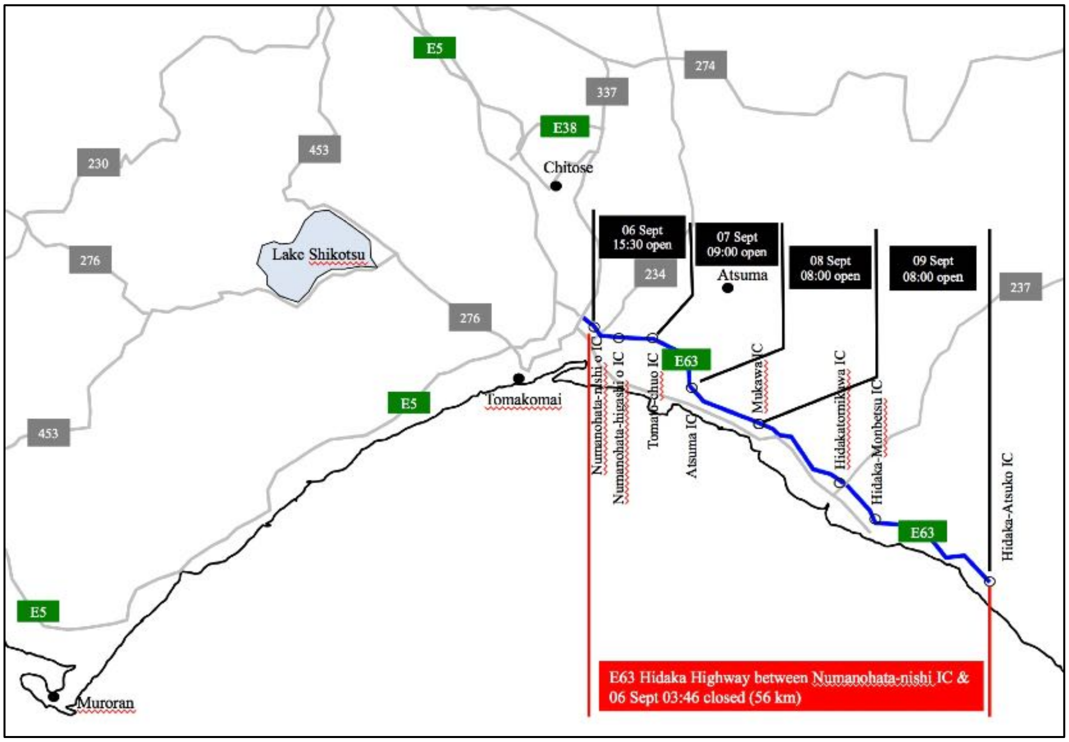

Figure 7-20. Hikada Highway repair time line (re-open time line). (Credit: MLIT)

The damage of the road surfaces is shown in Figures 7-21 and 7-22.

Figure 7-21. Mukawa Interchange area road surface damage. (Credit: MLIT)

Figure 7-22. Mukawa Interchange road surface just beneath the overpass (Credit: MLIT)

Secondary Road Damage

In the major landslide areas west of Atsuma, road damage was caused mainly by debris covering the road or mud carrying trees and other large objects pushed the road over. The repair to open these roads were very labor intensive. Figures 7-23 to 7-24 give a general idea of the intensity of the material covering the roads and the number of locations.

Figure 7-23. Three locations on this secondary road were covered by landslide. The one on the right is the largest. The road surface was not repaved as of mid-November 2018. (Source: Masataka Shiga)

Figure 7-24. This shows the extent of the landslide damage. The road was covered by the creek was also blocked. A retaining wall was temporary built to prevent mud flowing to creek. (Source: Masataka Shiga)

7.4 Major Observations and Recommendations

Although the intensity of this earthquake was quite high in many locations, the expressways, highways, and secondary roads performed quite well. Several tertiary roads not shown in Chapter 7 also failed due to landslides.

Road surface cracks and subsidence in areas where roads traverse liquefaction zones, soft ground zones, peats, at abutments, etc. cannot be easily prevented, unless suitable soil improvement techniques are used. Road failures through landslide zones cannot be prevented unless the landslides are mitigated.

The bridges and overpasses performed very well. This reflects the attention to details of joints (Figure 7-25).

Toll booths should have backup power to avoid closing the road simply due to power outage. Each toll booth area usually has a nearby building for the attendants, so including a backup power generator can typically be housed in or near this building. As the power consumption is not very large, a small generator with a 100 liter tank shall be enough to take care of power outage problem, at least to ensure that toll gates and barriers can be lifted to keep the road open and the quick restoration of vehicle movement as needed for emergency response. The issue of loss of toll revenue should also be considered, but likely the over-arching need of rapid restoration by society as a whole can be counterbalanced against the need for toll revenue by the operating agency, possibly by some form of post-emergency claim to the government.

The TEC-Force established by MLIT country wide is very important in executing the emergency response and repair co-ordination. The members of the TEC-Force are staff from the various regional development bureaus and departments of the Ministry. They are trained and exercise drill periodically to ensure their effectiveness in time of need. Figure 7-26 shows TEC-Force team was sent to the damaged site to gather information and plan their recovery.

Figure 7-25. The deck slide prevention key and the cable tying the decks provided a suitable measure to avoid unseating of the road decks at this location

Figure 7-26. TEC-Force at damaged sites performing a quick evaluation to plan the recovery. (Credit: MLIT)

7.5 References and Acknowledgements

The author is in debt to Prof Maruyama who provided lots of information relating to the expressway performance. The MLIT meeting set up Dr. Tsukada of JSCE was also valuable to our information collection. Again, Prof Konagai was extremely helpful in the meeting with MILT staff. Last but not least, our thanks are extended to Director General Mr. Mizushima who organized the meeting with his key staff giving us the details of their tasks during the post-earthquake period.

We are also grateful to Ms. Mayumi Nakata who took care of many logistical issues and kept us safe all the time, and to Mr. Masataka Shiga who operated the drone and provided excellent photos for the report.

Prof. Maruyama. Presentation charts and advice.

MLIT Hokkaido. Presentations and discussions.

8.0 Airports and Sea Ports

8.1 Summary of Airports and Sea Port of Hokkaido

There are 12 airports within Hokkaido Main Island and 3 airports serving the small islands of Hokkaido. Figure 8-1 shows the locations of the airports and the location the epicenter. There are other airports which are either for military or private services. Six airports on Hokkaido Island provide international services, and the other airports are for domestic services only. The volumes of international passengers at these airports are very small comparing with the volume of domestic passengers.

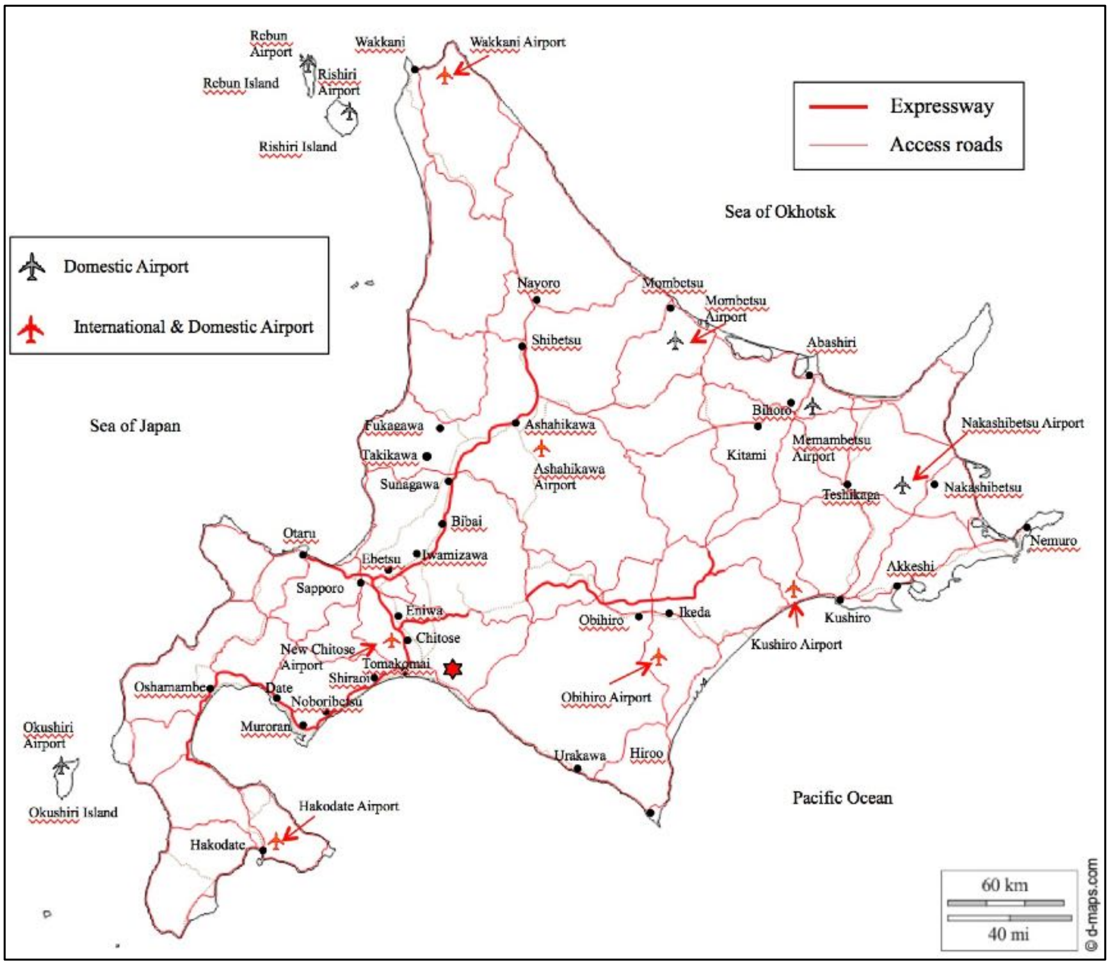

Figure 8-1. Airports within Hokkaido Prefecture. (Source: Modified from MLIT map)

The New Chitose Airport is the largest of all the airports within Hokkaido. Figure 8-2 shows the size of the terminals for both international and domestic service at the New Chitose Airport. The Chitose – Tokyo are route is one of the highest volume air traffic corridors in the world.

Figure 8-2. Aerial view of the New Chitose Airport terminal building. (Source: Google Earth)

There are 12 Sea Ports within Hokkaido Prefecture, Figure 8-3. There are two classes of Ports – Major Ports (10) and Specially Designed Major Ports (2). The only difference is the services of the port. Specially Designed Major Ports can handle cruise ships, container ships and ferry.

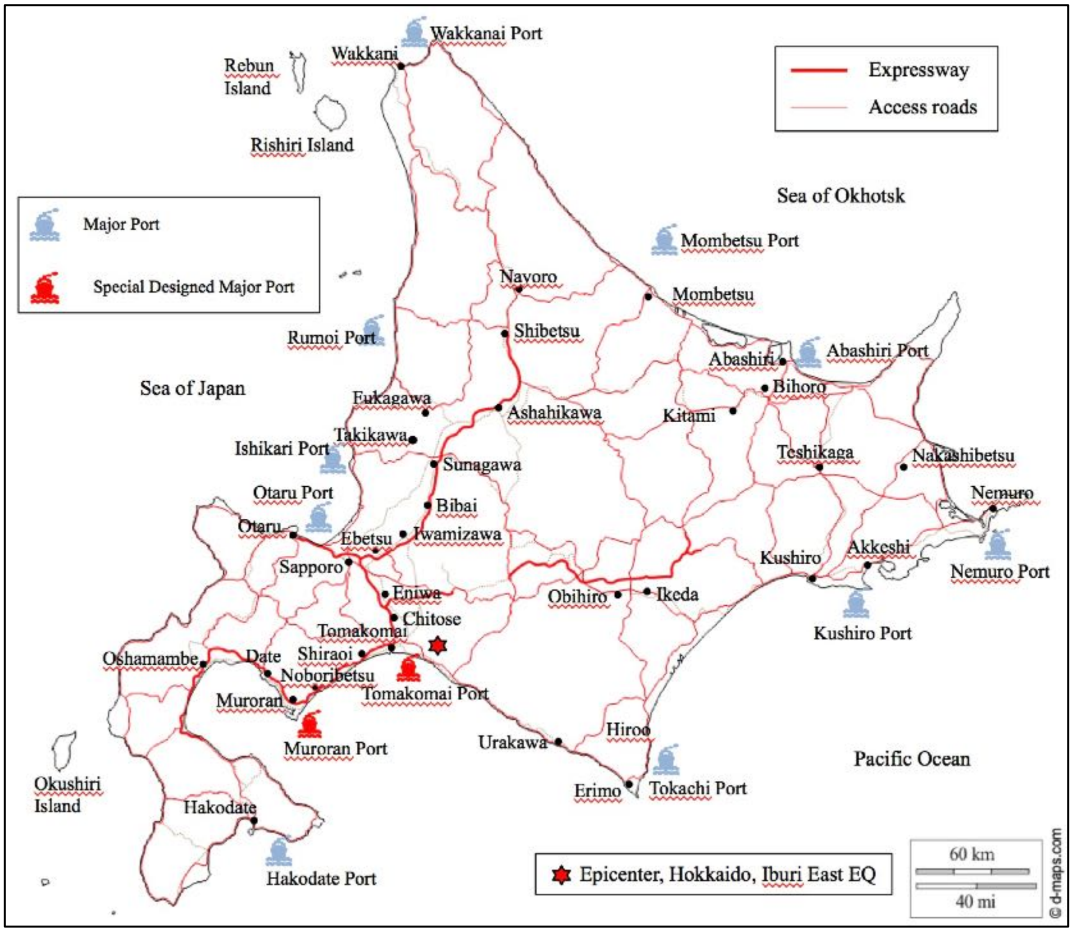

Figure 8-3. Locations of Ports in Hokkaido Prefecture. (Source: Modified from MLIT map)

8.2 Performance of New Chitose (CTS) Airport

The New Chitose Airport (IATA[7] abbreviation CTS, N42.7943°, E141.6728°) replaces the original Chitose Airport located nearby. CTS was opened in 1991. This airport was built to handle the increasing domestic traffic. Many passengers fly to international destinations, with transfers at either Narita or Haneda Airports that serve Tokyo. CTS handles about 20 million passengers annually.

Hokkaido is a tourist spot both in the summer and in the winter. Japan Railway has a direct connection from Sapporo to New Chitose Airport. There is a Self Defense Force (SDF) airport close to the New Chitose Airport.

[7] IATA = International Air Transport Authority

The New Chitose Airport is the airport closest to the epicenter, about 25 km. The runways did not sustain any damage. Due to both power outage and non-structural damage to passenger terminals (see Reference 1 and 2), the airport was closed to all flights after investigation on 06 September at 07:00[8]. Domestic cargo flights were allowed on 07 September 16:00. Both international and domestic flights were re-opened after 08 September 06:00. By 22 September 10:00 the airport returned to normal operation. See Section 9.3.5 for more details about the post-earthquake service at CTS.

8.3 Tomakomai-Atsuma West and East Ports

Figure 8-4 shows the aerial view of the Tomakomai-Atsuma West Port. Figure 1-6 shows the Tomakomai-Atsuma East Port. The West Port is the larger port (E42.6374°, N141.6404°). The West Port also handles coal in addition to cruise ships and cargo ships. There is a dock for ferry service as well. The East port sustained minor damage from liquefaction in two areas; ejected sand is seen at the Container port, Figure 8-5. The port was not closed after the earthquake. Some ferry routes to islands were closed. By 08 September 06:00 all port functions were normal.

Figure 8-4. Tomakomai-Atsuma West Port. (Source: Google Earth)

[8] Based on Hokkaido Prefecture daily report

Figure 8-5. Liquefaction at the International Container Port (Source: MLIT)

Tomakomai-Atsuma East Port is the International Container port for container ships (N42.6093°, E141.7854°), Figure 8-6.

Figure 8-6. Tomakomai-Atsuma International Container Port. (Source: Google Earth)

The East Port is about 15 km southwest of the epicenter. There was no damage to this port. It was used for bringing in fresh water, and industrial oil, Figures 8-7 and 8-8. The water and oil were for the temporary public baths for the local community.

Figure 8-7. Cargo ship unloading water to water tankers (Source: MLIT)

Figure 8-8. Heavy Oil unloading to oil tanker (note oil spill preparation)(Source: MLIT)

Figure 8-9 shows the port pier at Tomakomai; it was not damaged and a container ship is unloading container at the time. The cranes did not sustain any damage.

Figure 8-9. Tomakomai-Atsuma East Port

The International Container Port is very close to the seawall that sustained extensive damage due to permanent ground deformation) and liquefaction. Figure 8-6 shows the location of the seawall with respect to the port. Figure 8-10 shows the aerial view of damage. Figure 8-11 shows damage to the quay wall for the pier at the power plant.

Figure 8-10. Aerial view of damage to the road and part of the seawall. (Source: Masataka Shiga)

Figure 8-11. Bulging of the quay wall at Tomakomai-Atsuma Power Plant

The pier at the Tomakomai Ferry Port had liquefaction, Figure 8-12 shows the liquefaction damage. The location of the Ferry Port is shown in Figure 8-13 (42.6095°, 141.8209°).

Figure 8-12. Tomakomai Port pier liquefaction damage. (Credit: Hokkaido MLIT)

Figure 8-13 The liquefaction damage in Figure 8-12 was at the Ferry port on the right hand side of the figure. (Source: Google Earth)

8.4 Major Observations and Recommendations

The quay walls at the ports at Tomakomai-Atsuma performed well in earthquake. The level of shaking at these sites was about PGA ~0.25g to 0.35g. The heavy duty cranes at these ports were not damaged.

The sea wall shown in Figure 8-6 did not perform well. The primary function of this wall is to deflect potential incoming tsunami (there were no tsunamis caused by this onshore crustal earthquake). There was substantial liquefaction in the area immediately north of this sea wall, as evidenced by many widespread sand boils. The land at an industrial factory located immediately north of this sea wall suffered differential settlements, possibly aggravated by the movement of the sea wall.

Ports are critical for Hokkaido, which is an island. During the post disaster period, when supplies such as water, medication, etc. are very important, therefore both airports and ports are the lifelines to reduce hardship in the impacted area. When heavy equipment is needed, ports are the only solution. It is recommended that all the ports be assessed for their performance in future large earthquakes, and in particular the effects that liquefaction can have on sea walls, the potential damage to container cranes when subjected to PGDs, and the effects of nearby industrial facilities (gas tanks, factories, power plants, etc.) due to possible PGD effects as well as amplified ground motions due to deep soft soil sediments.

8.5 References and Acknowledgements

We are grateful of MLIT Hokkaido Director General, Mr. Mizushima's willingness to allow all his officials to provide us with quality time and valuable information for this report.

Photos of non-structural damage in the New Chitose Airport terminal building are available at the web sites below:

[1]. https://english.kyodonews.net/news/2018/09/47d0fe638361-in-photos-damage-from-major-earthquake-in-hokkaido.html?photo=200875

[2]. https://cdn.japantimes.2xx.jp/wp-content/uploads/2018/09/n-airport-b-20180911.jpg

9.0 Economic Impact

9.1 Economic Losses

The earthquake impacted the economic activity in Hokkaido. It is estimated that the Island of Hokkaido, with population of 5 million people, represents about 3.5% of Japan's annual gross domestic product.

Japanese GDP is reported on a quarterly basis. For the three months April to June 2018, GDP increase was +0.7% For the third quarter July to September 2018 period, during which time there were major disasters in Japan, GDP decrease was -0.6%. The following major natural disasters occurred during the July to September 2018 period:

- Heavy rains that caused flooding and landslides and killed hundreds of people in western Japan.
- Soaring temperatures that sent tens of thousands of people to hospitals with heat-related illnesses
- Typhoon Jebi in September 2018 that knocked out power to hundreds of thousands of buildings and closed Kansai International Airport.
- The Hokkaido M 6.7 earthquake of September 6 2018, which caused an Island-wide blackout, damaged various lifelines as described in this report, and damaged buildings can resulted in fatalities.

The drop in GDP in the third quarter of 2018 was the steepest quarterly contraction in Japan in several years, and reflects, in part, the impact of several flood and earthquake disasters during this quarter. This contraction reflects a drop in personal consumption and capital investment. Financial data is from www.tradingeconomics.com, accessed December 12 2018.

GDP per capita is about $48,556 (USD). Japan's population is about 126.8 million (2017 data). Hokkaido's population is about 5,377,435 (2016 data). This suggests that Hokkaido's GDP is about $261 Billion per year.

Within Hokkaido, the short term direct economic impacts can be divided into three categories:

- Losses due to the Island-wide Power Outage
- Losses due to damage to infrastructure (roads, bridges, power, gas, water, etc.)
- Losses due to damage to the regular building stock

There are also other losses that occur. The loss of life is the most important. In the long term, the short term losses might be somewhat offset by the additional economic activity needed to make long term repairs (especially if insurance money from outside Hokkaido is spent within Hokkaido); loss of sales in the days after the earthquake might be offset by delayed purchases in the weeks later, etc.

The short term losses due to the Island-wide power outage are estimated as follows:

- Estimate the number of Customer-Minutes (CM) of power outages that occurred.

- Value the loss of economic activity at $0.10 per CM. This $0.10 value is based on economic studies for industrialized western economies due to the temporary loss of power.

- CM is estimated at 6 Billion (see Section 9.2.6). Therefore, the economic impact of the power outage was about $600,000,000. This represents about $600 million / $261 billion = 0.230% drop in annual GDP in Hokkaido.

The short term losses due to damage to infrastructure are estimated at $300,000,000. This reflects mostly the repair of the damage to the electric and water systems, and repairs to roads and levees. This represents about $300 million / $261 billion = 0.115% drop in annual GDP in Hokkaido.

The direct damage to building stock is often considerably larger than damage to lifelines (See section 9.7 for counts of damaged buildings). In this earthquake, allowing about 450 destroyed (or nearly destroyed) single family buildings at $300,000 each, and 12,500 partially damaged single family buildings at $30,000 each, and 1,140 destroyed commercial buildings at $1,000,000 each, and 4,850 partially damaged commercial buildings at $100,000 each, then the direct building stock damage might be on the order of $2,135,000,000. The relative small losses to the building stock ($2.1 billion) reflects that the earthquake epicentral region was in a sparsely populated area, and that almost all buildings were designed for strong inertial seismic shaking loads (there were very very few traditional Japanese wooden houses, as were heavily damaged in the 1995 Kobe earthquake).

Therefore, the combined effect of power outages and lifeline repairs and building damage is about $3.035 Billion, or about -1.16% of Hokkaido's annual GDP.

As described in Section 9.8, agriculture losses may be in the range of $12.8 Billion. This would represent an additional -4.9% in Hokkaido GDP. Due to the methods of counting the losses, there may be some double counting in the agriculture losses with the building losses. If we were to set a single loss value for the earthquake, the total is about of $15 Billion, of which about 80% is from agriculture.

As time goes on and there are better estimates of actual damage and repair costs, these economic impacts will change.

9.2 Resilience

The following sections summarize various social and economic impacts as described in the daily reports of the Hokkaido Prefecture, Crisis Management Department of the Crisis Response Bureau. These reports describe, in a general way, the impacts of most of the lifelines, except telecommunication.

The intent is to document various statistics for social scientists to allow study on recovery and emergency management processes. Much more data is needed to quantify all the economic impacts, particularly well-documented costs. Resilience, a much quoted term, but often ill-defined term, can perhaps be better quantified if one uses documented economic impacts.

In a macro-sense, the greater Sapporo area was "Resilient" in this earthquake. Nearly all buildings in metro-Sapporo suffered no or little damage. Impacts to lifelines certainly reduced economic activity in Sapporo for a few days, but within a week or so after the earthquake, few visitors to Sapporo would have noticed that there had been an earthquake the week before. Sapporo was therefore Resilient. The main reasons Sapporo was Resilient can be characterized as follows:

- Seismic building codes have been adopted for a long time. The level of seismic design is high.
- Lifeline operators have invested considerable sums in installing seismic resistant buried pipelines.
- The level of shaking in Sapporo was generally moderate.

In the Atsuma area, the same "Resilient" observation cannot be made. Landslides destroyed many homes and caused loss of life. Strong shaking and ground failures severely damaged non-seismically-designed water irrigation system, and a landslide destroyed a seismically-designed water treatment plant. Strong shaking damaged all the thermal power plants located in the strong shaking area, the major cause of the Island-Wide power outage. Restoration of the impacted farming region to its pre-earthquake status may take years.

In the Atsuma area, the level of damage might have been largely avoided had the landslide hazard been better recognized, and had the irrigation system been installed using modern seismic techniques. Both of these two observations would have required substantial investment. For farming, it is not entirely clear that the extra investment of seismic-resistant water irrigation pipes is cost effective; that is a matter for future study. For housing stock, the destruction of homes and loss of life due to landslide is a severe consequence, and zoning-type measures to avoid occupancy in areas prone to destructive landslide are warranted. The challenge will be to develop rational landslide hazard maps and to quantify the landslide risk to society and then take the proper cost effective measures: this could take years establish suitable maps; and then decades to implement.

The loss of life and severe destruction due to landslide is not unique to this 2018 Hokkaido earthquake. The authors have seen these effects, on similar or much worse scales, in China Sichuan M 8 earthquake of 2008; Lushan China M 6.5 earthquake of 2013; Christchurch M 6.5 earthquake of 2011; and more earthquakes in Nepal and Pakistan over the past decade or so. In densely populated areas prone to landslide, 10s of thousands to 100s of thousands of people can be killed by earthquake-induced landslides. In the USA, a M 7± crustal earthquake near populated areas (examples: Slide Mountain near Reno Nevada, Oakland-Berkeley Hills in California, Little Cottonwood Canyon near Salt Lake City, etc.) are exposed to landslides (rock falls, avalanches) which are not well understood and the risk not well established. Lifeline operators nearly always have infrastructure that traverse landslide zones, and damage to lifelines can be expected.

The authors state the obvious: Resilience is an investment and not a cost. The losses (direct and indirect) can be materially reduced with better understanding of the risk, and thoughtful investment.

9.3 Lifeline Services

The time lines of lifeline services interruption in the sections below are based on the post-earthquake daily reports provided by the Hokkaido Prefecture, Crisis Management Department. The information provides a sense of the hardship the community experienced as a result of lifeline service interruptions. There were definitely economic losses associated with the interruption of lifeline services. A follow-up study by social scientists can provide more insight in the economic losses due to poor performance of lifelines in this earthquake. The result may justify the investment in developing more resilient lifelines.

9.3.1 Highways (National Roads)

National Roads are highways connecting major cities within the prefecture (In Hokkaido, these are non-toll). These highways are monitored by MLIT (Ministry of Land Infrastructure and Transportations/Tourism). The earthquake damaged a few routes and traffic was closed to the damaged highways. The damages to the National Roads were generally not catastrophic, they are mainly road surface damages such as buckled road surfaces, uplift of joints along road surface, large cracks on road surfaces and ground deformation around bridge abutment.

Table 9-1 shows the time line of road inspection, determination of actions (open or close), and repair and recovery for traffic on National Roads. Routes and Ku's mean the section of highway in the Ku or within the Ku's. A Ku is a region; in Japanese is 町 (Chō). All National highways were re-opened by September 11 2018 at 10 AM local time.

Date	Time	Routes	Ku (Chō)	Comment
06 Sept 2018	06:00	1	1	Closed
06 Sept 2018	09:00	3	3	Closed
06 Sept 2018	11:30	2	3	Closed
06 Sept 2018	15:00	2	2	Closed
06 Sept 2018	18:30	2	2	Closed
06 Sept 2018	22:00	2	2	Closed
07 Sept 2018	05:30	2	2	Closed
07 Sept 2018	11:00	1	1	Closed
07 Sept 2018	16:00	1	1	Closed
07 Sept 2018	22:00	2	3	Closed
08 Sept 2018	06:00	2	2	Closed
08 Sept 2018	11:00	1	1	Closed
11 Sept 2018	10:00	0	0	All open

Table 9-1. National Road Closures

9.3.2 Expressways (Toll Roads)

Expressways are owned and operated by NEXCO (Nippon Expressway Company). A toll is collected at exit booths. Entry points are monitored so the toll cost for individual vehicles can be determined. Under normal operation, many people use the electronic access device so that there is no waiting time at the toll gates.

The maximum number of routes that were required to repair before opening to traffic was 5 in 6 Ku's. There was no bridge damage reported. The majority of the damages were cracked road surfaces, subsided, up lifted and abutment sunken due to ground deformation. The time line of identifying damage, repair and decision to close and open are shown in Table 9-2. Repairing the non-significant damages were not time consuming, therefore the Expressways were opened within one day after the initial shock.

Date	Time	Routes	Ku (Chō)	Comment
06 Sept 2018	07:00	1	1	Closed
06 Sept 2018	09:00	1	6	Closed
06 Sept 2018	11:30	5	6	Closed
06 Sept 2018	15:00	3	6	Closed
06 Sept 2018	18:30	1	1	Closed
06 Sept 2018	22:00	1	1	Closed
07 Sept 2018	05:30	1	1	Closed
07 Sept 2018	16:00	0	0	All routes open

Table 9-2. Expressway Toll Road Closures

All Expressways were re-opened on September 7 2018 at 4 PM local time.

9.3.3 Secondary roads

This category of roads is basically paved one-lane roads for local community traffic. These roads connect the communities within each (町) Chō. These roads that were in the hardest hit areas sustained significant damage and most requiring a lot of effort (resources) to repair. As note in Table 9-3, the number of damaged locations was considerably higher than the Highways and Expressways. Most of the damage to these roads occurred in the foothills where huge landslides occurred.

Table 9-3 shows the number of routes to be fixed and the timeline of opening the repaired roads. When more resources were available to inspect road damages, the number of routes to be closed became more during the early part of the emergency response period.

There were two routes in two Ku's were still closed as of 07 December 2018. These two routes were in Atsuma Chō, the hardest hit area of this earthquake.

Date	Time	Routes	Ku (Chō)	Comment
06 Sept 2018	07:00	2	2	Closed
06 Sept 2018	09:00	2	5	Closed
06 Sept 2018	11:30	4	11	Closed
06 Sept 2018	15:00	7	18	Closed
06 Sept 2018	18:30	15	20	Closed
06 Sept 2018	22:00	16	20	Closed
08 Sept 2018	06:00	16	16	Closed
08 Sept 2018	11:00	13	15	Closed
09 Sept 2018	22:00	12	13	Closed
10 Sept 2018	10:00	10	13	Closed
11 Sept 2018	21:00	9	12	Closed
12 Sept 2018	20:00	9	12	Closed
16 Sept 2018	17:30	9	11	Closed
19 Sept 2018	17:30	7	9	Closed
20 Sept 2018	17:00	7	10	Closed
24 Sept 2018	17:00	7	9	Closed
27 Sept 2018	17:00	7	10	Closed
17 Oct 2018	17:00	6	8	Closed
31 Oct 2018	17:00	5	6	Closed
19 Nov 2018	17:00	3	3	Closed
28 Nov 2018	17:00	2	2	Closed
07 Dec 2018	17:00	2	2	Closed

Table 9-3. Secondary Road Closures

9.3.4 Railway

By "Railway", we include in this section all JR trains, Shinkansen, and local light rail (subway and tram).

Shinkansen (high speed trains). The Shinkansen has not yet extended all the way to downtown Sapporo City. As of September 2018, the Shinkansen terminates close to Hakodate, see Figure 9-1. The level of shaking at Hakadote in the September 2018 earthquake was JMA intensity 5 minus to 4; or in the range of PGA = 0.01g to 0.05g over the course of the length of the current Shinkansen right-of-way in Hokkaido. There was no reported interruption to this service or damage to the equipment. At time of the earthquake there was no service on the Shinkansen line.

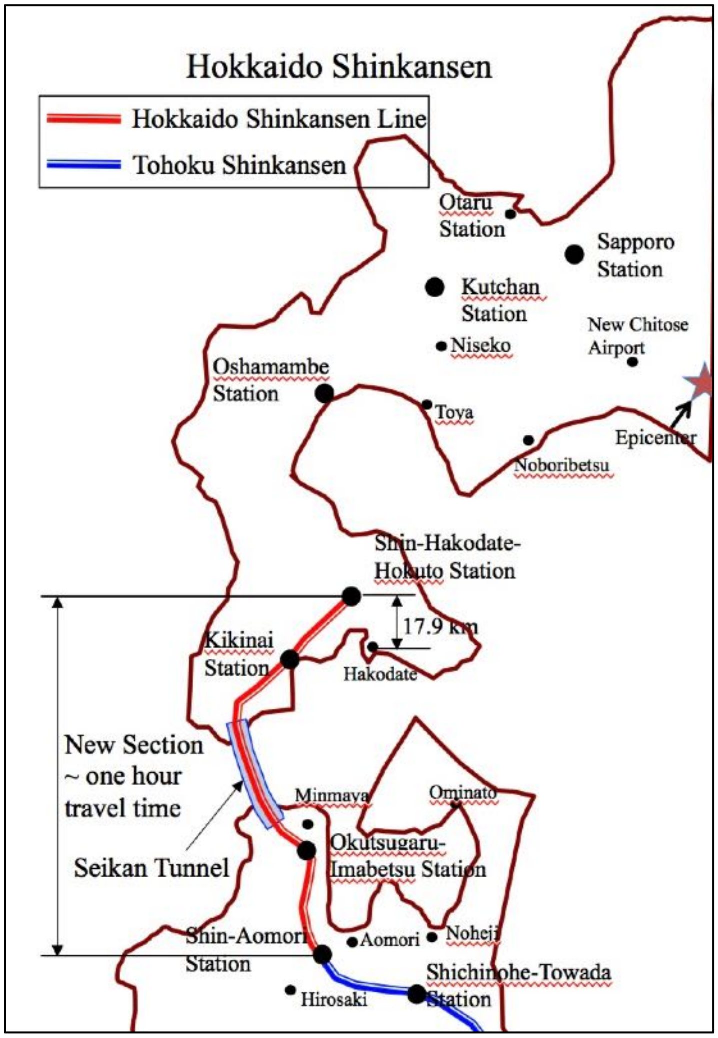

Figure 9-1. Location of the Shinkansen terminal in Hokkaido.

Both JR and the light rail system sustained service interruption mainly due to power outage. Sapporo City and Iburi Sub-prefecture suffered long duration of service interruption to public transportation services. A section of the track between Tomakomai and Samani was buckled (Figure 9-2) due to permanent ground movement that forced the steel rails into compression. This section of rail service took about three weeks to repair and return to partial service; about six weeks to restore entirely to normal service.

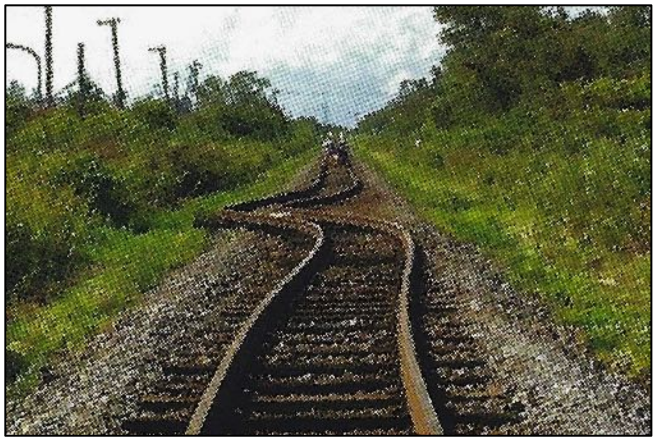

Figure 9-2. Buckled JR track on Hidaka Line. (Source: JR)

The time line of service restoration is shown in Table 9-4.

Lifelines	Date	Time	Report
Railway, Trains, and Trams	6-Sep-18	07:00:00	All operations suspended. JR train, subway, Sapporo tram
	7-Sep-18	16:00:00	Limited service resumed after noon
	7-Sep-18	22:00:00	Many service routes resumed, normal operations
	8-Sep-18	06:00:00	Normal operations for most subway routes except limited express closed all day
	8-Sep-18	22:00:00	Part of express train routes restarted
	9-Sep-18	17:00:00	JR is 50% normal, and regional trains started
	9-Sep-18	22:00:00	Subway routes normal operation
	10-Sep-18	10:00:00	No Change
	18-Sep-18	17:00:00	JR 79% normal
	19-Sep-18	17:00:00	JR 83.5% normal
	20-Sep-18	17:00:00	No Change
	21-Sep-18	17:00:00	JR 87.4% normal
	22-Sep-18	17:00:00	No change
	23-Sep-18	17:00:00	JR 91.1% normal
	24-Sep-18	17:00:00	JR 91.1% normal. Except Hidaka Line - twisted track.
	27-Sep-18	17:00:00	JR 94.3% normal. Except Hidaka Line with the twisted track not repaired.
	28-Sep-18	17:00:00	The track between Tomakomai and Samani was repaired and trains are operating slowly and part still suspended.
	19-Oct-18	17:00:00	All operations normal

Table 9-4. Railway system return to operation

9.3.5 Ports (Airport and Harbor)

The airport that was impacted by the earthquake was New Chitose International Airport. It is about 25 km from the epicenter of this earthquake. There was no reported structural damage to the terminals, runways, flight guidance equipment and related systems. However, there were some non-structural damages and broken water pipes, which did not take long to repair. The Island-wide power outage was one of the main reasons of the initial airport closure.

The chronological events of the airport closure are shown in the table below.

Date	Time	Event
06 Sept 2018	07:00	Started investigation
06 Sept 2018	09:00	Decide to cancel all flights, close New Chitose Airport
06 Sept 2018	11:30	New Chitose Airport remained closed
06 Sept 2018	15:00	New Chitose Airport remained closed
06 Sept 2018	18:30	443 domestic flights were allowed, and 52 international flight were cancelled
06 Sept 2018	22:00	No change to allowed flights. Two relief supply flights were allowed. They were JAL and ADO flights from Haneda.
07 Sept 2018	05:30	Determined to cancel all flights.
07 Sept 2018	11:00	Airport was still closed
07 Sept 2018	16:00	Decided to allow all domestic flights. International flights were still cancelled.
07 Sept 2018	22:00	Decided to cancel 186 domestic flights, and 50 international flights.
08 Sept 2018	06:00	Decided to allow all domestic flights, and international flight were also allowed.
08 Sept 2018	11:00	New Chitose Airport remained open
08 Sept 2018	16:00	New Chitose Airport remained open
27 Sept 2018	06:00	New Chitose Airport was back to normal operations.

(JAL = Japan Airline, ADO = Air Do formerly Hokkaido International Airline)

Table 9-5. CTS return to operation

The international terminal was flooded due to broken pipes; the water was mopped up within five hours by airport crews and a cleaning company.

The power outage at the airport resulted in loss of refrigeration; this resulted in spoiled food, which had to be removed.

CTS hosted many stranded passengers. On Friday September 7, it was reported that the terminal resembled an evacuation center filled with people sleeping on the floor. The amount of food available at the airport was limited for the first two days.

By Saturday September 8, offsite power had been restored and all flight operations resumed.

9.3.6 Electric Power

Section 3 provides a lot of detail about the electric power supply and its performance during this earthquake. In this section, we focus on the duration of the power outages and the number of households that were impacted by power outages.

The data is separated into three restoration stages:

- First stage. The Island-wide black out of millions of households, see Section 3 and Table 9-6.

- Second stage. The outage to 20,000 plus households to within two thousands of households.

- Third stage. The restoration of power to the last 400 plus households.

Date	Time	Comment
06 Sept 2018	07:00	2.95 Million households without power
06 Sept 2018	22:00	2.46 Million households without power
07 Sept 2018	05:30	1.83 Million households without power
07 Sept 2018	22:00	1.09 Million households without power

Table 9-6. Power Outages during the first two days after the main shock (See Section 3 for outages between 3:08 am and 7:00 am Sept 6)

The graph in Figure 9-3 represents the recovery after the main shock.

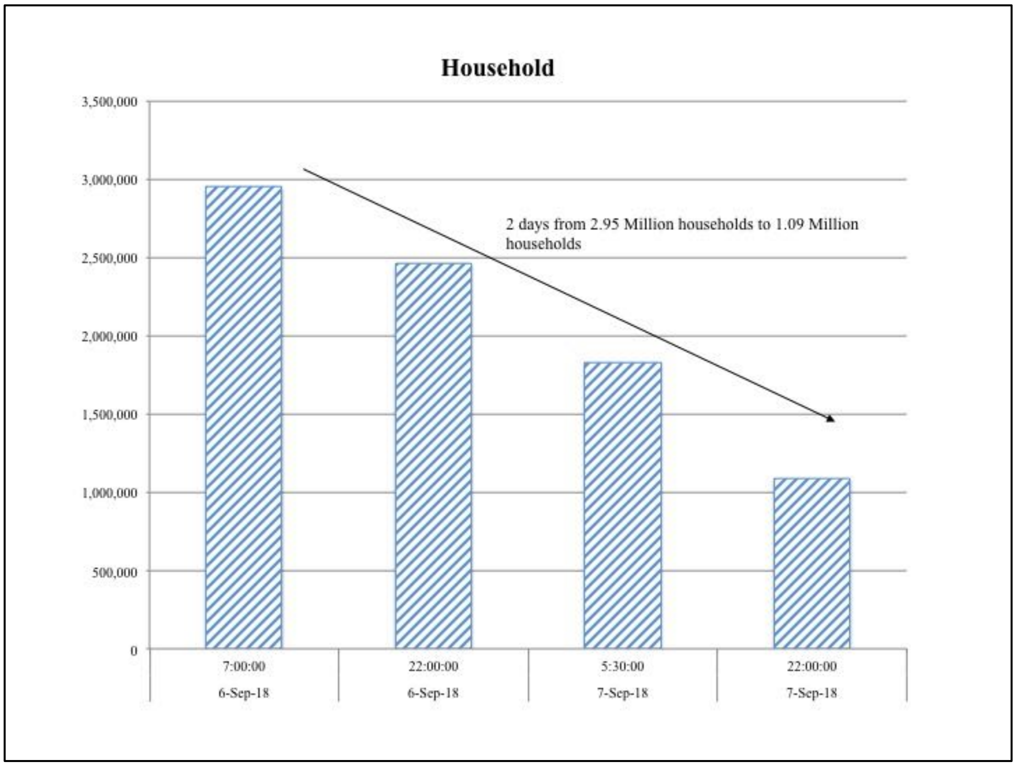

Figure 9-3. Reduction of households without power from Sept 6 to Sept 7

During the first stage, the approximate number of customer minutes of outage are as follows:

- 3:08 am to 3:27 am. During this time frame, a portion of the island was blackout out due to load shedding. About 1.3 million customers were dropped during this time period, lasting about 21 minutes.
- From 3:27 am to about 7:00 am Sept 6, the entire Island was blackout out.
- Around 7:00 am Sept 6, black start operations began, and the power was restored in blocks. From 7 am to 10 pm Sept 6, assuming a linear restoration of power to 500,000 customers.
- From 10 pm Sept 6 to 530 am Sept 7, power was restored to another 630,000 customers.
- From 530 am Sept 7 to 10 pm Sept 7, power was restored to another 740,000 customers.
- From 10 pm Sept 7 to 600 am Sept 8, the last of the bulk power outages were restored, then leaving 21,300 customers without power.

Total CM outages (Stage 1), assuming linear restoration based on this data, was 6.014 Billion.

In the second stage of the power recovery, the number of customers with outages dropped from 21,300 to 1,793. This reflects various repairs being made in the distribution system.

Date	Time	Comment
8 Sept 2018	06:00	21,300 households without power
8 Sept 2018	22:00	1,793 households without power

Table 9-7. The second portion of households recovering from power outage

The graph in Figure 9-4 represents the recovery during Stage 2.

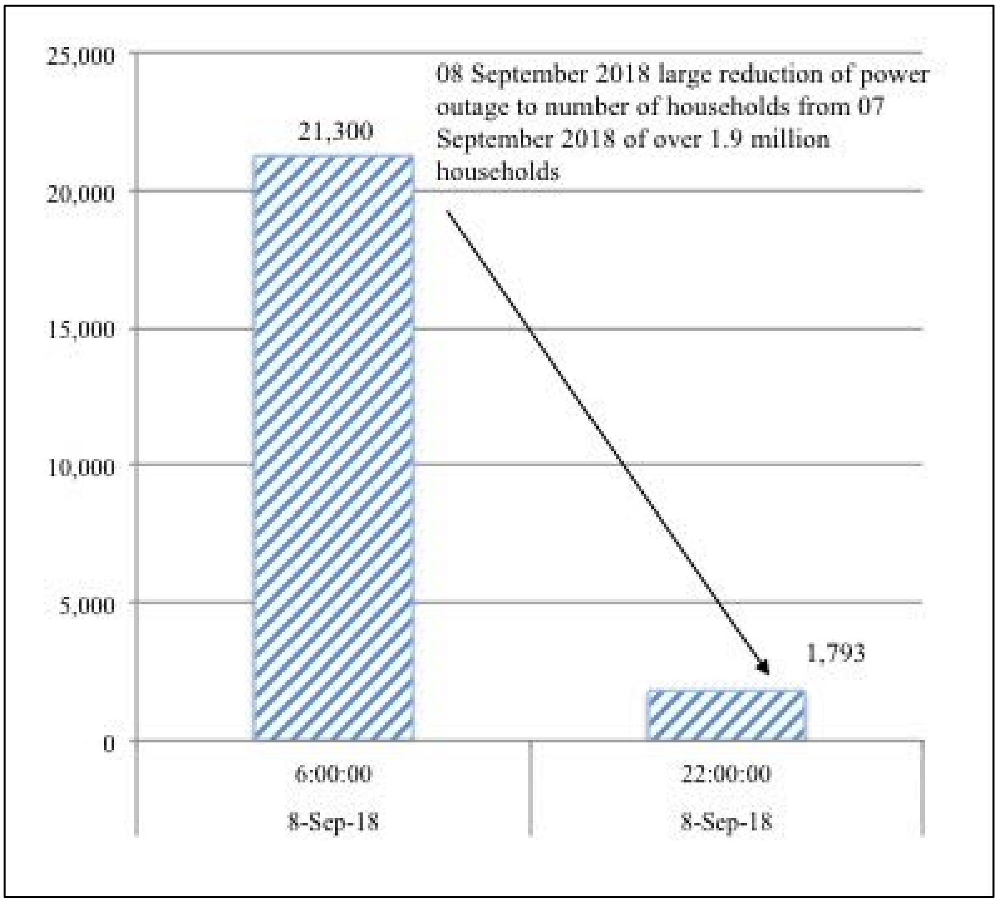

Figure 9-4. Reduction of household without power from 6 AM to 10 PM on Sept 8

During the second stage, the approximate number of customer minutes of outage 10.17 million.

Table 9-8 lists the power outages during the third stage of recovery.

Date	Time	Comment
9 Sept 2018	05:00	456 households without power
9 Sept 2018	22:00	403 households without power
10 Sept 2018	10:00	403 households without power
10 Sept 2018	21:00	312 households without power
11 Sept 2018	10:00	247 households without power
11 Sept 2018	21:00	173 households without power
12 Sept 2018	20:00	165 households without power
13 Sept 2018	10:00	161 households without power
13 Sept 2018	20:00	144 households without power
14 Sept 2018	10:00	90 households without power
14 Sept 2018	17:00	82 households without power
15 Sept 2018	10:00	82 households without power
15 Sept 2018	17:00	65 households without power
16 Sept 2018	10:00	63 households without power
16 Sept 2018	17:30	59 households without power
17 Sept 2018	10:00	59 households without power
17 Sept 2018	17:00	59 households without power
18 Sept 2018	10:00	55 households without power
18 Sept 2018	17:00	50 households without power
19 Sept 2018	10:00	50 households without power
19 Sept 2018	17:30	50 households without power
20 Sept 2018	10:00	45 households without power
20 Sept 2018	17:00	33 households without power
21 Sept 2018	10:00	33 households without power
21 Sept 2018	17:00	28 households without power
24 Sept 2018	17:00	28 households without power
25 Sept 2018	17:00	25 households without power
26 Sept 2018	10:00	11 households without power
27 Sept 2018	10:00	6 households without power
27 Sept 2018	17:00	3 households without power
28 Sept 2018	17:00	2 households without power
03 Oct 2018	10:00	1 household without power
05 Oct 2018	10:30	0 household without power

Table 9-8. The third stage of households recovering from power outage.

The graph in Figure 9-5 represents the power recovery of the remaining households

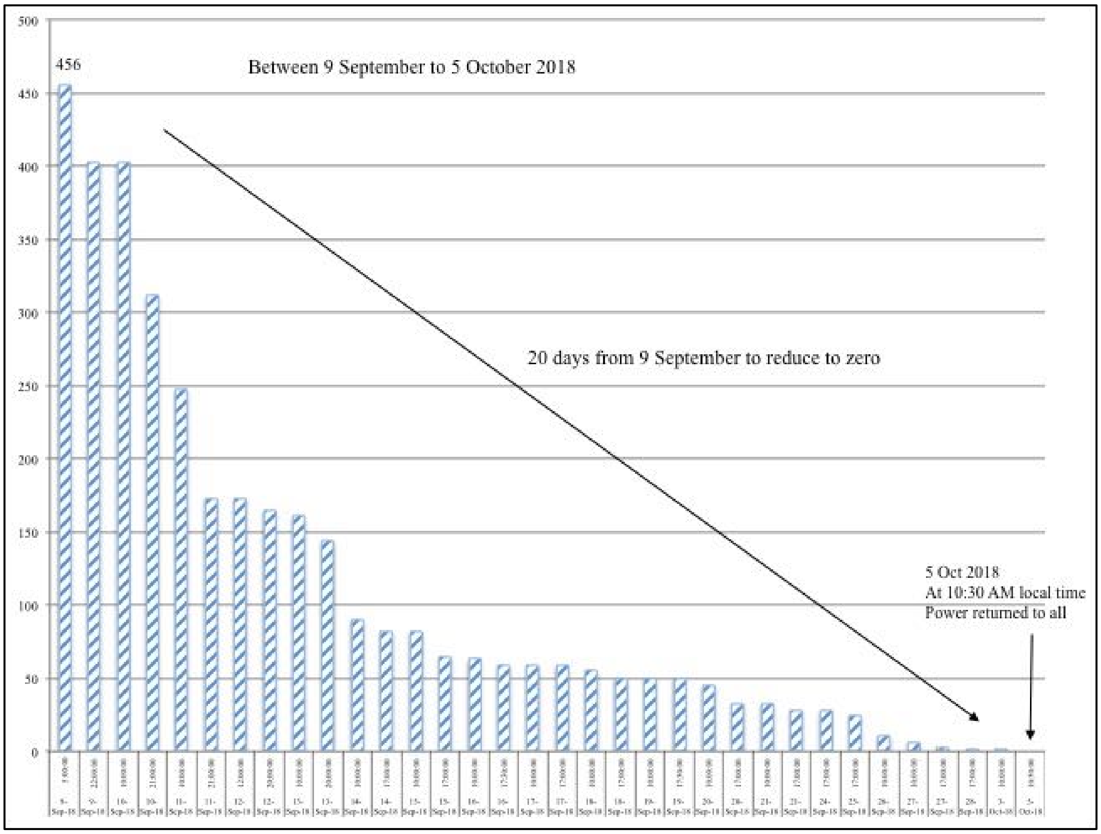

Figure 9-5. Recovery of the power of households from Sept 9 to Oct 10

The CM during the third stage was 2.68 million.

The total CM was 6.014 Billion + 10.17 million + 2.68 million = 6.026.9 Million. Of this amount, about 6 Billion was due to damage in the generation + transmission system (Stage 1), and 13 million due to damage in the distribution system.

The recovery of power to all households in the Prefecture took 23 days (3 weeks and 2 days). This does not include ongoing power outages to customers with destroyed buildings (on the order of 200).

9.3.7 Water Supply

The performance of the water supply system is presented in Chapter 5. Table 9-9 lists the cities (or smaller communities, called Chō) with water outages as a function of time after the earthquake. The outages are listed in terms of households (generally, one household = 1 billing account).

Table 9-9 does not have complete data for every community for every time. For example, it was reported that Mukawa Cho had no water supply at 10 pm on September 6; but we do not have data for Mukawa Cho from the time of the earthquake at 3:08 am until 10 pm on September 6.

Some observations:

- On September 6, the number of households without water is estimated at about 37,250 households based on the highest counts listed in Table 9-9.

- By the morning of September 7, the number of households without water is reasonably well known. Most outages are caused either by power outages (loss of pumping for hillside zones / or from wells in some areas) or in some areas, damaged water pipelines. See Figure 5-2 for a map of outages that are presumed to have been due to power outages.

- By the evening of September 7, water was restored to several smaller communities (reduction from 31 to 20 communities with partial outages between 7 am and 10 pm on September 7), as the Island-wide power outage was partially restored, and some repairs to infrastructure damage were completed.

- By the morning of September 8, part of Abira was restored with water; 4 other communities continued to have water outages.

- By the morning of September 9, the large water outage in Sapporo City (~15,000) had been greatly reduced to (211); this largely reflects the restoration of power to allow pumping to hillside pressure zones; but areas with pipeline damage (like Kiyota-ward) remained without water.

- By September 24, there remained only a few pockets of water outages, in Sapporo City (52), Atsuma (231) and Abira (99). These outages largely reflect continued issues with due to liquefaction or landslide effects.

- By October 4, only Atsuma (65) had remaining outages.

- By October 9 (34 days) water was restored to the entire area.

Date and Time	Complete (# households)	Partial Outage (# households)
Sept 6 3:08 am	Main Shock Occurs	Main Shock Occurs
Sept 6 6:00 am	Abira Chō has broken pipes in many locations	Uryu Cho and Urausu Cho (30)
Sept 6 9:00 am	Abira Chō, Atsuma Chō	Hidaka Chō (~ 2,000), Kuriyama Chō, Nanporo Chō, Ebetsu Chō, Ishikari Chō, Uryu Chō, Urausu Chō
Sept 6 11:30 am	Abira Chō, Atsuma Chō	Hidaka Chō (~ 2,000), Kuriyama Chō, Nanporo Chō, Ebetsu Chō, Ishikari Chō, Uryu Chō, Urausu Chō, Nemuro Shi
Sept 6 3:00 pm	Abira Chō, Atsuma Chō	Hidaka Chō (~ 2,000), Kuriyama Chō, Nanporo Chō, Ebetsu Chō, Ishikari Chō, Uryu Chō, Urausu Chō, Nemuro Shi, Sapporo City, Obihiro Shi, Otofuke Chō, Ikeda Chō, Kushiro City, Esashi Chō, Kaminokuni Chō, Imakane Chō, Setana Chō
Sept 6 6:30 pm	Abira Chō, Atsuma Chō	Mukawa Chō, Noboribetsu City, Toyako Chō, Hikada Chō, Urakawa Chō, Sapporo City, Eniwa City, Ebetsu City, Kuriyama Chō, Nanporo Chō, Uryu Chō, Urausu Chō, Akabira City, Chippubetsu Chō, Mikasa City, Otaru City, Kimbetsu Chō, Kyogoku Chō, Yoichi Chō, Akaigawa Mura, Aibetsu Chō, Horokanai Chō, Mashike Chō, Obihiro City, Sarabetsu Mura, Ikeda Chō, Monbetsu City, Saroma Chō, Tsubetsu Chō, Oketo Cho, Kushiro Chō
Sept 6 10:00 pm	Abira Chō, Atsuma Chō, and Mukawa Chō	Mukawa Chō, Noboribetsu City, Toyako Chō, Hikada Chō, Urakawa Chō, Sapporo City, Eniwa City, Ebetsu City, Kuriyama Chō, Nanporo Chō, Uryu Chō, Urausu Chō, Akabira City, Chippubetsu Chō, Mikasa City, Otaru City, Kimbetsu Chō, Kyogoku Chō, Yoichi Chō, Akaigawa Mura, Aibetsu Chō, Horokanai Chō, Mashike Chō, Obihiro City, Sarabetsu Mura, Ikeda Chō, Monbetsu City, Saroma Chō, Tsubetsu Chō, Oketo Cho, Kushiro Chō
Sept 7 5:30 am	Abira Chō, Atsuma Chō	Mukawa Chō (investigating), Muroran City (2,910), Noboribetsu City (30), Toyako Chō (20), Date City (300), Sobetsu Chō (10), Hidaka Chō (2,285), Urakawa Chō (55), Sapporo City (15,108), Eniwa City (14), Uryu Chō・Urausu Chō (20~30), Chippubetsu Chō (10), Yubari City (4), Otaru City (48), Kyogoku Chō (40~50), Yoichi Chō (50), Akaigawa Mura (65), Hakodate City (496), Kaminokuni Chō (6), Biei Chō (3~4), Mashike Chō (17), Haboro Chō (~ 3,600), Hamatonbetsu Chō (4), Obihiro City (1], Sarabetsu Mura (1), Otofuke Chō (5), Ikeda Chō (45), Tsubetsu Chō (17), Oketo Chō (15~20), Kushiro Chō (54)
Sept 7 10:00 pm	Abira Chō (5,900), Atsuma Chō (2,100)	Mukawa Chō (~ 4,000), Muroran City (2,910), Noboribetsu City (30), Toyako Chō (20), Date City (300), Sobetsu Chō (10), Hidaka Chō (2,285), Urakawa Chō (55), Sapporo City (15,108), Uryu Chō ・ Urausu Chō (48), Otaru City (48), Hakodate City (442), Kaminokuni Chō (6), Biei Chō (1), Mashike Chō (6), Obihiro City (1), Tsubetsu Chō (17), Oketo Chō (15～20), Kushiro Chō (54)
Sept 8 11:00 am	Atsuma Chō (2,100)	Abira Chō (3,351), Mukawa Chō (~ 3,200), Hidaka Chō (2,285), Biratori Chō (750), Sapporo City (15,000)
Sept 9 11:00 am	Atsuma Chō (2,100)	Abira Chō (3,351), Mukawa Chō (~ 3,200), Hidaka Chō (2,285), Biratori Chō (60 households), Sapporo City (211 households)
Sept 9 5:00 pm	Atsuma Chō (2,100)	Abira Chō (3,222), Mukawa Chō 826), Hidaka Chō (2,087), Biratori Chō (40), Sapporo City (125)
Sept 24 5:00 pm		Astuma Chō (231), Abira Chō (99), and Sapporo City (52)
Oct 4		Astuma Chō (65)
Oct 9 5:00 pm		All households restored with water supply

Table 9-9. Number of Households without Water

9.4 Casualty and Injury

The series of reports provide a daily collection of casualty and injury number. As each day goes by the number keeps increasing as more and more information are coming in to the department. This section presents the final number collected as of December 7 2018.

The total casualties (fatalities) was 41. Table 9-9 shows the number of casualties in different locations.

Location	Sapporo	Tomakomai	Atsuma	Mukawa	Shinhidaka
Number	1	2	36	1	1

Table 9-9. Number of casualties, by area

In recent months, there has been a popularized concept that the number of "additional casualties" in a disaster (estimated at 2,975 people due to the effects of Hurricane Maria in Puerto Rico in September 2017) should include not only the number of casualties due to direct damage (documented at 64 people in Puerto Rico due to causes like collapse of a building), but also the incremental number mortality over a longer term (like a year) period due to the lasting economic / infrastructure / damage impacts of the disaster. We do not agree that one can easily discern that if a person dies from pulmonary disease, several months after a disaster, that this death can be directly ascribed to have been uniquely caused by the disaster. In this report we make no estimate of the longer term increase (or decrease?) of the Hokkaido mortality rate due to the Island-wide power outage or the other aspects of this earthquake. After the 1989 Loma Prieta and the 1994 Northridge earthquakes in California, health officials from UCLA did statistical studies to examine the causes of the observed casualty rates. Some of the statistically significant results were that "people with pets were more likely to be injured" and "non-Hispanics were more likely to be injured than Hispanics". These studies, including the recent one in Puerto Rico, are filled with many assumptions, many of which can be challenged. The authors suggest that this concept of "additional casualties" be left to others to discern, and in this report we avoid the dubious forecast of "additional casualties" and we try to avoid political posturing and finger pointing using hypothetical casualty data that some politicians have been wont to do.

Table 9-10 lists the count of seriously injured people (19 total). There were also 8 additional people that were classified as sustaining between serious and light injury. They were from Ebetsu (1), Hidaka (2) and Hakodate (5).

The total number of lightly (minor) injured are 723. Table 9-11 lists the number of light injuries in different locations.

Location	Number
Kuriyama	1
Sapporo	1
Ebetsu	1
Kitahiroshima	1
Ishikari	1
Tomakomai	7
Abira	2
Mukawa	2
Niikappu	1
Obihiro	1
Shihoro	1

Table 9-10. Number of serious injuries, by area

Location	Number
Mikasa	2
Ashibetsu	1
Yuni	2
Sapporo	295
Ebetsu	3
Chitose	1
Eniwa	3
Kitahiroshima	6
Ishikari	1
Muroran	2
Tomakomai	15
Date	1
Atsuma	61
Abira	10
Mukawa	250
Hidaka	34
Biratori	3
Hakodate	5
Obihiro	12
Honbetsu	1
Makubetsu	2
Otofuke	1
Sarufutsu	1

Table 9-11. Number of minor injuries, by area

9.5 Shelters and Community Services

More than 100 locations were allocated within Prefecture as temporary shelters for victims until properly constructed shelters were available. The constructed shelters are standard type of row units to house families. Power, gas, and water are the three main utilities set up for the units, Figure 9-6.

By 22:00 on September 6, there were 3963 dis-located people used 11 campsites in two districts – Sorachi and Ishikari.

By 05:00 on September 7, there were 6,749 dis-located people at 41 campsites.

By 16:30 on September 8, the accumulated total dis-located people using the campsites was 16,554.

Figure 9-6. Constructed shelters

9.6 Schools

No schools (primary, secondary, high school) collapsed in the earthquake. There was a host of minor damage at many schools. As the earthquake occurred at 3:08 am, there was effectively no occupancy in the schools, and we do not have any data suggesting that this minor damage led to any injuries.

The modes of minor damage to schools were: broken glass windows, fallen light fixtures, un-secured objects such as statues fell and broken, water tank and water pipes leaks, surface crack on plaster walls, outdoor sports field sunken or deformed with surface cracks or liquefaction, and external concrete walls cracked.

Table 9-12 shows the number of schools in each location/region that sustained these minor damages. There were 159 schools from primary to high schools.

Location	Number of schools
Sorachi	10
Ishikari	20
Yoichi	1
Iburi	16
Oshima	4
Hiyama	1
Hidaka	12
Sapporo City	95
Total	159

Table 9-12. Damaged Schools

School closures were announced starting on September 7 in the morning; the timeline of re-opening is listed in the Table 9-13. We do not have reported school closure data for September 6, but presumably it would be similar or perhaps a bit higher as reported for September 7.

Region/ Location	Schools closed					Total number of schools in Region/Location
	07 Sept	10 Sept	11 Sept	12 Sept	13 Sept	
Sorachi	108	10	2	1	0	138
Ishikari	162	18	2	0	0	162
Sapporo	324	92	1	0	0	324
Yoichi	82	0	1	0	0	116
Iburi	142	20	21	18	14	142
Hidaka	44	12	2	1	0	51
Oshima	166	0	0	0	0	166
Hiyama	19	1	0	0	0	38
Kamikawa	180	1	1	0	0	222
Rumoi	30	1	0	0	0	39
Soyamura	49	0	0	0	0	67
オホーツク	155	22	0	0	0	160
Otofuke	128	3	1	0	0	175
Kushiro	104	0	0	0	0	114
Nemuro	59	2	1	1	0	59
	1,752	182	32	21	14	1,973

Table 9-13. School Closures

The primary reason for the closure was the Island-wide power outage, with other reasons being the clean-up for minor damages, as well as the widespread shutdown of transportation and other issues immediately post-earthquake.

All schools in Iburi were open on September 15. Iburi was the area having very strong ground motions, coupled with many landslides that impacted roads.

Figures 9-7 and 9-8 show a damaged outdoor sports field and broken concrete wall.

Figure 9-7. Outdoor sports field damaged due to permanent ground deformation

Figure 9-8. Concrete wall broken due to permanent ground deformation

9.7 Building Damage

Two categories of buildings are used in the report – Household and Commercial. The states of damage are divided into three; 1. Destroyed, 2. Half of the building damaged, and 3. Part of the building damaged. In Japan, the "red / yellow / green" tag system is used to document the damage and banners are posted on each building. There is not necessarily a "one-to-one" correspondence in these categories with respect to ‘not allowed to use = red tag’, ‘limited use = yellow tag’ or ‘allow to use = green tag’; but based on our observations, it would be reasonably to assume a nearly one-to-one correspondence. The date of the data collected below was September 27 2018.

9.7.1 Household Residential Buildings

The various states of damage and number of buildings damaged are listed in the table below. The number in bracket after the name of the location is the number buildings in that location damaged.

State of Damage	Number	Location[9]
Destroyed	452	Sapporo City (87), Ebetsu City (1), Chitose City (1), Kita-Hiroshima City (17), Atsuma Chō (222), Abira Chō (93), Mukawa Chō (28), Hidaka Chō (3)
Half Damaged	1,524	Yuni Chō (2), Sapporo City (648), Ebetsu City (21), Chitose City (1), Kita- Hiroshim (19), Tomakomai City (1), Noboribetsu City (1), Atsuma Chō (308), Abira Chō (349), Mukawa Chō (116), Hidaka Chō (54), Biratori Chō (3), Hakodate City (1)
Partly Damaged	11,159	Yubari City (1), Bibai City (5), Mikasa City (18), Fukagawa City (1), Yuni Chō (9), Naganuma Chō (27), Kuriyama Chō (12), Numata Chō (1), Nanporo Chō (4), Sapporo City (3,918), Ebetsu City (141), Chitose City (177), Eniwa City (12), Kita-Hirshima City (186), Ishikari City (9), Muroran City (31), Tomakomai City (154), Noboribetsu City (22), Shiraoi Chō (3), Atsuma Chō (1,045), Toyako Chō (1), Abira Chō (2,402), Mukawa Chō (2,746), Hidaka Chō (426), Biratori Chō (120), Shin-hidaka Chō (35), Hakodate City (10), Mori Chō (2), Obihiro City (1)

Table 9-14. Damaged Residential Buildings

9.7.2 Commercial Buildings

All buildings that are not used as a family residences are in this category. The word commercial is used for simplicity. Table 9-15 lists the number of buildings that were in

[9] Co-ordinate of the location is listed in 9.9 References

the three different states of damage. The number in bracket after the name of the location is the number buildings in that location damaged.

State of Damage	Number	Location[1]
Destroyed	1,141	Sapporo City (7), Ebetsu City (4), Atsuma Chō (659), Abira Chō (340), Mukawa Chō (131).
Half Damaged	1,287	Sapporo City (21), Ebetsu City (2), Atsuma Chō (656), Abira Chō (549), Mukawa Chō (58), Biratori Chō (1)
Partly Damaged	3,573	Kuriyama Chō (2), Sapporo City (178), Ebetsu City (11), Chitose City (1), Ishikari City (4), Tobetsu Chō (1), Tomakomai City (8), Noboribetsu City (1), Atsuma Chō (798), Abira Chō (2,155), Mukawa Chō (412), Nanae Chō (2)

Table 9-15. Damaged Commercial and Multi-Family Buildings

9.8 Agriculture Losses

Agriculture is a major industry in Hokkaido. There were four major types of losses:

- Losses of fields covered by landslide debris (and removal of the debris)
- Losses due to the damaged and broken irrigation channels
- Losses due to forest damage
- Losses to farming and ranching

The loss due to agricultural field damage, debris from landslides covering the fields, broken irrigation channels, and equipment damage have been estimated to be in the range of 850B ¥ (~7.73 Billion US$).

Forest land damage, and access roads damage was estimated to be 474B ¥ (~4.3 Billion US$).

Damage to agricultural products was estimated to be around 85B ¥ (~770 Million US$).

Combined, these losses are about $12.8 Billion ($US). Over time, these agriculture losses may be revised, but it would be not unreasonably to state that the long term total will approximate about one-year's loss in farm product in the affected areas.

9.9 Acknowledgement

We are grateful to Prof Maruyama and Prof Konagai for directing the author to the department to collect the data. Interpretation of the material may have some differences; there was no intention to undermine the data presented on the reports.

9.10 References

The information in this chapter is collected from the daily report by Hokkaido Prefecture, Crisis Management Department.

Location Name	Co-ordinates (Lat, Long)
Sapporo City (札幌市)	43.0620^0, 141.3544^0
Ebetsu City (江別市)	43.1037^0, 141.5363^0
Kitahiroshima City (北広島市)	42.9852^0, 141.5633^0
Atsuma Chō (厚真町)	42.7222^0, 141.8768^0
Abira Chō (安平町)	42.7627^0, 141.8179^0
Mukawa Chō (むかわ町)	42.5748^0, 141.9267^0
Hidaka Chō (日高町)	42.4801^0, 142.0743^0
Biratori Chō (平取町)	42.5848^0, 142.1285^0
Bibai City (美唄市)	43.3329^0, 141.8538^0
Mikasa City (三笠市)	43.2454^0, 141.8753^0
Yuni Chō (由仁町)	42.9994^0, 141.7903^0
Naganuma Chō (長沼町)	43.0094^0, 141.6949^0
Numata Chō (沼田町)	43.8058^0, 141.9345^0
Chitose City (千歳市)	42.8199^0, 141.6502^0
Eniwa City (恵庭市)	42.8825^0, 141.5778^0
Muroran City (室蘭市)	42.3149^0, 140.9737^0
Tomakomai City (苫小牧市)	42.6342^0, 141.6053^0
Noboribetsu City (登別市)	42.4127^0, 141.1067^0
Shiraoi Chō (白老町)	42.5503^0, 141.3556^0
Toyako Chō (洞爺湖町)	42.5509^0, 140.7633^0
Shin-hidaka Chō (新ひだか町)	42.3415^0, 142.3684^0
Hakodate City (函館市)	41.7684^0, 140.7287^0
Nanae Chō (七飯町)	41.8957^0, 140.6943^0
Yubari City (夕張市)	43.0562^0, 141.9738^0
Nanporo Chō (南幌町)	43.0635^0, 141.6501^0
Mori Chō (森町)	42.1046^0, 140.5765^0
Tobetsu Chō (当別町)	43.2235^0, 141.5169^0
Ishikari City (石狩市)	43.1709^0, 141.3513^0
Fukagawa City (深川市)	43.7232^0, 142.0536^0

Table 9-16. Locations Mentioned in this Chapter