PERFORMANCE OF POWER, GAS AND WATER LIFELINES IN THE 2018 HOKKAIDO EARTQHUAKE

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Abstract

This paper examines the performance of Power, Gas and Water lifelines in the M 7.0 Hokkaido Earthquake of September 2018.

Power. The Electric Power System was damaged by the earthquake, resulting in an Island-wide power outage. The damage included shaking-related damage to three coal-fired power plants; landslide-related damage to two 66 kV transmission lines; conductor-dynamics-related damage to two 275 kV transmission lines; and collapse of several hundred distribution poles, primarily due to landslide. Much of this damage could have been predicted before the earthquake. The totality of the damage led to an "N-5" event, whereby five major elements of the electric grid were damaged at the same time (3 power plants and 2 key transmission lines). Rapid load shedding and ramp up of other power supplies occurred in the first few minutes after the earthquake. However, ongoing damage led to a loss of sufficient generation to maintain system-wide frequency of 50 Hz, and then the entire electric grid for Hokkaido Island went black, even though the damage was concentrated in a very small portion of Hokkaido. The paper examines the underlying causes of the physical damage, as well as the network implications as to why the Island-wide blackout occurred.

Gas. The Gas system in Sapporo did well. Almost all gas pipelines are "seismic tough", and there was modest seismic damage. The level of shaking in Sapporo was not high enough to trigger automatic seismic shut-off valves. There was sporadic damage to the gas system infrastructure, and no gas-fed fires. There was a modest effort by the gas company to check for gas leaks and to do re-lights.

Water. There are many independent water systems in the region that suffered damage from the earthquake. In the epicentral area, where shaking was highest, there was extensive damage to the Atsuma potable water system, including many pipe breaks due to strong shaking and liquefaction, as well as complete failure of a water treatment plant due to a landslide. A raw water irrigation pipeline system near Atsuma suffered many failures. Neither water system near Atsuma appears to have been constructed using seismic-tough pipelines. In Sapporo, the level of shaking was modest, and portions of the water system were constructed with seismic-tough pipes; in these areas, there was very little damage. In one Sapporo subdivision, the ground liquefied, and non-seismic-tough water pipelines broke, leading to outages.

Summary. The Island-wide power blackout was the result of over-concentration of generation power plants in one area (all these were damaged) coupled with underlying weaknesses in transmission lines (wire dynamics and landslides at towers). Seismic-tough buried pipes, for both gas and water, did well in this earthquake; non-tough buried pipes did poorly.

Keywords: Power, Gas, Water, Lifelines

1. The Earthquake

The M_w = 6.7 earthquake occurred at 3:08 am, September 6 2018 local time. Fig. 1 shows the epicenter (red star) and 15 other M ≥ 6.0 earthquakes that have affected Hokkaido since 1970. Given the location and shallow depth of the September 6 2018 event, the 2018 earthquake resulted in higher level of shaking near the epicentral locations (near the red star) than any of the prior events since 1970.

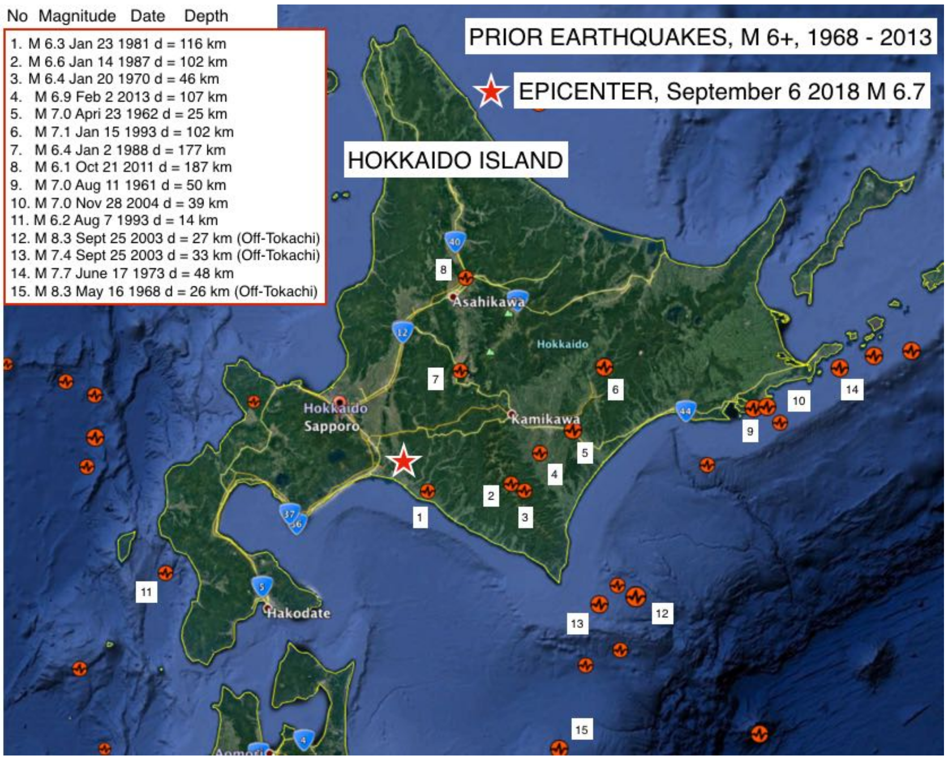

Fig. 1. Epicenter of M= 6.7 Earthquake, 6 September 2018, and Prior Earthquakes with M ≥ 6.0 since 1970

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. The highest recorded horizontal PGV was 153 cm/sec. The highest recorded horizontal PGA was 1.34 g. 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, see Fig. 2. 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).

It is well established that under dry conditions, most soil slopes are stronger than under wet conditions. In Sapporo, it is not uncommon for typhoons to show up in mid to late August. September is the rainiest month of the year. For the period Aug 1 - Sept 5 2018, the actual cumulative rainfall, as recorded at New Chitose Airport, was 65.3 cm. So, at the time of the earthquake, slope conditions reflected saturated conditions. Many of these slides were on moderately steep slopes (20° to 30°, such as the slides in Fig. 3); a few were on very shallow slopes (under 5°). The common surface geologic unit in the landslide area is 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 by inertial overload of the slope as well as by liquefaction at the toe of the landslide zone adjacent to creeks. The Ky and Newmark sliding block analogies might not be sufficient to predict the chance of occurrence and movement of these slides.

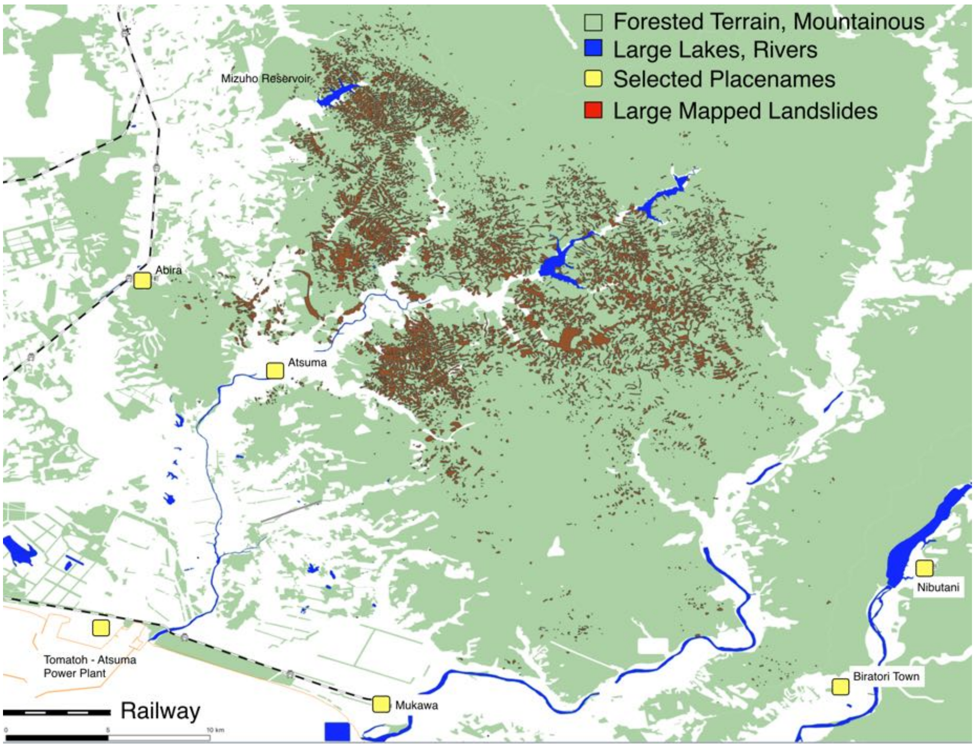

Fig. 2. Mapped Landslides (full scale = 10 km)

Fig. 3. Landslides east of Atsuma (credit: Shiga)

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.

Performance of a single lifeline (like electric power) is often impacted by the performance of other lifelines. See Tang [1] and Eidinger and Tang [2] for discussion of the performance of communication and transportation lifelines, as well as more in-depth discussion of the performance of power, gas and water systems in this earthquake.

2. Electric Power

Fig. 4 shows an overview map of major elements of the HEPCO electric system. Nearly the entire electric power system for Hokkaido Island is operated by Hokkaido Electric Power Company (HEPCO). The system normally operates at 50 Hz.

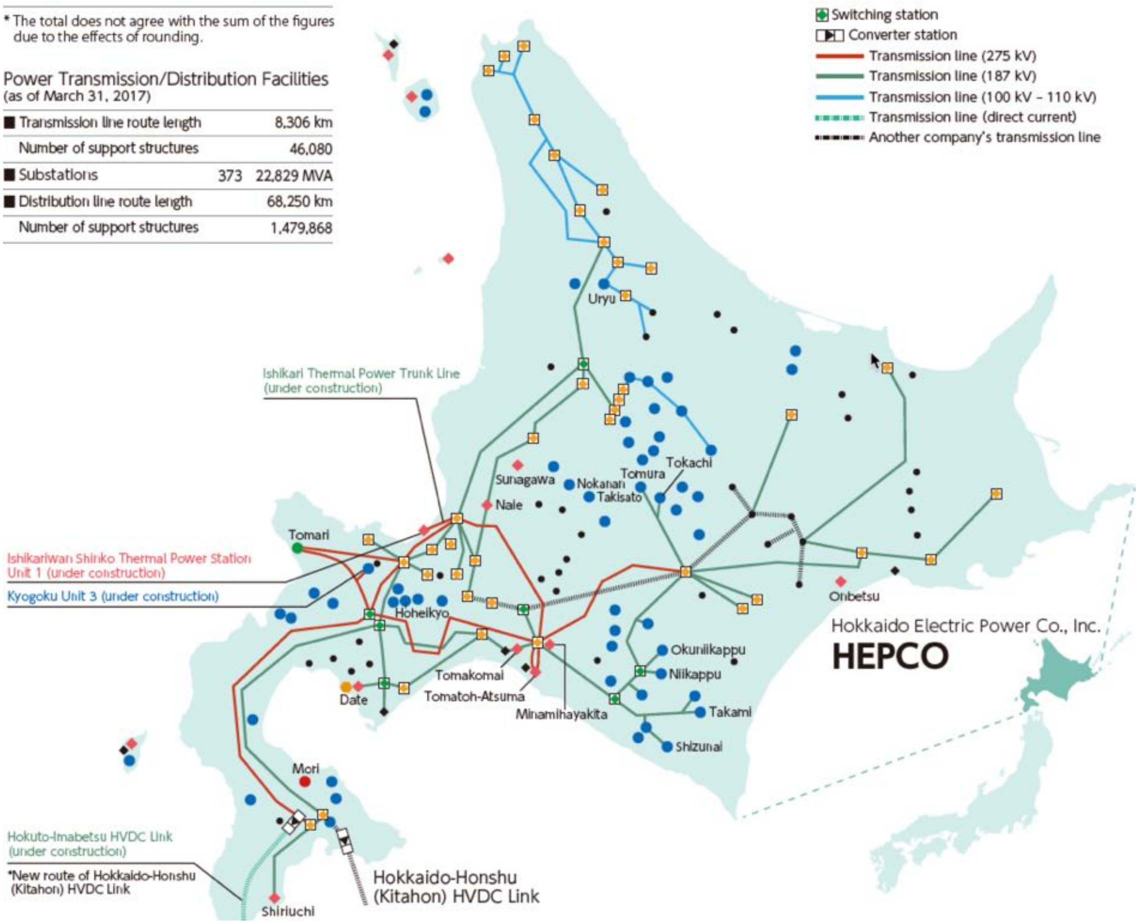

Fig. 4. HEPCO Transmission System (March 2017)

At the time of the earthquake (3:08 am local time), Island-wide power demand was about 3,087 Megawatts (MW). Fig. 5 highlights the system response from 3:08 am (a few seconds before the earthquake) until 3:25 am.

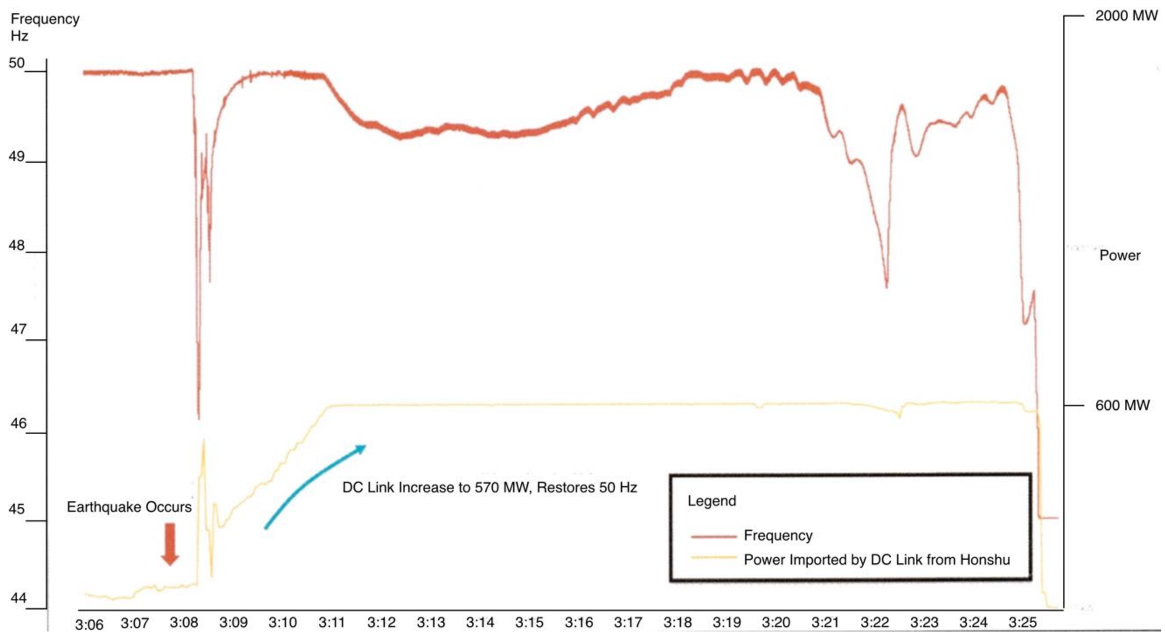

Fig. 5. System Frequency and DC Link Power Flow

Immediately after the earthquake, the coal-powered 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 (due to conductor dynamics leading to line faults), dropping another 600 MW of supply from remote hydro and wind and other 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. 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 two undamaged power plants on undamaged parts of the transmission grid was ramped up (138 MW ramping up to 525 MW). 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 two undamaged 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 resulted in unstable power, and output from Unit 1 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, three other un-damaged operating power plants all tripped, 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.

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.

Power outages were also caused by damage to equipment at high voltage substations (relatively few in this earthquake), and damage to lower voltage distribution feeders (extensive in this earthquake). 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 required weeks to months for repair. This meant that peak power demand could not be reliably supplied during the first weeks post-earthquake. HEPCO initially requested customers to conserve 10% to 20% power during the peak hours between 8:30 am to 8:30 pm on weekdays.

Fig. 6 shows the approximate level of shaking (with regards to horizontal PGA) throughout the power grid.

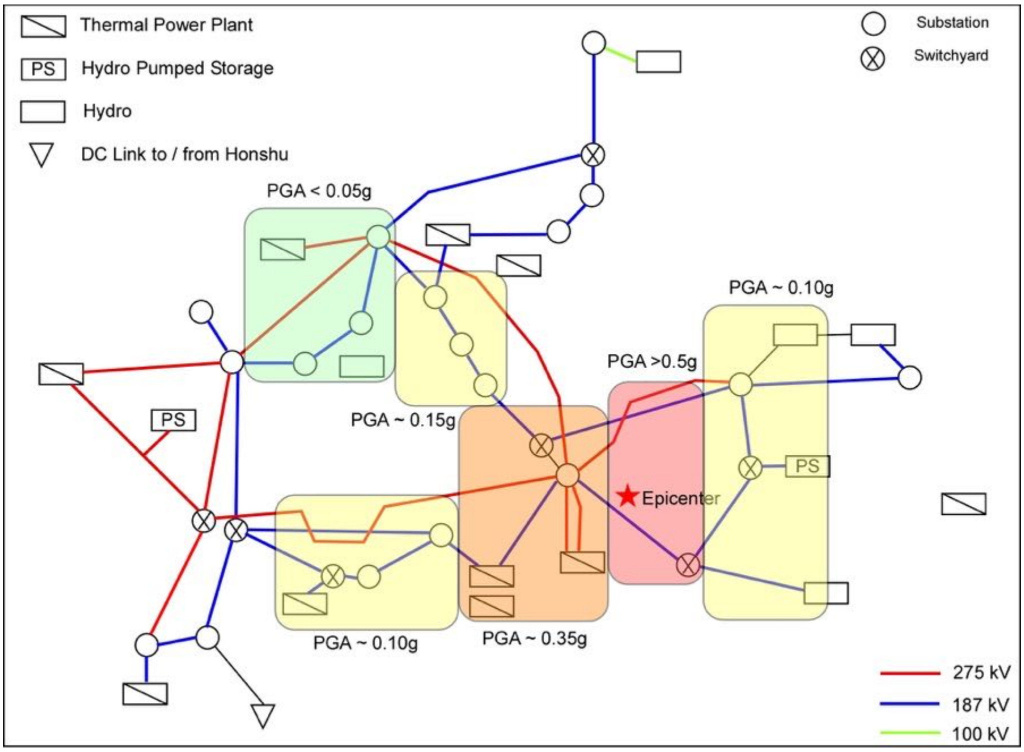

Fig. 6. Shaking Levels in the Transmission Grid

In the area highlighted in red, including the epicenter, the ground shaking was commonly over 0.5g. In this area, there were 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 power 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. 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.
The bulk of the physical damage to the power grid occurred in the red and orange areas. This includes damage to the Tomatoh-Atsuma coal 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. Fig. 7 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. All the damaged towers are located in the red zone from Fig. 6. Five lines faulted due to high inertial loading on the conductors (20, 26, 29, 409, 135). Three towers were damaged due to landslides (52, 71, 107).

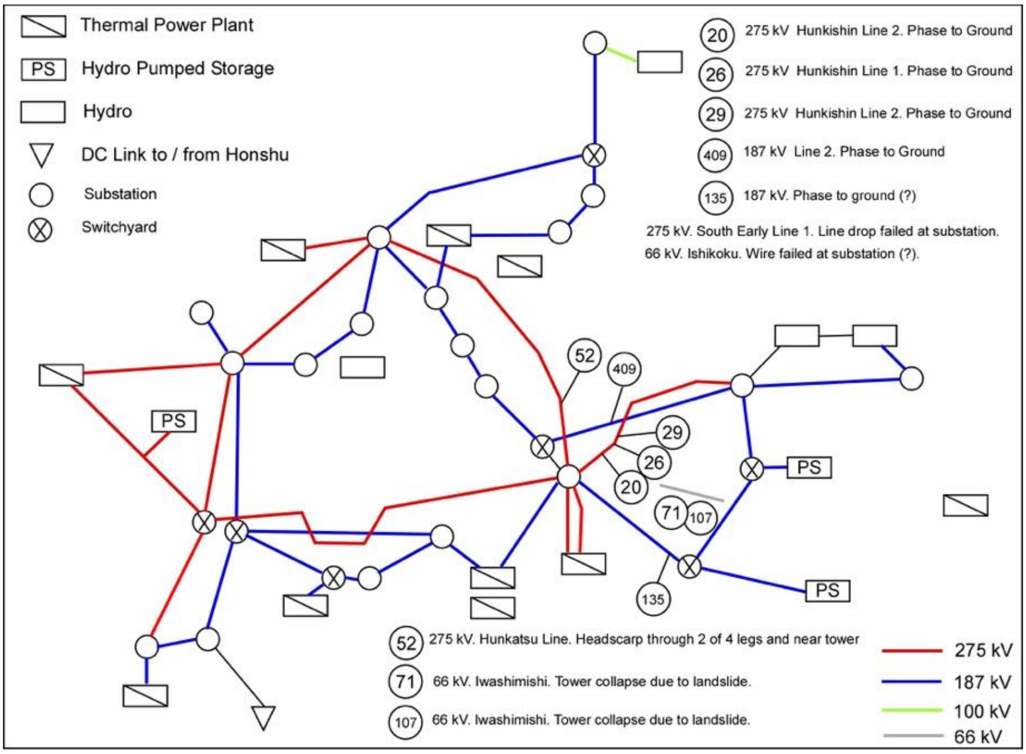

Fig. 7. Locations of Transmission Tower Damage

Fig. 8 show Tower 29 on the 275 kV lines (see Fig. 7 for location). The line jumpers and string insulators in the black circles moved during sufficiently during the earthquake to cause phase-to-ground faults.

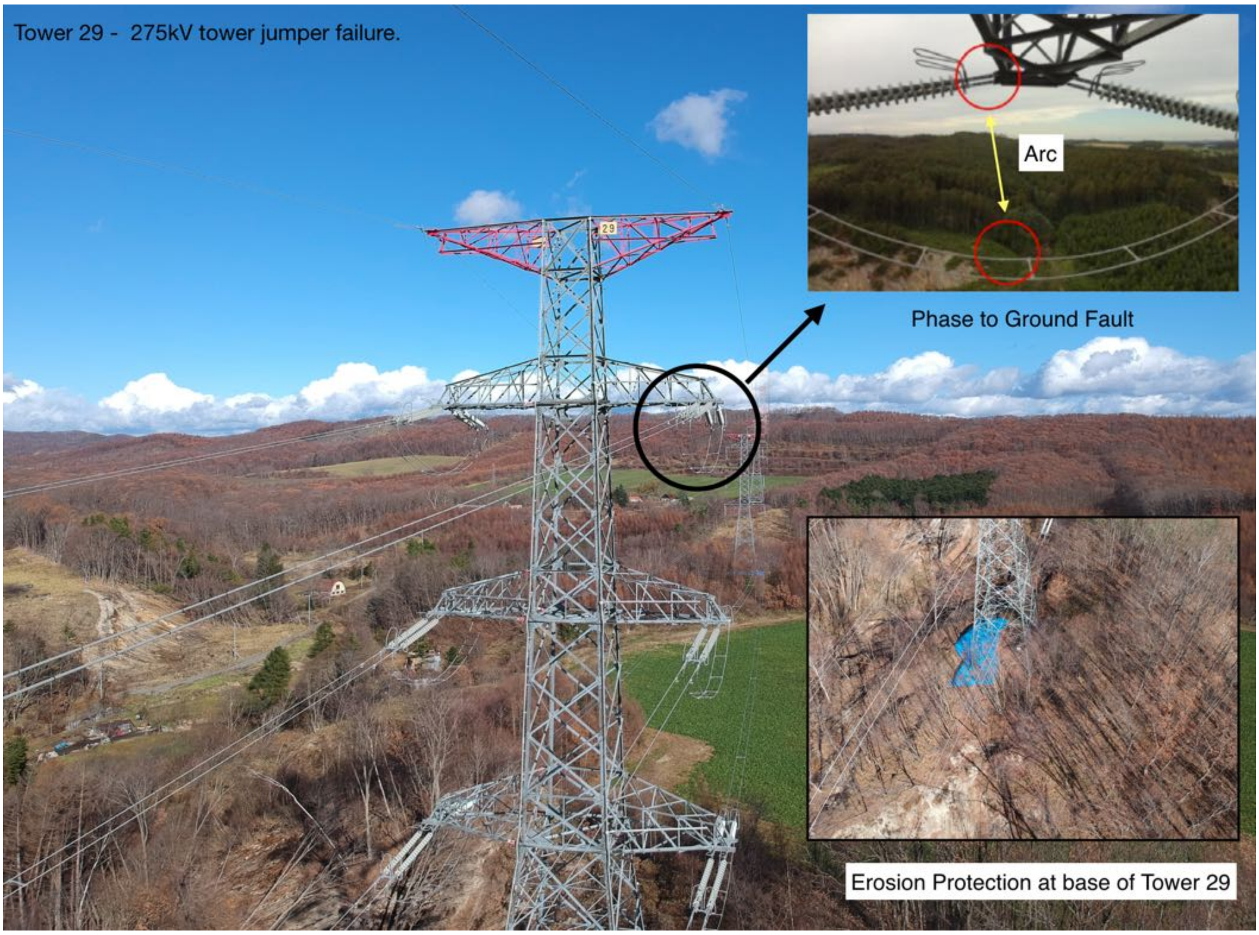

Fig. 8. Tower 29, Line Fault

The distribution system 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 included the following: broken concrete poles: 35 (almost all due to massive landslide); tilted concrete poles: 166 (some due to minor landslide, some due to embankment slides, some due to liquefaction); 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. 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. In this area, feeder conductors are often insulated, reflecting the severe winter weather that sometimes produces icing and snow build up on the wires; hence the entanglement did not result in a line fault.

3. Natural Gas

Kita Gas operates the natural gas system in Sapporo. The gas is imported as liquefied natural gas (LNG). The LNG terminal had PGA < 0.05g, and no damage. The gas is then distributed by medium pressure steel transmission pipes and low pressure plastic distribution pipes.

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 that are part of the automated gas shut-off system reported ground motions less than 60 cm/sec (highest recordings of 57.7, 35 or 26 cm/sec). The automated shut-off system has a 60 cm/sec trigger. Therefore, operations continued.

By 3:53 am September 6, 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.

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 gas 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. Low to medium pressure pipe is commonly fusion welded medium density polyethylene pipe. Both leaking low pressure 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). There were also 11 leaks on service laterals to houses; 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 was no reported damage to either the Tomakomai Gas system (PGA ~0.25g to 0.35g) or the Muroran Gas system (PGA ~ 0.10g).

Since the gas systems were 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.

The low level of repairs made to the gas systems reflects that leaks were commonly identified using odor (requiring a relatively high rate of gas leakage); coupled with modest level shaking; coupled with common use of seismically "tough" pipe; coupled with few (if any) gas pipes in PGD zones. Had highly sensitive gas sensing instruments been used (say able to detect leaks on the order of about 100 parts per billion), then likely more gas leaks might have been identified; gas leak rates need to be at least 50,000 parts per million for the leaking gas to be ignitable. More research is needed as to what rate of gas leakage constitutes a critical post-earthquake issue that requires rapid response and repair.

4. Water

The largest water system in the area affected by the earthquake is the waterworks of the City of Sapporo. The Sapporo 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.

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. See Eidinger and Tang [2] for a discussion of the water systems near Atsuma.

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 had 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. The September 6 2018 earthquake damaged water mains in Sapporo (150 to 500 mm diameter) at about 14 locations. The approximate locations of the pipeline and appurtenance damage is shown in Fig. 9.

The most concentrated pipeline damage location was in the area called Kiyota Ward, (heavy black rectangle in Fig. 9) where significant liquefaction resulted in 3 broken water mains. City-wide, the number of damaged appurtenances was 17 air valves and 1 fire hydrant. Fig. 10 shows photos of a damaged pipe in the Kiyota-ward area. The exact number of damaged service laterals (commonly 25 mm or smaller) is uncertain.

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 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.

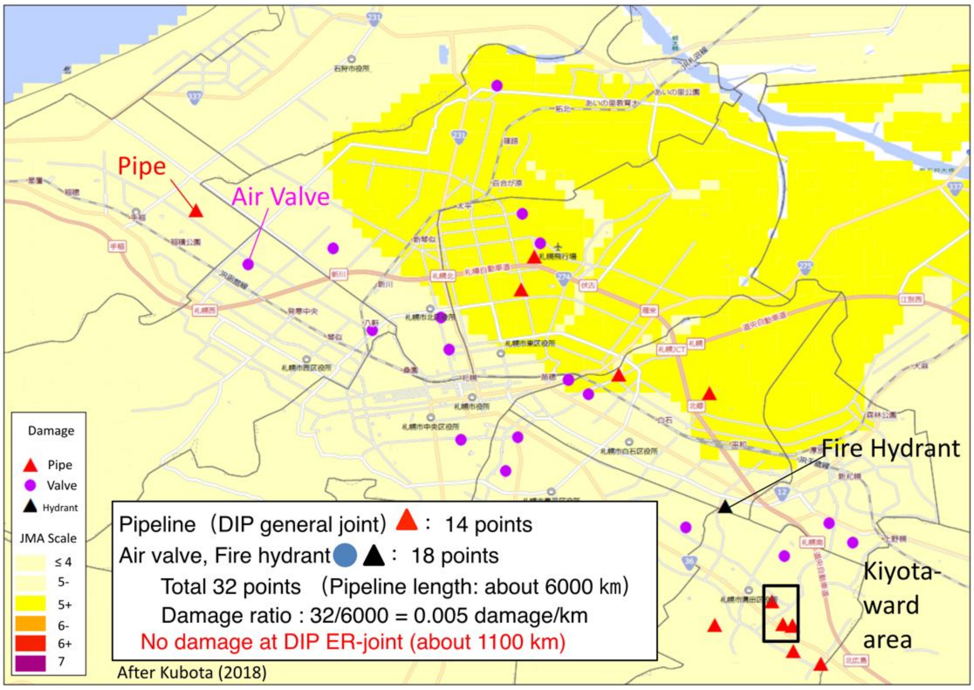

Fig. 9. Location of Water Pipeline Damage

Fig. 10. Pipe Damage in the Liquefaction Zone (credit: Kubota)

The following describes the Hokkaido Island-wide performance of water systems:

- On September 6, the number of households without potable water supply was about 37,250.
- By the morning of September 7, 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.
- By the evening of September 7, water was restored to several smaller communities, 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 households) 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.

5. Acknowledgements and Limitations

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While it is believed the information contained in this paper reasonably reflects what occurred (or did not occur), this paper does not contain all possible information, and it may contain inaccuracies. Nothing in this paper should be considered as an endorsement of any particular product or company. This paper makes mention of major Japan corporate and local government entities; some are listed on stock exchanges. While these entities shared information, the readers should know that none of these entities have endorsed the facts, conclusions or recommendations in this paper.

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[2] Eidinger, J.M., Tang, A.K. (2019): Hokkaido, Japan Mw 6.7 Earthquake of September 6 2018, Lifeline Performance. *The Council of Lifeline Earthquake Engineering*, TCLEE No. 4, G&E Report No. R98.23.01, www.geEngineeringSystems.com, Revision 1, March 18.

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