M 9.0 Tohoku Earthquake
March 11 2011
Performance of Water and Power Systems

Prepared by:

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June 25, 2012

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Abbreviations

AC	Asbestos Cement
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
BPA	Bonneville Power Administration
CI	Cast Iron pipe
DI	Ductile Iron pipe
g	acceleration; 32.2 feet/sec/sec = 9.81 m/sec/sec = 1 g = 981 Gal
GIS	Geographical Information System
GS	Galvanized steel pipe
GW	Gigawatt (= 1,000 MW)
HDPE	High Density Polyethylene
Hz	Hertz
IEEE	Institute of Electrical and Electronic Engineers
km	kilometer
M	Magnitude (moment magnitude unless otherwise noted)
MG	Million Gallons
MGD	Million Gallons per Day
MW	Megawatt
PGA	Peak Ground Acceleration (measured in g)
PGD	Permanent Ground Displacement (measured in inches)
PGV	Peak Ground Velocity (measured in inches/second)
PG&E	Pacific Gas and Electric
PVC	Polyvinyl chloride pipe
psi	pounds per square inch
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
SERA	System Earthquake Risk Assessment
TEPCo	Tokyo Electric Power Company
Tohoku EPCO	Tohoku Electric Power Company
WTP	Water Treatment Plant
WWTP	Wastewater Treatment Plant

Units

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

This report uses both common and metric units: inches, feet, millimeters (mm), meters (m). The conversion is 12 inches = 1 foot. 1 inch = 25.4 mm. 1000 mm = 1 m. 100 cm = 1 m. 1 kilometer (km) = 0.621371 miles. 1 kPa (kiloPascal) = 1 kN/m^2 = 0.145 psi (pounds per square inch). 1 pound (force) = 4.448 Newtons = 0.45 kilograms (force). 1 liter = 0.264 gallons (US liquid measure). MGD = million gallons (US liquid measure) per day.

Limitations

As is not uncommon in post-earthquake reconnaissance, incomplete information in the weeks and months after the event can lead to omissions and misunderstandings. Hidden damage might become known only some time after the earthquake. 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 damage to water and electric systems is available.

The authors of this report do not assume any responsibility for any such omissions or oversights.

1.0 Great Tohuku Japan 2011 Earthquake

The M 9.0 Great Tohuku earthquake of March 11, 2011 was strongly felt by more than 35,000,000 people in Japan.

The earthquake is named after the Tohuku region of Japan. The Tohuku region is the shaded region in Figure 1-1, located in northeastern Honshu Island in Japan, north of Tokyo, Figure 1-1.

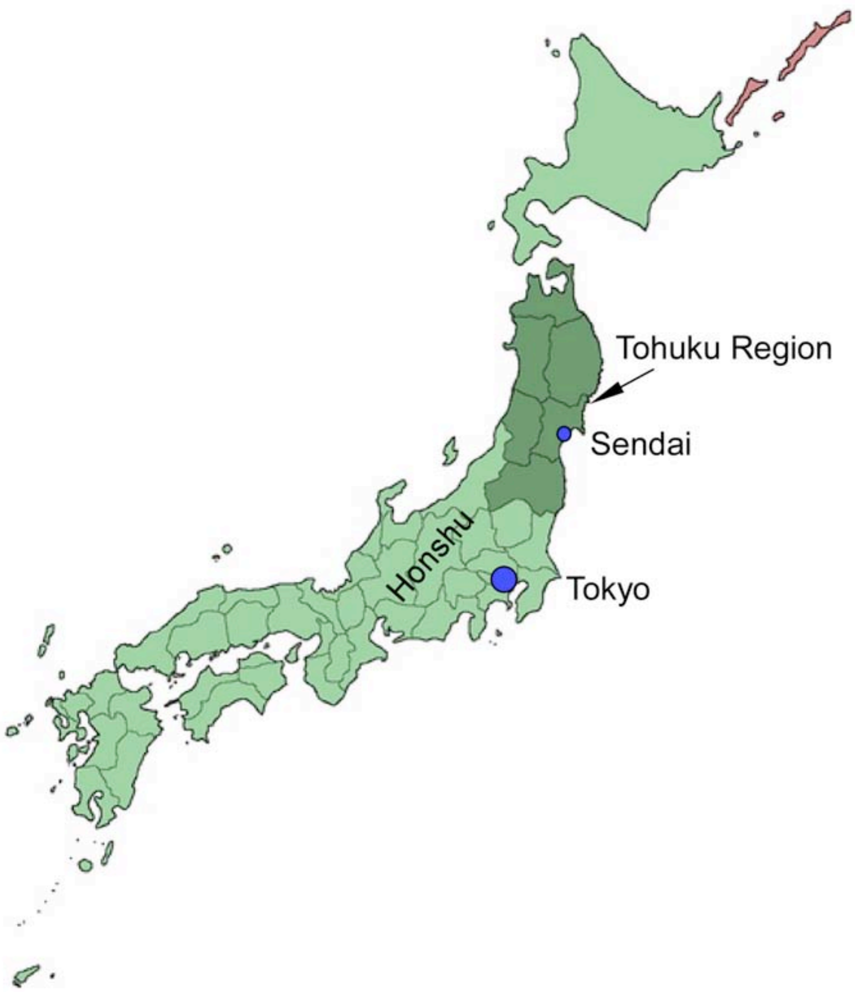

Figure 1-1. Tohuku Region (Shaded Area)

Japan is subdivided into 47 Prefectures. Figure 1-2 shows the names of the Prefectures . The Prefectures that suffered impacts from the earthquake are:

- Iwate – 1,400,000 people. Severe tsunami impacts
- Miyagi (including the City of Sendai) – 2,400,000 people. Severe tsunami impacts

- Fukushima – 2,100,000 people. Severe tsunami impacts
- Ibaraki – 3,000,000 people. Widespread liquefaction impacts
- Chiba – 5,900,000 people. Widespread liquefaction impacts
- Tokyo – 12,100,000 people. Slight impact
- Kanagawa (including the City of Yokohama) – 8,500,000 people. Slight impact

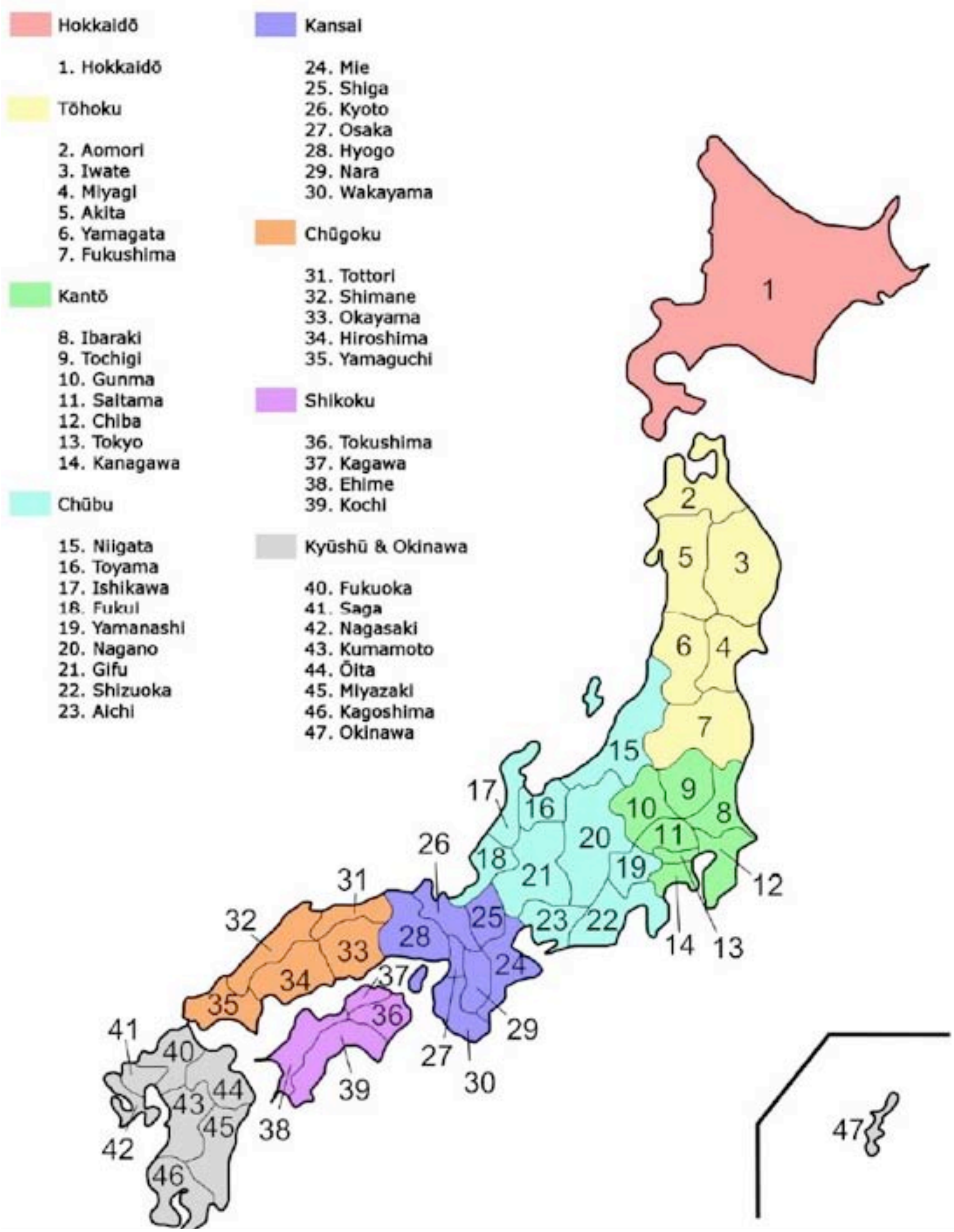

Figure 1-2. Prefectures in Japan

The worst effects from the tsunami extended along the coast, including Fukushima, Miyagi and Iwate Prefectures. The tsunami effects led to about 19,000 people dead or missing, and more than $200 Billion (US) in damage.

Outside the tsunami zone, there were a wide range of impacts due to strong ground shaking, liquefaction and landslides. The largest city close to the fault rupture was the City of Sendai.

Potable water systems suffered moderate to major damage in Iwate, Miyagi, Fukushima, Ibaraki and Chiba Prefectures. Owing to the similarity to water treatment plants, this chapter also includes the earthquake effects on selected wastewater treatment plants.

In the following sections, we describe the impacts of the earthquake as follows:

- Section 2.1. This covers the seismicity of the region and recorded ground motions from the earthquake.

- Section 2.2. This covers the effects of the tsunami along the coastal areas.

- Section 4.3. Miyagi Prefecture Sennen Senan water transmission system. This is the largest water transmission system near the epicenter. This system serves the City of Sendai and nearby towns, serving a population of about 1,500,000 people.

- Section 4.4. City of Sendai water system. This is the largest water system that suffered major damage, serving a population of about 1,040,000 people.

- Section 4.5. Ishinokami water system. This water system serves a population of about 250,000 people.

- Section 4.6. Chiba Prefecture. This water system serves a population of about 6,000,000 people. Damage was concentrated in Urayusa City, primarily due to liquefaction effects.

- Section 4.7. Ibaraki Prefecture. We examine the damage to a water treatment plant (liquefaction effects).

- Section 4.8. We describe the impact of the tsunami on a large wastewater treatment plant near Sendai.

- Section 4.9. We briefly describe leaks that occurred to axial slip joints (bellows-type) to a large diameter water transmission pipeline in Yokohama, part of the Kanegawa Water Supply Authority water transmission system.

- Section 4.10. We describe response issues.

- Section 4.11. We describe fires. Most of these were due to the effects of the tsunami.

- Section 4.12. Seismic Design of Water Pipelines. We describe the recent advances in water pipeline design and construction in Japan.

- Section 4.13. We list major observations and recommendations.

There are two areas which likely had impacts to water systems, but which this report does not address.

- Fukushima Prefecture. We do not address this area partly because of the nuclear incident that prevents entry along the much of the Pacific coastline in Fukushima. Also, there are no major towns, and thus no major water systems along the strongly shaken coastline of Fukushima Prefecture.

- Iwate Prefecture. The Iwate coastline includes a number of mid-sized communities, including the larger cities of Ofunato (including Sanriku, population 40,000) and Rikuzentakata. These cities, as well as nearly all of the smaller towns along the coast (Otsuchi, Kesen), suffered great destruction due to the tsunami. While each of these towns included potable water systems, we did not meet with local water department officials in these towns.

Key Findings - Water

The tsunami effects (water velocity, inundation) created severe damage and thousands of fatalities. However, with a few exceptions due to erosion or direct impact of pipes hanging under bridges, the tsunami had little effect to potable water systems. The tsunami had major effects on several wastewater treatment plants located along the coastline. Strong ground shaking damaged a major water transmission pipeline serving the Sendai area (48" to 96" diameter) at 53 locations. Liquefaction severely damaged buried pipes and buried a utility corridor at the Wanigawa water treatment plant. Liquefaction, road fill slumps and ground shaking contributed to hundreds of broken water distribution pipes (generally 2" to 16" diameter). Given the lessons learned from the 1995 Kobe earthquake, some of the water utilities had adopted seismic mitigation measures in the intervening years; as well as had improved post-earthquake emergency response plans. There were 287 fire ignitions reported due to the main shock and major aftershocks.

In Miyagi Prefecture, water outages were estimated to have been 310,000 households (March 13, 2011), increasing to 450,000 households (March 17, 2011), increasing to 460,000 households (March 21, 2011). Most cities in Miyagi Prefecture had water supply restored to households *able* to receive water by about April 23, 2011. Road fill slumps broke water pipes in the hilly areas around Sendai. Erosion broke buried 3-foot diameter pipes in the tsunami inundation zone. High speed water inundation destroyed several pump stations and above-grade equipment and processes at wastewater treatment plants at the coastline.

In Ibaraki Prefecture, water outages were estimated to have been 470,000 households (March 13, 2011), decreasing to 130,000 households (March 17, 2011), increasing to 180,000 households (March 21, 2011). Liquefaction (12" settlements observed) was substantial in many areas; and severely damaged one water treatment plant. Most cities in Ibaraki Prefecture had water supply restored to households *able* to receive water by about April 23, 2011.

In Chiba Prefecture, water outages were estimated to have been 300,000 households (March 13, 2011), decreasing to 60,000 households (March 17, 2011), staying steady at 60,000 households (March 21, 2011). Most cities in Chiba Prefecture had water supply restored to households *able* to receive water by about April 23, 2011. Much of the damage in Chiba Prefecture appears to be attributed to liquefaction (2-3" settlements common, locally 6" observed).

In Iwate Prefecture, water outages are estimated to have been 80,000 households (March 13, 2011), remaining at 80,000 households (March 17, 2011), decreasing to 50,000 households (March 21, 2011). All small cities and towns along the coastline in Iwate Prefecture had serious destruction due to the tsunami, and re-build of the water systems for these cities and towns may take years to complete.

In Fukushima Prefecture, water outages are estimated to have been 190,000 households (March 13, 2011), increasing to 450,000 households (March 17, 2011), decreasing to 120,000 households (March 21, 2011). We did not visit any water utilities in Fukushima due to the ongoing nuclear radiation contamination exclusion zone.

In Tokyo, a few customers lost water supply; all customers had water supply restored by March 13, 2011.

The primary earthquake hazards that caused direct damage to pipelines were: liquefaction (especially in Ibaraki and Chiba Prefectures); road fill slumps and landslides (in Sendai City); ground shaking; and erosion-scour effects at selected areas in the inundation zones. There was no surface faulting in this earthquake.

Key Findings - Power

The performance of the electric power systems in this earthquake was marginal. Power outages to end users were rather lengthy (a few days to more than a week), caused by a combination of factors: damage to more than 14,000 MW of generation plants (largely due to tsunami effects, but some caused by shaking effects); damage to high voltage (154 kV to 500 kV) substation equipment (due to shaking effects); damage to medium voltage substations (typically 66 kV) (due to tsunami effects); and a great amount of damage to the low voltage distribution systems (due to tsunami effects). Shaking-caused damage to high voltage transmission lines (including equipment at substations as well as insulators at towers) lead to loss of power to several nuclear plant sites.

Two investor-owned power utilities suffered the brunt of the earthquake damage: Tohoku Electric Power Company, and Tokyo Electric Power Company (TEPCo). Damage to a few other power plants also occurred.

Tsunami-caused damage at TEPCo's Fukushima Daiichi 6-unit nuclear power plant resulted in complete loss of units 1, 2, 3, 4, and release of radiation to the general environment. Tsunami-caused damage also occurred at Tohoku Electric Power's Onegawa 3-unit nuclear power plant (unit 2). Ground shaking also contributed to some damage at these plants. The tsunami-damage at Fukushima Daiichi led to a general loss of confidence in the safety of remaining non-damaged nuclear power plants in Japan, leading to shutdown of those other plants over the course of the year following the earthquake. The combination of physical damage to the nuclear power plants (about 6 GW) plus non-nuclear power plants (an additional 12 GW), led to a loss of system reliability for the peak summer-time power loads in July-August 2011, and required demand curtailment. The additional loss of the remaining undamaged nuclear power plants for regulatory reasons may lead to further need for demand curtailment in the summer of 2012. With the loss of nuclear power, the power utilities are using all of their remaining portfolio of thermal power plants (burning gas, coal and oil), leading to increases in costs to purchase fuel, and increases in carbon emissions. How Japan will collectively find a solution to the loss of generation remains uncertain, having to balance the need for sufficient power for system reliability and general economic activity, the cost to purchase fossil fuels, the emissions of carbon in violation of "green" power initiatives and climate change impacts, and the need for seismic safety. The underlying root cause of this ongoing drama is the inadequate design for tsunami height and velocity; a factor which similarly resulted in wholesale destruction of many thermal power plants, wastewater treatment plants and other industrial facilities along the Tohoku coastline.

For more than two decades, Japanese power utilities have been installing new equipment at high voltage substations that meet Japanese seismic qualification guidelines. Still, quite a number of components at substations still failed. The underlying causes of these failures are a combination of older non-qualified equipment; and higher-than assumed ground motions at the substations.

More than 40 steel-lattice transmission towers collapsed; all but two were due to impacts cause by floating debris carried by tsunami-waters; the others due to landslide.

Landslides in the hills damaged penstocks and headraces at small hydroelectric power facilities.

The vast majority of the electric distribution system relies on above ground low voltage power lines on concrete or steel power poles. There are relatively few buried high voltage or distribution power lines in Japan, as compared to the USA or New Zealand. Accordingly, the damage to buried power lines due to liquefaction was low.

Outside the tsunami inundation zones, earthquake shaking effects caused little damage to the general building stock. While a number of ground motion instruments recorded PGAs over 1.0g, the vast majority of the urbanized areas along the Tohoku coast felt ground shaking levels with PGVs in the 10 to 15 inch/sec range. This was fortunately low enough to avoid the widespread collapse of traditional Japanese houses. Lacking the damage to the houses, there were relatively few "pull downs" of distribution power poles.

For the long term, the lessons learned from this earthquake include the following:

- Ground shaking: prudent design along the seismically-active coastlines of Japan calls for site specific ground motions of at least PGA = 0.55g for conventional power plants; possibly 50% higher (about PGA = 0.80g) if set at an 84^{th} percentile not-to-exceed level for the maximum credible earthquake) for nuclear power plants. All conventional (gas, oil, coal) and nuclear power plants should be designed to suffer, at most, minor damage that can be repaired within a few days, given occurrence of a maximum credible earthquake.

- Ground shaking: the current Japanese seismic design standards for substation equipment should be reviewed, and upgraded where suitable, and then enforced to ensue that all 275 kV to 500 kV transformers have reliable anchorage, bushings and surge arrestors, assuming PGA = 0.5g (with corresponding spectral shape) or greater. This should be done for all existing high voltage transformers (except those that have fully redundant and seismically qualified transformers), in all high seismic zones of Japan, to be implemented within 5 to 10 years; all new installations should have this requirement. For remaining yard equipment, seismic qualification to these levels should be done for all new installations. For transmission towers that are part of circuits that deliver power to / from nuclear power plants, all towers in the maximum credible inundation zone should be shown reliable assuming tsunami run-up with debris; for at least one circuit to a nuclear power plant, all insulators should be shown to be highly reliable under a maximum credible earthquake.

- Tsunami inundation along the Pacific coastline: Nuclear power plants should have reliable cooling water systems, even with consideration of the maximum credible tsunami run-ups given the local bathymetry; this should be put in place before plant re-start. All power plant facilities with on-site work forces (nuclear or thermal) should have at least one wave-resistant building with a top floor elevation well above the maximum tsunami run-up height, for vertical evacuation purposes; plus sufficient consumables for at least three days. The portfolio of power plants in the region (nuclear, thermal, hydro and renewables) should have sufficient generation capacity to support the summer time demand, with adequate reliability, assuming one-year loss of all power plants without tsunami protection for the maximum credible tsunami run-up. With the 2011 occurrence of the M 9 event, the annual probability of another 7 meter+ tsunami is low within the next 100 to 200 years; even so, planning should be started immediately to construct new power plants in such a manner such that Japan reaches these goals within the next 50 years.

2.0 Seismicity and Tsunami

2.1 Ground Motions

Japan has been exposed to several large earthquakes since the Great Hanshin (Kobe) earthquake of 1995, Figure 2-1.

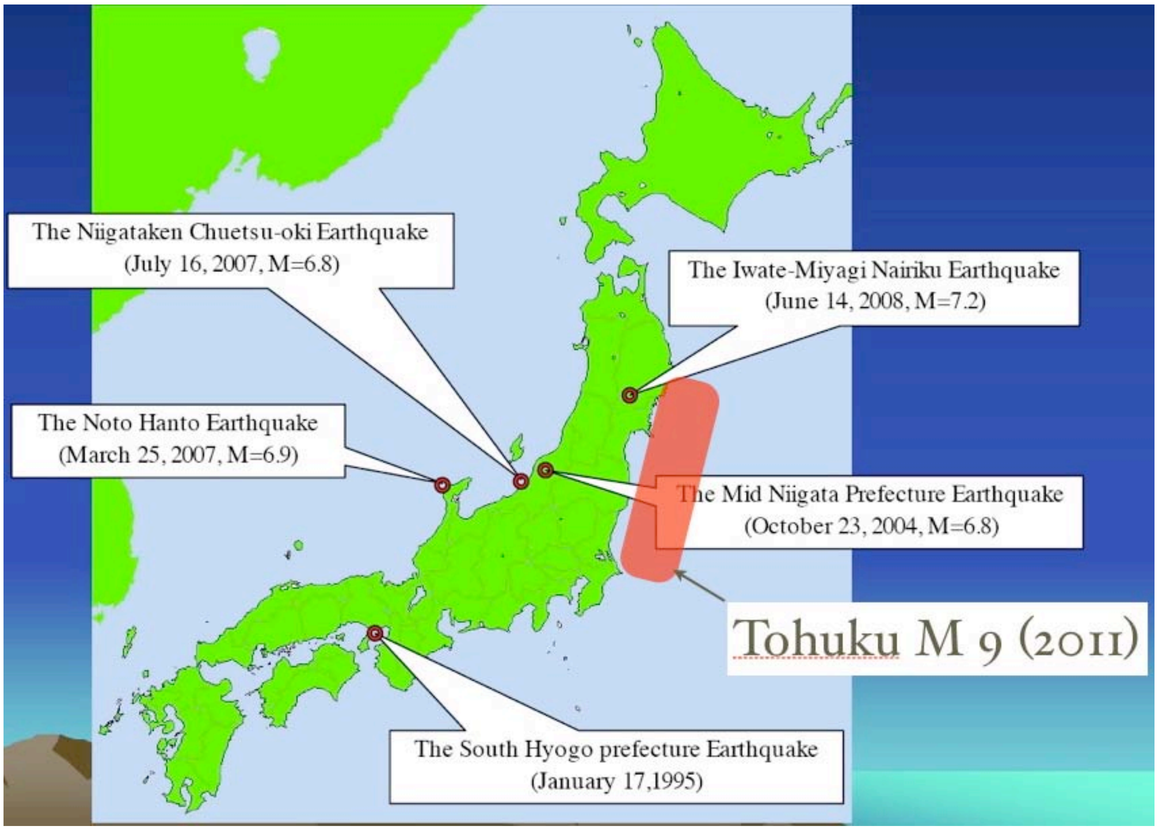

Figure 2-1. Large Earthquakes in Japan Since 1995

Several thousand strong ground motion instruments recorded the motions from the M 9 March 11 2011 Great Tohuku earthquake. Figure 2-2 shows a map that is developed using the *highest* of the recorded ground motions for various areas. Note: the units "Gals" refers to 1 Gal = 1 cm/sec/sec; or 981 gal = 1 g. Thus, the contour labeled "500"corresponds to about PGA = 0.5g.

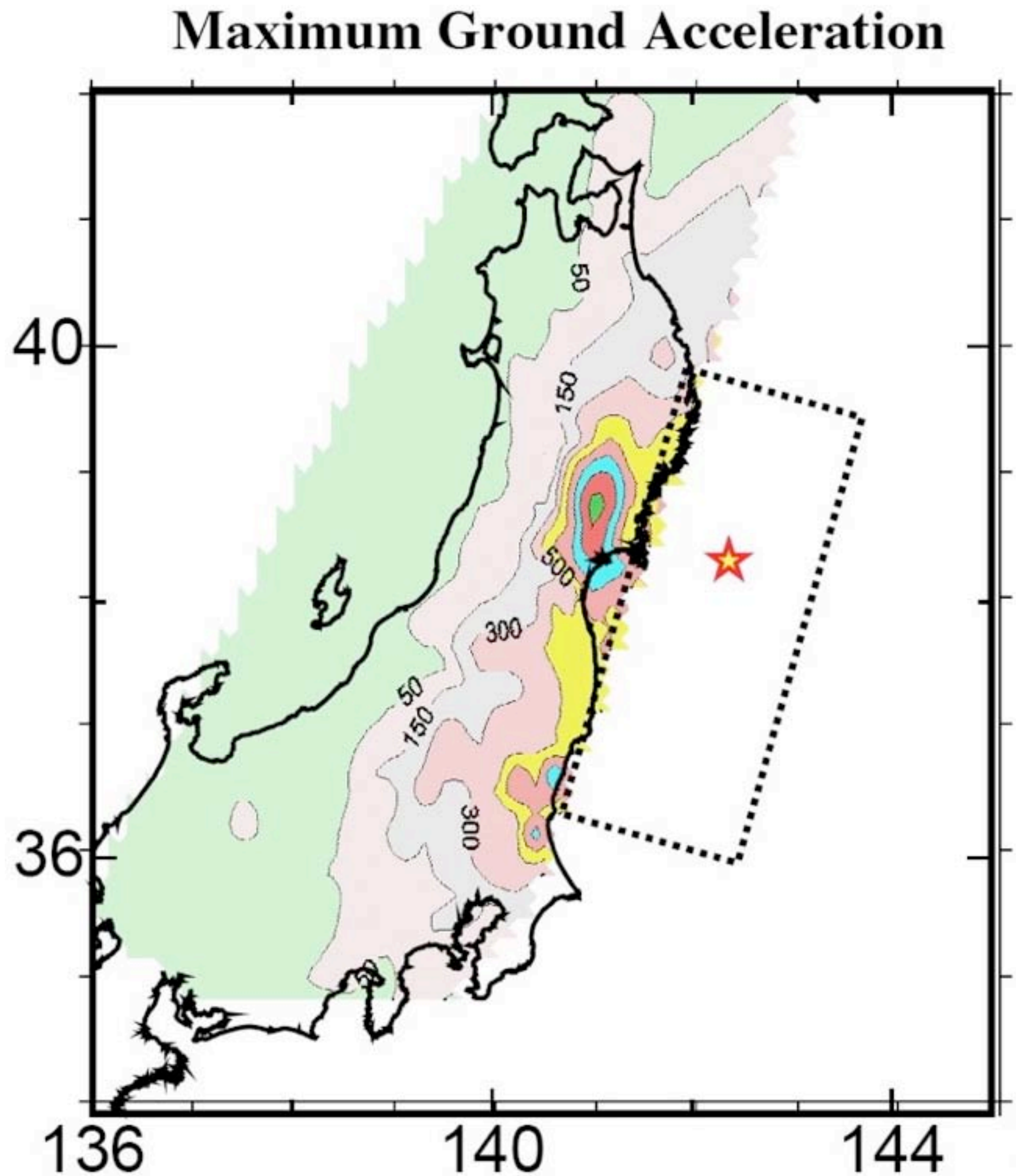

Figure 2-2. Maximum Recorded PGA, March 11 2011 Earthquake

To appreciate the damage to the power system infrastructure, one needs to have an understanding of the spatial variation in ground motions, as well as the effects of the tsunami along the coastline. Figure 2-3 provides a map of Japan that highlights the locations of various recording instruments, with colors to denote the "highest" levels of shaking in various regions. It is very important to understand that the colors in this map greatly exaggerate the actual levels of shaking in most of the areas that were exposed to strong ground shaking.

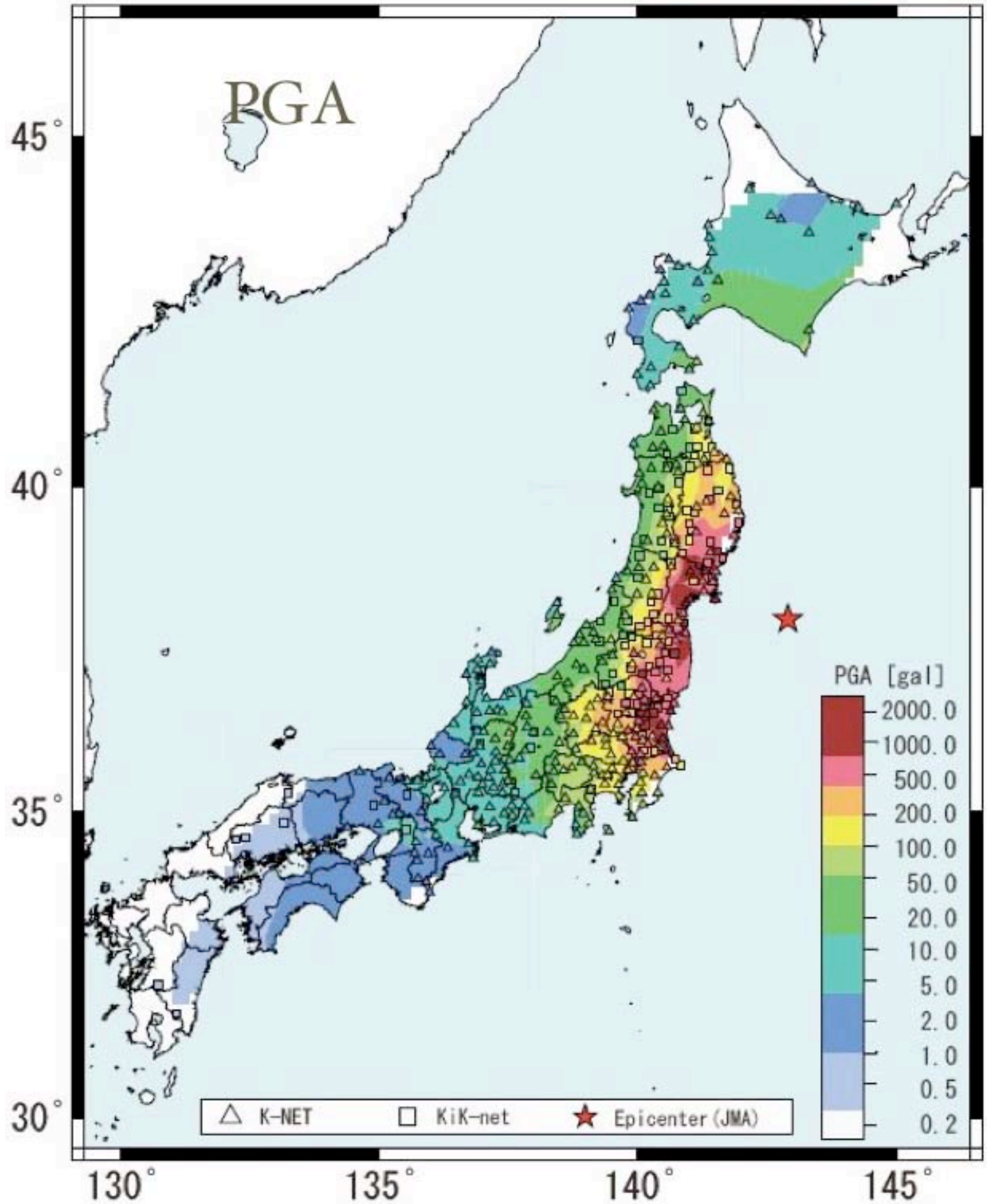

Figure 2-3. High Level Recorded PGA Values(Horizontal) in Regions of Japan

Table 2-1 lists the ten highest ground shaking records from this earthquake. While these ten recordings are well in excess of PGA > 1.0g, these are not representative of common ground motions.

No.	Station Name	PGA (Gal)
1	MYG004	2933
2	MYG012	2019
3	IBR003	1845
4	MYG013	1808
5	IBR013	1762
6	FKSH10	1335
7	TCGH16	1305
8	TCG014	1291
9	IBRH11	1224
10	MYGH10	1137

Table 2-1. Ten Highest Recorded PGA Values (Horizontal) (980.7 Gal = 1 g)

Figure 2-4 shows a plot of hundreds of recorded ground motions (maximum of two PGA values per station), showing that along the coastline (at the location of several power plants), the median PGA value was about PGA = 0.55g, falling to about PGA = 0.30g at a distance of about 100 km from the ruptured fault (about central Sendai). While the very high motions from Table 2-1 are shown (up to 2.9g), there are equally a number of instruments that showed motions of PGA = 0.1g or so at equal fault distances.

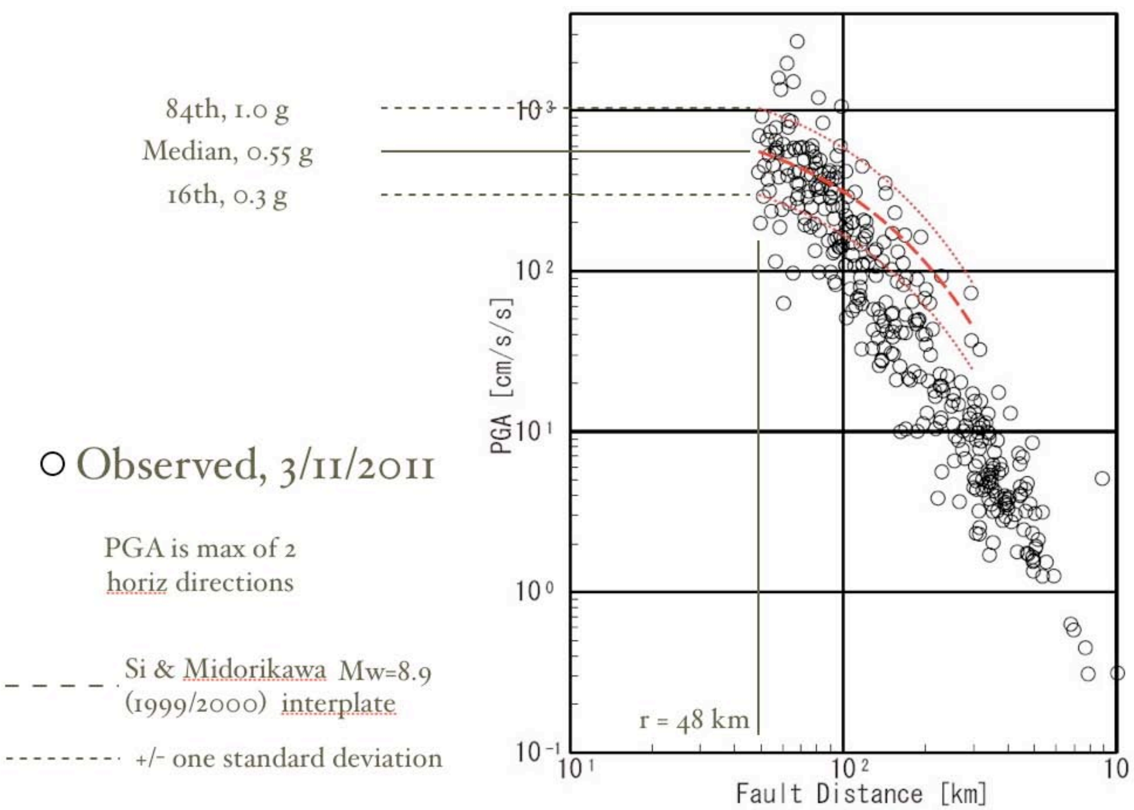

Figure 2-4. Attenuation of Ground Motion (PGA)

Figure 2-5 shows similar information, but for peak ground velocity. This shows that at along the shoreline, median PGVs were about 12 inches per second (well under the median expected from the listed attenuation model); at a distance of about 100 km (densely populated areas of Sendai), typical PGVs were about 6 to 8 inches/second. It is by understanding the implications in Figure 2-5 can one appreciate the rather low levels of damage to buildings observed throughout the strong-shaking region (excluding the tsunami inundation regions).

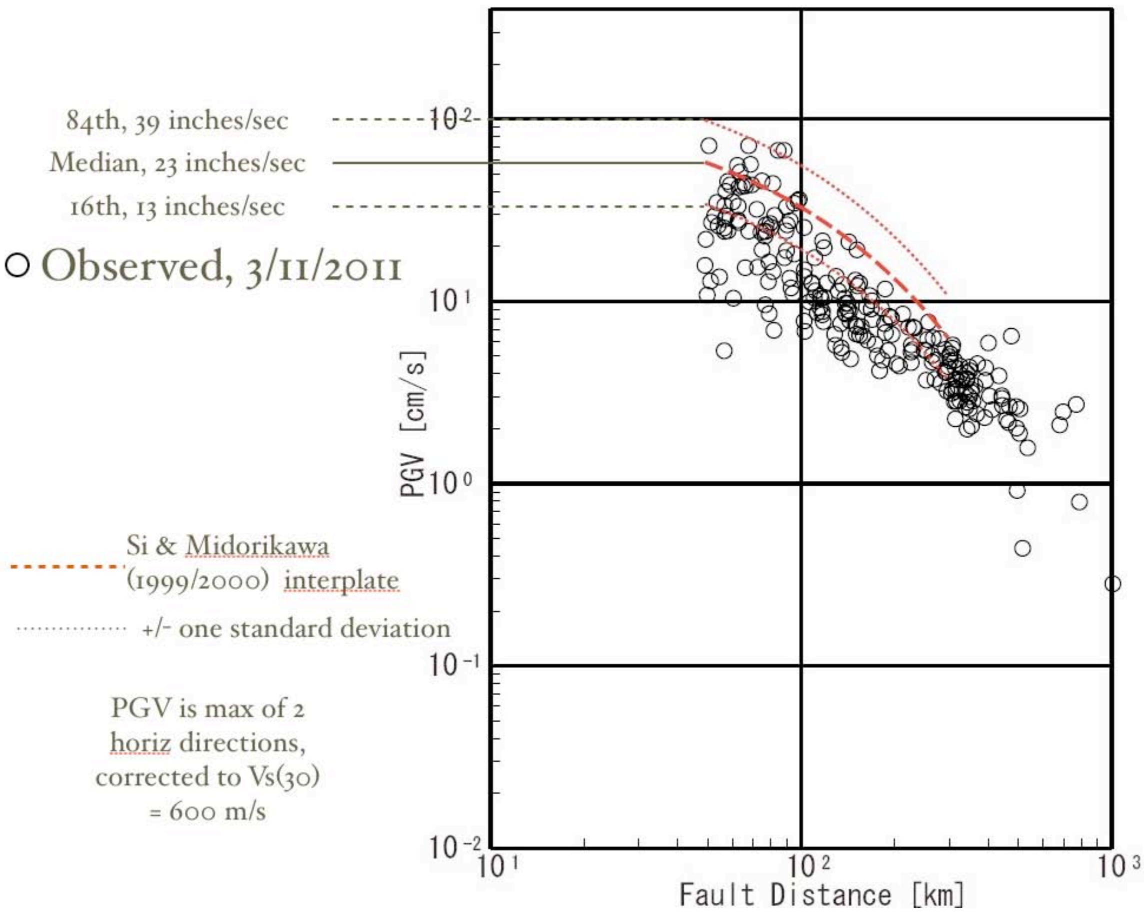

Figure 2-5. Attenuation of Ground Motion (PGV)

A very common numbering system used in Japan is the Japan Meteorological Agency (JMA) seismic intensity scale. It is measured in units of Shindo ("degree of shaking"). The JMA scale has maximum of 7, and then is commonly listed as 6+, 6-, 5+, 5-, etc. The numerical scale was set in 1898, and descriptions for each unit are based on their perceived effect on people. Following the Great Hanshin (Kobe) earthquake of 1995, levels 5 and 6 were divided into two. Table 2-2 describes the Shindo scale. The rightmost column, PGA, is an approximate range assuming no PGD effects; and can have great disparity from instrumented values should there be any PGD (or tsunami) effects.

JMA	People	Indoors	Outdoors	Wooden houses	Reinforced concrete buildings	Lifelines	Ground and slopes	PGA (g) approximate
0	Imperceptible.							< 0.001
1	Felt only by some people indoors.							0.001 - 0.003
2	Felt by most people indoors.	Hanging items swing slightly.						0.003 – 0.008
3	Some people frightened.	Dishes in cupboards rattle occasionally.	Electric wires swing slightly.					0.008 – 0.03
4	Many people frightened. Most sleeping people are awoken.	Hanging objects swing a lot. Unstable ornaments fall occasionally.	Electric wires swing a lot.					0.03 – 0.08
5-	Most people try to escape from a danger. Some people find it difficult to move.	Hanging items swing violently. Most unstable ornaments fall. some books fall.	Light poles swing. A few windowpanes break. Some unreinforced block walls fall.	A few less resistant houses suffer damage.	A few cracks in less resistant buildings.	Gas shutoff valves operate at some houses. Water pipes rarely damaged.	A few cracks in soft ground, rockfalls and small slope failures.	0.08 – 0.15
5+	Many people are considerably frightened and find it difficult to move.	Most dishes in cupboards fall. most books fall.	Many unreinforced walls collapse, tombstones overturn. Some poorly installed vending machines fall.	A few less resistant houses suffer heavy damage.	A few large cracks in less resistant buildings.	A few gas / water pipes damaged.	A few cracks in soft ground, rockfalls and small slope failures.	0.15 – 0.25
6-	Difficult to keep standing.	A lot of furniture moves.	Some windowpanes break.	A few less resistant houses collapse.	A few collapses of less resistant buildings.	Many gas / water pipes damaged. A few power outages.	Some cracks in ground and landslides.	0.25 – 0.35
6+	Impossible to keep standing.	Most unfixed furniture moves.	Many buildings have broken windowpanes. Most unreinforced block walls collapse.	Many less resistant houses collapse.	Some collapses of less resistant buildings.	Some gas, water mains fail, widespread water + gas outages. Power outages.	Some cracks in ground and landslides.	0.35 – 0.50
7	Thrown by the shaking.	Some items jump.	In some cases, reinforced concrete block walls collapse.	A few more resistant houses collapse.	A few more resistant buildings collapse.	Power, water gas outages over wide areas.	Large cracks in ground. Large landslides.	0.50+

Table 2-2. JMA Scale

The JMA scale is somewhat similar to the US MMI scale, and historically was meant to be a measure of observed damage. After the Kobe 1995 earthquake, the JMA scale was calibrated to observed damage and ground motions in Kobe, and a model was developed that can be used to predict JMA based on instrumented ground motion recordings. As of

April 1, 1996, Shindo values produced by the JMA are commonly based on a network of seismic instruments; without any need for human observations using the scales described in Table 2-2. These instruments compute JMA from the actual recorded time history, following the following procedure (simplified):

- Apply a low pass and high pass filter to each recorded ground motion (NS, EW and Vertical)

- Calculate the absolute amplitude, = sqrt(NS^2 + EW^2 + Vertical^2)

- Sort the resulting time history over 6,000 sample points (about 60 seconds) from highest to lowest, and drop the 29 top-most values. Take the 30th- top-most value, call it A.

- JMA = $2*\log_{10}(A)+0.94$

For the most part, the maps produced using JMA intensities, for the 2011 M 9 earthquake, were so-constructed, resulting in the map seen in Figure 2-6. However, it seems that the conversion method suggested by Kawasumi, based on empirical observations between ground motion and damage in the 1995 Kobe earthquake, are not applicable to the observations seen in the 2011 earthquake; the primary reason being that the rather low medium-to-longer period energy content in the 2011 event, as evidenced by the low PGV values in Figure 2-5. The PGV values in Figure 2-5 are, on average, only about half the expected PGV values for the corresponding PGA values. This would imply that most JMA scale values reported by the JMA (using instrumental data) are about 0.6 too high. This also implies that use of instrumental values to forecast actual damage to the building stock, as is done by Wald (Shakemaps). Shakemaps produce "forecast MMI" using similar models used by JMA to make "forecast Shindo". Both the JMA and ShakeMap forecasts of Shindo and MMI intensity scales can result in unexpected and poor results if the energy content in the actual earthquake differs from that assumed by the underlying conversion process. Today (2012), it would be better to use recorded PGA, PGV and spectra, coupled with PGDs for landslides, liquefaction and fault offset, using suitable fragility functions, to make forecasts of actual damage, as is done by Eidinger (SERA).

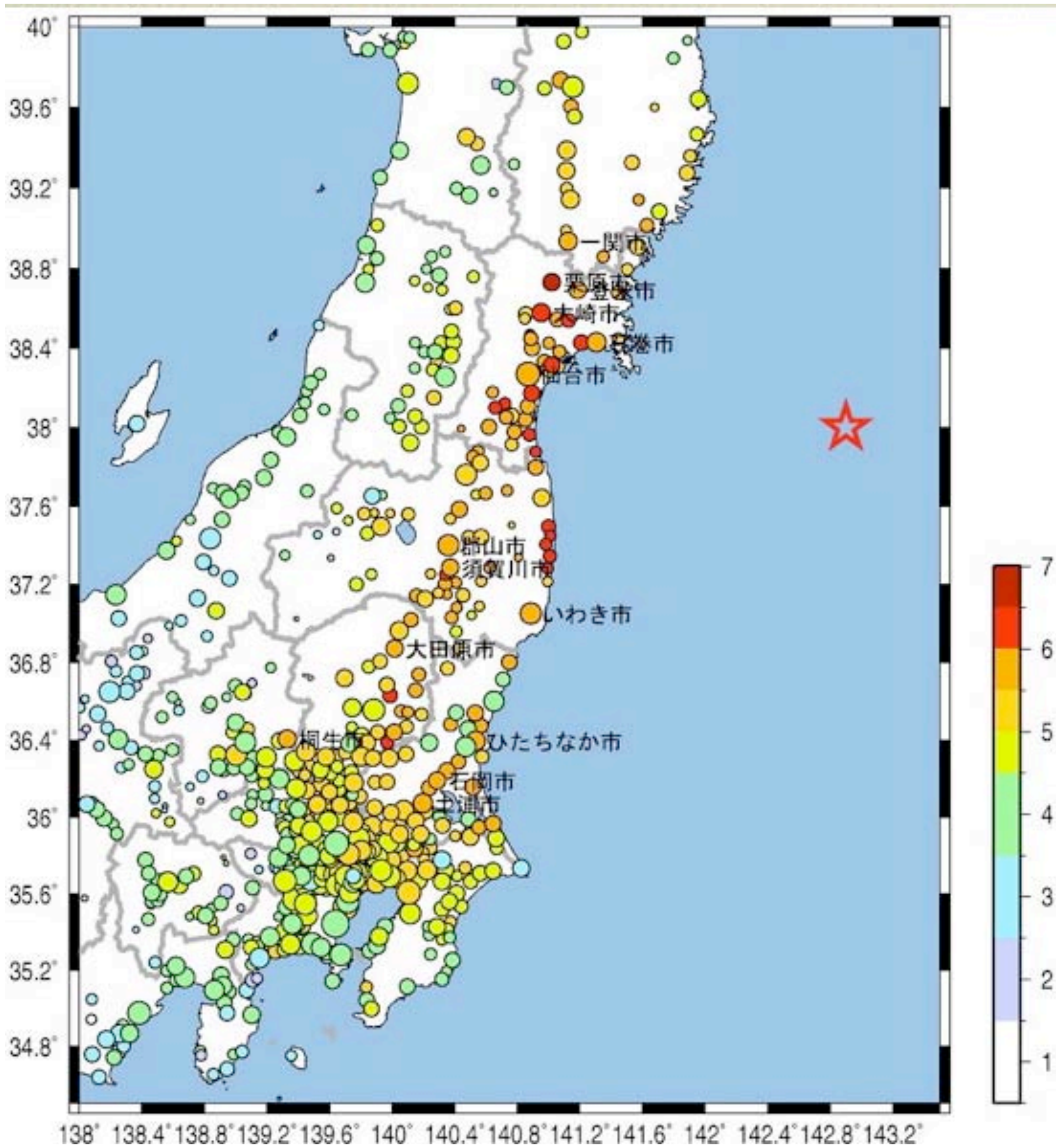

Figure 2-6. JMA Intensity

Table 2-3 shows the population exposed to various JMA intensities, along with the common corresponding MMI value. However, based on the field reconnaissance by the ASCE team, covering nearly the entire coastal areas, as well as the harder hit parts of Ibaraki, Chiba and Tokyo, we estimate a different distribution based on observed damage. In the ASCE estimate, we set JMA 7 to reflect coast town zones with tsunami inundation (essentially complete destruction); JMA 6+ to include coastal (man-made islands) areas near Tokyo Bay and the Tona River with liquefaction (commonly 2 to 4 inches of settlements, and some lateral spreads near creeks) or landslide (very few populated areas); JMA 6- in strong shaken coastal areas (not inundated); JMA 5+ (some of downtown Sendai), JMA 5- (most or remaining parts of Sendai, urbanized areas in the eastern Kanto plain outside of liquefaction zones), and JMA 4 and JMA 3 for most of urbanized Tokyo and points southwest of Tokyo.

JMA	MMI	Population Exposed: Japanese estimate	Population Exposed: This report estimate
7	IX + PGDs + Tsunami inundation	80,000	80,000
6+	IX + PGDs (X)	510,000	200,000
6-	VIII - IX	4,247,000	500,000
5+	VII - VIII	11,163,000	1,500,000
5-	VI - VII	20,614,000	3,000,000
4	V - VI	18,206,000	5,000,000
≤3	≤ IV	25,906,000	70,446,000

Table 2-3. Population Exposed to JMA / MMI

The use of JMA (such as the Figure 4.6 or third column in Table 4.3) can lead to a seriously misleading understanding of the actual damage patterns. Clearly, the use of the instrumental-based JMA maps, overstates the observed damage.

Figures 2-7, 2-8 and 2-9 show selected recorded time histories form the region. These time histories show the long duration of shaking from the main shock; with the following trends:

- Near the epicenter (Sendai), there were two distinct events, separately by about 30 seconds. This reflects the timed delay of the rupture along the fault, and the time needed for arrival of the shock waves.

- Both north and south of the epicenter, the ground motion records show about 60 seconds (or so) of strong ground motion.

- For the most part, maximum vertical PGAs are on the order of 2/3 (or less) than the corresponding horizontal PGAs.

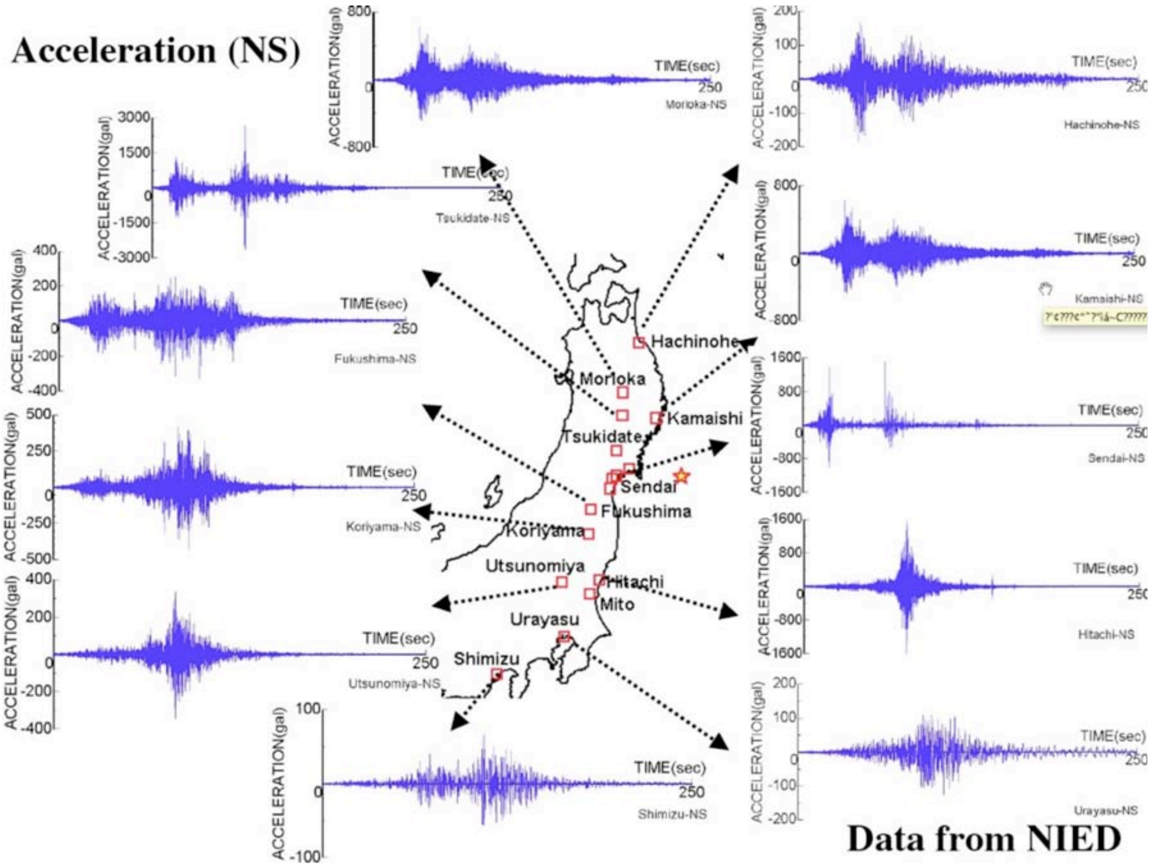

Figure 2-7. Acceleration (North-South)

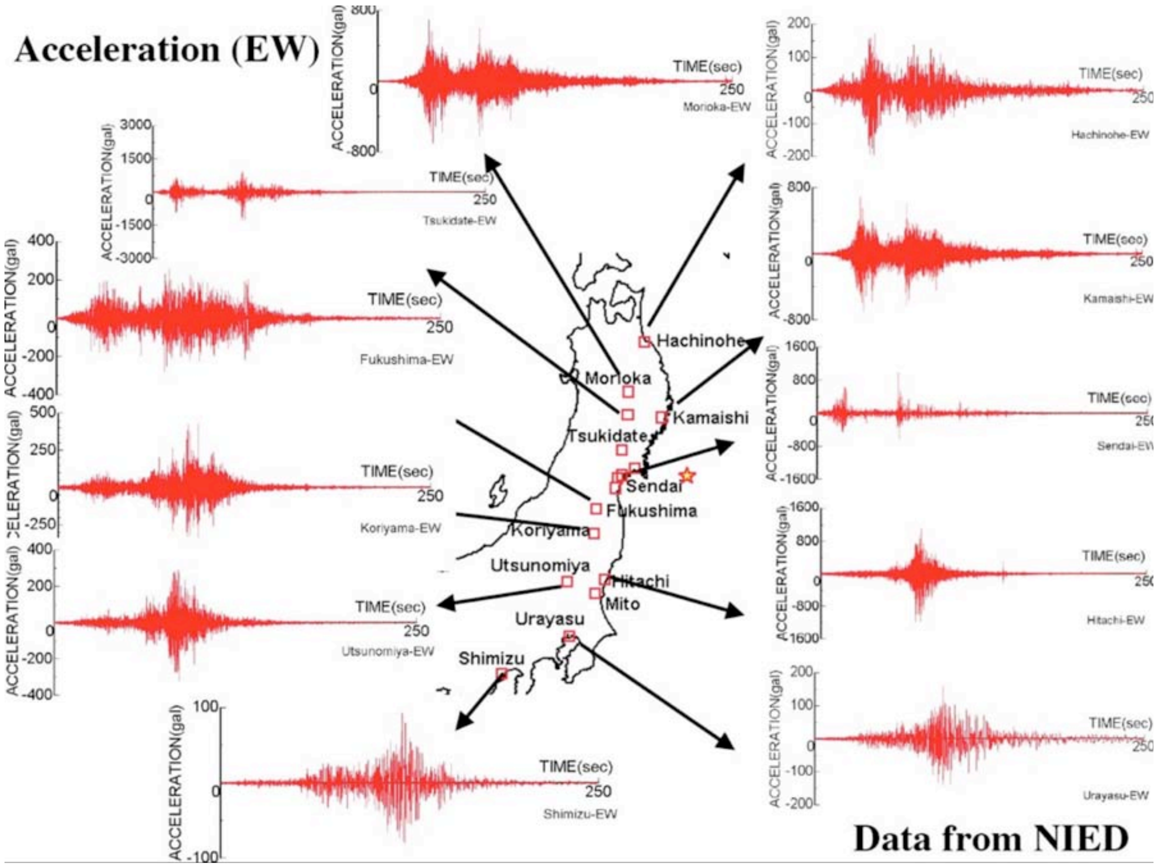

Figure 2-8. Acceleration (East-West)

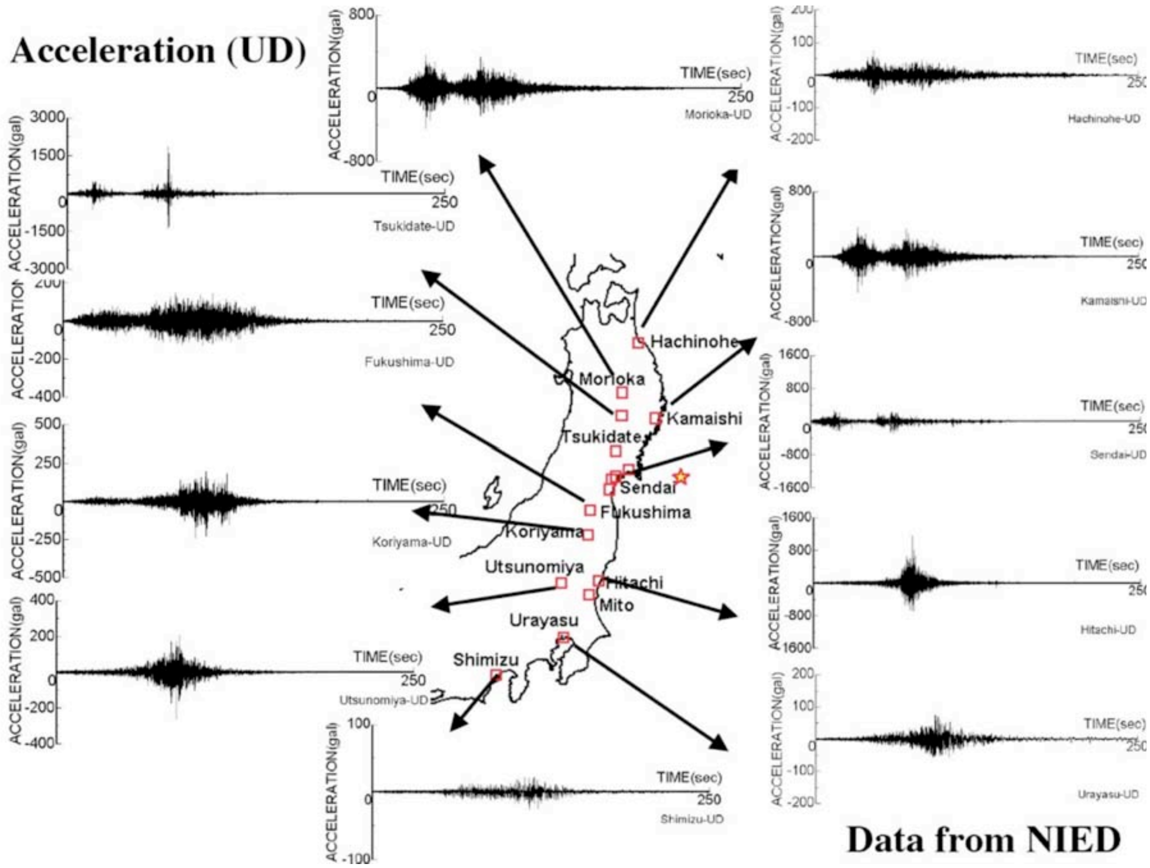

Figure 2-9. Acceleration (Vertical)

Figure 2-4 shows the range of ground motions (PGA) versus distance. The dashed lines show the attenuation model for Mw = 8.9, after Si and Midorikawa (2000), for firm soil sites. The open dots show the maximum of two horizontal directions.

2.2 Tsunami Considerations

The Great Tohuku earthquake caused tsunamis that resulted in vast areas of destruction along the Pacific coastline. When discussing the tsunami, we use the following definition for the height of the tsunami: as measured in the ocean just offshore, at a sea depth of 10 meters.

2.2.1 Tsunami Heights

In the 2011 earthquake, these heights commonly reached 6 to 10 meters off the coast of Iwate, Miyagi and Fukushima; more commonly 1 to 2 meters off the coast of Ibaraki and Chiba. Figures 2-10 and 2-11 show graphs of the tsunami heights as calculated by simulation for this event.

One of the hardest hit cities was Ofunato, in southern Iwate Prefecture, Figure 2-10. The 2011 earthquake was not the first earthquake to cause tsunamis in Ofunato:

- The 1896 Meiji-Sanriku earthquake caused a tsunami with 25 meter height (basis unreported) that killed 27,000 people in Sanriku.

- The M 8.4 1933 Sanriku earthquake caused a tsunami with 28 meter height (basis unknown) that killed 1,522 people.

- The M 9.0 2011 Great Tohuku earthquake caused a tsunami that killed 305 people. The tsunami waves impacted many coast-side industrial facilities. While perhaps the best know impacts were to the Fukushima Daiichi 6-unit nuclear power plant, very similar effects occurred to a lot of other facilities along the coastline, including a 600 MW power plant in Sendai; a 1,000 MW power plant in Soma; a refinery in Sendai; two large wastewater treatment plants in Sendai; almost all the port facilities; as well as a lot of other facilities (wood and pulp factories, the Sendai airport, gas holders, etc.) Tens of thousands of residential and commercial facilities were similarly impacted by the tsunami.

As of the time of writing this report, we do not know of material impacts of the tsunamis on water systems. This is not to say that there were no impacts, as we expect that as the coast line facilities get re-built over the years to come, that damage to buried water distribution pipes and appurtenances will become known. We expect that some water system damage will have occurred in the inundation zones either due to liquefaction (some); or erosion effects (more likely).

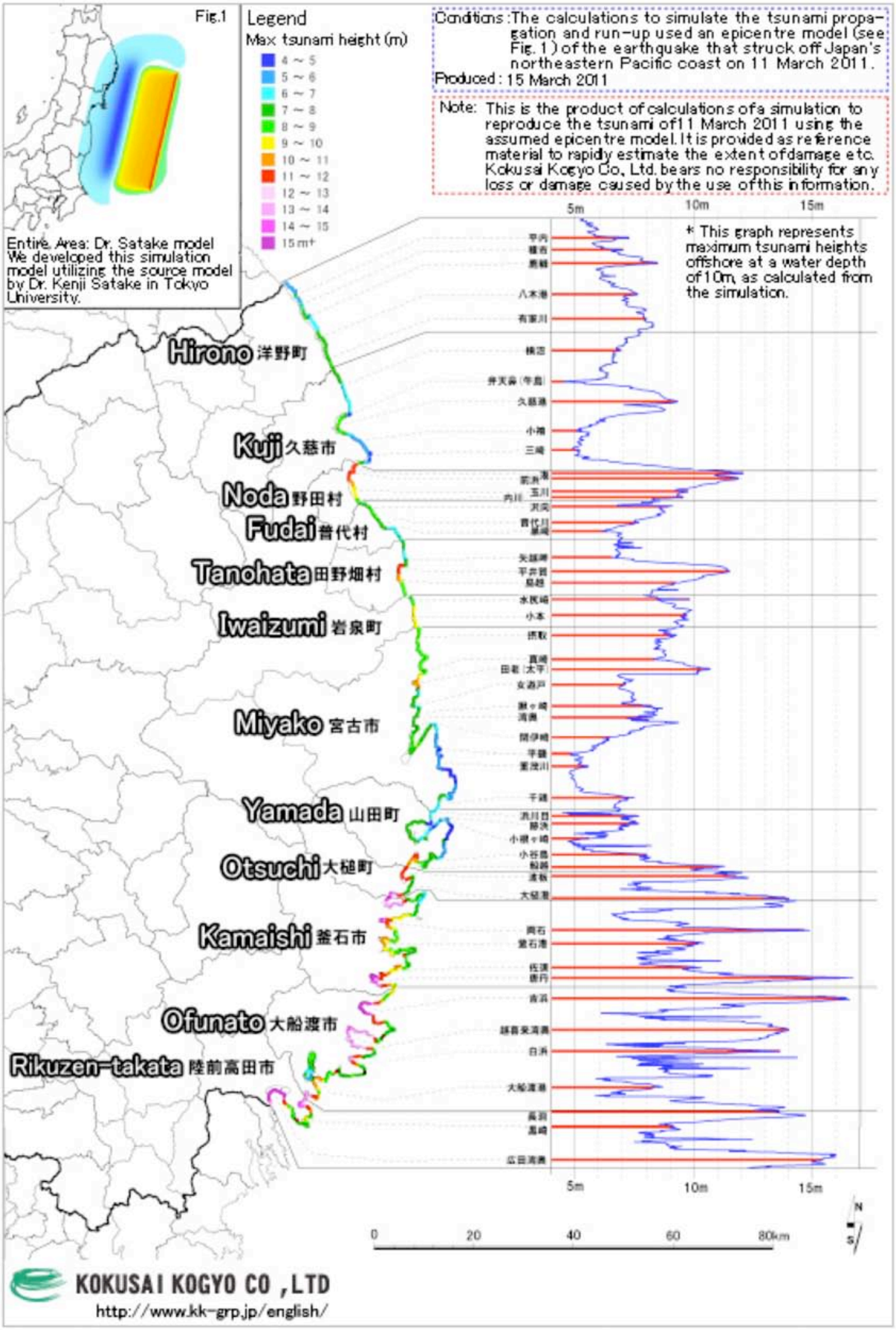

Figure 2-9. Tsunami Heights, Iwate Prefecture Coastline (Kokusai Kogyo Co)

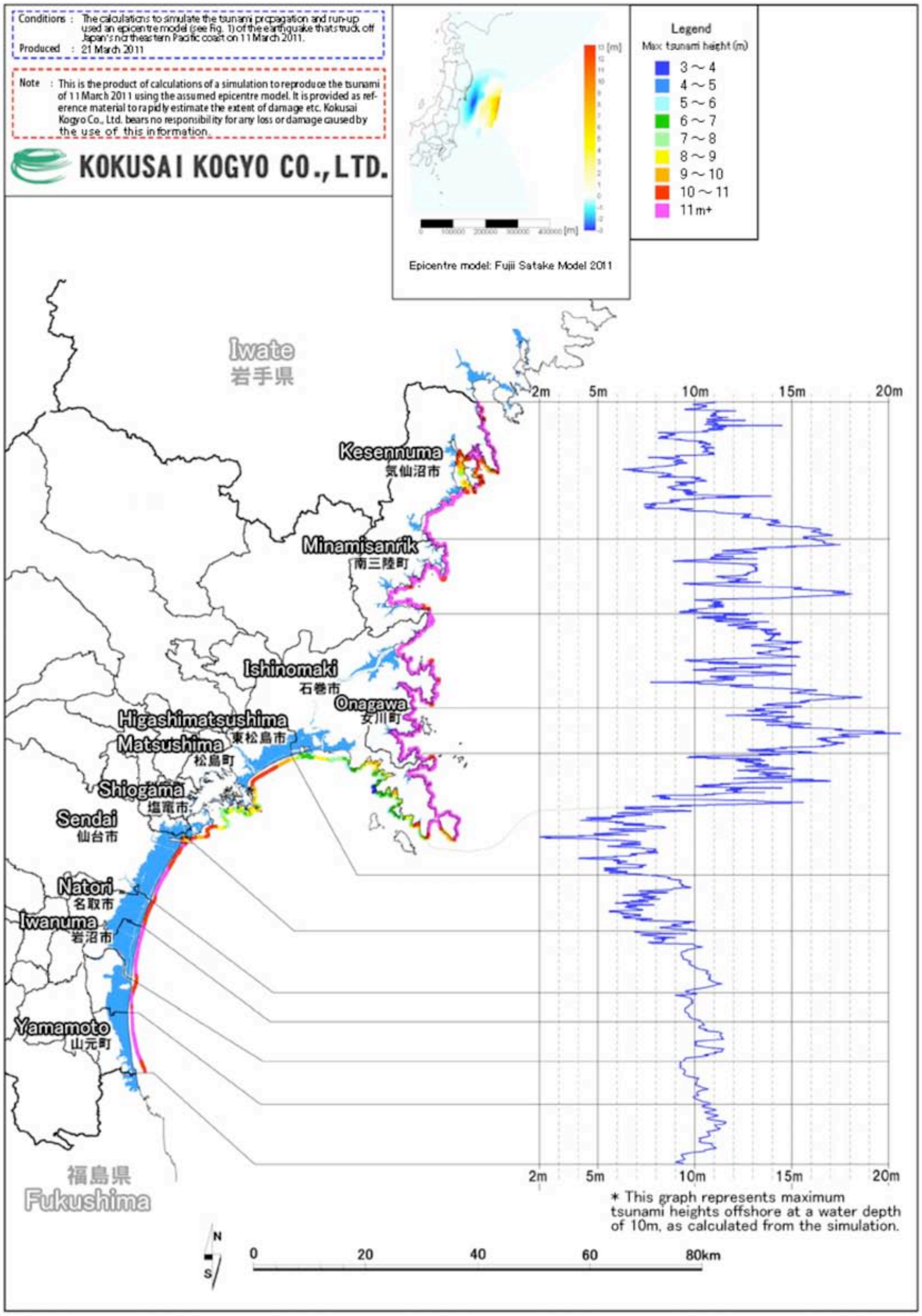

Figure 2-10. Tsunami Heights, Miyagi Prefecture Coastline (Kokusai Kogyo Co)

2.2.2 Tsunami Design Basis

Given the history of high tsunamis along the northeast coast of Japan, an important question arises: what was the design base tsunami height for construction of modern facilities along the coastline? We questioned several Japanese engineers, including those working at coastal wastewater treatment plants, and were told "about 1 to 2 meters". Other Japanese engineers told us that high tsunamis (on the order of 10 m high) were not expected for perhaps another thousand (several thousand?) years. Probabilistic hazard maps for this region in Japan seem to suggest that occurrence of a M 8.9+ type offshore event was considered to have a very long return period, and thus would not show up in maps with return periods like 3% in 30 years (about a 1,000 year event), Figure 2-11.

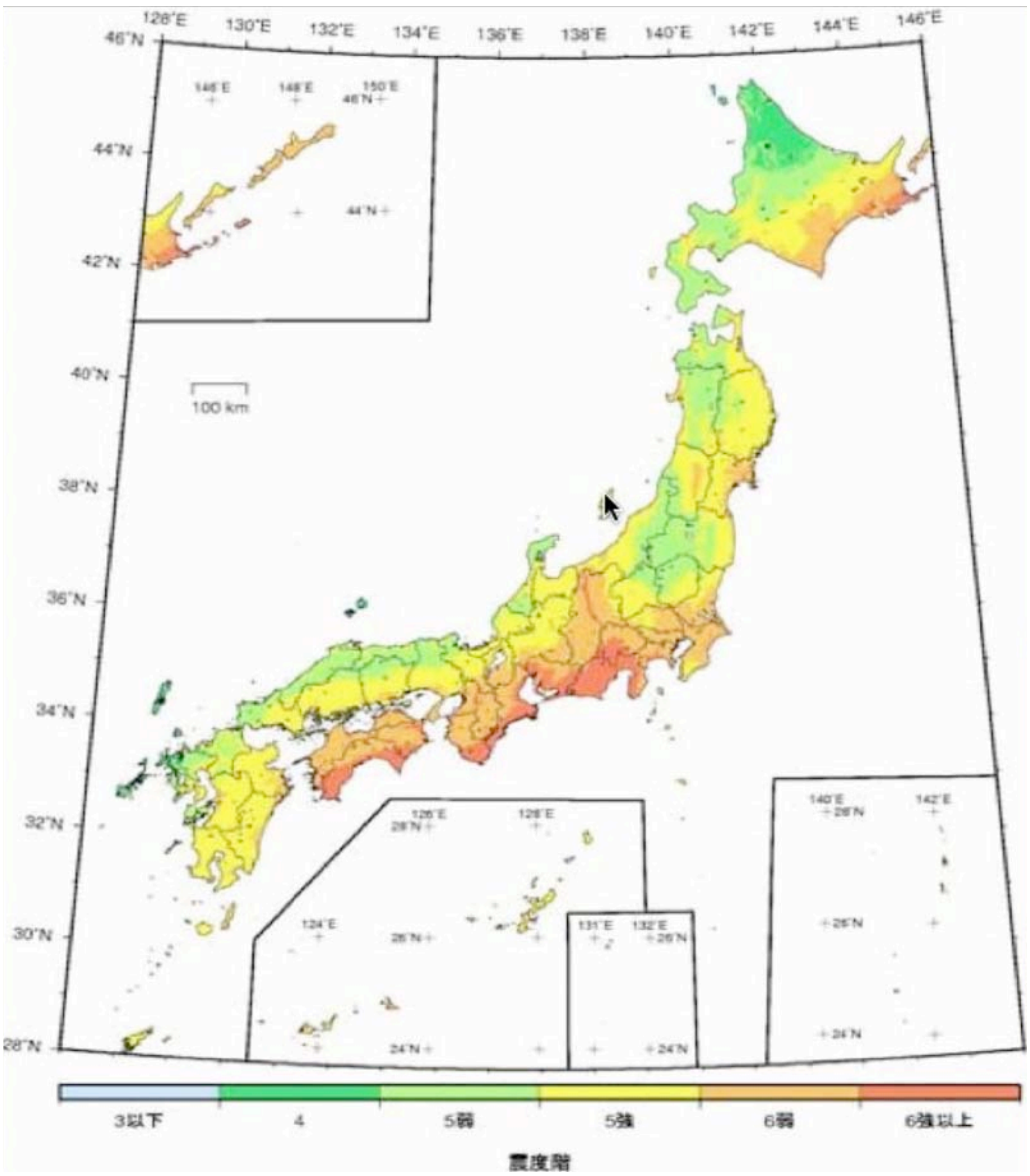

Figure 2-11. JMA Intensity, 3% in 30 Years (Fujiwara, NIED, 2004)
(Horizontal scale: 3, 4, 5-, 5+, 6-, 6+)

It is evident from this 2004-vintage map that most people in Japan placed highest seismic hazard along the Pacific Coastline from Tokyo and westwards; while motions along the eastern Tohuku coast were commonly two JMA intensity levels lower (5+). The actual M 9 earthquake produced much stronger motions in Tohuku than the probabilistic motions shown in Figure 2-11.

In the high seismic regions of the USA, most common structures are designed for probabilistic motions with return periods on the order of 500 years; but critical infrastructure facilities are designed assuming the probable maximum magnitude earthquake, commonly with return periods of 2,500 years (water systems) or 10,000+ years (nuclear power plants).

It is difficult to reconcile the tremendous adverse impact of the tsunami at the Fukushima Daiichi power plant. Had a higher tsunami height been considered for the safety-related backup power systems at that site, then little damage would have occurred, and the radiation disaster would not have occurred. But lest the reader believe that the Fukushima disaster was unique, we point out that *many* power plants and wastewater treatment plants along the eastern Tohuku coastline suffered the same fate as the Fukushima Daichi nuclear power plant: wave inundation that damaged power and other systems, sometimes rendering the entire facility a near total economic loss.

At the main Sendai wastewater treatment plant, a major seismic structural upgrade had recently been completed: we observed no damage to structures caused by inertial loading. Yet, the tsunami waves completed inundated the site, resulting in nearly complete damage and functional outage of the plant, with estimated re-build costs of $1 Billion. Similar instances occurred at major coal and gas-fire power plants, 400 MW or larger. It seems to us that high water tsunami loading effects were greatly under-predicted to the designers of these facilities, while at the same time the inertial effects were considered in a prudent fashion. This mis-match of seismic design (adequate inertial design, inadequate tsunami design) is inadequate: both effects needs to be concurrently considered.

2.2.3 Tsunami Impacts

The tsunami had several types of impacts on power and water facilities.

One of the more common effects of the tsunami was due to flotation of tanks. If one is to place tanks in an area prone to inundation (tsunami or flood), and if the tank is kept partially or totally empty (or in any case, lighter than the displaced volume of water), the tank will float.

The anchor systems commonly used for tanks for seismic loading will generally *not* be able to resist the uplift forces involved. Within a few seconds of being flooded, the uplift forces on the tank will break the anchors, and then the tanks will float with the water. If the water is moving at high velocity, the tank will move at the same velocity, and the floating tank becomes a impact hazard. We observed impact damage due to floating tanks to wastewater treatment plant office buildings, high voltage transmission towers, etc.

We observed more than 20 floated steel tanks in the tsunami zones. Figure 2-12 shows three oil tanks in Onegawa. The tsunami floated two of the tanks that were at about 20 feet above sea level; but the third tank, at about 50 feet above sea level, was placed high enough on a hill to avoid the tsunami. All three tanks were anchored; the anchors on the two lower tanks broke in the anchor bolts, Figure 2-13. The anchored upper tank appears to have survived the strong ground shaking effects without damage.

Figure 2-12. Two Floated Tanks, One OK Tank (Onegawa)

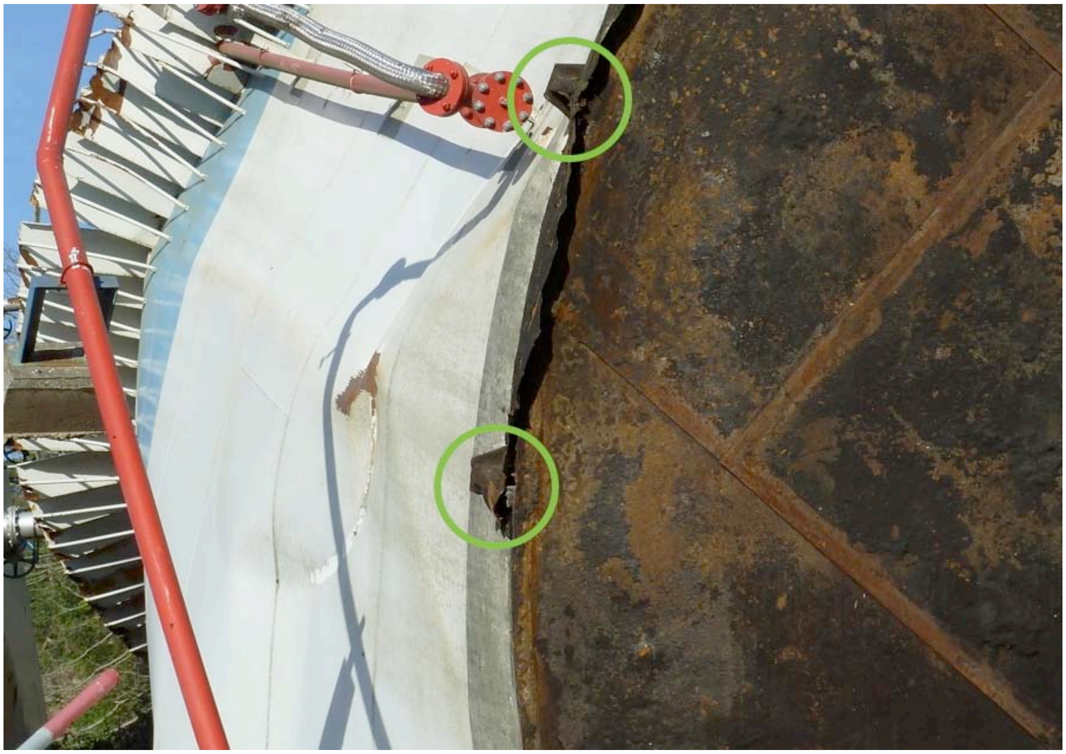

Figure2-13. Failed Anchors on one of Two Floated Tank (Onegawa)

At the Port of Sendai, there are two identical 5,000,000 liter fire water tanks at the Shin Sendai power plant, Figure 2-14. Water heights from the tsunami were about 8 feet above local grade at these locations. Both tanks are welded steel, unanchored, resting within a concrete containment ring, Figure 2-15. Observations of Tank 1 show that it started to float / and or rock due to the tsunami; but the adjacent Tank 2 showed no distress at all. The performance of these tanks is further described later in this report.

Figure 2-14. Two Water Tanks that were Inundated

Figure 2-15. Tank 1, Showing Evidence of Distress / Uplift

3.0 Performance of Water Systems

3.1 Miyagi Prefecture Water Transmission System (Sennan Senen)

In 1980, a major treated water wholesale water transmission system was constructed. This system is called the Sennen Senan regional transmission system, Figure 3-1.

Source water is from surface water sources about 50 miles southwest of Sendai, treated from the Shiroishi water treatment plant (200 MGD). The treated water is then moved via two larger diameter pipes: the "high elevation" pipe goes towards Sendai City, and the :low elevation" pipe goes towards Natori City.

For the City of Sendai, the water from this system represents about a third of its water supply; for the other cities, the water from this system represents a major fraction to nearly 100% of regular water supply.

Figure 3-1 shows a map of this system. In total, this water transmission system was damaged in 53 locations. The large red arrow indicates probably the most critical of these damage locations, where a 96" (2400 mm) diameter pipe suffered breaks in two locations. Figure 3-2 shows an aerial view, taken on April 7 2011 (26 days after the earthquake). The pipe can be seen exposed in two locations within the red circle. At this location, the pipe was originally designed and routed to go around the freeway on/off ramps, as well as go under a drainage creek. As seen in Figure 3-3, the pipe also makes a sharp turn under the creek, to match the alignment around the freeway ramps.

The basic design of the pipe at this location was to encase the pipe in concrete where it goes under the creek; the concrete is used primarily for scour protection and to prevent flotation in case the pipe is empty. There are slip joints immediately outside the concrete encasement on either side of the creek undercrossing.

The pipe alignment and damage locations are shown in Figure 3-3. Figure 3-4 shows the damage to the pipe (at the lower left highlighted location in Figure 3-3), with the photo taken 30 minutes after the earthquake. The water being released (Figure 3-5) rapidly eroded the backfill and some surrounding soils, and undermined the concrete encasement in spots; but nearly all the water was routed into the storm drainage channel, so there was no flooding of the nearby highway. The water being released was then isolated by closing suitable valves in the system.

Repair of this pipe so that this section could be re-pressurized (there were still many other places on the pipe that remained to be repaired) took about 8 days, Figures 3-6, 3-7. Three days after the earthquake, the site was prepped for construction work (the failed slip joint sections were removed). On March 17, new steel pipe sections were brought to the site, and then welded into the places where the slip joints had been. By the end of the day on March 18, the pipe was welded closed. Figure 3-8 shows the repaired pipe as of

April 9, 2011; superimposed is a blue line showing (very approximately) the pipe route. The net offset of the pipe was about 70 cm (2.3 feet).

Most of the damage at the other 50+ locations along this pipe was also to the opening of slip joints. Site inspection of the nearby highway embankment could not reveal evidence of any permanent ground deformations for the site in Figure 3-3. The level of shaking at this site would be about PGA = 0.20g to 0.25g range based on common attenuation models. Possible explanations as to why the encased section moved and caused the slip joints to pull apart are as follows:

- The vibration of the pipe in the ground results in hydrodynamic forces. This resulted in higher-than-normal thrust forces on the encased bend.

- There was almost certainly insufficient soil resistance available from the concrete encasement to "anchor" the pipe during this earthquake. Possibly, the soil backfill behind the bend liquefied, or was otherwise weakened, by the effects of the earthquake. With a reduced passive soil capacity, the soil could not resist the water thrust force. The thrust force then forced a passive soil wedge-type failure, allowing the encased bend to move over by about 70 cm. As the slip joints were not restrained, the pipe could offer no resistance to this movement, and the joints opened up, resulting in the water flows as seen in Figures 3-4 and 3-5.

- ALA (2005) provides some guidance as to how to estimate these hydrodynamic forces. In most situations, there would be little additional construction cost to restrain these forces, even assuming a weaker soil resistance at the bend.

- Lacking computation of such hydrodynamic forces, a simple approach would be to avoid placing slip joints into pipelines at any location near bends over 5° or so, or next to closed isolation valves, unless the pipe is provided with anchors or sufficient soil strength (including earthquake effects) to resist maximum hydrostatic forces with at *least* a factor of safety of 3.

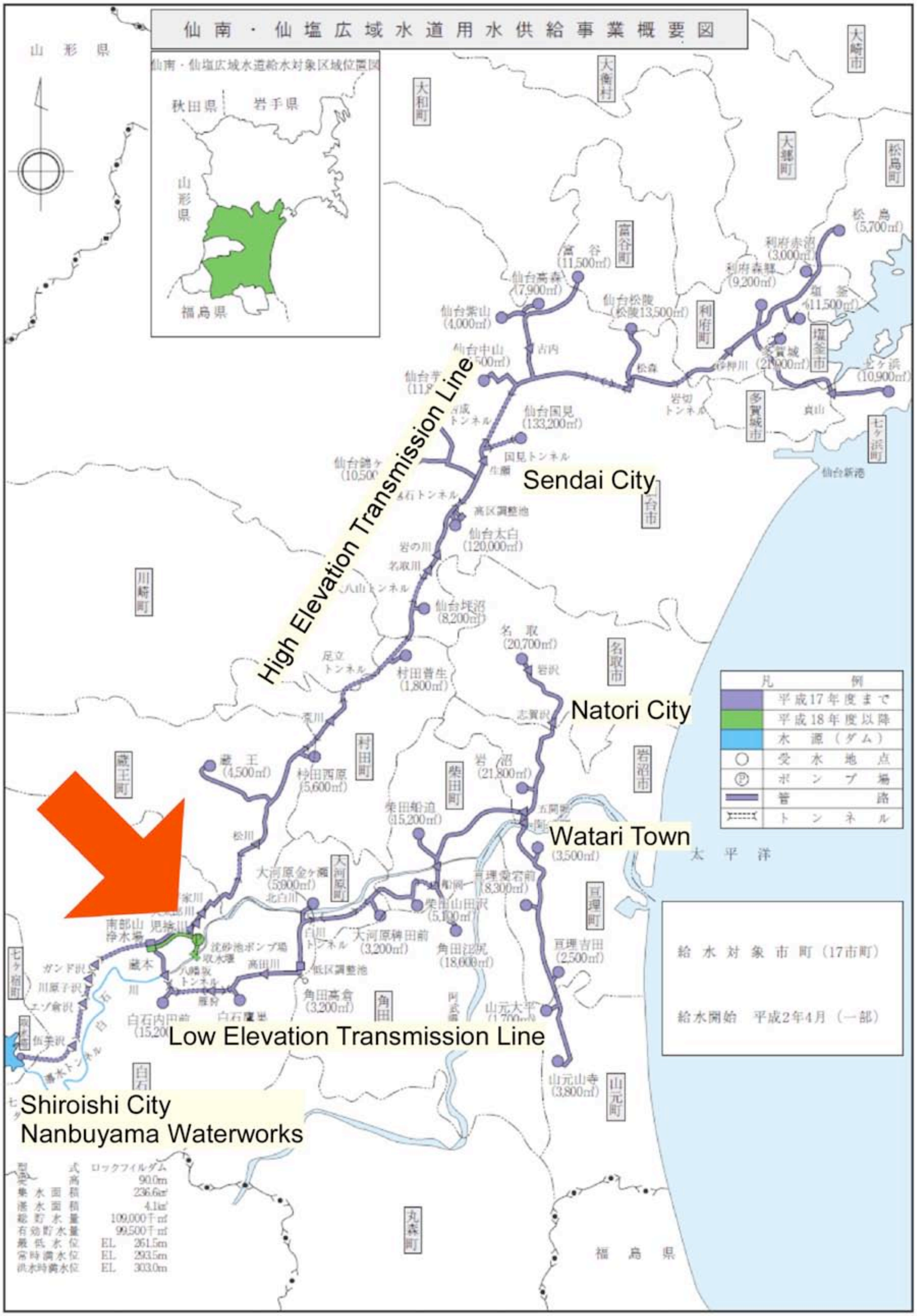

Figure 3-1. Sendai Regional Water Transmission System

Figure 3-2. Location of Pipe Damage

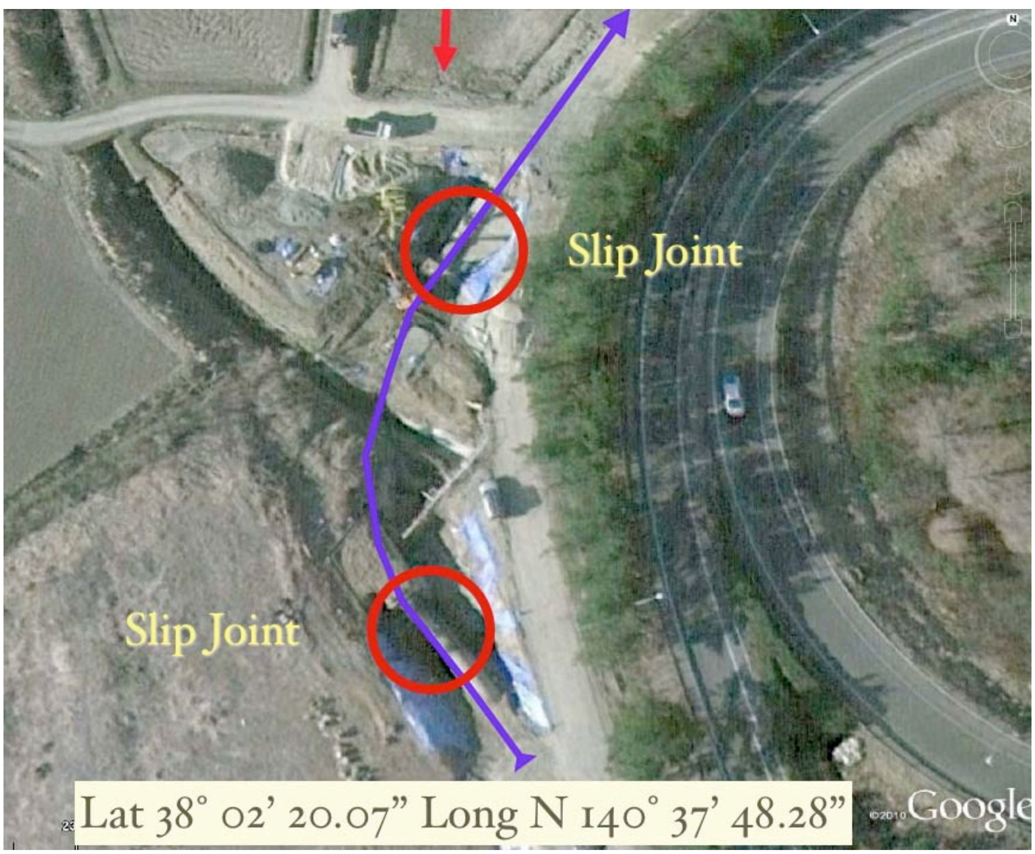

Figure 3-3. Location of Pipe and Damage Points

Figure 3-4. Damage Point 1, (96", 2400 mm Diameter Pipe)

Figure 3-5. Water Being Released, 30 minutes after the earthquake

Figure 3-6. Offset at Slip Joint

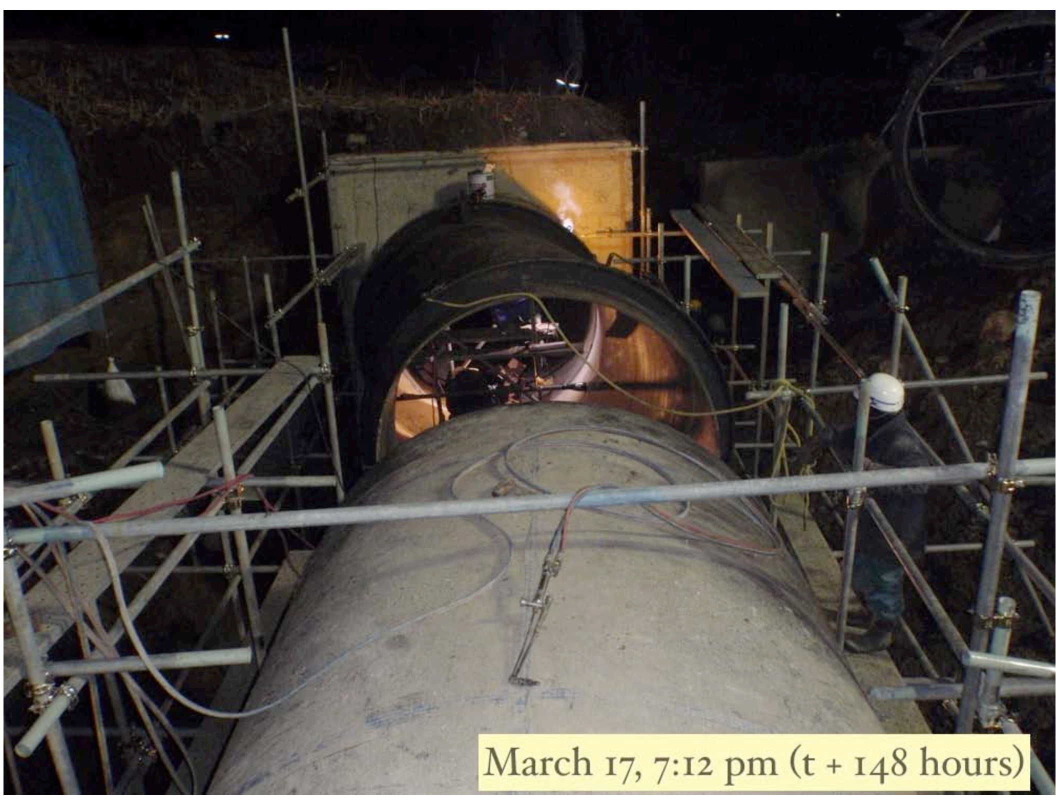

Figure 3-7. Repair Efforts, Night time, (96", 2400 mm Diameter Pipe)

Figure 3-8. Repaired Pipe, Point 1 (96", 2400 mm Diameter Pipe)

Figure 3-9 shows repairs being made to a 1.2m (48") diameter steel pipe will pulled couplings. This pipe is located along Route 4 near Shiroshi. This pipe is part of the "low" zone that delivers water to Natori.

Figure 3-9. Pipe Under Repair, (48", 1200 mm Diameter Pipe) (Kuwata)

3.2 Sendai City Water

The Sendai City water department operates a water system that delivers potable water for a population of 1,040,000 people. The water supply comes from a series of damage and water treatment plants in the hills west of Sendai (about 75% of total supply, total capacity about 336,000,000 liters per day 87 MGD); coupled with two major turnouts from the Sennen Senan water transmission system (100,000,000 liters per day, 26 MGD) described in Section 3.1.

The Sendai water system includes 4 main water treatment plants, Figure 3-10:

- Moniwa WTP. 150,750,000 liters per day
- Kunimi WTP. 90,000,000 liters per day
- Nakahara WTP. 34,500,000 liters per day
- Fukuoka WTP. 44,000,000 liters per day

The Sennen Senan transmission pipeline also delivers potable water into the Sendai water distribution system, normally about 108,100,000 liters per day.

The city also has 3 small WTPs that serve some small communities in the mountainous areas west of Sendai.

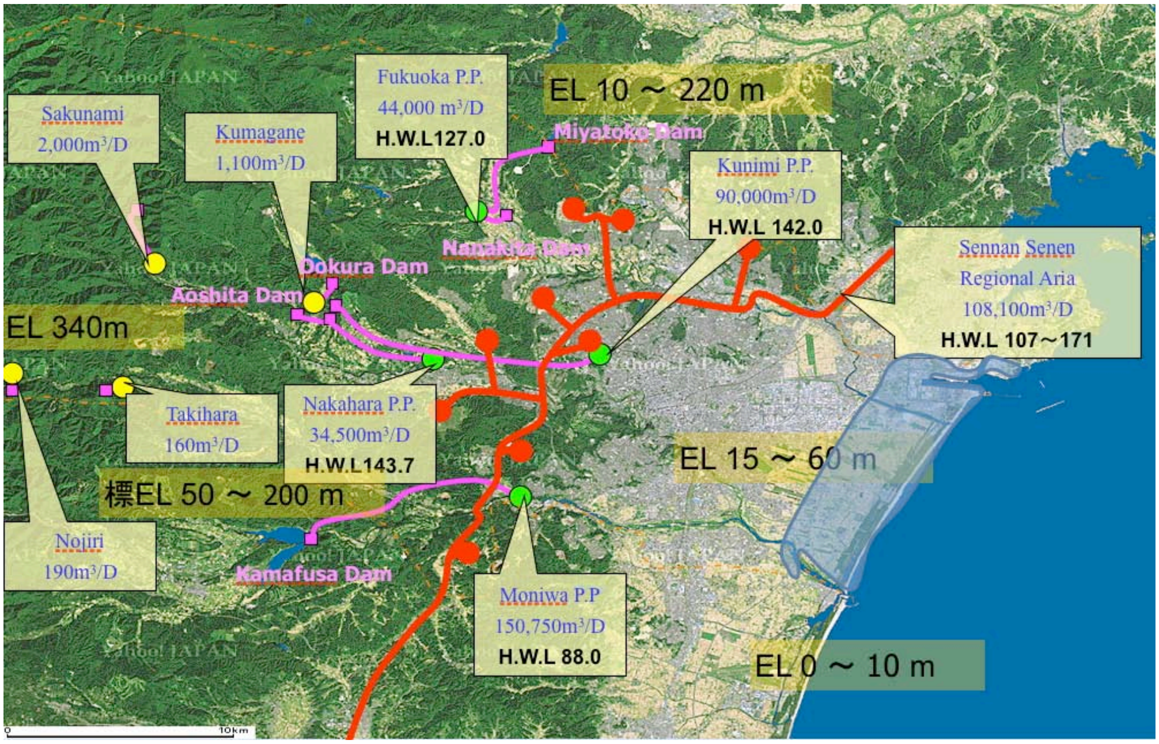

Figure 3-10. Sendai Water System

Generally speaking, there was no large scale damage to any of the WTPs. At the Moniwa WTP, inclined basin plates and baffle boards in the sedimentation tanks were displaced, Figures 3-11 and 3-12; these were readily repaired.

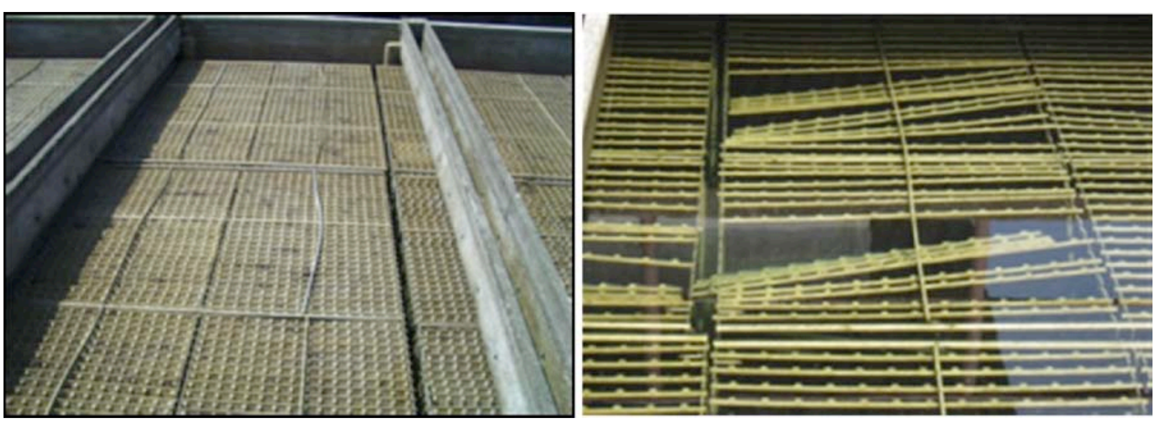

Figure 3-11. Inclined Basin Plates, Moniwa WTP (Left: before; Right: after)

Figure 3-12. Baffle Boards, Moniwa WTP (Left: before; Right: after)

At one distribution tank (Anyoji), an internal unreinforced masonry baffle wall collapsed, Figure 3-13.

Figure 3-13. Baffle Wall, Anyoji Reservoir

Unanchored lab equipment fell over to the floor at the Fukuoka WTP, Figure 3-14.

Figure 3-14. Unanchored Laboratory Equipment Toppled, Fukuoka WTP

All of the large WTPs include on-site permanently installed backup diesel generators. Due to power outages fro Tohuku Electric Company (the local power company), the diesels were used after the earthquake, Table 3-1.

Water Treatment Plant	Electric Generator Usage Post Earthquake, Hours	Tohuku Electric Power Restoration Date	Type of Oil	Tank Capacity (Liters)	Operational Hours / Tank Capacity, Hours
Moniwa	98	March 15	Kerosene	6,500	28.7
Kunimi	58	March 14	Light Oil	950	13.1
Nakahara	54	March 13	Kerosene	12,000	29.4
Fukuoka	68	March 14	Kerosene	10,000	29.9

Table 3-1. Backup Power at Sendai WTPs

There were 120 cases of various types of damage to water treatment plant buildings, landscaping, architectural, electrical and mechanical components. In total, the repair cost for these items was about $4,000,000.

Pipeline damage included the following (see locations in Figure 3-15):

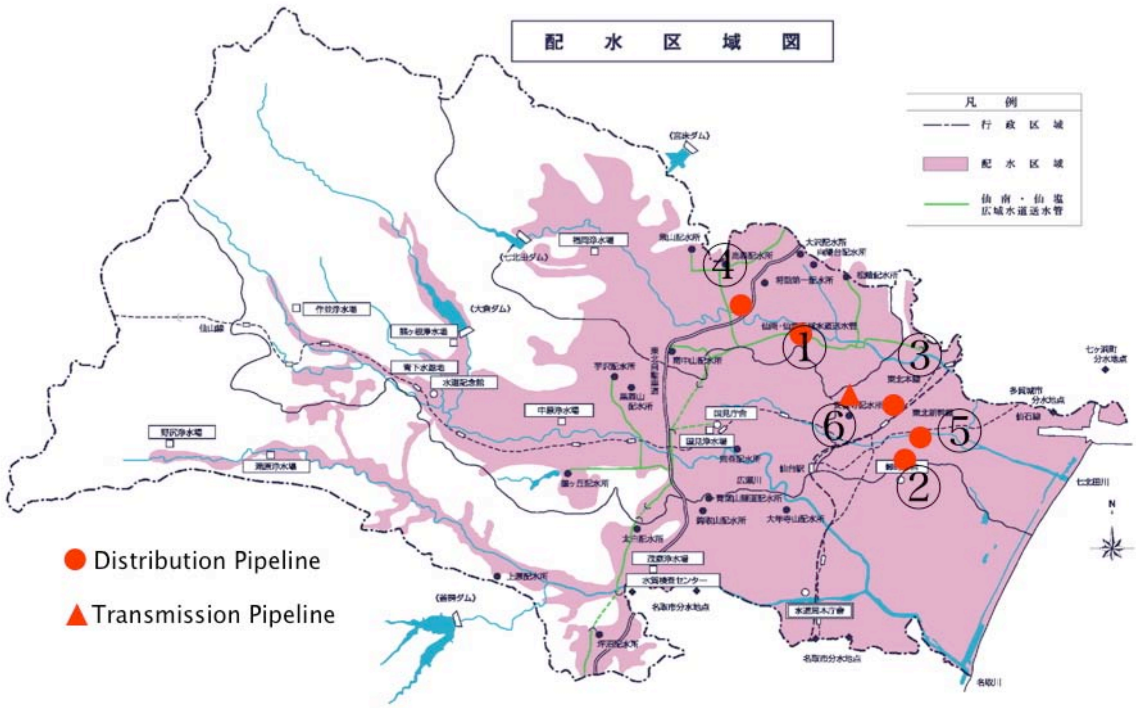

Figure 3-15. Damage to Large Diameter Pipes, Sendai

- 1. 800 mm (32") Kunimi No. 2 pipe broke. Installed 1988, DIP (K joints), Figure 3-16. "K type" joints in Japan are similar to Mechanical Joints used in the USA, whereby a bolted joint is made from a ductile iron gland and an internal rubber gasket.
- 2. 600 mm, installed 1973, DIP (K)
- 3. 500 mm, installed 1977, DIP (K)
- 4. 400 mm, installed 1972, DIP (K)
- 5. 400 mm, installed 1977, DIP (K)
- 6. 600 mm, installed 1974, Steel, subsidence, Figure 3-17.
- 41 cases of damage to appurtenances (for example, fire hydrants, air valves, gate valves) on large diameter (400 mm or larger) pipes.
- Many damaged distribution pipes, Figures 3-18, 3-19.
- There was no damage to any "seismically designed" pipes of the type that uses chained joints (see Section 3.X).

Figure 3-16. 800 mm Kunumi 2, DIP, Sendai

Figure 3-17. 600 mm Masue 2, Steel, Sendai

Figure 3-18. Leaking Pipe, Sendai

Figure 3-19. Typical Distribution Pipe Repair being made in Sendai (Kuwata)

System-wide, 30 air release valves collapsed (Figure 3-20), indicating the importance of system over-pressurization in some locations (hydrodynamic loads) or rapid de-pressurization and negative pressures (due to pipe breaks).

Figure 3-20. Leaking Air Valve, Sendai

Figure 3-21 shows a map with the concentrated areas of smaller diameter pipeline damage in Sendai. A significant portion of the pipeline damage occurred in the western hilly areas of Sendai. The level of ground shaking in these areas would have been commonly PGA = 0.15g to 0.25g; although no doubt there was some local amplifications much above these values. Many of these hilly areas had been constructed using cut-and-fill methods, including the roads. There were many road-fill slumps. Where the roads were damaged (commonly a few inches to a foot or so), or where houses near the roads suffered settlements (slides), (Figures 3-22, 3-23) the buried water pipes were also damaged. It would seem that there was no seismic design considered for the roads, nor for the pipes within these roads to counter the effects of road-fill slumps.

Table 3-2 (parts 1 and 2) summarizes the damage statistics for the City of Sendai water system.

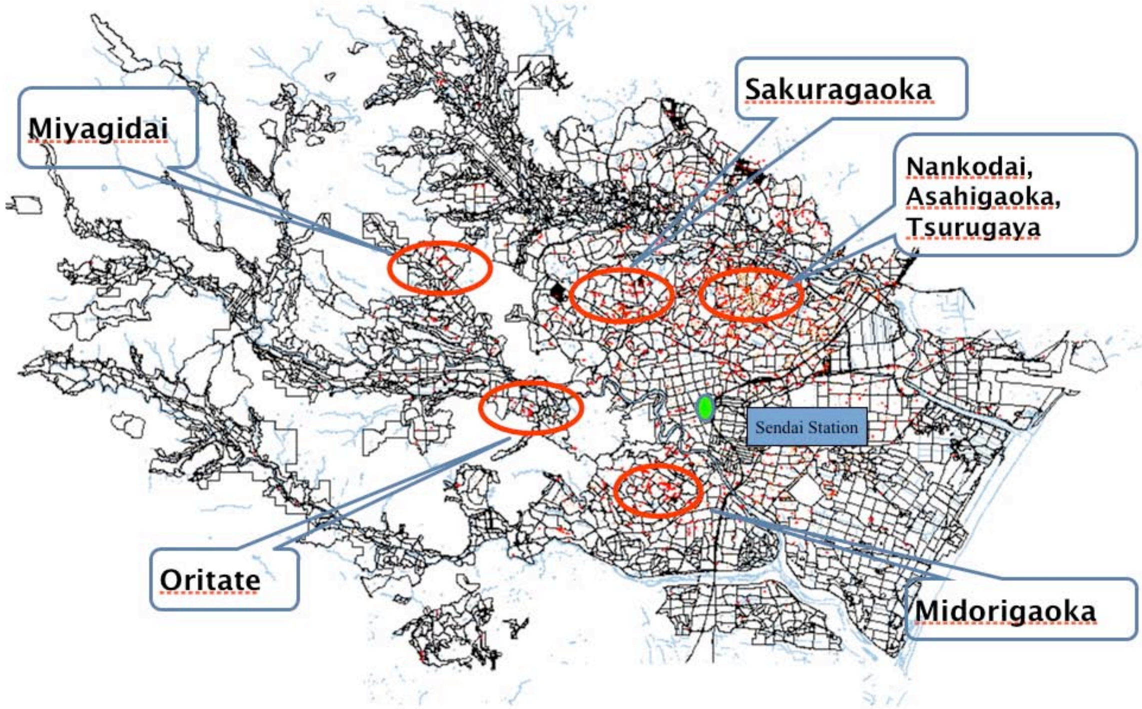

Figure 3-21. Areas of Concentrated Damage to Pipe, Distribution System, Sendai

Figure 3-22. Damage to Road – Hillside Area, Nakayama, Sendai

Figure 3-23. Damage to Road – Hillside Area, Nakayama, Sendai

		DIP	A	K	T	Others	**SP**	**VP**	TS	RR
Diam (mm)	Under 40		——	——	——	——	3	21	21	
	40		——	——	——	——		40	39	1
	50		——	——	——	——		86	73	13
	75	17	12	1	3	1	1	77	70	7
	100	41	23	8	8	2	3	73	57	16
	150	33	20	4	9		3			
	200	10	6	1	1	2	1			
	250	4	4						——	——
	300	7	5		1	1			——	——
	400	2		2					——	——
	500	1		1					——	——
	600	1		1			1		——	——
	800	1		1					——	——
	total	117	70	19	22	6	12	297	260	37
Pipe extension (km)		2,723.1	1,088.7	494.2	262.2	878.0	137.3	1,514.5	864.6	649.9
Rate of breaks (/km)		0.04	0.06	0.04	0.08	0.01	0.09	0.20	0.30	0.06

Table 3-2. Sendai City Water Damage (Part 1 of 2)

		LP	PP	GP	total	pipe extension(km)	rate of breaks (/km)
Diam (mm)	Under 40	1	3	1	29	63.4	0.46
	40	1		1	42	95.9	0.44
	50			4	90	535.9	0.17
	75	——	——	——	95	438.9	0.22
	100	——	——	——	117	1,299.5	0.09
	150	——	——	——	36	935.3	0.04
	200	——	——	——	11	354.8	0.03
	250	——	——	——	4	98.1	0.04
	300	——	——	——	7	265.9	0.03
	400	——	——	——	2	105.5	0.02
	500	——	——	——	1	68.3	0.01
	600	——	——	——	2	43.5	0.05
	800	——	——	——	1	15.3	0.07
	total	2	3	6	437		
Pipe extension(km)		3.4	52.7	4.9	——	4,458.0	——
Rate of breaks(/km)		0.59	0.06	1.22	——	——	0.10

Table 3-2. Sendai City Water Damage (Part 2 of 2)

City-wide, there were about 437 repairs made to water pipes. The highest repair rates were for small diameter pipes (4 inch and under). Repair rates for larger diameter pipe (6" to 32") were rather low: on the order of 64 repairs for 1,886.7 km of pipe. If we assume the bulk of this damage was due to ground shaking (some was due to landslide in the hill areas, and some due to erosion in the tsunami inundation areas), and if we assume the ALA (2001) pipe fragility model of:

Repairs per 1,000 feet = k * 0.00187 * PGV, PGV in inches/second

Then the repair rate per 1,000 feet was 64 / (1886.7 km * 3.3 thousand feet/km) = 0.0103, and if was assume k = 0.5 (commonly using push-on joint DIP) the inferred average PGV for the City of Sendai was 11 inches per second. A PGV of 11 inches/second is a modest level of shaking, as confirmed by observations of nearly zero significant building damage in Sendai in outside of the tsunami inundation zone or landslide zones. While various reported maps show PGA values in Sendai on the order of PGA = 0.5g or higher, our observations of lack of building damage, coupled with these pipeline statistics, almost certainly suggests that the common PGA values in Sendai were more like PGA = 0.15g to 0.25g.

Table 3-2 also shows that the higher damage rates apply to small diameter (1" 2", 3" and 4") pipe. In the US, these small diameter pipes are limited to service line connections. In Sendai, the highest repair rates for these small diameter pipes were for "VP" (a type of thin-walled PVC pipe with cemented joints) and galvanized steel pipe; both these types of pipes are archaic in the USA, and typically little, if any, remain in use today. Even so, the damage to small diameter service line connections cannot be overlooked, as each one needs to be repaired; each one causes a service outage on the pipe main. It is readily apparent that seismic design of service laterals needs also to be considered. In ALA (2005), this topic is addressed for service laterals located in areas prone to landslide.

The repair cost for the 437 pipe repairs (Table 3-2) plus another 627 repair locations was about 800 million yen ($10.4 million dollars).

The water restoration effort in Sendai included efforts to (Figure 3-24):

- Restore water service to parts of the City that lost water due to damage of the large diameter Sennen Senan transmission line. This was done by rerouting water to the affected areas, to one of the Sendai WTPs.

- By March 21 (ten days after the earthquake), service was restored to almost all of the city that normally obtains water from the City's own WTPs. Repairs on the Sennen Senan Transmission high elevation pipeline were completed March 19, allowing service from that system to be restored to Sendai by March 22.

- Service was restored to almost all areas by March 29, except for coastal areas hit by the tsunami, and hillside areas affected by landslides.

- Installation of temporary above ground water pipes (hoses) to temporarily restore water supply to houses where buried pipes were damaged.

- At the peak, there were about 230,000 households without water (about 500,000 people). By March 29, 99.4% of customers outside of the tsunami zone had water supply restored, Figure 3-25.

- Placement of water tanks / tank trucks and delivery points to deliver water to smaller communities (for example, a few dozen habitable houses) with broken pipes (some) but mostly to supply "pockets" of houses in communities within the tsunami inundation zones.

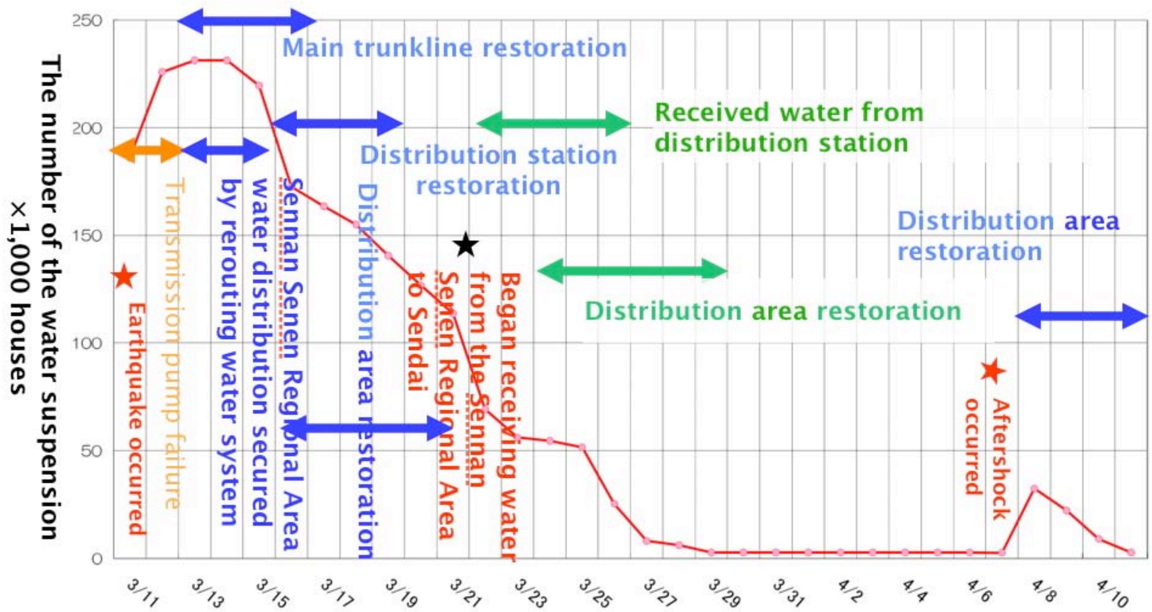

Figure 3-24. Restoration Timeline, Sendai

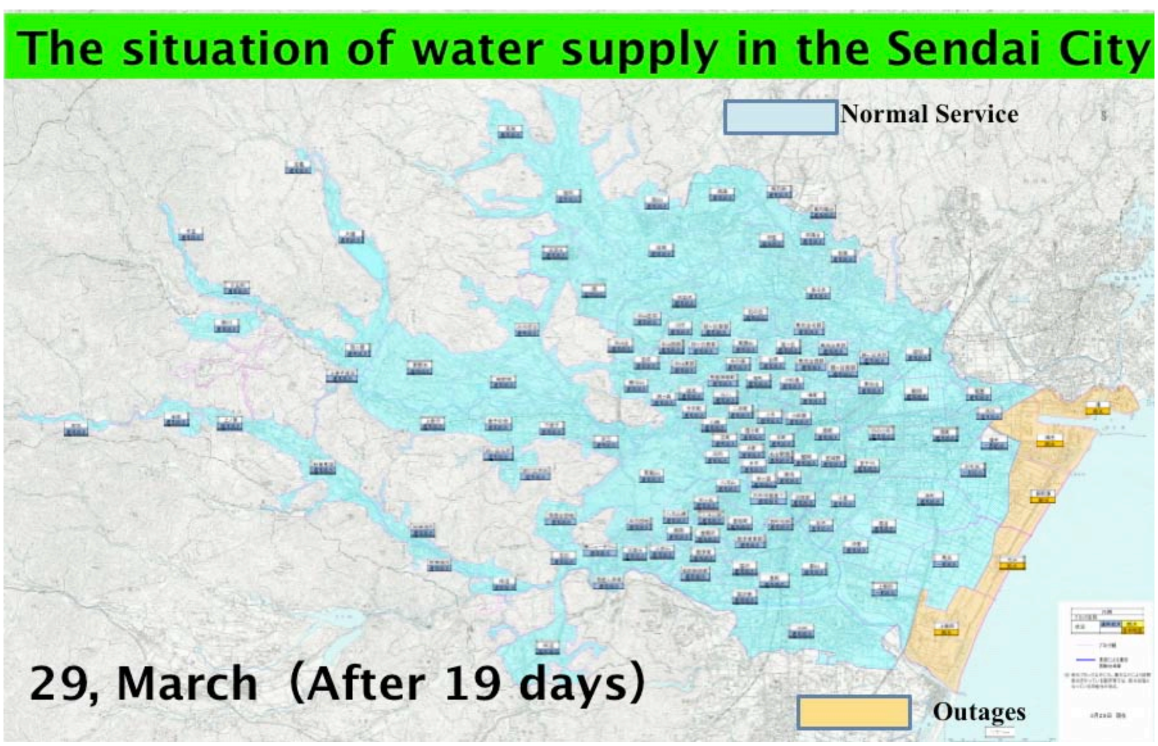

Figure 3-25. Water Outages as of March 29, 2011, Sendai

As Sendai City has many hilly communities, the water system uses many pressure zones. All told, there are 49 pump stations in the system. All of the pump stations lost offsite electric power after the earthquake. While some of the pump stations had backup generators, they commonly had about 1-day fuel supply, and this was soon exhausted. Due to the tsunami, there was nearly complete devastation of refinery and other liquid fuels facilities in the port area of Sendai, so regular re-supply of fuel was impossible for many days. Initial re-supply of liquid fuels came via tanker truck from Niigata via mountain highways, as well as from other locations in Japan; however, movement of liquid fuels via tanker truck is not in widespread use in Japan, so there were few available trucks. Sendai City officials told us that of all the issues they had to face post-earthquake, the loss of liquid fuel supply was the most troublesome.

The City of Sendai had installed 21 buried water tanks since the 1995 Kobe earthquake. The design of these tanks, which include isolation valves, was to provide for about 100,000 liters (26,000 gallons) of water in the tank, for purpose of post-earthquake drinking supply for customers, even if the main pipeline network was damaged. Of these 21 tanks, 19 were used after the earthquake, as intended; the other 2 were in inundation zones.

Figure 3-26 shows a map with locations for emergency water supply stations in Sendai, as of March 23, 2011. While repairs were being made to the damaged buried pipe, water was delivered to various locations in the city by using water trucks that delivered water to water supply stations. Priority was given to emergency medical establishments. The largest number of water trucks (Figure 3-27) in operation was 75 in any single day; these trucks and the personnel involved came from various other waterworks organizations (other cities) as well as from private contractors. The number of "truck-days" is estimated to have been 1,055. The total number of people who helped was about 2,800.

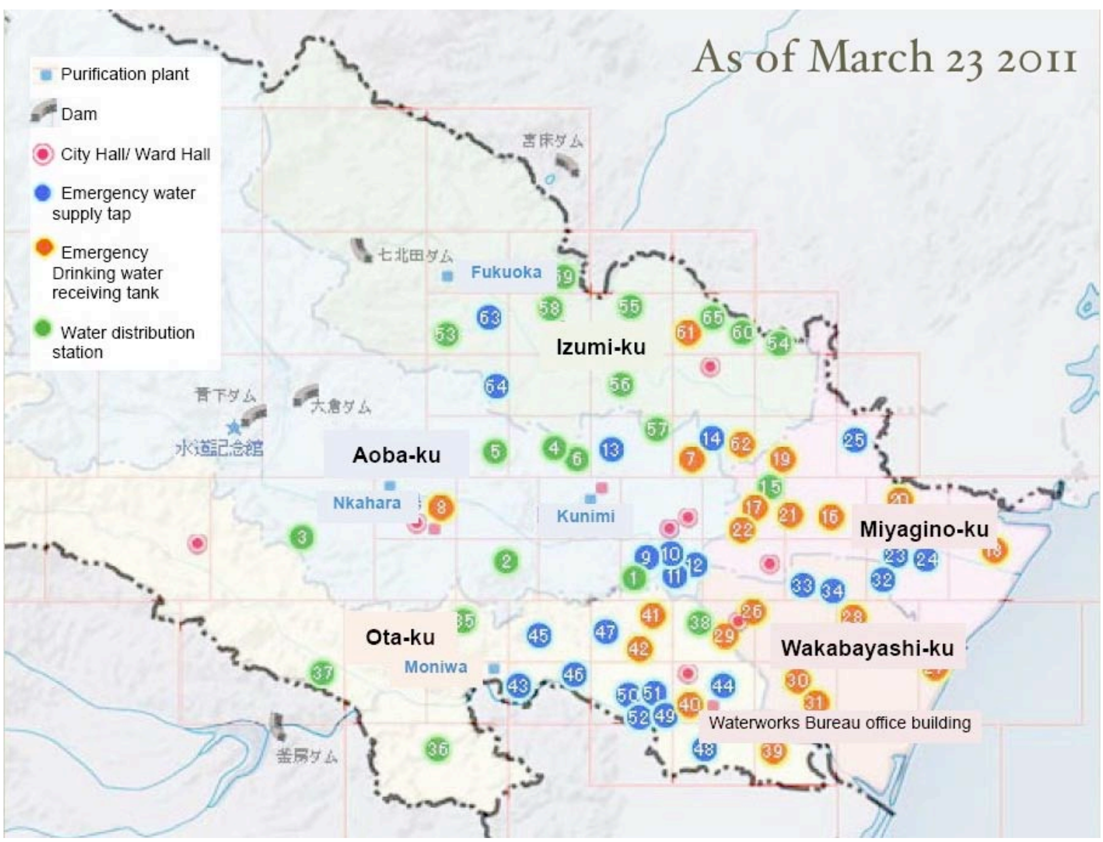

Figure 3-26. Emergency Water Supply Stations in Sendai City

Figure 3-27. Emergency Water Supply Trucks

Figure 3-28 shows the number of water trucks being used to deliver water to emergency supply stations (right axis) as well as the total volume of water delivered per day. The average water delivered, per person without piped water, was on the order of 2 liters per person per day,

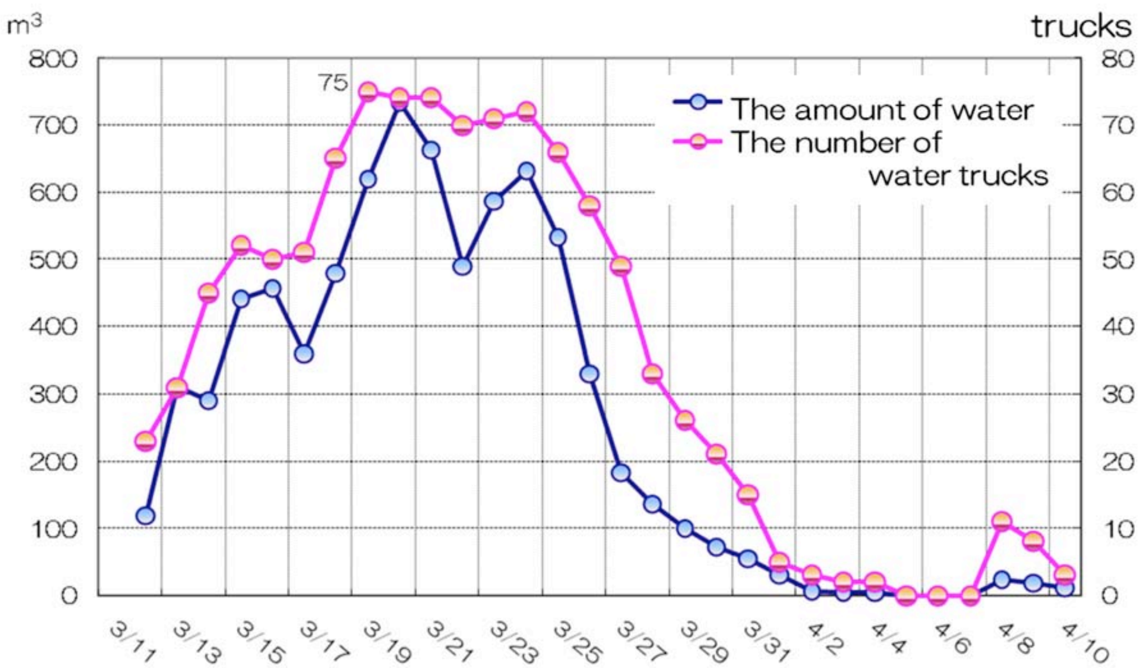

Figure 3-28. Emergency Water Supply Operation Timeline in Sendai City

The emergency delivery of water included 21 emergency storage tanks set up at various locations in the City; of these 5 were set up on March 11, the day of the earthquake. 43 smaller canvas tanks were also used, of which 30 came fro Niigata city, and 13 from Sendai City; these smaller tanks were placed in refuge areas lacking any water storage facilities.

Figure 3-29 shows the number of emergency water supply points.

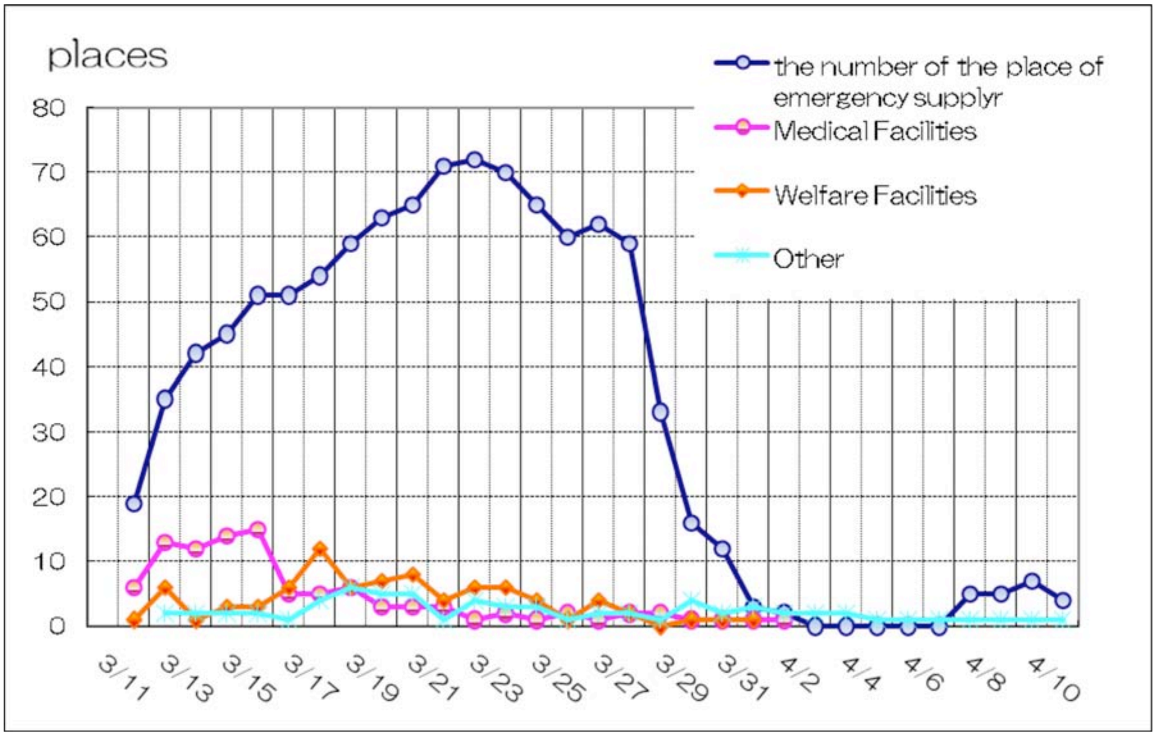

Figure 3-29. Emergency Water Supply Locations Timeline in Sendai City

3.3 Abuta WTP, Ishinomaki City, Miyagi Prefecture

Inertial loading failed some of the walls at the pump station at the Abuta water treatment plant in Ishinomaki City, Figure 3-30. Liquefaction is apparent at the site, Figures 3-31 and 3-32.

Figure 3-30. Pump Station, Abuta WTP, Ishinomaki City

Figure 3-31. Ground Deformation, Abuta WTP, Ishinomaki City

Figure 3-32. Settlement Next to Sedimentation Basin, Abuta WTP, Ishinomaki City

3.4 Chiba Prefecture

Chiba prefecture is located just east of Tokyo. The water system in this area includes about 9,000 km of water pipe, serving about 5,900,000 people.

Urayusa City is located on Tokyo Bay. Much of this area is built on reclaimed land. About 40% of the area liquefied (apparently including parts of Disneyland); ground motions in this area were recorded or estimated in the range of PGA = 0.10g to 0.17g or so. There was widespread water pipeline damage due to the liquefaction, and surface settlements of a few inches to a foot or more were typical in many areas.

Unlike some other water utilities in Japan, Chiba Prefecture water department had not instituted a widespread water pipeline replacement program since the 1995 Kobe earthquake. While they did suffer a number of pipe breaks, and a large effort to repair the breaks, there were zero fire ignitions requiring fire department response in their service area. It could thus be argued that the cost savings (avoiding costly pipe replacement) may have been more cost effective in Chiba Prefecture over the past 15+ years (1996 to 2011), but it remains uncertain whether the existing infrastructure will hold up well enough in a future earthquake that will produce higher levels of shaking in Chiba Prefecture.

Figure 3-33 shows an uplifted seismic storage tank in Urayusa. This tank had been installed to provide potable water after earthquakes. The area here liquefied, and it is apparent that the high pore pressures uplifted the tank. The tank could not be used for its intended purpose.

Figure 3-33. Urayusa City Uplifted Water Tank

Figure 3-34 shows an uplifted cistern located in Asahi City. Asahi city is located in northeastern Chiba Prefecture, about 100 km from Tokyo, and near the Pacific Ocean. This area has ground motions on the order of PGA = 0.20g or so. There were many areas in this region that suffered liquefaction.

Figure 3-34. Ashaki City Cistern (photo: Kuwata)

3.5 Ibaraki Prefecture

3.5.1 Wanagawa Water Treatment Plant

Figure 3-35 shows the Wanagawa Water Treatment Plant, Ibaraki Prefecture. Raw water from an intake on the nearby Wanagawa River comes into the plant at the northwest corner of the site. The site is built around a central lagoon area, towards which there were lateral spreads.

The raw water is then pumped to the industrial water treatment plant (north side of central lagoon area) or the domestic water treatment plant (south side of central lagoon area).

Figure 3-35. Wanagawa Water Treatment Plant

Figure 3-36 shows the domestic water treatment plant, looking to the northwest. The transmission towers are in the central lagoon area. The large scarp is caused by uplift of a buried concrete utility corridor, as well as ground settlements.

Figure 3-36. Wanagawa Water Treatment Plant, Uplifted Utility Corridor

The washwater tank is located at the top of a reinforced concrete building, on piles. The pipes leading into this building, to the tank, failed due to settlement of the ground; the pipe joints failed, Figure 3-37 and 3-38.

Figure 3-37. Wanagawa Water Treatment Plant, Failed Pipe

Figure 3-38. Failed Pipe, Wanagawa WTP

3.5.2 At Grade Storage Tanks

About 1 km from the Wanagawa WTP are two at-grade circular prestressed concrete tanks, Figure 3-39. This area is characterize as almost flat. Much of this area liquefied. Figure 3-40 shows the inlet-outlet pipe for this tank that has been excavated. One of the joints on this 300 mm DI pipe cracked.

Figure 3-39. Concrete Tank Site

Figure 3-40. Damaged 300 mm Pipe

Figure 3-41. Leakage at the Flexible Joint Next to the Tank (Not Flexible Enough)

Figure 3-42 shows a temporary pipe installed across a bridge over a creek. A combination of inundation, inundation-caused erosion and/or creek embankment movement laterally, breaking the original water pipe at this location, Figure 3-43.

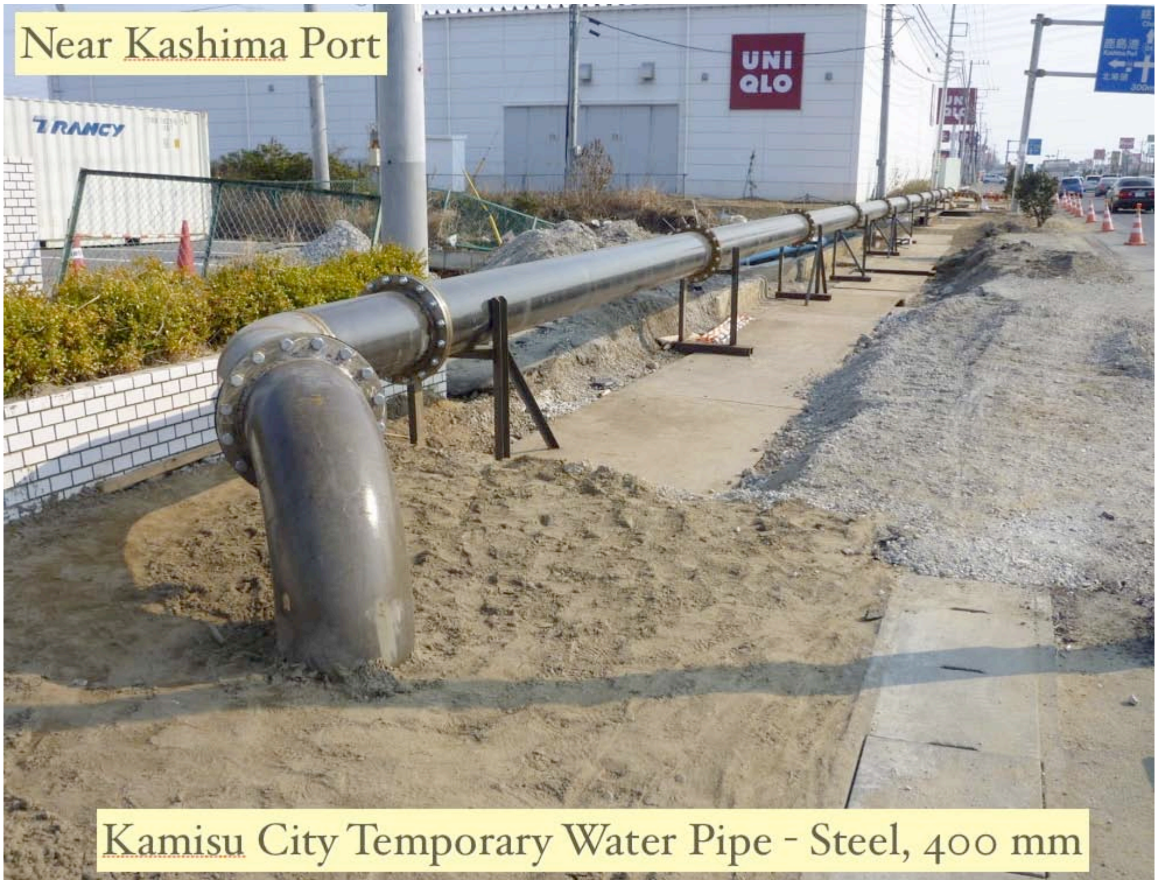

Figure 3-42. Temporary Pipe Installed Across a Creek

Figure 3-43. Failed Water Pipe, Kamisu City (Temporary Pipe seen on right)

3.6 Wastewater Treatment Plant with Tsunami Inundation

Figure 3-44 shows an aerial view of the WWTP. This plan is located about 5 km south of the Sendai airport. It was inundated by the tsunami.

Figure 3-44. WWTP

Figure 3-45 shows the intake pump station at the wastewater treatment plant, located about 400 m from the coastline. This reinforced concrete structure was inundated by the tsunami, to a height of about 1.5 meters above grade (see high water marks next to first floor windows). The structure includes basement levels with pumps and motors. It does not appear that there was any settlement of the building. At the ground level, the soil has dropped by about 2 to 3 feet, as evidences by the soil scar marks and drop at the staircases.

Figure 3-45. Pump Station – Erosion Impacts due to Tsunami

Figure 3-46 shows the three outlet pipes from this pump station to the rest of the plant. The middle pipe has been capped (a piece of the original flange is seen above the water line). The furthest pipe is partially seen; just outside of this photo to the right, workmen are repairing this pipe. Subsequent to the time this photo was taken, the near pipe was also discovered to be leaking. There was some discussion as to whether the damage was due to liquefaction or erosion; whichever the case, it is likely the soil covering these pipes dropped 1 to 2 feet; leading to high loads on the pipes, and thus damage. More likely than not, this was due to erosion, when the tsunami waters receded and scoured the soils around the corners of buildings. We observed many such sites with similar scour effects near the corners of buildings.

Figure 3-46. Three Large Diameter Pipes Damaged due to Tsunami-Caused Erosion

Figure 3-47 shows the effects of tsunami scour on a pipe rack next to digester tanks at the WWTP.

Figure 3-47. Damage to Pipe Racks Next to Digesters, due to Erosion

Another form of damage is due to the unbalanced loading due to wave loads. Two processes are involved: the difference in hydrostatic head (generally modest), and the impact forces of the water hitting the structure (pipe) at velocity. The impacted structure must be able to take both these forces, at capacity below yield, else it will be damaged. For design purposes, both the height of the wave and the velocity of the wave need to be known. The velocity of the water imparts a drag force on the structure as it goes around the structure; the shape of the structure will also affect the drag force. The design approach for these types of loads is similar to that used for seismic loading of pipes and internals within water tanks. As can be seen in Figure 3-48, the designers of this WWTP did not consider these loads.

Figure 3-48. Damage to Air Pipes due to Tsunami Velocity Effects

The concrete saddles under the pipe in Figure 3-49 were displaced by the tsunami.

Figure 3-49. Movement of Pipe Concrete Saddle Supports due to Tsunami Velocity Effects

3.7 Kanagawa Water Supply Authority

The Kanagawa Water Supply Authority (KWSA) is a wholesale water transmission operator, serving the communities of Yokohama City, Kawasaki City, Yokosuka City and Kanagawa prefecture. The average day supply was about 365 MGD in 2010. The KWSA service area is to the south and west of Tokyo; the area experienced ground shaking, but no tsunami.

Water leaks occurred on a 3.1 meter diameter raw water pipe (steel) near the Sakawa River, immediately after the earthquake. Repairs took until April 22 to complete (42 days). The section of pipe that had the leaks had been designed to include 47 bellows-type expansion joints, spaced at about 100 to 200 meter intervals. Each bellows was able to sustain about 6 inches of axial expansion / contraction.

Three water leaks occurred on this 4.7 km-long pipeline, over the course of 5 weeks after the earthquake. The leak rates were small: about 2 gpm to 40 gpm.

Evaluation of the causes of the leaks suggest that the expansion joints moved excessively, damaging the bellows-to-steel pipe welds. It appears that the movements on the joints were due to ground shaking effects only. KWSA observed that the joint movements may have been concentrated due to adjoining concrete thrust blocks on the pipeline (Oe, 2011).

The preliminary assessment suggests that it would be useful to design for ground shaking effects on axial slip-joint type assemblies, especially for larger diameter transmission mains. Newer design guidelines like ALA (2005) provide methods to estimate the slip joint movements due to ground shaking.

3.8 Response Issues

Table 3-3 lists the number of customers that lost potable water supply, by prefecture, as of March 13, 2011 (as of 6 pm local time, 2 days after the earthquake). This data was developed by JWWA in the weeks immediately after the earthquake. With this large number of people without piped potable water service, there was considerable effort to deliver drinking water to many people. Section 3.2 discusses some of these efforts in the City of Sendai. Below, we highlight some additional efforts at other locations; this was repeated at hundreds of other locations.

Prefecture	Number of Customers
Aomori	1,800
Iwate (North of Sendai City)	80,000
Miyagi (including Sendai City)	310,000
Fukushima (south of Sendai City)	190,000
Akita	1,700
Yamagata	6,000
Ibaraki (east of Chiba, south of Fukushima)	470,000
Tochigi	40,000
Gunma	2
Saitama	70
Chiba (east side of Tokyo Bay)	300,000
Niigata	140
Nagano	1,000
Gifu	30

Table 3-3. Customers without Potable Water Supply, as of March 13, 2011

Figure 3-50 shows portable showers that were set up in Urayusa.

Figure 3-50. Urayusa City Portable Showers (March 26, 2011) (photo: Kuwata)

Figure 3-51 shows a typical site for people obtaining water from emergency temporary supply points. This photo was taken in Iwaki City, Fukushima,

Figure 3-51. Emergency Water Supply Distribution Point, Iwaki City, Fukushima

Figure 3-52. Emergency Water Supply Distribution Point, Ishinomaki, Miyagi Prefecture

3.9 Fire Following Earthquake and Fire Following Tsunami

Over the entire area affected by the earthquake, about fire ignitions were reported, either from the main shock or the larger aftershocks. This count will be subject to change as updated data becomes available. Table 3-4 lists the fire ignitions as reported by the Japan Association for Fire Science and Engineering (315 ignitions total). Other sources suggest a total of 286 fire ignitions. Under "earthquake" fires, some may have been ignitions controlled by local residents (such as by using fire extinguishers).

Prefecture	Tsunami	Earthquake	Unknown	Total
Aomori	6	7	0	13
Iwate	27	13	3	43
Miyagi	81	45	9	135
Fukushima	4	19	0	23
Ibaraki	6	19	6	31
Akita	0	1	0	1
Gunma	0	2	0	2
2	0	10	6	16
Saitama	0	12	0	12
Tokyo	0	33	0	33
Kanagawa	0	6	0	6
Total	124	167	24	315

Table 3-4. Fire Ignitions (Ref. Japan Association for Fire Science and Engineering (2011)

Of these, only the fires due to tsunami lead to fire spread. There were three main types of tsunami-induced fires:

- Type 1. Propane tanks broken as houses floated and were smashed, followed by an ignition.
- Type 2. Floating oil tanks that leaked their contents, followed by an ignition.
- Type 3. Smashed automobiles (failed fuel tank / filler caps / battery), followed by an ignition.

Of the remaining ignitions (Fire Following Earthquake, FFE), about half occurred within a few hours after the main shock; the remaining at some time thereafter.

Even with the large number of fire ignitions, the ignition rate from Japan appears to be much lower than what has occurred in past earthquakes around the world. Figure 3-53 shows the combined fire ignition rate from the Japan 2011 (blue dots), New Zealand September 2010 and February 2011 (orange dots), and Chile 2010 earthquakes (green dots). The black squares represent the historical ignition rate from California earthquakes (1906 through 1989), through which an ignition model (as used in HAZUS) is drawn. If one were to include the data from these recent 2010-2011 earthquakes, the ignition model would be substantially lower (orange line).

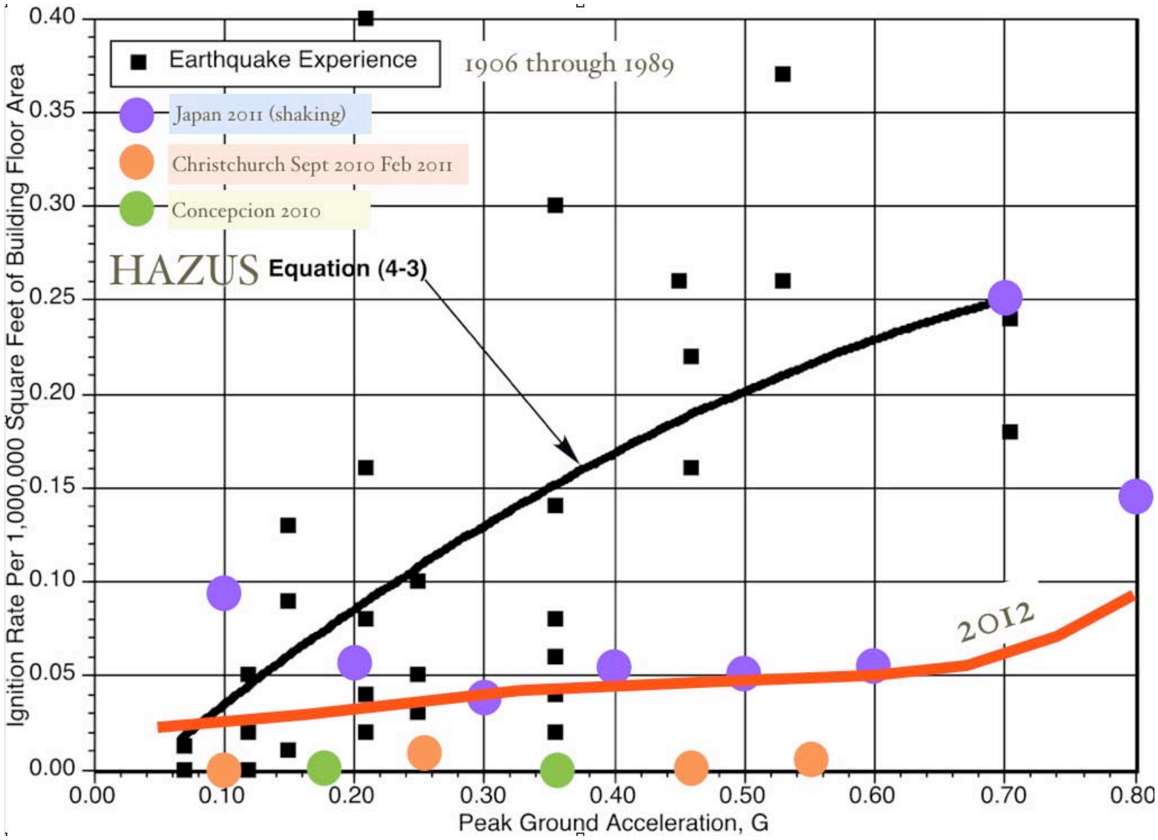

Figure 3-53. FFE Ignition Model (HAZUS, Japan 2011, Christchurch 2010-2011, Chile 2010)

The reasons for the lower ignition rate model (orange line) include the following:

- The black dots (HAZUS model) include fire ignitions due to chimney fires, many collapsed brick buildings, etc. The modern building stock largely excludes these hazards, and thus will have a lower ignition rate.
- Modern buildings used modern electrical wiring with presumably better insulation. Thus, there are fewer electrical-caused ignitions as the buildings sway.
- There were few ignitions in the 2010-2011 earthquakes of ruptured natural gas pipes. This is because, in part, the buried natural gas pipe networks in New Zealand and Japan used almost entirely seismic resistant pipes (few, if any, natural gas pipe breaks).
- In Concepcion Chile, much of the building stock is made from non-combustible materials (concrete), and thus an initial ignition might not have much fuel supply (wood). the only fire ignitions in Concepcion were arson caused.

There were two fires of note in refineries. One fire was in the Sendai refinery, Figure 3-54, and the cause was inundation. It appears that the tsunami waves broke an inlet-outlet pipe to a tank holding asphalt; the spilt contents were ignited, leading to the fire. The fire did not spread to the adjacent power plant or gas facilities. It is unknown if there was any fire fighting activities to control the fire.

Figure 3-54. Fire at Refinery, Port of Sendai

Figure 3-55 shows a fire at the tank yard at the Cosmos Refinery, Chiba Prefecture. The seismic cross bracing for one of the gas holder tanks was damaged by the main shock of the M 9.0 earthquake; 30 minutes later, a M 7.2 aftershock collapsed the tank, leading to the ignition. Figure 3-56 shows the collapsed tank after the fire; power outages after the M 9.0 earthquake had prevented closure of isolation valves.

Figure 3-55. Fire at Refinery, Chiba

Figure 3-56. Collapsed tank, after fire

The two largest water systems in the strongly-shaken areas were operated by the City of Sendai and the Chiba Prefecture public works department. Both water companies reported that there were no large fires in their service areas.

Figure 3-57 shows the fire scars on a cargo building at the Sendai Airport. According to staff at the airport, the tsunami carried a burning car to this building; the fire scars are due to the burning car, and not to an ignition within the building.

Figure 3-57. Fire at Sendai Airport

Figure 3-58 shows a fire atop an office building near the port of Tokyo. It was reported that this fire was caused by toppling of welding equipment that was being used to make repairs atop the building.

Figure 3-58. Tokyo Office Building Fire

3.10 Seismic Pipeline Design Measures

To understand the performance of water systems in this earthquake, the US reader needs to appreciate that there is an ongoing *huge* effort to replace older water pipes with new, seismic-designed water pipes in many cities in Japan. The effort involved is very large, with capital costs commonly approaching or exceeding $1 Billion (US) for cities of 1,000,000 people or more. Today (2011), about 78% of all new ductile iron water pipe installed in Japan uses "chained" seismic joints; a lot of smaller diameter (2" to 4" diameter) distribution water pipe is being installed using HDPE pipe with "clamped" electro-fused joints.

From about 1990 to 1995, about 2% of all pipe installed in Japan used seismic design. After the 1995 Kobe earthquake, the adoption take-up of these kinds of pipe increased. Take up has been a slow and evolving process, and today (2011) it is estimated that more than 75% of all new water system pipe installed in Japan includes seismic design. In comparison, in the USA, we estimate that less than 1% of all water distribution pipe installed in California, Oregon and Washington (some of the higher seismic zones in the USA) use seismically-designed pipe; since 1992, a few California utilities have installed seismically-designed water transmission pipes as part of earthquake countermeasures.

None of these two types of pipes are known to have had any failures due to the effects of ground shaking, liquefaction of landslide in this earthquake.

Figure 3-60 shows the chained joint used for 6" to 12" diameter (150 mm to 300 mm) ductile iron pipe. the seismic design principles involved are as follows:

- Assume the pipe will be exposed to ground deformations due to liquefaction.
- Observed ground strains over wide distances from past earthquakes has been commonly on the order of 1% or less.
- Assume each new pipe segment installed is about 16 feet long (5m). At each joint, the spigot (male) end can slip into or out of the bell (female end) by about 2 inches, or about 1% of the length of the pipe segment.
- Should the pipe be pushed in by more than 1%, then the spigot end hits the main barrel, and then transfers the thrust force to the next joint along the pipe, and thus activating its slip capability.
- Should the pipe be pulled out by more than 1%, then the spigot projection hits the protruding lock ring; the lock ring is designed to be able to take a pull force of about 100 kips (450 kN) (6" pipe) to 200 kips (900 kN) (12" pipe), before it pops out. If the pull forces are less than these values, the lock ring transfers the tension force to the next joint along the pipe, and thus activating its slip capability.
- Each joint is also able to rotate without load for about 6° to 8°, depending o pipe diameter.
- The outer coating of the pipe barrel is an epoxy system, meant to be installed in a sand-type trench. Thus, the axial slip force that would typically be placed on the pipe by the sand trench, if the pipe wants to move axially, is limited to perhaps 2 kips per foot of pipe (12" pipe); possibly a lot less. Assuming 2 kips per foot, then the spigot system can transfer enough load to about 8 adjacent pipe joints, allowing up to about 8 x 2 inches = 16 inches of pipe movement. This is more than enough to accommodate most liquefaction zone issues.

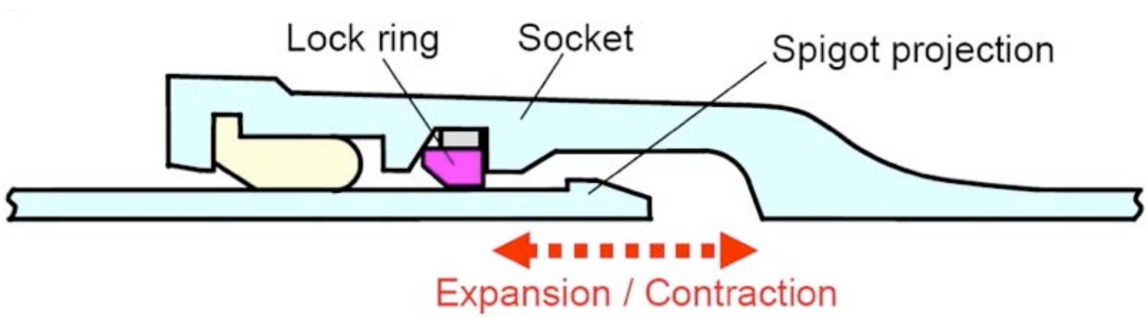

Figure 3-60. Chained Joint for Medium Diameter Ductile Iron Pipe

As of 2011, the manufacturer of this type of pipe joint (Kubota), believes that the extra cost of the joinery can be offset by the simplicity of installation; coupled with a relatively narrow trench (as there are no external bolts to be torqued). Thus, the net capital cost for installation of pipe + labor for this type of joint might be about the same as for a conventional mechanical-joint system sometimes used in Japan or the USA. If one also includes the net present value of avoided damage and economic impacts of water outages due to earthquake damage, the total efficacy of this type of joint is readily apparent.

For larger diameter pipes (24" to 60"+), the "chained" joint can be created using a similar concept, but relying on external bolted followers, as seen in the pipe cut-away in Figure 3-61.

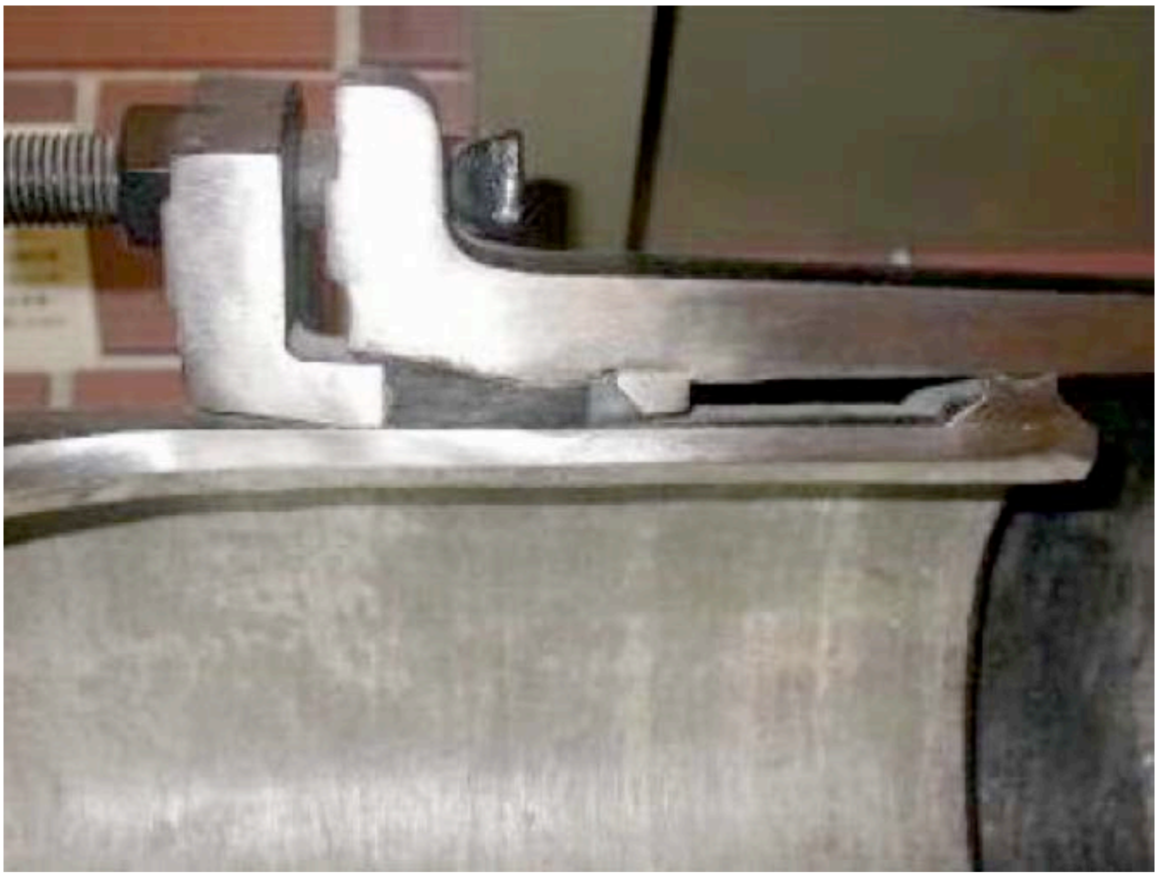

Figure 3-61. Chained Joint for Large Diameter Ductile Iron Pipe

3.11 Major Observations and Recommendations

The issue of large scale pipe replacement is an ongoing topic in Japan and the United States. In the United States, it is often felt that pipe replacement for seismic reasons along is not cost effective, except for the most critical pipelines and in areas with high chance of liquefaction. In Japan, a similar concept has been adopted over the past 15 years, except the rate of such pipeline replacement is sometimes as much as 10 times that of the USA. In both countries the primary motivating force for water pipeline replacement is aging infrastructure, to address corrosion, leakage, etc. By combining both reasons (seismic plus aging), a cost effective pipeline replacement program can be developed for any locality.

Even while some Japanese water utilities are undertaking widespread pipe replacement, some of the larger water utilities in the major population areas affected by this earthquake (like Chiba) have not done widespread pipeline replacements.

Large diameter transmission pipes in Miyagi failed at many places due to lack of seismic detailing, and this contributed to multi-week water outages in cities without redundant supply.

Liquefaction caused substantial damage at one water treatment plant, as well as some smaller ones. Seismic countermeasures to avoid such damage, such as pipe with very flexible joints at the interface of pile-supported structures to ground, or ground improvement strategies, were not observed at this plant.

Liquefaction caused uplift of buried water tanks. In one case, a tank floated (and failed) even though it had been designed post-1995 Kobe earthquake for emergency water supply.

There are no known (yet) instances when water from any cisterns was used to control any fires.

Road-fill slumps failed many pipes in the hilly areas where exposed to ground shaking of PGA = 0.2g to 0.3g or so.

Erosion and several feet of scour at selected tsunami inundation zones uncovered, undermined and broke several larger diameter (36" and larger) buried pipes.

For new pipeline installations, we would recommend seismic design of buried water pipes per ALA (2005) or equivalent Japanese JWWA guidelines, using either HDPE, DIP-ER or welded steel pipes in areas prone to liquefaction.

3.12 Acknowledgements

The observations in this report reflect the findings by John Eidinger and Craig Davis during four field trips after the earthquake: June 2011; July 2011, September 2011, March 2012.

Much of this information was gathered with the assistance of the following water departments: City of Sendai; Miyagi Prefecture; Chiba Prefecture. Professor Yasuko Kuwata of Kobe University provided invaluable assistance, including spending many days in the field between March 13 and June 17 2011.

4.0 Performance of Power Systems

Section 4 describes the performance of the electric systems that were affected by the earthquake and tsunami. Two electric companies provide power in the affected areas: Tohoku Electric Power Company (Tohoku EPCO) and Tokyo Electric Power Company (TEPCo).

As seen in Figure 4-1, TEPCo is the largest power company in Japan, while Tohoku electric is still quite large. For comparison, the summer time power demand in California is about 45 GW.

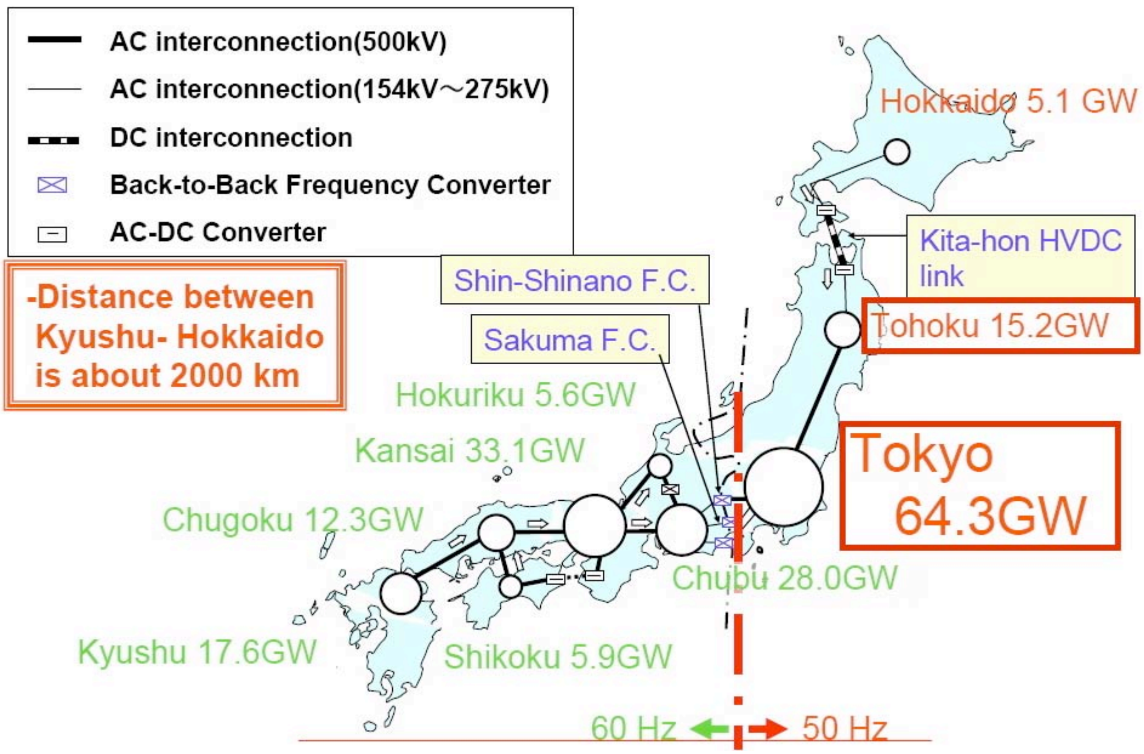

Figure 4.1 System Description (Peak summer time demand)

4.1 Seismic Qualification of Equipment

Prior to the 2011 earthquake, Tohoku EPCO had taken some seismic countermeasures. For high voltage substation equipment, Japan has adopted a shake table test type of qualification method, highlighted by shaking the equipment for three cycles at PGA = 0.3g, with the input frequency set to that of the equipment, Figure 4-2.

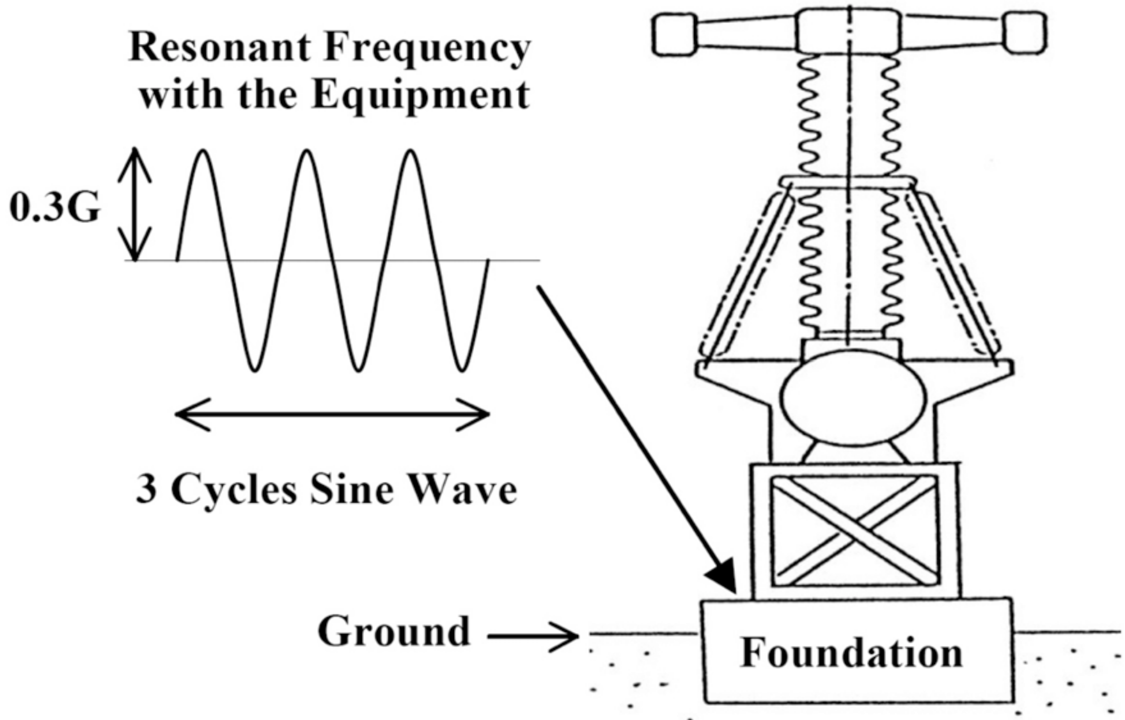

Figure 4-2. Japanese Approach to Seismic Equipment Qualification at Substations

This test procedure is different than that adopted in the USA, via IEEE 693, Figure 4-3. On June 21, 2012, a meeting was held with knowledgeable engineering representatives from PG&E, SCE, SDG&E (3 largest investor-owned electric utilities in California) and BPA (high voltage transmission system operator for Oregon and Washington), as well as leading industry consulting engineers (10 total). The question was posed to all, as to "has the IEEE 693 seismic qualification procedure been effective in reducing damage to high voltage substation equipment?". By voice vote, it was unanimous that the IEEE 693 procedures have been very effective. Even so, as of mid-2012, the qualification procedures in IEEE 693 are ongoing updates and modifications, with the intent to improve the qualification procedures, in the following areas: variation of damping values at different shaking (response) levels; adding "fragility" testing (test to destruction) after the "qualification" test; and other considerations. Members of the ASCE reconnaissance queried as to whether the existing Japanese standard (three sine waves) should be updated. Clearly, in both Japan and the USA, the seismic qualification procedures will likely change over time, factoring in the lessons learned from past earthquakes. Changes to be considered over time will include the specification of the proscribed input motions; the methods to test equipment components (such as transformer bushings) that cannot be cost effectively shake table tested; and the establishment of seismic margins, to consider the variation in capacity of individual test specimens (true strengths between individual porcelain components and porcelain-attachment fittings appear to have a high range of variability), etc. The long term intent of such efforts is to have substation equipment installed such that under large earthquakes, the total damage is kept to a manageable minimum, to avoid long term power outages; to the extent that such damage is repairable within about a day after a major earthquake (excluding must-run power situations), seems to be a reasonable goal of the seismic qualification process, for society as a whole.

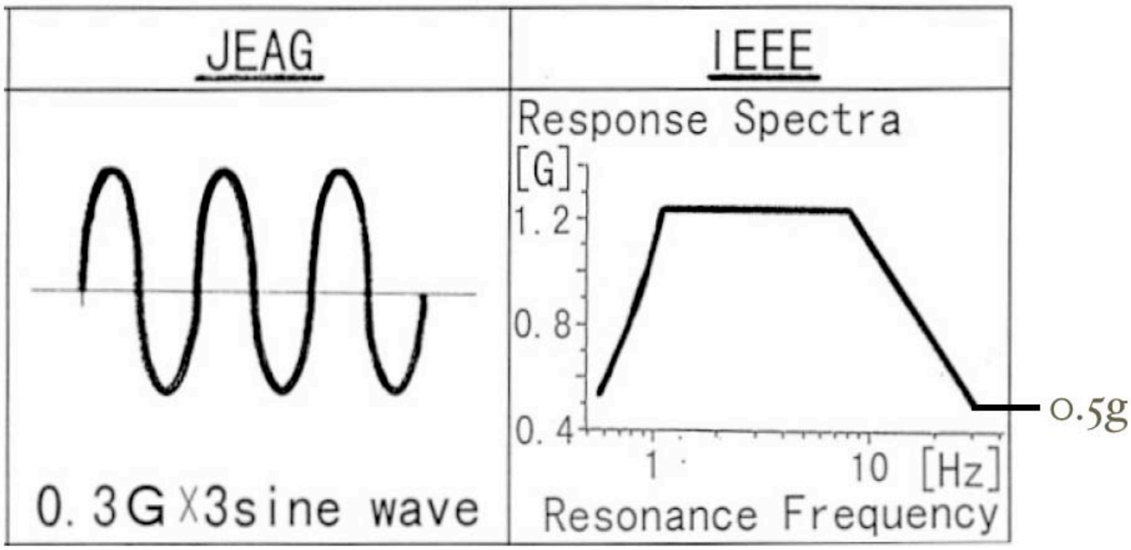

Figure 4-3. Comparison of Japanese and USA Approach to Seismic Qualification

Prior to the 2011 earthquake, Tohoku EPCO had been doing substation seismic qualification and seismic upgrades. For example:

- Add cross bracing to 275 kV disconnect switches. The intent of this cross bracing is to stiffen the underlying support structure, with the hope that this will reduce the net seismic loads on the switches above, as well as reduce the top-level drifts, and hence the slack requirements, between adjacent pieces of equipment on the bus.

- Add split rings around the lower circumference of transformer bushings, so as to limit the potential for bushing slip and oil leakage.

- Replace old porcelain-style lightning arrestors with new seismically-qualified composite polymer-type lightning arrestors.

- At the Onegawa nuclear power plant, Tohoku EPCO had installed nearly 6,600 pipe supports in the three years prior to the 2011 earthquake.

Working with Dr Shumuta of CRIEPI, Tohoku EPCO had a working software program that could rapidly forecast the amount of damage to low voltage distribution power poles, given recorded or simulated ground motions. This model had been developed and calibrated using damage to utility poles in past earthquakes, including Kobe (1995) and Niigata (2007). Further research in this area will lead to continual improvement to such tools, and hopefully can lead to cost-effective mitigation strategies.

4.2 Performance of Tohoku Electric Power

Tohoku EPCO is the electric utility serving the northern most part of Honshu. The service area includes the Tohoku region (7 prefectures), plus Niigata Prefecture (see Figure 1-2).

Tohoku EPCO is a rather large electric power company, with about 12,500 employees, serving 6,783,000 residential customers and an additional 905,000 commercial and industrial customers (1 customer = 1 billing account). Annual revenue was about $8.8 Billion ($1 US = 80 Yen) in 2010. Power sales in fiscal year 2009 (ending March 2010, last full year before the earthquake) were 79 billion kWh in 2010, of which 54 Billion was to residential customers, and 25 billion to commercial/industrial customers (average 11 cents per kWh). Tohoku generating plants provided: nuclear 20.4 billion kWh; thermal (coal, gas, oil) 44.6 billion kWh; hydroelectric 7.6 billion kWh; and geothermal 1.0 billion kWh; 13.3 billion kWh from net imports.

Tohoku EPCO's system includes most of the local area's power generation, high voltage transmission and low voltage distribution. Tohoku EPCO also purchases power from a few local independent power producers, and the earthquake effects to those IPPs will be addressed in this section.

Table 4-1 lists the power generation for Tohoku EPCO. In total, Tohoku EPCO owned 16,550 MW of generation. As indicated in Figure 4.1, Tohoku EPCO's system operates at 50 Hz, same as TEPCo. Through the 275 kV AC high voltage transmission network, Tohoku EPCO can share power with TEPCo. Power imports from western Japan to Tohoku EPCO must go through one of three flow control substations, to covert 60 Hz to 50 Hz, and then through TEPCo's transmission network. Plans to further interconnect the 500 kV AC networks between Tohoku EPCO and TEPCo network had not yet been constructed at the time of the 2011 earthquake.

Type	Number (year of operation)	MW
Hydro	210 power stations	2,420
Thermal (gas, coal, oil)	17 power stations	10,580
Nuclear	Onegawa 1 (1984) Onegawa 2 (1995) Onegawa 3 (2002) Higashidori 1 (2005)	524 825 825 1,100
Total		16,550

Table 4-1. Tohoku Electric Power – Generation Facilities

Table 4-2 lists the transmission and distribution system facilities in the Tohoku EPCO system.

Type	Number
Transmission Lines (154 kV, 275 kV, 500 kV)	14,809 km
Substations	612
Distribution Lines	574,205 km

Table 4-2. Tohoku Electric Power – Transmission and Distribution Facilities

Figure 4-4 show a map of the Tohoku EPCO service area, with major generation and transmission components.

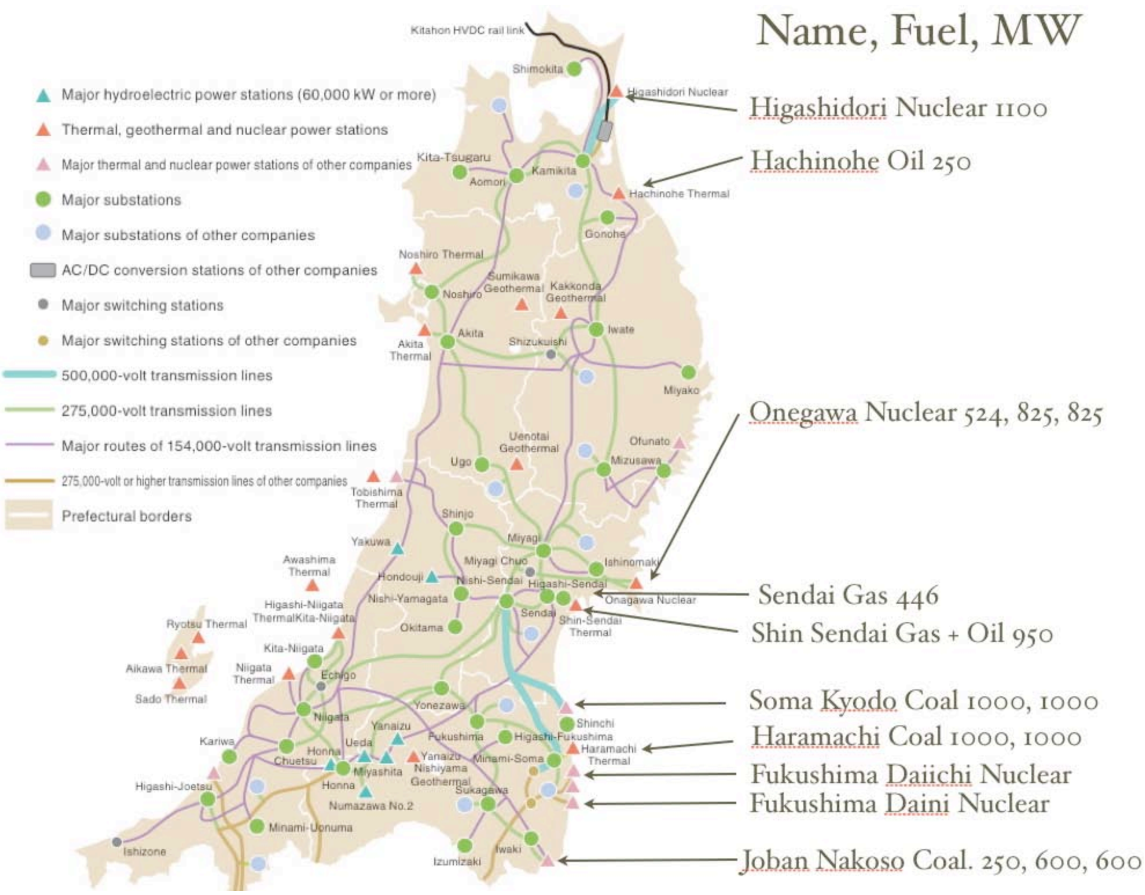

Figure 4-4. Power Plants and Major Facilities in Tohoku Service Area

Table 4-3 highlights the damage and restoration times for several significantly damaged power plants along the Pacific coast. The total lost generation capacity due to damage (Tohoku EPCO, TEPCo and others) is 18,232 MW, of which about 8,270 MW normally serve the Tohoku EPCO service area. Given that peak summer time demand can reach 15 GW in the Tohoku service area (see Figure 4-1), the loss of about 8 GW of generation leads to long term issues with respect to providing sufficient electric power to support the entire economy of the region.

Power Station	Owner	Fuel	MW	Restoration
Shin Sendai	Tohoku EPCO	Gas, Oil	350, 600	Not in service, March 2012
Sendai	Tohoku EPCO	Gas	446	February 2012
Haramachi	Tohoku EPCO	Coal	2,000	est. June 2013
Hachinohe	Tohoku EPCO	Oil	250	June 2011
Sinchi	Soma Kyodo	Coal	2,000	Restored 50% December 2011. Est. 100% Summer 2012
Nakoso	Joban	Coal	250, 600, 600	250: Not in service, 2012 600, 600: July 2011
Hitachi-Naka	TEPCo	Coal	1,000	May 15 2011
Hirono	TEPCo	Coal	600	July 2011
Kashima	TEPCo		600, 600, 1,000, 1,000	
Ohi	TEPCo		350	
Kanagawa Unit 1	TEPCo		1,000	
Onegawa Unit 1	Tohoku EPCO	Nuclear	524	Not in service, June 2012
Onegawa Unit 2	Tohoku EPCO	Nuclear	825	Not in service, June 2012
Onegawa Unit 3	Tohoku EPCO	Nuclear	825	Turbine damaged. Not in service, June 2012
Fukushima 1 Unit 1	TEPCo	Nuclear	460	Never
Fukushima 1 Unit 2	TEPCo	Nuclear	784	Never
Fukushima 1 Unit 3	TEPCo	Nuclear	784	Never
Fukushima 1 Unit 4	TEPCo	Nuclear	784	Never
		Total	18,232	

Table 4-3. Significantly Damaged Large Power Plant and Restoration Times

Compounding the damaged power plants are the loss of generation capacity for the country to non-damaged nuclear power plants. Table 4-4 lists the non-damaged (or slightly to moderately damaged) shut-down nuclear power plants along the Pacific coast in the area of the March 11 earthquake. These total an additional 8,484 MW of lost generating capacity.

Power Station	Owner	Fuel	MW	Notes
Higashidori Unit 1	Tohoku EPCO	Nuclear	1,100	Kept in service after earthquake, now shutdown
Fukushima 1 Unit 5	TEPCo	Nuclear	784	
Fukushima 1 Unit 6	TEPCo	Nuclear	1,100	
Fukushima 2 Unit 1	TEPCo	Nuclear	1,100	
Fukushima 2 Unit 2	TEPCo	Nuclear	1,100	
Fukushima 2 Unit 3	TEPCo	Nuclear	1,100	
Fukushima 2 Unit 4	TEPCo	Nuclear	1,100	
Tokai Unit 2	Japan Atomic Power Co	Nuclear	1,100	Cooling pump damaged
		Total	8,484	

Table 4-4. Non (or Moderately) Damaged Large Power Plant Along the Pacific Coast in the Earthquake Region

A survey questionnaire was sent out to various power plant owners (including Tohoku EPCO, TEPCo and others) as to the style of damage and emergency response at various power plants (re. Prof. Shiratori, Yokohama National University, JSME Survey between May 2011 to July 2011). The questionnaire was sent to 233 facilities, of which 118 reported damage and 115 reported no damage. Tables 4-5 and 4-6 summarize the findings.

Item	Damage due to EQ Vibration	Damage due to EQ PGDs	Damage due to Tsunami	Damage due to Tsunami + Earthquake	Damage Mitigated
Foundations / Walls	66	23	1	4	10
Large machinery	52	8	2	2	11
Tanks	5	9	1	1	4
Boilers – Cooling – HVAC	24	8	3	2	4
Pumps	13	4	3	2	2
Pipe	54	14	0	2	8
Generation, transmission, distribution equipment	20	7	1	1	6

Emergency power	1	2	0	2	2
Crane	23	3	2	0	3
Elevators	17	3	2	1	2
Transportation – train related	4	3	3	1	1
FRP Tank	14	4	1	1	0
Medical equipment	2	1	0	0	0
Base isolation – vibration control	3	0	0	0	2
Other machinery	23	4	1	3	6
Production network	23	5	6	13	4

Table 4-5. Power Plant Survey Results – Types of Damage

Emergency Response Manual	Yes: 88	No: 25	Partial: 1		
Usefulness of Emergency Response Manual	Useful: 31	So so: 47	Useless: 10		
Most helpful method to contact the head office from the facility	Phone: 61	email: 50	direct visit: 16		
Number of days to grasp reality of the damage	< 1 day: 30	5 days: 50	10 days: 11	10-30 days: 13	30-50 days: 3
Inconvenience at work	With problem: 38	So so: 74	without problem: 49		

Table 4-6. Power Plant Survey Results – Emergency Response

Damage to Tohoku EPCO-owned facilities is summarized in Table 4-7.

Facility	Main Shock 3/11/2011	After shock 4/7/2011	After shocks of 4/11, 4/12/2012	Kobe 1995
Thermal power plants (Table 4.6)	4	0	0	10
Hydro power plants	10	2	7	0
154 kV – 500 kV transformers	70 (43 shaking, 23 tsunami)	15 (shaking)	1 (shaking)	52
154 kV – 500 kV circuit breakers	197	15	1	10

154 kV – 500 kV air switches, others	179	0	2	41
Transmission steel lattice towers	42	0	0	20
Transmission – lines / insulators	22	5	5	339
Transmission – underground cables	14	0	0	405
Distribution poles	23,744	7,831	572	11,289
Distribution lines	23,550	13,711	1,085	7,760
Distribution transformers, switches	7,112	2,288	121	5,346

Table 4-7. Damage to Tohoku EPCO Facilities

Figure 4-5 shows the power outages in the Tohoku EPCO system.

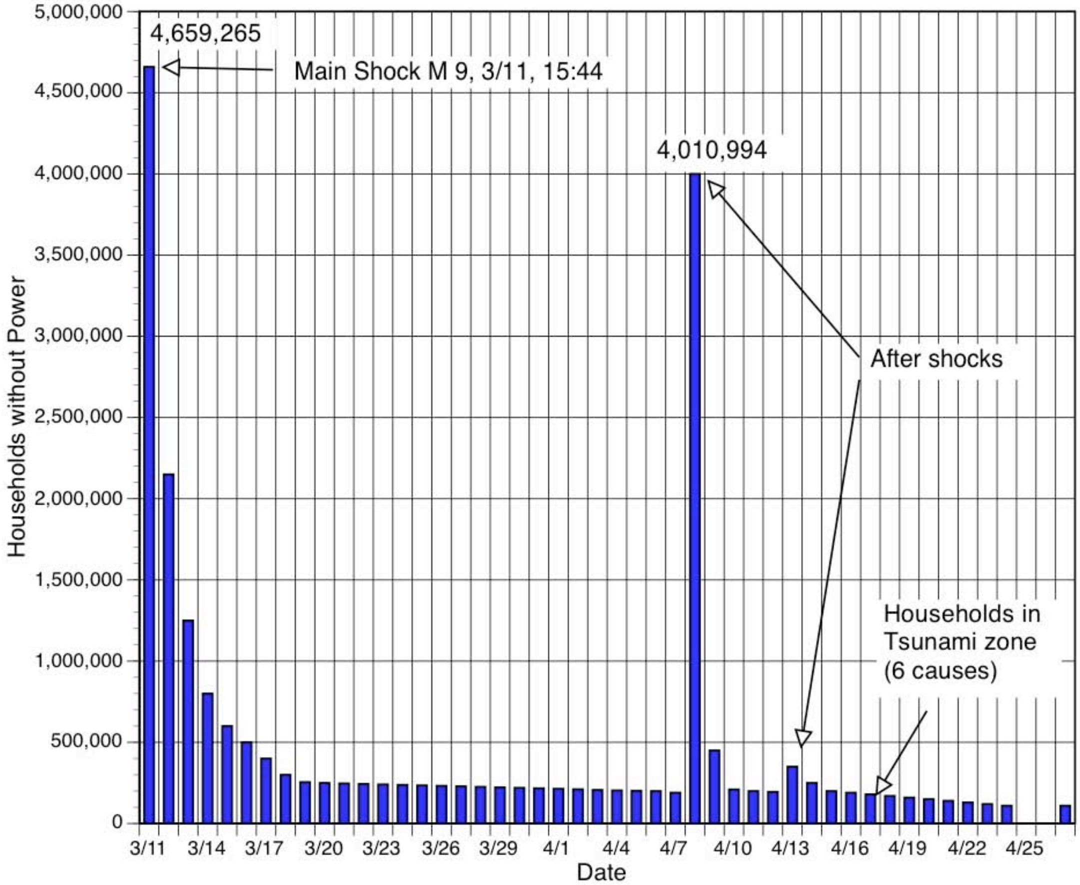

Figure 4-5 Power Outages - Tohoku EPCO

Figure 4-6 shows maps with the outage areas denoted as shaded areas. As can be seen, most of the Tohoku region was black within a few minutes of the earthquake on March 11; outages on the west coast (Japan Sea) are largely due to system imbalances and initial tripping of transformers. By March 14, the west coast areas are re-energized, and the remaining outage areas are along the Pacific coast (due to tsunami effects) and in and around Sendai (due to damage at high voltage substations). By March 19, outage areas are mostly confined to the tsunami inundated zones.

We observe that although Tohoku EPCO suffered damage and long term shutdown (at least 1 month or more) of essentially all of its coastal generation plants (coal, oil, gas and nuclear), this huge loss of generation capacity did not lead to long term power outages. However, even as of June 2012, the long term loss of several generation power plants (coal, oil, gas and nuclear) is requiring that Tohoku EPCO tell its customers that there will likely be brownouts (selective outages) during the peak power demand times during the summer of 2012 (a similar issue for summer 2011 also occurred).

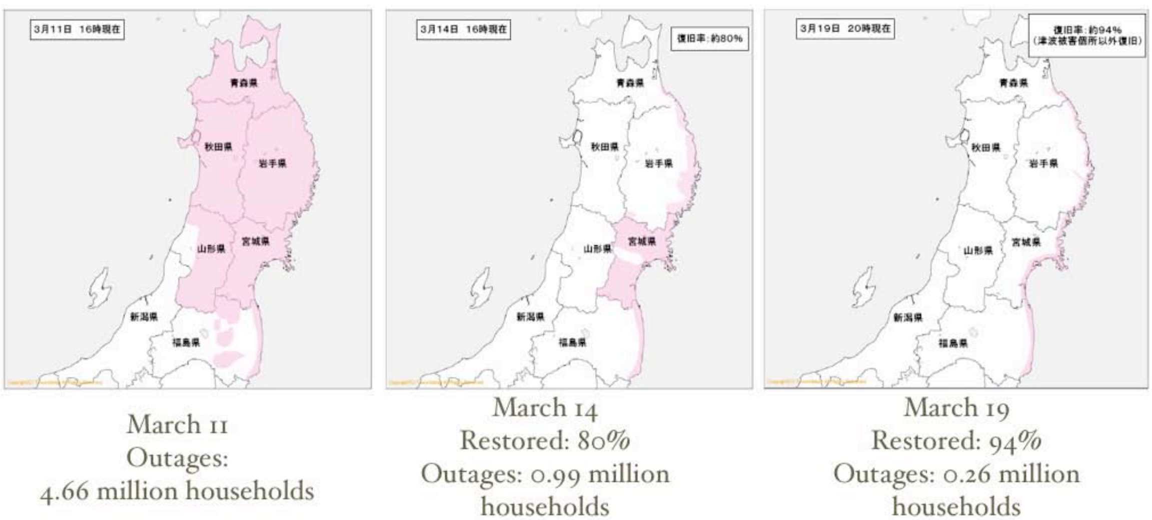

Figure 4-6. Power Outage Maps - Tohoku EPCO

Figure 4-7 shows the power outages in the Tohoku EPCO service area by Prefecture (no outages in Niigata Prefecture).

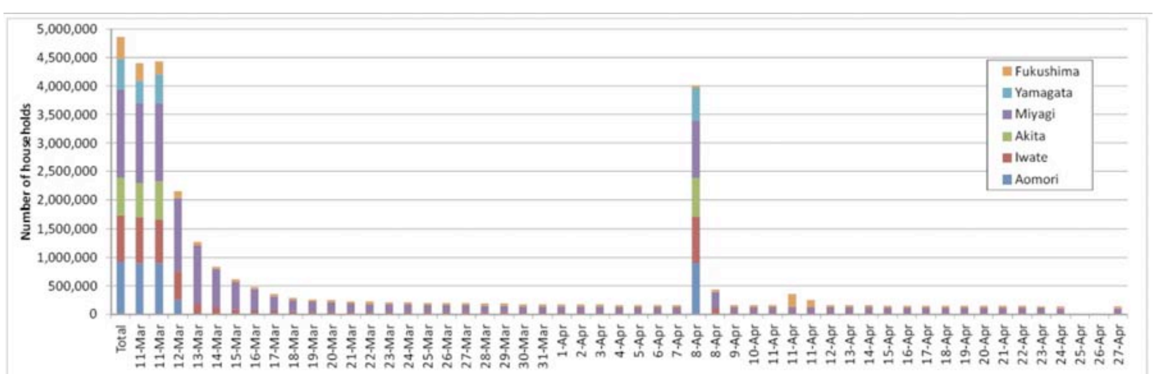

Figure 4-7. Power Outages - Tohoku EPCO – By Prefecture (after Nojima, 2012)

Figure 4-8 shows the breakdown of the main reasons for the long term power outages in the Tohoku EPCO service area:

(1): houses / infrastructure washed away by tsunami (~ 50%)

(2): areas blocked by tsunami debris (~ 40%)

(3): substations inundated / damaged by tsunami (~ 5%)

(4): absence of users (~ 3%)

(5): ready for power to be restored, but not yet (< 1%)

(6): No entry zone around Fukushima Daiichi nuclear power plant (< 2%)

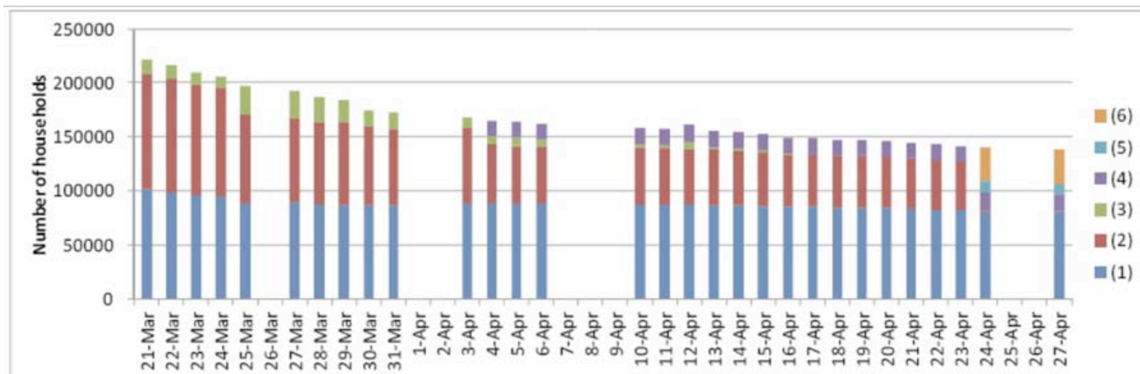

Figure 4-8. long Term Power Outages - Tohoku EPCO (after Nojima, 2012)

If one defines a restoration ratio as the number of households (billing accounts) with power, divided by the pre-earthquake number of households (billing accounts), then the power restoration values are as listed in Table 4-8.

Electric Company	TEPCo	Tohoku EPCO	Kansai Electric
Service Area	Chiba, Ibaraki, Tokyo	Miyagi, Iwate	Kobe
Event	March 11 2011 M 9.0	March 11 2011 M 9.0	January 17 1995 M 6.9
90%	4 days	6 days	2 days
95%	7 days	10 days	3 days
100%			7 days

Table 4-8. Power Restoration Ratios – Tohoku EPCO

For TEPCo, the power outages peaked at 4.05 million households. Restoration for TEPCo, by Prefecture, is listed in Table 4-9.

Prefecture	100% Restoration
Tokyo	March 12
Kanagawa	March 12
Gunma	March 12
Yamanashi	March 12
Shizuoka	March 12
Saitama	March 13
Tochigi	March 14
Chiba	March 14
Ibaraki	March 19

Table 4-9 Power Restoration – TEPCo

4.2.1 Hydroelectric Power Plants

Figure 4-9 shows damage to the penstock and forebay at one of Tohoku EPCO's hydroelectric power plants (Kushma, southwest of Sendai). The failure mode appears to have been initiated by a landslide, undermining the top concrete support, followed by erosion from the failed forebay.

Figure 4-9 Damaged Penstock and Forebay – Tohoku EPCo

Figure 4-10 shows damage to about 30 meters of a headrace (water channel) at a hydroelectric facility.

Figure 4-10. Damaged Headrace – Tohoku EPCo

4.2.2 Thermal (Non Nuclear) Power Plants

Table 4-10 summarizes the main damage at the four heavy damaged thermal power plants in the Tohoku EPCO system.

Power Station	Type	Damage
Shin Sendai	950 MW Oil, LNG	First floor flooded, damaged boiler, turbine and main station buildings. Substation yards flooded. Part of the site settled / had scour.
Sendai	446 MW LNG	First floor flooded, damaged switchgear and motors. Turbine damaged by shaking. Substation yard facilities flooded.
Haramachi	2,000 MW Coal	Third floor of main station building flooded. Four coal unloaders and heavy oil storage tank collapsed. All transformers flooded. Building broken by tsunami.
Hachinohe	250 MW Oil	First floor of turbine building flooded. A part of circulating water pump flooded. Base of heavy oil unloading facility sank by liquefaction.

Table 4-13. Tohoku Electric Power – Damage to Thermal Generation Facilities

4.2.2.1 Shin Sendai Power Station

Figure 4-11 shows an aerial view of the Shin Sendai power station. the blue arrows show the general direction of the tsunami inundation. The yellow arrow indicates the ground level view in Figure 4-12.

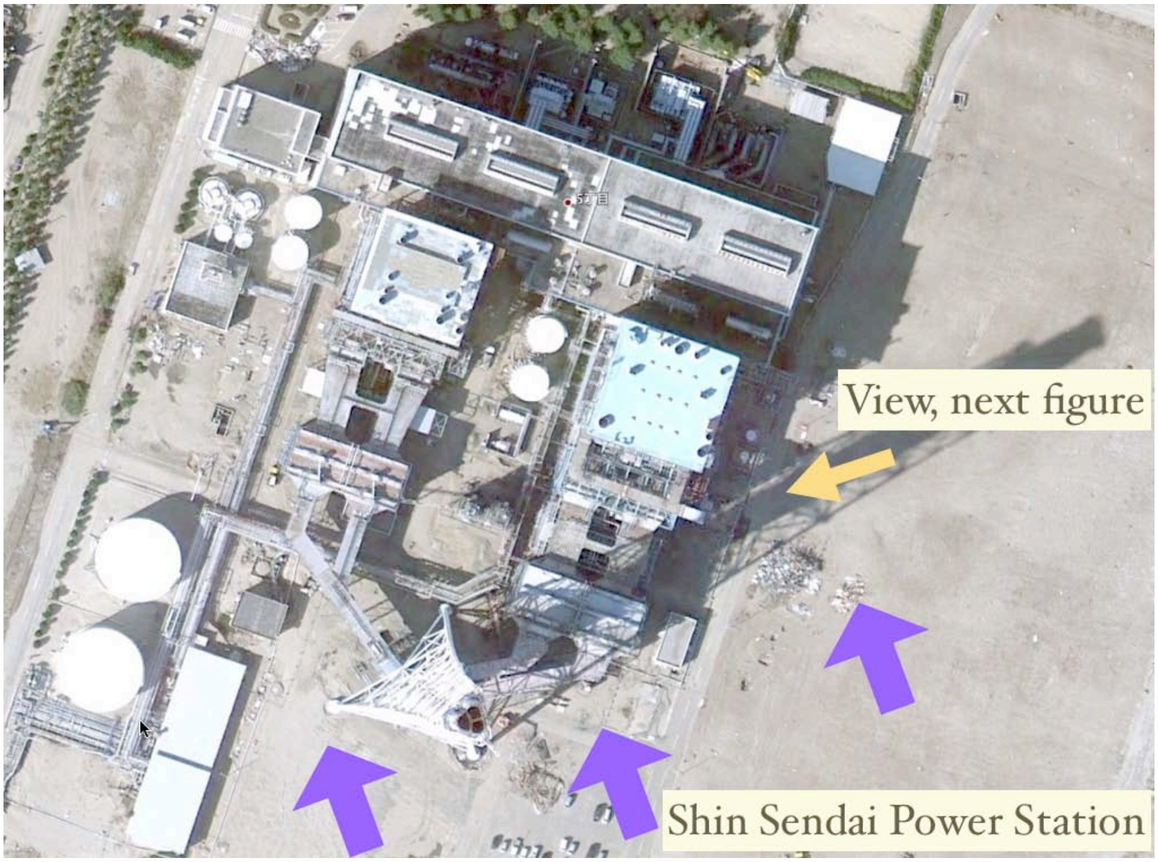

Figure 4-11. Shin Sendai Power Station – Tohoku EPCo

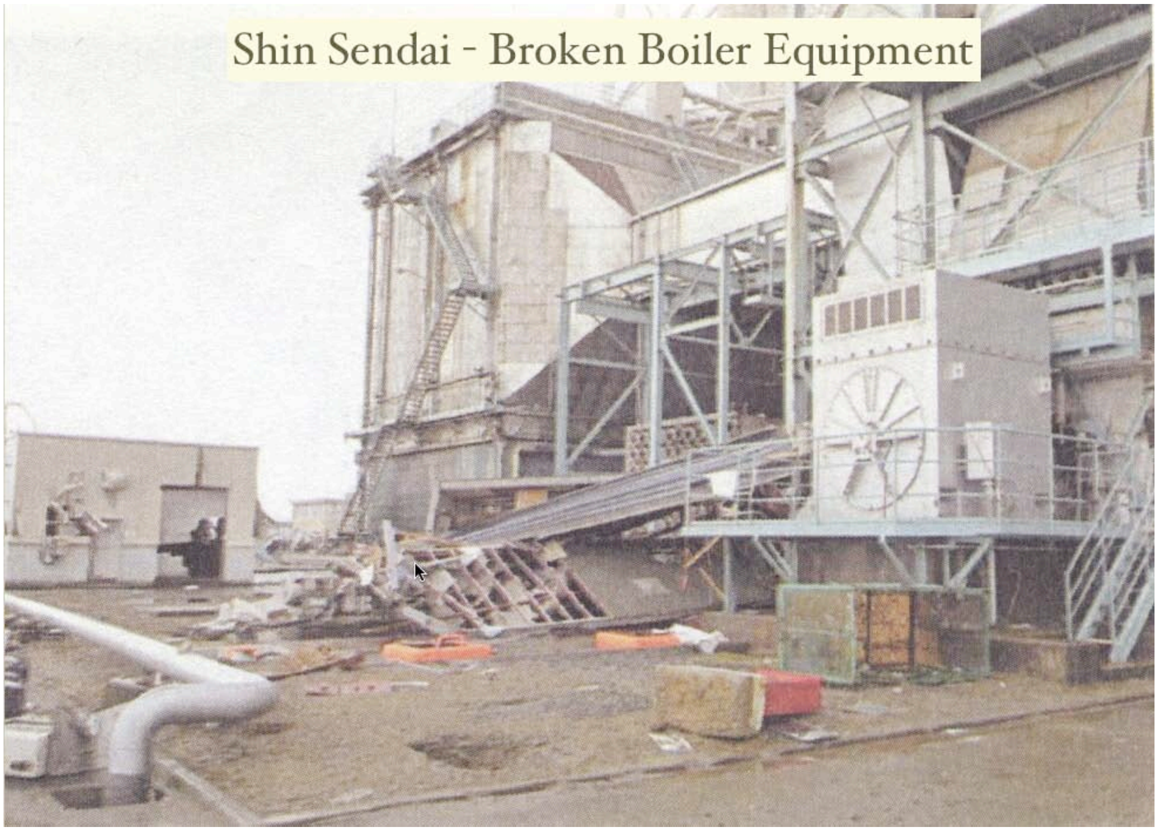

Figure 4-12. Shin Sendai Power Station – Tohoku EPCo

Figure 4-13 shows the direction of the high velocity tsunami impact on one of the maintenance buildings at the Shin Sendai power plant. Figure 4-14 shows the damage to the wall of that building due to the tsunami impact. Note the large soil erosion around the corners of the building, caused by the tsunami.

Figure 4-13. Shin Sendai Power Station (see Fig 4.22 for view of building)

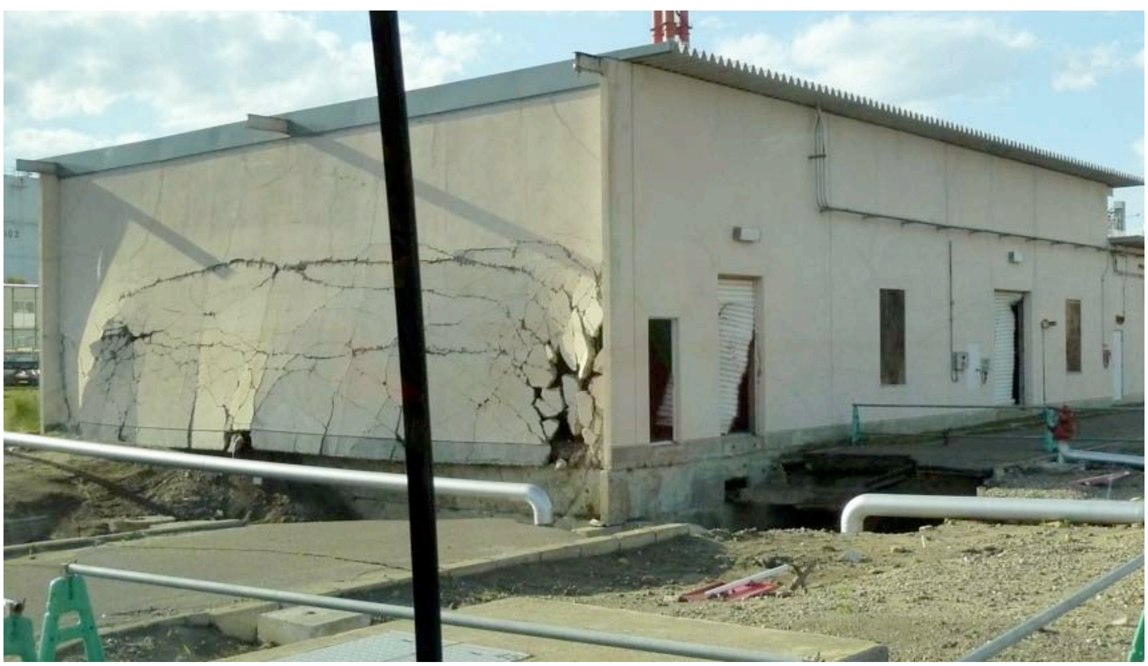

Figure 4-14. Shin Sendai Power Station – Tohoku EPCo

Figure 4-15 shows the building that surrounds the transformers at the Shin Sendai substation. Note the damaged metal wall cladding, that led to inundation of the transformers for this power station.

Figure 4-15. Shin Sendai Power Station – Inundated Transformer Building

Figure 4-16 shows one of two identical 5,000,000 liter (1.32 MG) steel tanks at the Shin Sendai power plant site (two tanks in lower left of Figure 4-11, see also Figure 2-14). Each tank has the following characteristics: at-grade, unanchored; 1.32 million gallon capacity; 76 feet diameter; 40 feet high, 8 courses, each 5 feet high; concrete ring girder; all attached pipes had flexible connections to allow for tank wall uplift. Tank No. 1 showed clear signs of uplift all around the tank (Figure 2-15); Tank 2 showed no sign of any uplift. Both tanks would have been flooded by about 8 feet of water. This suggests that Tank 1 (northernmost) was nearly empty at the time of the earthquake, while Tank 2 had at least 8 feet of water.

Figure 4-16. Shin Sendai Power Station – Water Tank

Figure 4-17 shows the south side of Tank 1, with part of the concrete ring wall exposed due to scour from the water inundation. One of the flexible connections is seen on an inlet pipe. The scour depth here is about 2.5 feet deep.

Figure 4-17. Shin Sendai Power Station – Water Tank 1, Scour

Figure 4-18 (looking north) shows the extensive sour of the pedestal supports around the pipe chase; the damage to one of the cross braces is thought to have been from vehicle impact. The scrapes at the "X" locations on the rod cross bracing suggest that the top level of pipe chase moved back and forth at least several inches; several cross brace rods are buckled, and some rod-frame connections are broken.

Figure 4-18. Shin Sendai Power Station – Pipe Chase, Scour, Bracing Damage

4.2.2.2 Sendai Power Station

The Sendai thermal power plant, Figure 4-19, was heavily damaged by the tsunami. This LNG-fired power plant was designed in 2007, and put into initial operation in 2010. As such, it is the newest power plant along the Pacific coast that was affected by the tsunami. the main features of the plant are as follows:

- 446 MW Combined cycle gas fired, Mitsubishi
- The gas is from LNG, coming from Niigata via a gas pipeline, 260 km long. there was no damage to this gas pipeline.
- Put into initial operation in July, 2010.
- Repaired and restored to service, February 5, 2012.
- At the time of the earthquake, the plant was running at full power. At 14:46 pm (local time), the earthquake hit. The plant was shut down automatically, as the turbine vibration instrument reported high.
- There was a station blackout. There was no on-site power except for emergency lighting (the backup generator failed to start).

- At 15:51 pm, (65 minutes later) the tsunami arrives.

Figure 4-19. Sendai Power Station

The earthquake-related damage (excluding tsunami effects) at the station included the following (highlights in Figure 4-21):

- Some broken pipe supports, but no broken pipe
- The turbine had slight damage. this turbine had reportedly been qualified for PGA = 0.5g.
- There were damaged supports at the top end of the chimney.
- The wheels on one of the overhead gantry cranes broke, when the crane was moved after the earthquake. This was reportedly due to the crane rails being out of alignment.
- Soft drink machines fell over in the lunch room.
- The tsunami-related damage at the station included the following (highlights in Figure 4-21):
- Air compressor

- Boiler feed water pump set
- Bearing cooling water pump set
- Condensate pump set
- Main transformer (yard equipment)
- Starting transformer (yard equipment)
- Ground floor electrical facilities were destroyed
- Circuit breakers
- Emergency generator failed to start

The ground motions at this power plant site were as follows (recorded by a free field instrument in the switchyard area):

Free field (Gal)	+470 / -263 NS	+451 / -550 EW	+227 / -227 vertical
Top of heat recovery steam generator (Gal)	1373		

Table 4-11. Recorded Motions – Sendai Power Plant

The tsunami design basis for the plant was established as follows:

- The plant was designed in 2007.
- The plant site, being on the Tohoku coast, was considered at risk from tsunami and storm surge.
- The 1933 earthquake caused a 3.046 meter tsunami at this location.
- The 1948 typhoon caused a 2.635 storm surge at this location.
- The 1960 M 9.2 earthquake in Chile had produced a maximum recorded tsunami of 4.21 meters.
- Given all of the above, the tsunami height for the site was selected as 4.51 meters.

In the March 2011 earthquake, the actual tsunami at this site was about 8 meters high. A nearby instrument recorded 6 meters, before going off scale. Figure 4-20 shows the plant entrance (on March 2, 2012), showing the maximum run-up height of +5 meters above grade at the front door entrance to the power plant building. The people in the photo include Alex Tang (ASCE team, far left), Mr. Noba (Plant Manager, far right), Mr. Mike Salmon (LANL) and Ruben Boroshek (Chilean expert for subduction zone ground motions).

Figure 4-20. High Water Mark (+5m), Sendai Power Plant (photo taken March 2 2012)

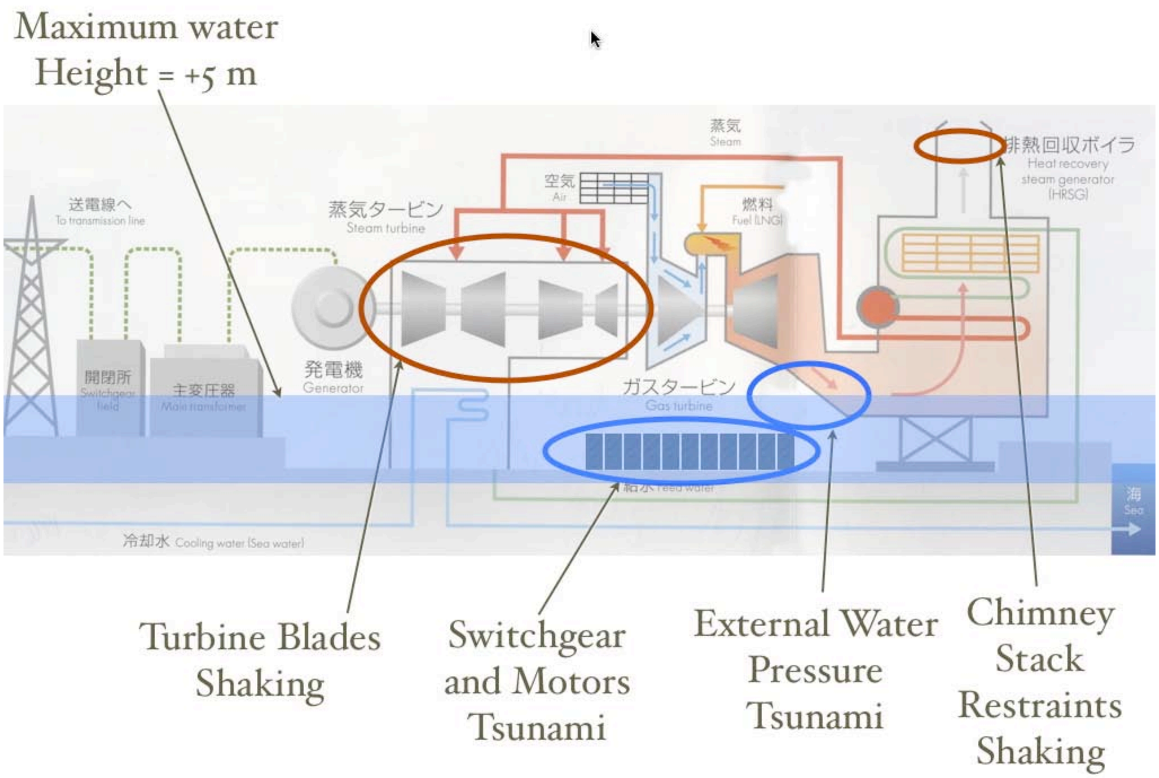

Figure 4-21. Main Damage Locations at the Sendai Power Plant

Figure 4-22 shows a photo, taken about 66 minutes after the earthquake, showing the tsunami water rushing into the plant switchyard and inundating the gas-insulated switchgear. Figure 4-23 shows the same switchyard after retreat of the water.

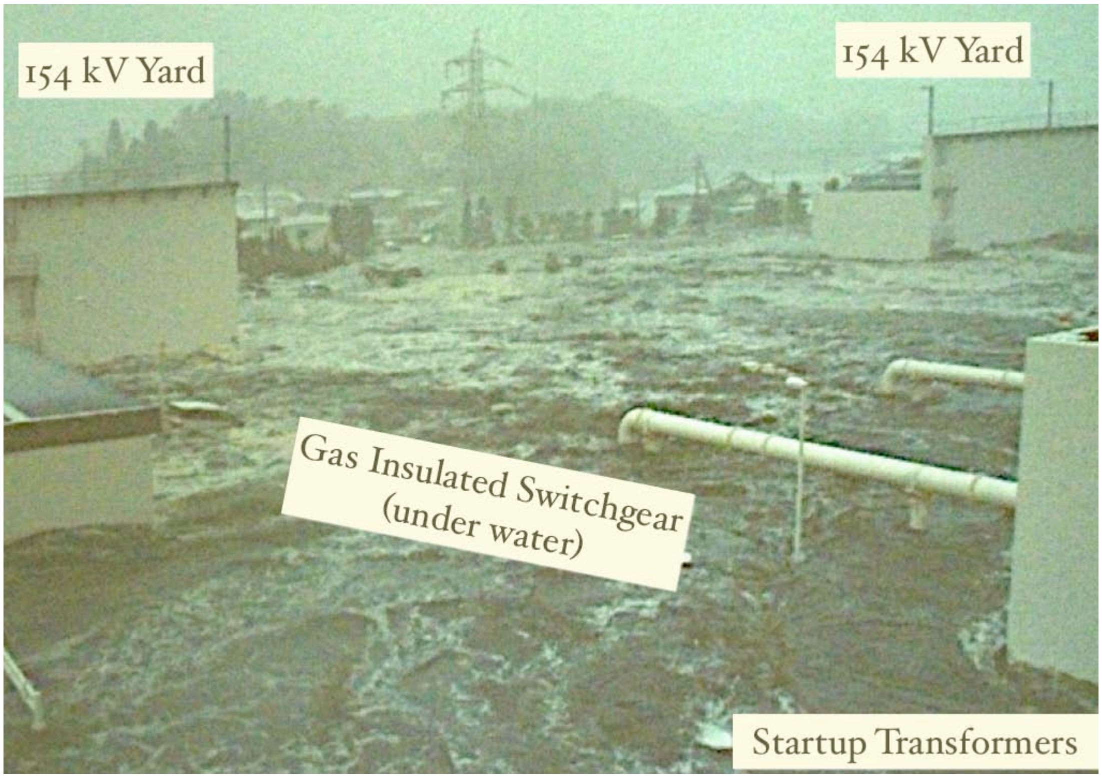

Figure 4-22. Tsunami Inundating the Switchyard

Figure 4-23. The Switchyard after the Tsunami Retreated

Figure 4-24 shows the operating deck of the power plant, with the generator, steam turbine and gas turbine. The operating deck is located above the high water mark, so this room was not inundated. Note that every bay is braced with K-type braces (restrained against buckling), indicating a much higher lateral design force used for design than used in the USA for high seismic zones, even with "I=1.5" type factors are used. We examined the plant carefully, and could see no obvious signs that any of the braces yielded (no permanent deformations, no chipped paint).

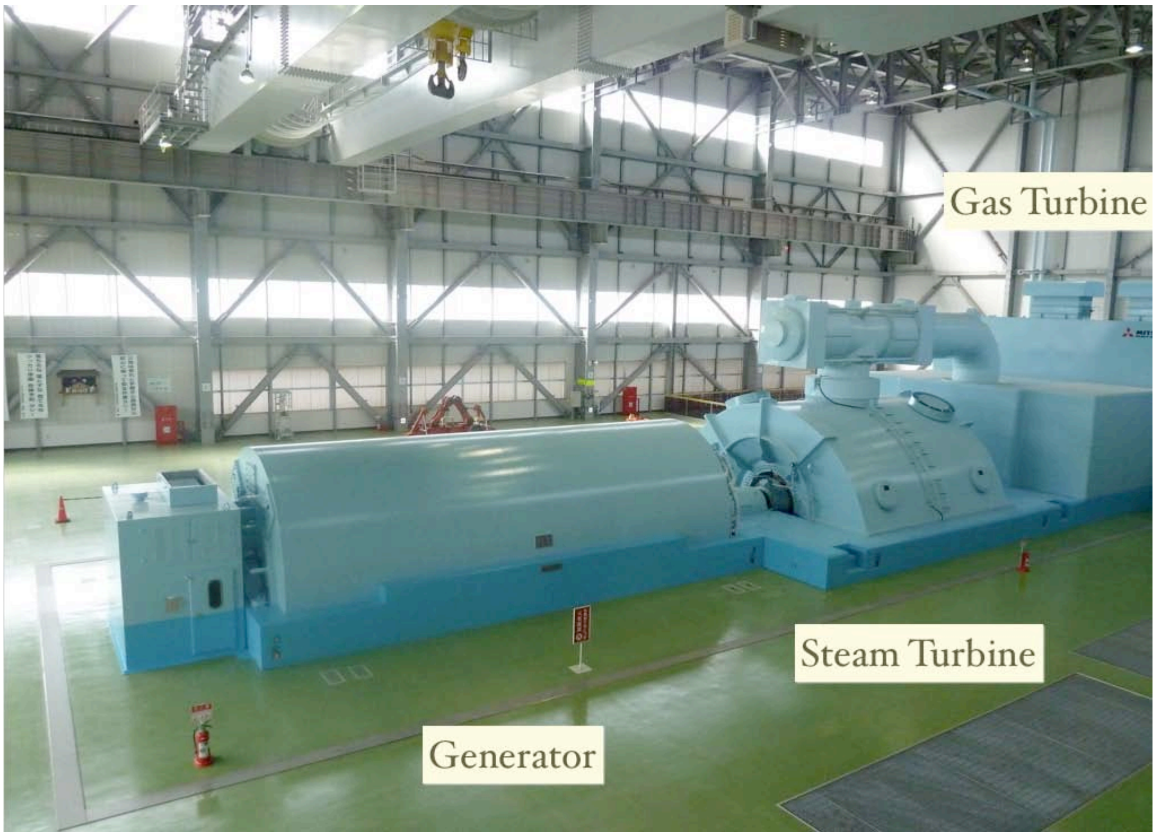

Figure 4-24. Operating Floor with Main Equipment

Figure 4-25 shows the overhead gantry cranes. One of the crane rails broke when the crane was attempted to be moved after the earthquake. Apparently, the crane rail was out of alignment.

Figure 4-25. Crane Rail

Figure 4-26 shows the operating room for the power plant. According to plant staff, none of the desktop monitors fell over during the earthquake.

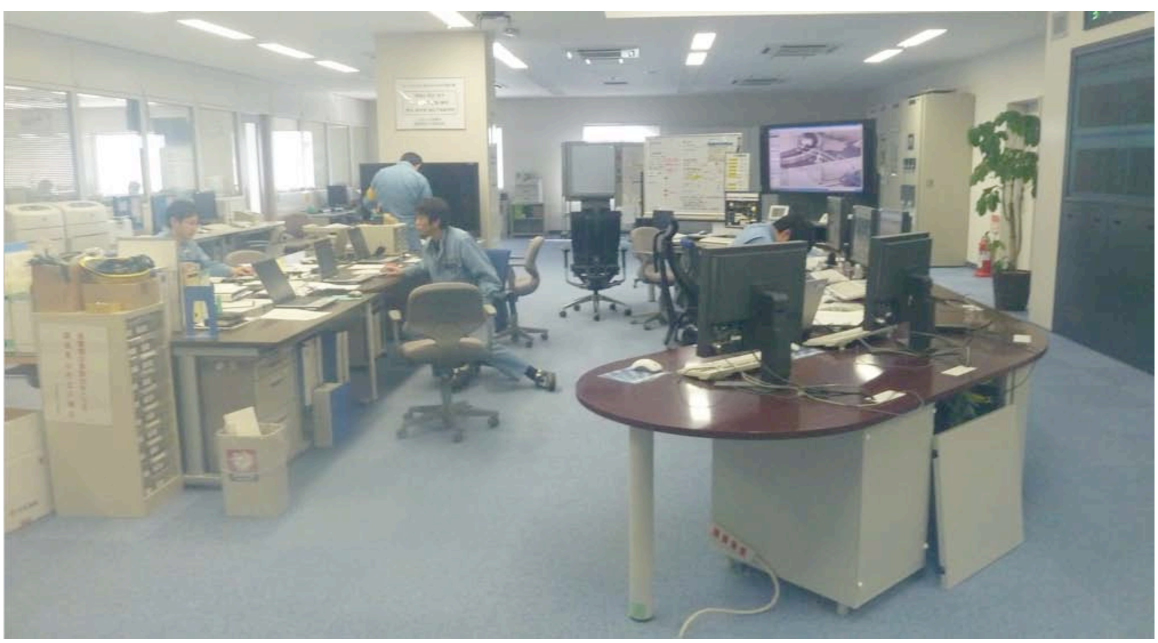

Figure 4-26. Operations Room

Figure 4-27 shows one of the sliding pipe supports in the plant. This particular support uses a graphite-type running surface to allow for thermal (and seismic) movements. At this location, scratch marks show the pipe slide sideways up to about 6 inches. As noted earlier, there was no damage to any pipes in the plant, although there were some damaged pipe supports. this type of "good pipe" and "damaged pipe support" has been observed at other power plants around the world, and the reader is cautioned that the "design by rule" requirement in many modern US codes (including ASCE 7-2010, IBC 2009, SMACNA, NFPA) to place lateral seismic supports about every 10 feet, is largely based on warrantless assumptions and without regard to empirical observation that nearly all large bore (4 inches diameter and larger) power plant pipes perform extremely well in past earthquakes; over-constraint of pipes will lead to higher pipe stresses, more fatigue, and increase chance of pipe failure; the authors recommends that any power plant piping be designed to the stress rules of ASME B31.1 (or similar) codes; should the owner wish to assure good post-earthquake performance, the pipes should be designed to remain nearly elastic (perhaps 20% over yield) under the design basis earthquake motion and pipe supports designed accordingly; if screwed pipe connections are used, they should have elastically computed stresses no more than about 60% of nominal pipe yield; if welded pipe connections are used, suitable stress intensification factors should be considered.

Figure 4-27. Sliding Movement on pipe Support

Figure 4-28 shows a rod-hung small bore pipe, located near the roof level of the plant (floor level motions in excess of 1 g). There was no damage to this pipe, even though it does not have lateral supports at 10-foot spans as required by modern US codes such as ASCE 7, IBC 2009, NEC, SMACNA, NFPA. Clearly, the non-structural provisions in these codes for seismic supports on commodities (pipes, cable trays, conduits) need to be revised, as these installations appear to be a waste of money, and may actually degrade day-to-day performance of the commodities.

Figure 4-28. Small Bore Pipe with Rod Hanger Supports had Good Performance

Figure 4-29 shows the outside of the chimney stack, highlighting (yellow lines) the approximate elevation where the chimney within damaged its restraints (Figure 4.38).

Figure 4-29. Enclosure Around Chimney Stack. Yellow Lines Indicate Lateral Braces for Chimney Within

Figure 4-30. Braces Around Chimney Stack.

Figure 4-31 shows the exhaust chase at the bottom of the steam generator. This is located at the ground level of the plant, where water height reached 5.1 meters. The arrow shows the location where upwards pressure from the tsunami water buckled the exhaust manifold.

Figure 4-31. Damage Location to Steam Generator Exhaust Manifold

4.2.2.3 Other Tohoku-Area Power Stations

Figure 4-32 shows the collapsed coal unloader at the Haramchi power plant. The conveyer belts at Haramachi were damaged. Inundation damaged most of the equipment on the turbine floor, Figure 4-33. By December 2012, the plant had been returned to about 50% of capacity.

Given the damage to Tohoku EPCO's and TEPCo's coal plants, both utilities reportedly declared force majeure on its coal shipments.

Figure 4-32. Haramachi Power Station – Damaged Coal Unloader

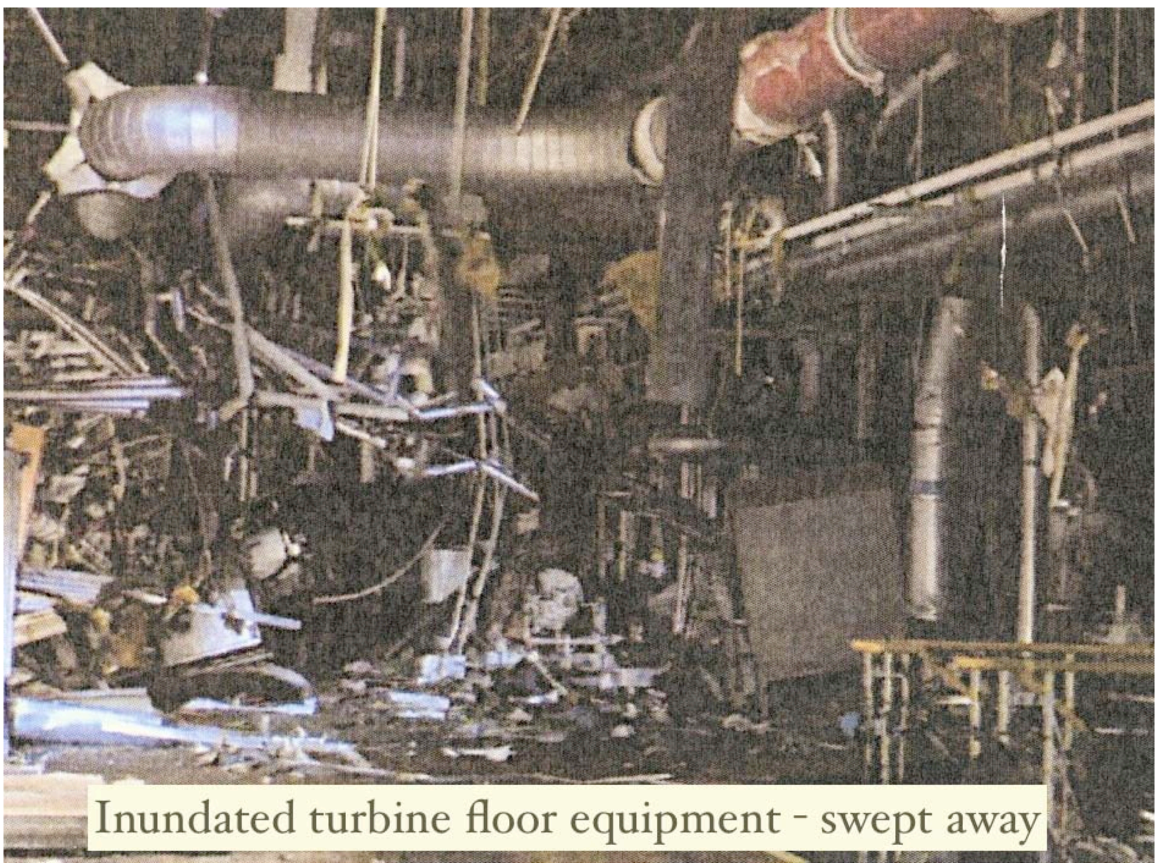

Figure 4-33. Haramachi Power Station – Damage due to Tsunami Inundation

A 7.3 meter tsunami hit the Soma port, resulting in damage to the Soma coal-fired plant.

Coal stockpiles at the Joban coal-fired power plant were likely to have been washed away by the tsunami, or contaminated by seawater. Three coal carriers, the Shiamizu, Shirouma and Coral Ring, had run aground while discharging or preparing to unload cargoes because of the tsunami.

4.2.3 Substations

Damage to substations was due to two causes: tsunami inundation near the coastline, and ground shaking away from the coastline.

The 64.5 kV Tagajyo substation (38.2789, 141.0176) was inundated by the tsunami. This substation is close to the Sendai port area, located about 10 feet above sea level. the large quantity of floating debris caused most of the damage in the yard; salt water damaged the electric equipment in the control building.

Figure 4-34 shows the yard in March 2009. Figure 4-35 shows the yard on April 6, 2011, before debris has been removed from the yard.

Figure 4-34. Tagajyo Substation Pre-Earthquake

Figure 4-35. Tagajyo Substation Post-Earthquake

In Figure 4-35, one can see the portable 66 kV substation (truck-mounted) just outside the yard to the north. This portable truck-mounted transformer is seen in Figure 4-36, along with the newly-constructed temporary yard equipment (as of June 14, 2011).

Figure 4-36. Portable Transformer at Tagajyo Substation, June 14, 2011

Figure 4-37 shows the yard after cleanup, with the three transformer banks in the background (John Eidinger in the foreground).

Figure 4-37. Transformer Banks at Tagajyo Substation, June 14, 2011

Figure 4-38 shows one of the 15 MVA 64.5 kV-6.9 kV transformers. Based on high water marks on the control room building, the inundation level was about 11 feet above grade at this location. There is no sign of flotation of this transformer; we also did not see any flotation of bulk oil circuit breakers, or any other yard equipment). The transformer was anchored to a concrete slab below (Figure 4.47, showing soil residue left by the receding water). We did not observe any material scour at this substation site.

Figure 4-38. Transformer at Tagajyo Substation, June 14, 2011

Figure 4-39. Transformer Anchorage at Tagajyo Substation

Figure 4-40 shows the radiator on one of the transformers, indicating impact from debris, as well as a sand-filled-collection sack hanging under the radiator (to try to catch dripping oil).

Figure 4-40. Transformer Radiator Damage at Tagajyo Substation

Figure 4-41 shows the control building, with broken steel skin due to water inundation pressure. Figure 4-42 shows the panel boards within the control building, along with the broken z-lock skin sheathing. Battery racks were anchored, but all the lead-acid batteries were submerged.

Figure 4-41. Control Building at Tagajyo Substation

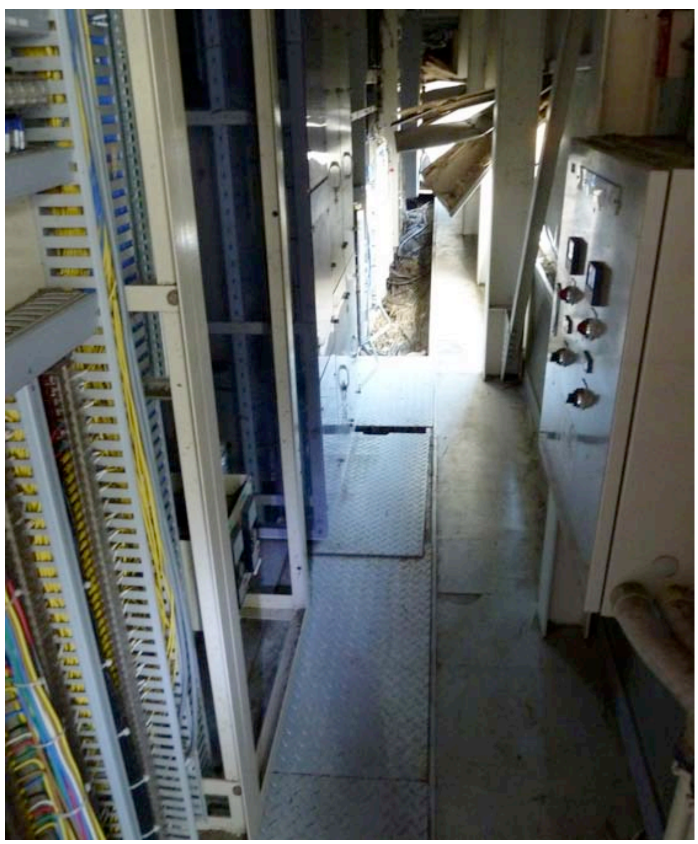

Figure 4-42. Control Building Interior at Tagajyo Substation

The Sendai substation (38.2766, 140.9946 Figure 4-43) is located about 1 mile from the Tagajyo substation, at the western end of the Sendai Port. Its ground elevation is about 15 feet above sea level, but it was still inundation from the southeast corner of the substation; debris entered the yard and covered about 10% of the yard (southeast corner).

Figure 4-43. Sendai Substation

Figure 4-44 shows the Sendai Substation (38.3186, 140.9084). This substation (275 kV and 154 kV) is located about 13 km west of the coastline, and was subjected to ground shaking only. We observed no material damage to any of the regularly-build homes and small commercial buildings around the site. Possibly, PGA at this site was about 0.25g, with PGV about 10 inches/second. It is located at the base of a hilly area, so the site can likely be characterized as be thin soil over rock.

Figure 4-44. Sendai Substation

Bushings on the 275 kV transformers were damaged, Figure 4-45.

Figure 4-45. 275 kV Bushing Damage, Sendai Substation

275 kV CVTs next to pot heads were damaged (Figures 4-46 and 4-47).

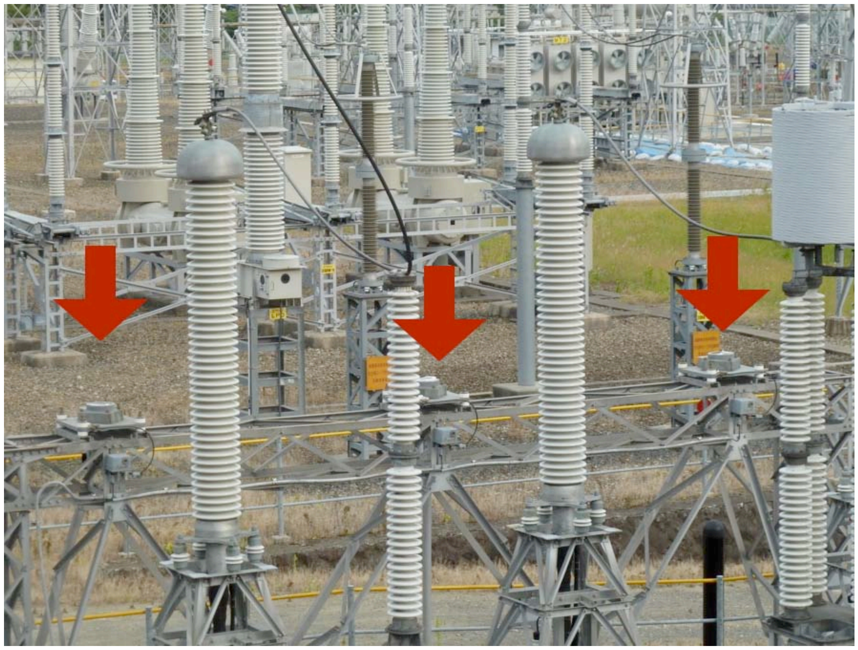

Figure 4-46. 275 kV CVT Damage, Sendai Substation

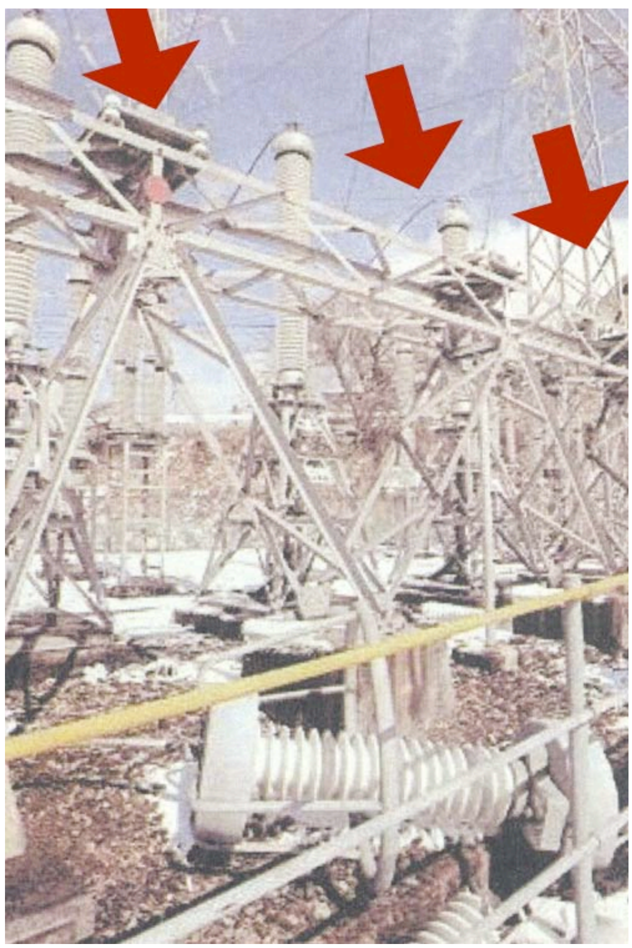

Figure 4-47. 275 kV CVT Damage, Sendai Substation

Two 275 kV center-break disconnect switches failed, Figure 4-48.

Figure 4-48. 275 kV Disconnect Switch Damage, Sendai Substation

A 275 kV instrument transformer (left side of Figure 4-49) failed; a similar one to the right side of this photo remained intact, as also did the post-mounted wave traps. The device may have broken due to inertial overload on the porcelain; or perhaps cable slack interaction with the adjacent wave trap.

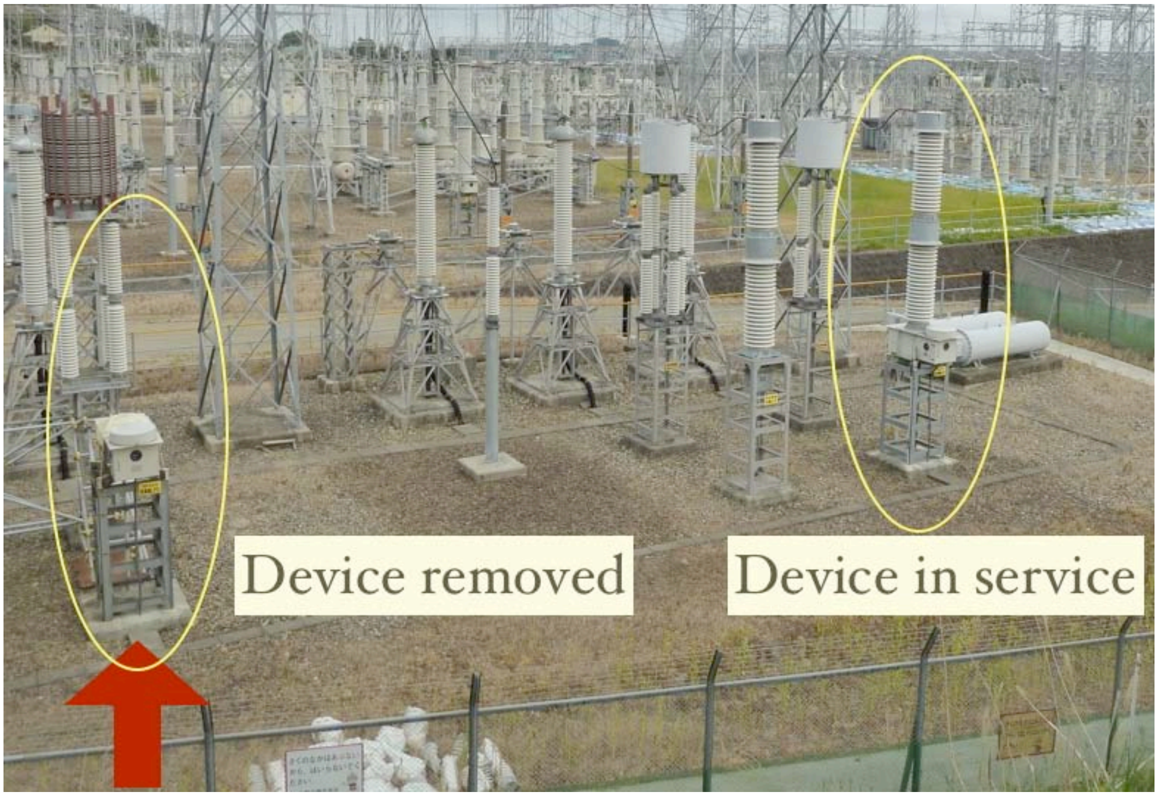

Figure 4-49. 275 kV Instrument Transformer , Sendai Substation

At another substation, a 275 kV live tank circuit breaker (braced) collapsed, likely leading to pull down of the adjacent disconnect switch, Figure 4-50.

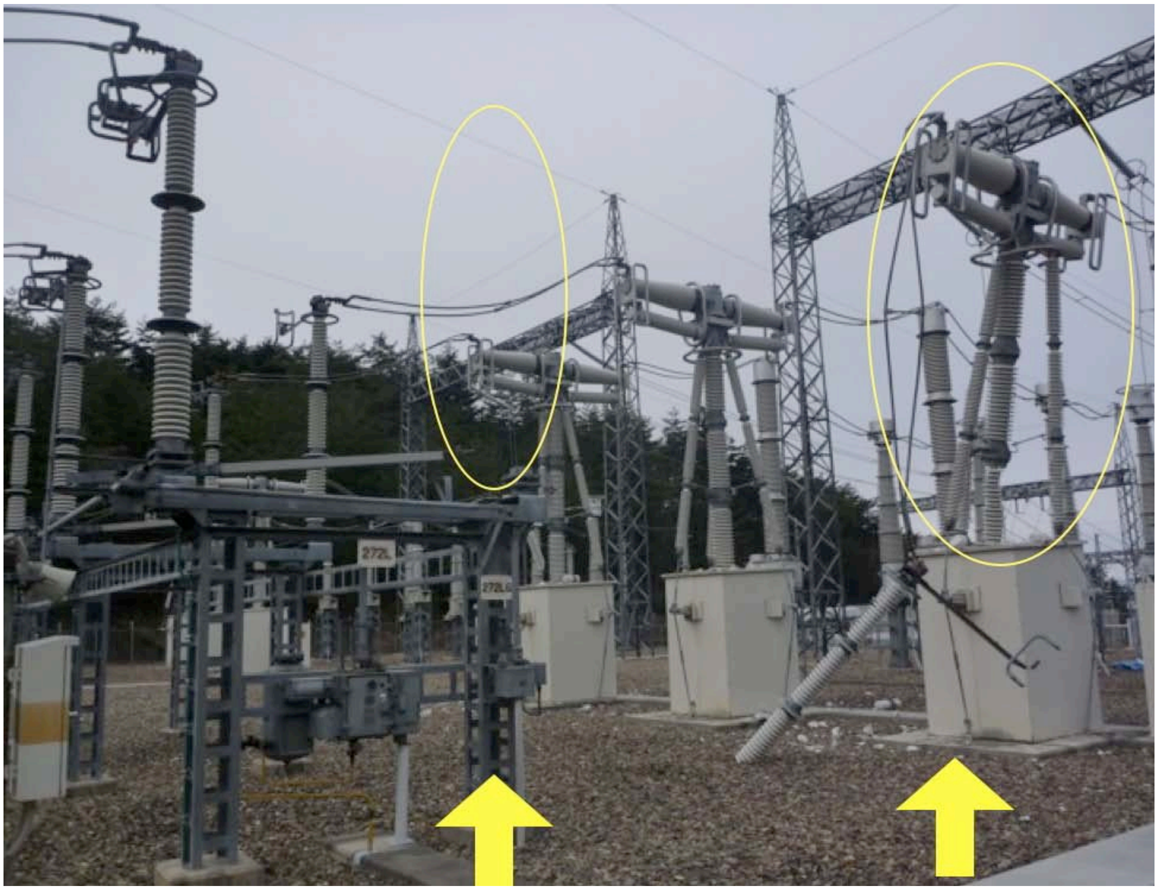

Figure 4-50. 275 kV Live Tank Circuit Breaker

At another substation, two 275 kV surge arrestors failed, Figure 4-51.

Figure 4-51. 275 kV Surge Arrestors

At another substation, an oil leak occurred at the bottom pipe flange fitting to a radiator on a transformer, Figure 4-52.

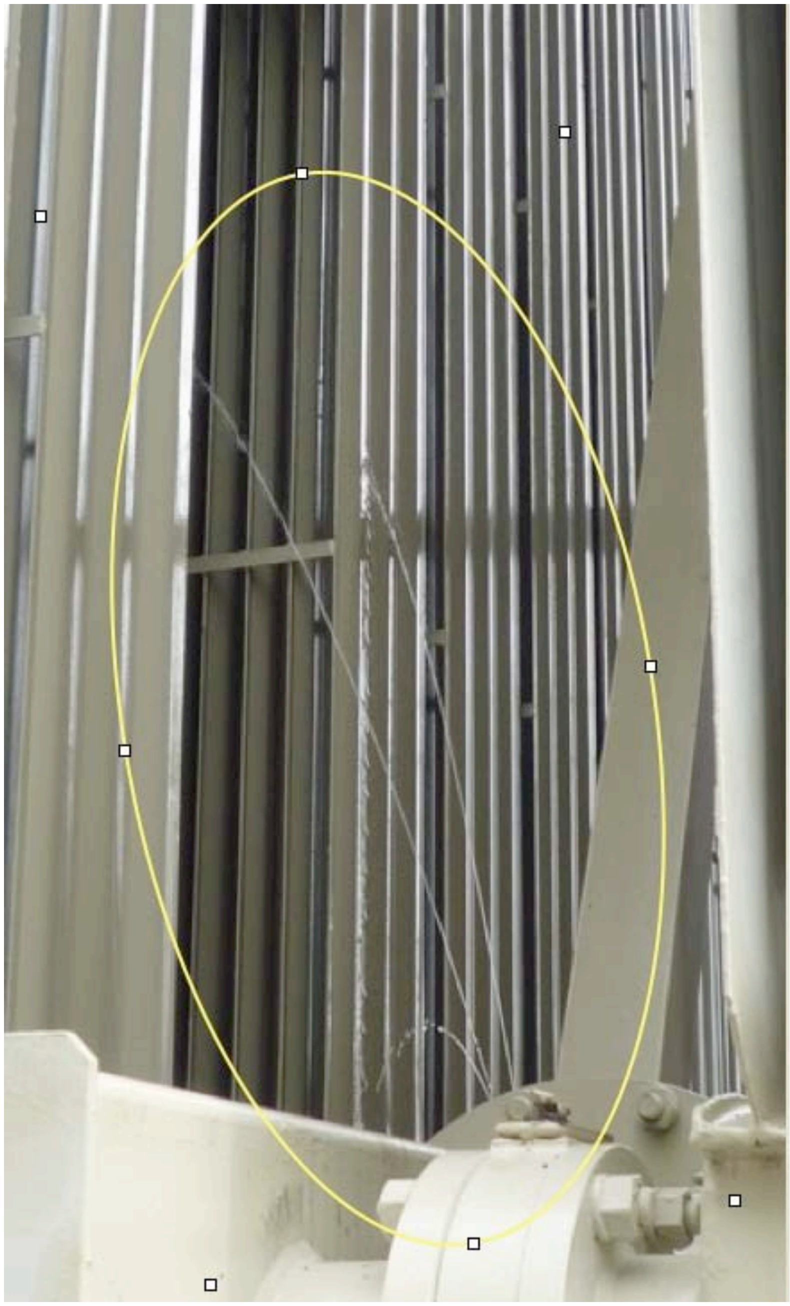

Figure 4-52. Oil Leak at Radiator Pipe Fitting

At another substation, all three bushings are being replaced on a transformer, Figure 4-53. Figure 4-54 shows another failed transformer bushing.

Figure 4-53. Bushing Replacements on Transformer

Figure 4-54. Bushing Failure on Transformer

Figure 4-55 shows a control building damaged by tsunami inundation, near Ishinomaki. Figure 4-56 shows one of the transformers just adjacent to this control building, having about 4 feet of scour under its pile-supported concrete pad foundation; this transformer has since been removed from the system.

Figure 4-55. Control Building Failed due to Inundation, Ishinomaki

Figure 4-56. Transformer Undermined by Scour, Ishinomaki

Figure 4-57 shows a portable truck-mounted 66 kV transformer. This truck was located about 200 meters from the waterfront in Ishinomaki. The tsunami waves hit this location perhaps 1 hour after the earthquake; however, no one had the time to drive these critical pieces of equipment away from the tsunami inundation area in the interim. Clearly, it would have been better to keep these pieces of equipment parked at locations outside any possible tsunami run-up zone. Figures 4-58 and 4-59 show three others with similar damage, stored nearby.

Figure 4-57. Portable 66 kV Transformer Damaged by Inundation, Ishinomaki

Figure 4-58. Portable 66 kV Transformers Damaged by Inundation, Ishinomaki

Figure 4-59. Portable 66 kV Transformer Damaged by Inundation, Ishinomaki

4.2.4 Transmission Lines

High voltage steel lattice tower-type transmission towers suffered damage in the earthquake. Of the 42 steel lattice towers that were damaged, 40 were due to tsunami inundation, and 2 from landslide. Figures 4-60, 4-61, 4-62 show some of the damaged towers. We observed several of the damaged towers, and we believe that the collapse of these towers was not due to water forces (or scour); instead, the primary reason for collapse was due to the towers being hit by tsunami-floated cars, containers and other types of debris. From a mitigation point of view, for towers that must be placed in potential tsunami run-up zones with floating debris, the tower legs can be readily protected at modest cost by installed suitable bollard-type structures, all around the tower (downstream and upstream). Scour protection in these area would also be useful. While we did not survey all towers in tsunami run-up zones, we estimate that perhaps 85% to 90% of all inundated towers did survive the inundation without material damage.

Figure 4-60. Collapsed Transmission Tower – Tsunami Debris

Figure 4-61. Collapsed Transmission Tower – Tsunami Debris

Figure 4-62. Collapsed Transmission Tower – Tsunami Debris

4.2.5 Onegawa Nuclear Power Plant

Tohoku EPCO owns and operates two nuclear power plants. Onegawa is a three unit plant, located close to the epicenter. Higashidori is a single unit plant, located at the northern end of Honshu Island, distant from the epicenter.

Figure 4-63 shows the Onegawa nuclear power plant site. Plant staff reported to us that they had difficulty in standing up during the M 9.0 earthquake, owing to the very strong ground shaking; Table 4-12 lists the recorded motions at a borehole on site, as well as at the reactor building basemats. All three units are founded on rock. The original design basis for Unit 1 was PGA = 375 Gal; in 2007, a re-evaluation was undertaken for PGA = 580 Gal, and that resulted in installation of 6,600 pipe supports between the three units.

At the time of the earthquake, Units 1 and 3 were in operation, and Unit 2 was in the process of start-up, having the first control rod withdrawn at 2:00 pm. The earthquake occurred at 2:46 pm. The following summarizes the plant performance in the immediate aftermath of the earthquake:

- Unit 1. Plant has automatic shutdown at 2:46 pm. The plant went into cooldown, and at 0:58 am March 12 2011, achieved cold shutdown (water temperature in the reactor vessel under 100°C).

- Unit 2. Plant has automatic shutdown at 2:46 pm. The plant went into cooldown, and at 2:49 pm March 11 2011, achieved cold shutdown (water temperature in the reactor vessel under 100°C).

- Unit 3. Plant has automatic shutdown at 2:46 pm. The plant went into cooldown, and at 1:17 am March 12 2011, achieved cold shutdown (water temperature in the reactor vessel under 100°C).

The stack and other radiation monitors showed normal radiation levels immediately after the earthquake. A short term increase in radiation levels was detected as the radioactive cloud from Fukushima passed overhead; this soon subsided to background radiation levels.

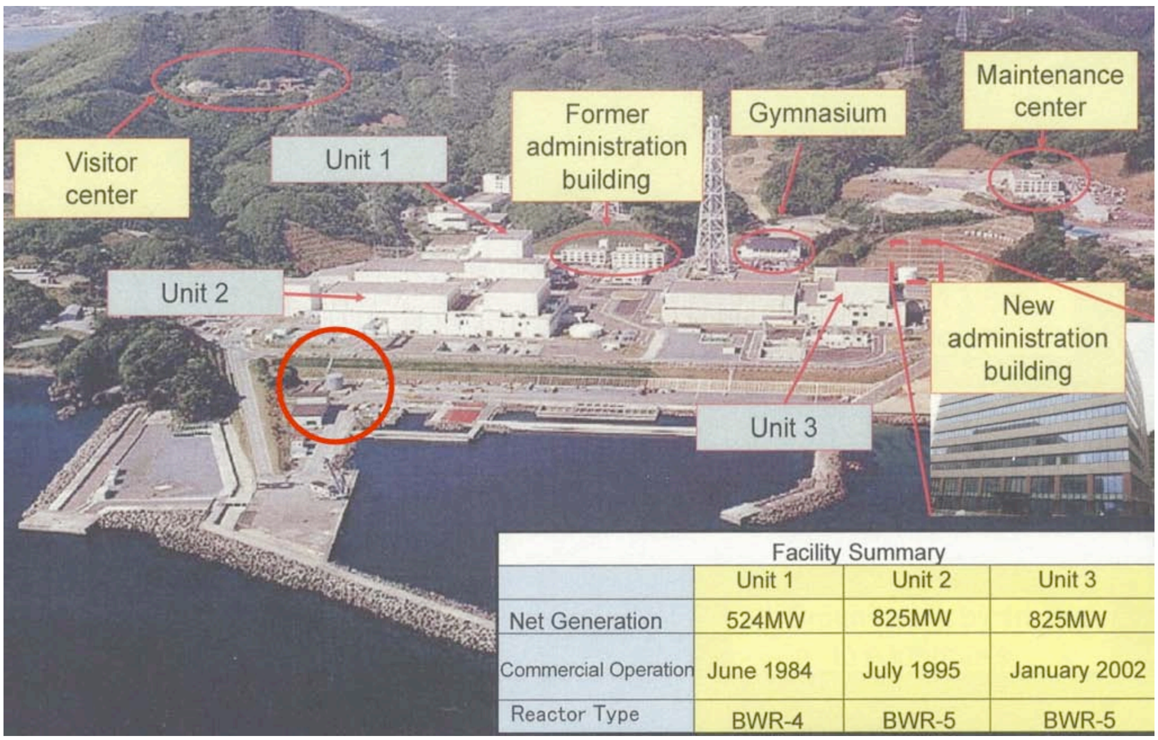

Figure 4-63. Onegawa Nuclear Power Plant Site

Event	NS	EW	Vertical
M 9.0 March 11 Borehole (-8.6m)	467	421	269
M 7.1 April 7 2011 Borehole (-8.6m)	321	396	203
M 9.0 Unit 1 Reactor Building Basemat	540	587	439
M 9.0 Unit 2 Reactor Building Basemat	607	461	389
M 9.0 Unit 3 Reactor Building Basemat	573	458	321

Table 4-12. Recorded Motions – Onegawa (Gal)

Figure 4.-64 shows the recorded time histories by a downhole instrument located at -8.6 meters, for the M 9.0 event. Prior to the March 11 2011 earthquake, the largest recorded ground motion at the site was 251 Gal, on August 16, 2005.

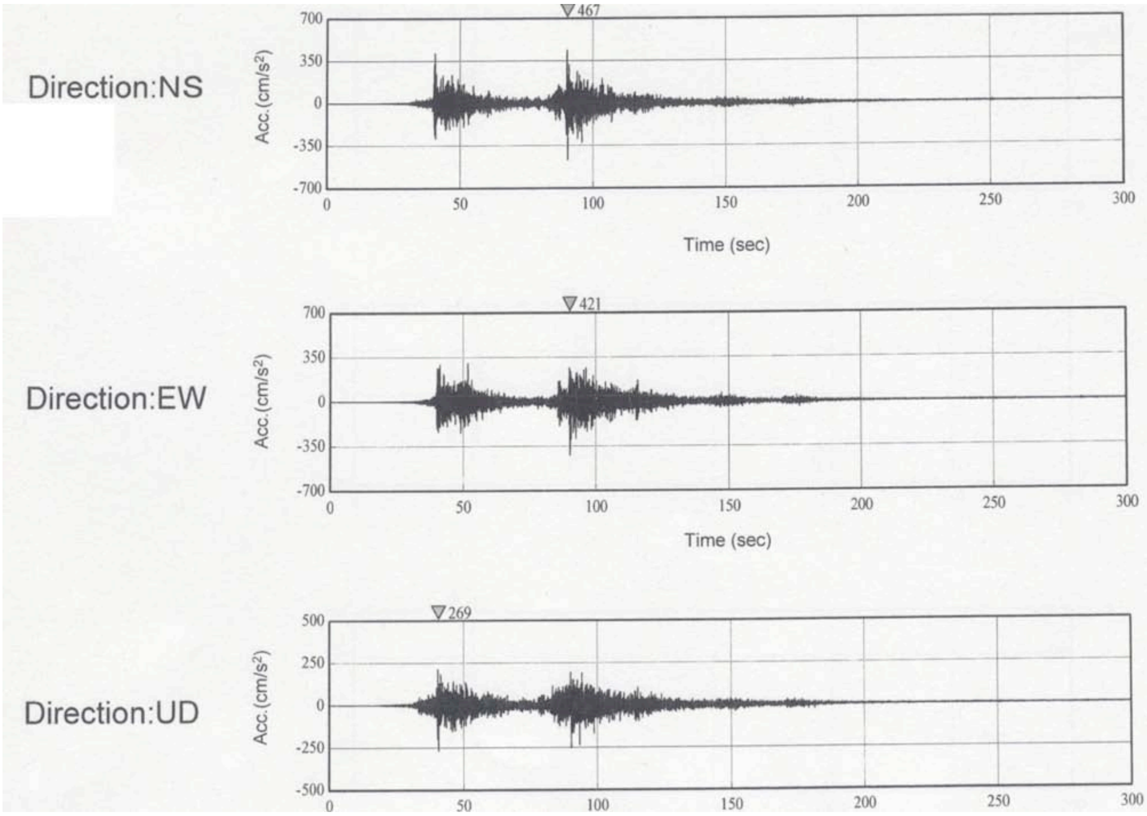

Figure 4-64 Recorded Motions – Onegawa (Gal)

Figure 4-65 highlights the five transmission lines leading from the plant. Four of the five lines faulted, all due to ground shaking effects.

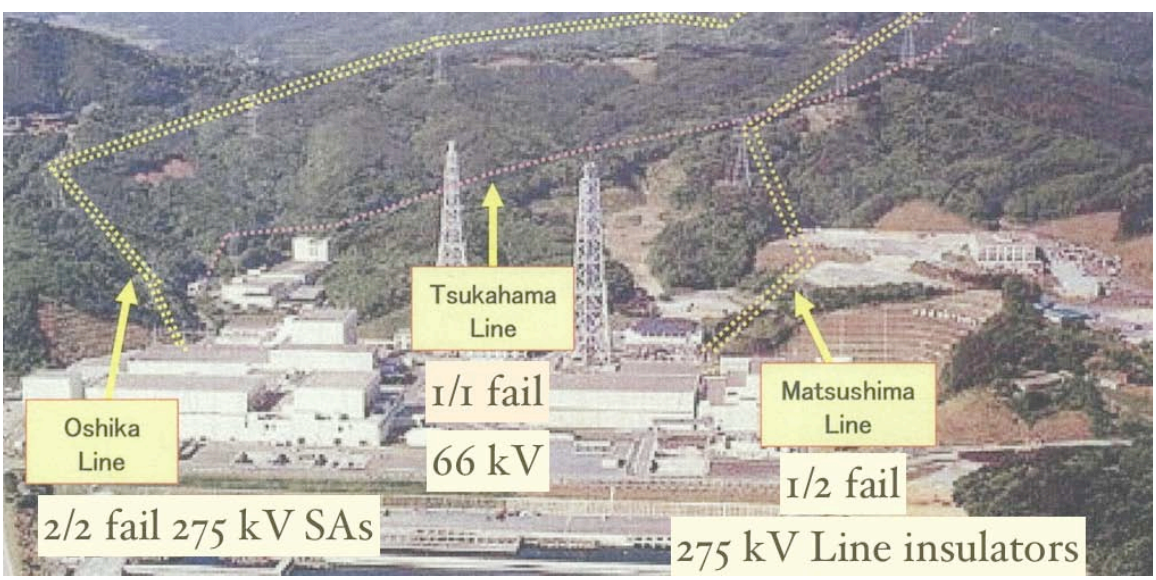

Figure 4-65. Transmission Lines – Onegawa

Figure 4-66 shows the modifications made to the transmission lines after the earthquake, to seismically-strengthen these lines. The two Oshika 275-kV lines faulted due to partial discharge of the lightning arrestors, possibly because under strong ground shaking the air gaps became too small, and the lines faulted due to discharge on lightning arrestors at the termination at Onegawa; the seismic upgrade was to further brace the supports, so that at higher frequency, there would be less displacement. One of the two Matsushima lines faulted when one of the phases swung sideways enough to fault; the seismic upgrade was to replace the hanging-type insulator with a v-type arrangement, to limit the potential for side-to-side swinging under strong ground shaking.

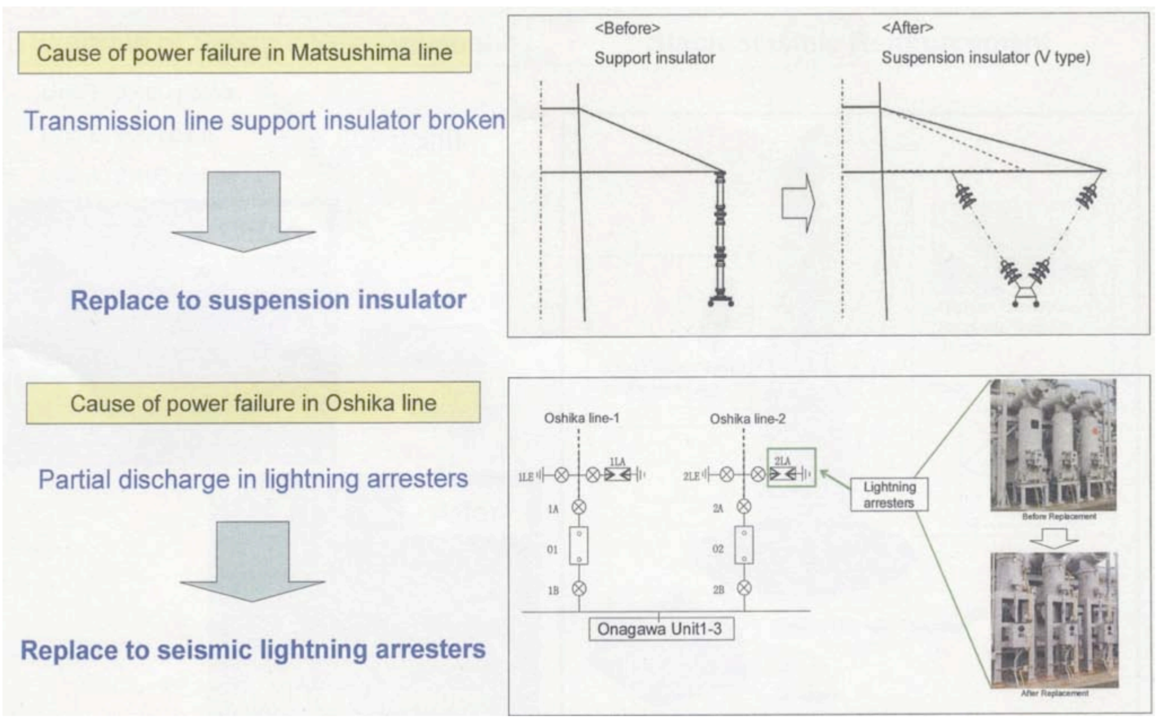

Figure 4-66. Transmission Lines Seisimc Upgrades – Onegawa

There are eight emergency generators at the plant. All were in standby after the earthquake. Two emergency generators for Unit 2 tripped after the arrival of the tsunami, due to loss of cooling water (the "B" and "HPCS" units); the "B" unit tripped offline due to a flooded cooling system at 3:35 pm; the "HPCS" unit tripped offline due to a flooded cooling system at 3:42 pm.

The heavy oil storage tank for Unit 1 floated and failed, Figure 4-67. This tank was located blow the sea wall, denoted by the large red circle in Figure 4-63. The tsunami came in and floated the tank. This tank provide fuel for HVAC and liquid radioactive waste treatment processed, and was not considered "safety related"… its location was outside the tsunami sea wall. The steel tank capacity was 960,000 liters, diameter 33 feet, height 36 feet; and was had about 600,000 liters at the time of the earthquake.

Figure 4-67. Oil Tank for Unit 1 (Non Safety Related) – Onegawa

One train of high voltage metal clad switchgear, Train A, failed in Unit 1. The unit rocked, the phases faulted, and this started a fire. Train B and C worked properly. Figure 4-68 outlines the power system. Figure 4-69 outlines the likely cause of the failure.

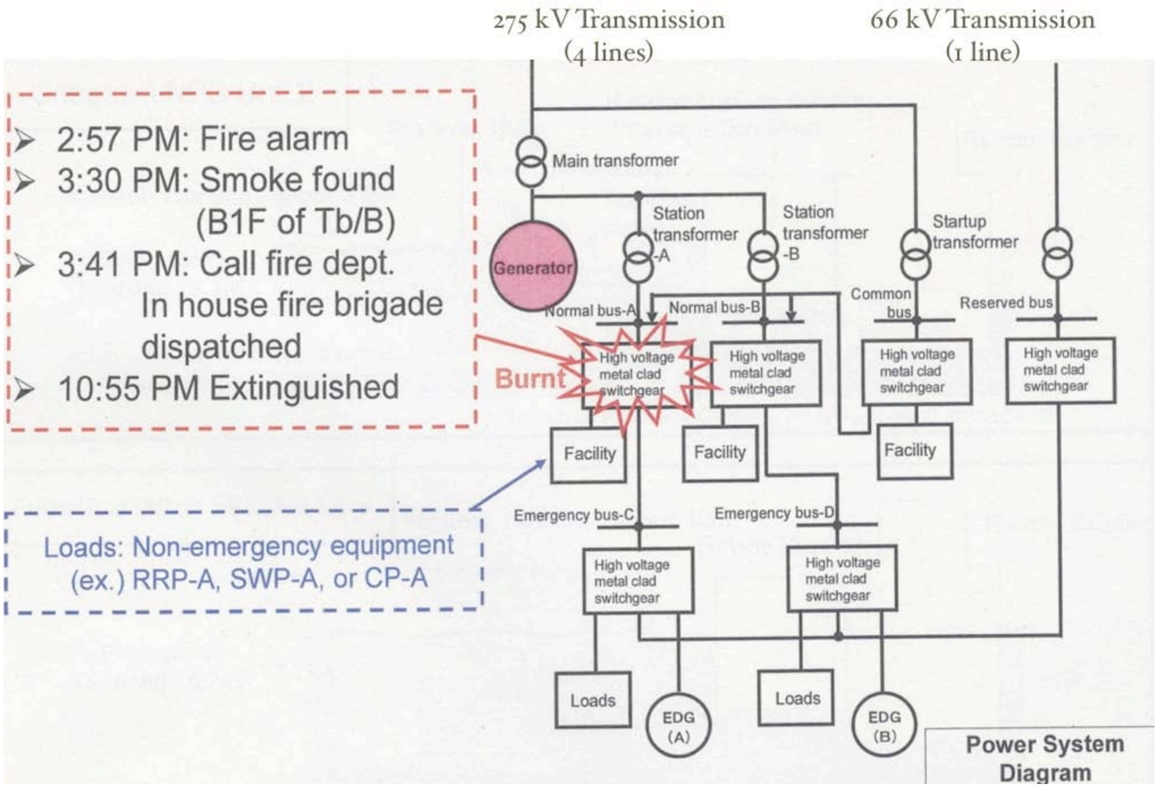

Figure 4-68. Power Diagram – Onegawa

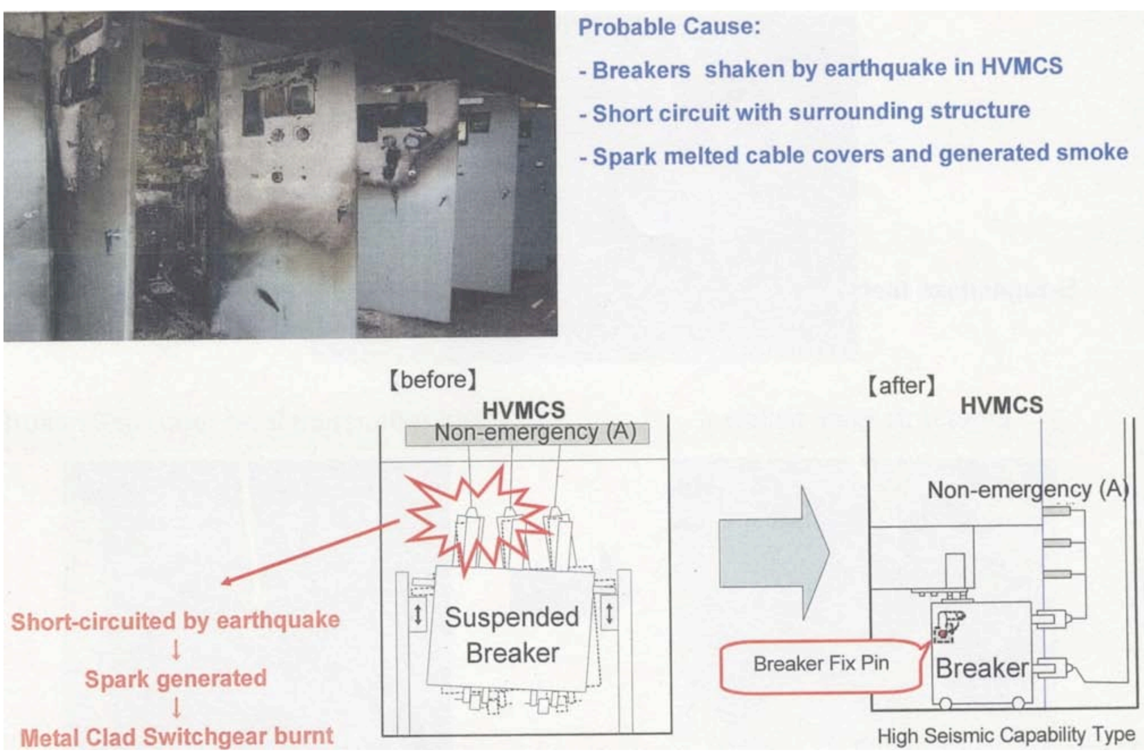

Figure 4-69. High Voltage Metal Clad Switchgear Failure and Upgrade – Onegawa

Seawater from the tsunami managed to enter into the basement of the Unit 2 Reactor Auxiliary building, flooding out the Reactor Cooling Water-B and High Pressure Cooling Water pumps. Thus, two of the three heat removal systems failed for Unit 2. Fortunately, Unit 2 was just in the process of start up, and the third cooling system worked to rapidly bring Unit 2 back to cold shutdown. Figure 4-70 shows a schematic cross section of Unit 2, and the path that allowed sea water to enter the basement of the Auxiliary building.

Note that in Figure 4.78 that the site tsunami wall (14.8 meters tall, reduced by 1 meter by tectonic subsidence) was tall enough to keep out the 13 meter tsunami; and the sea water pumps were fortunately high enough not to be flooded out by sea water. all the same, water pressure in the sea water wet well was high enough to cause pressure on the pressure transmitter tube cover, and this broke (Figure 4.79), allowing sea water into the concrete pit that housed the sea water pumps. This water then flowed via an open trench into the basement of the Auxiliary building, filling the basement to a height of 2.5 meters.

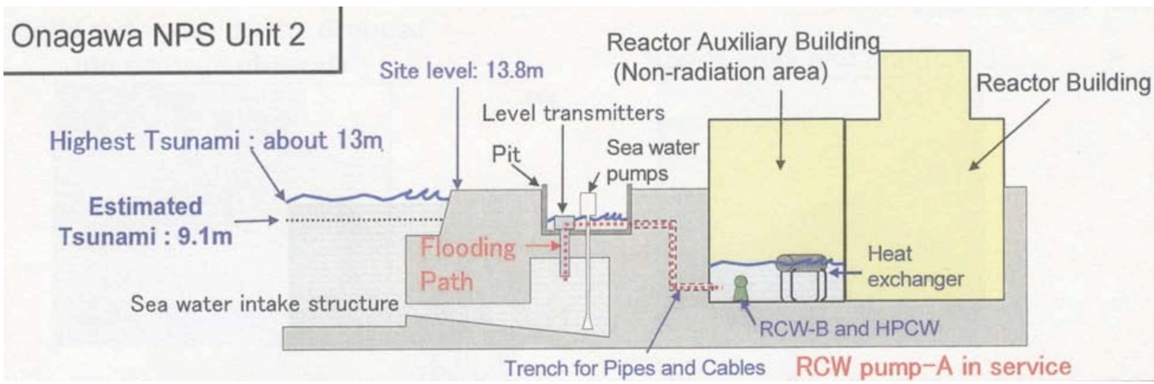

Figure 4-70. Path for Seawater to Flood Aux Building – Onegawa Unit 2

Figure 4-71. shows the flooded RCW-B heat exchanger, as well as the source of the flooding… a broken sea water level transmitter box. The retrofit was to install suitable steel members with the ability to resist the pressure from the highest tsunami.

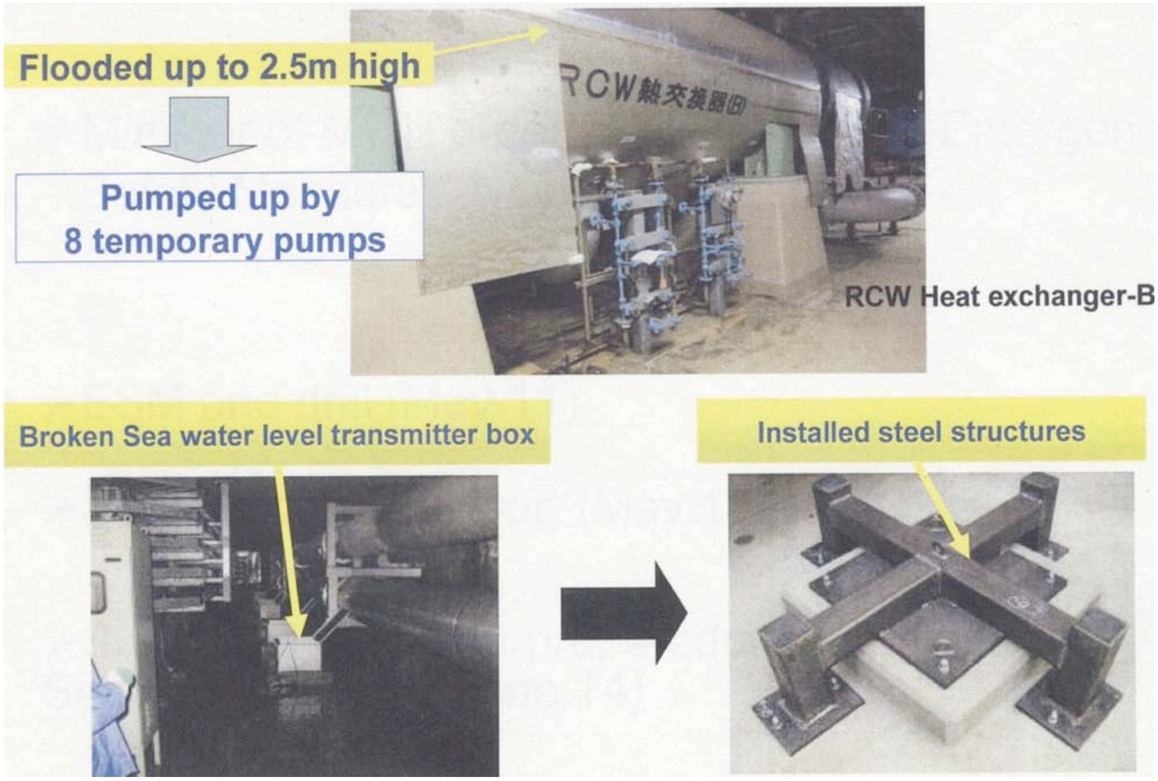

Figure 4-71. Flooded RCW-B Heat Exchanger and Pressure Transmitter Box – Onegawa Unit 2

Given that the plant had recently undergone an extensive seismic upgrade effort (starting in 2007), the question must be asked as to why the effort had not identified this weakness in the plant. Nearly 6,600 new pipe supports for seismic loads had been installed in the three units, so without doubt qualified engineers had gone over every safety-related system; yet had managed to overlook this potential failure mode. The authors suggest that PRA-type assessments of nuclear power plants are only as good as the people who conduct them, and careful site inspection by knowledgeable engineers would have been needed to have questioned the potential tsunami heights (including those beyond design basis), and checked that box could sustain the uplift forces (perhaps on the order of 2000 pounds). Certainly, the cost to upgrade this (perhaps a few thousand dollars) would have been obviously implemented had anyone determined it had been needed….

Figure 4-72 highlights some of the other 61 "minor damage points at the plant.

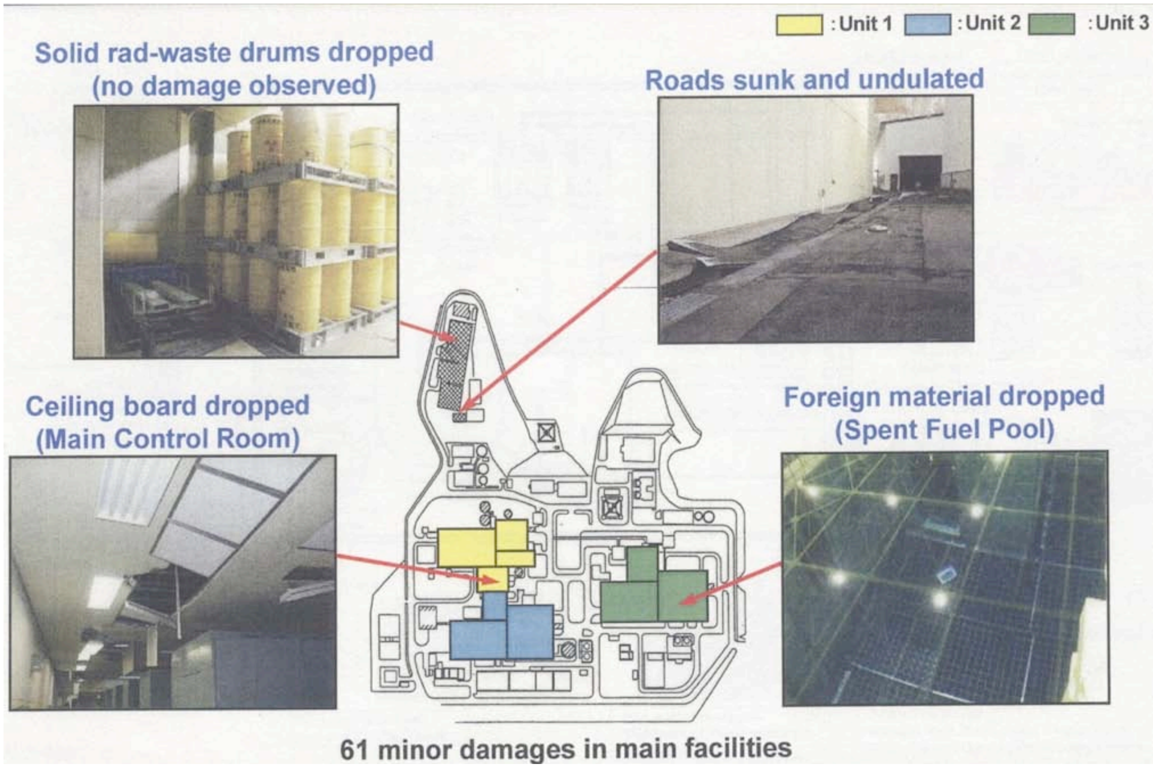

Figure 4-72. Examples of Minor Damage – Onegawa Units 1, 2, 3

Figure 4-73 shows the sea wall (an earthen berm with concrete protection) used to protect the power plant from tsunami. The elevation of the berm was 14.8 meters above sea level, before the earthquake. Tectonic subsidence of about 1 meter resulted in the dropping of the sea wall height to about 13.8 meters. The tsunami warning sounded at 2:49 pm. Then, at 3:29 pm, about 1 hour after the earthquake, the first and highest tsunami waves entered the cove, overtopped the breakwaters, and ran up to about 13 meters on the earthen berm sea wall.

The original design of the earthen berm included concrete protection up to 9.7 meters (8.7 meters after the earthquake) for erosion control. At about 5 times in the first few hours, the retreating tsunami waters reduced the water levels to below -5 meters, and reportedly, on one such retreat, the wet well was dry (no sea water available for cooling for a few minutes).

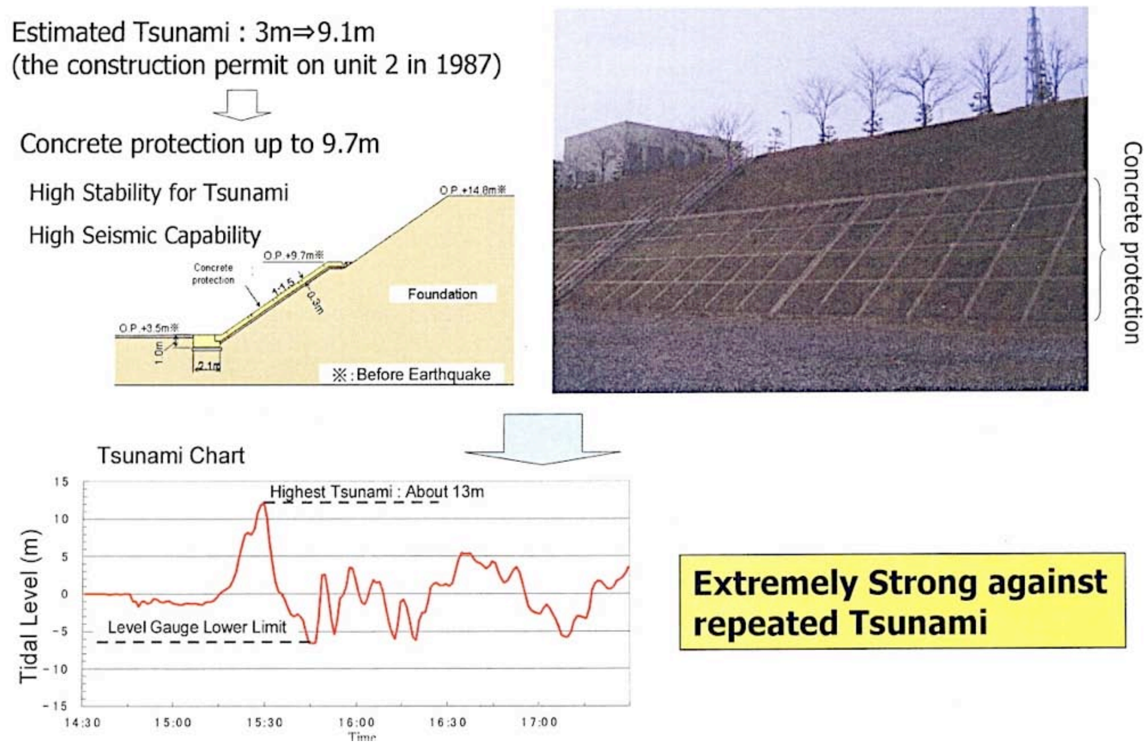

Figure 4-73. Tsunami Chart - Onegawa

John Eidinger and Alex Tang visited the plant on March 2, 2012. Tohoku EPCO staff provided a tour of the facility, and we entered into the Unit 3 Reactor block. The following additional observations are made:

- The reinforced concrete basement walls of the Unit 3 Reactor building showed distress, including many cracks. "X" type cracks (under 1 mm wide, but up to 2 meters long) were observed.

- We observed no distress to pipe supports.

- There was minor spillage of water (due to sloshing) from the Unit 3 spent fuel pool. Onegawa staff report that the quantity of overflow was less than 1/700 of the regulatory report level.

- There was ground settlement outside of the Unit 3 power block. When queried, staff reported that this had not caused damage and was not a priority for repair; lacking any underground utilities through these soils, we would concur.

- The Unit 3 turbine underwent movements (on the order of 1 cm), leading to scratching and hitting of the stator and the low pressure turbine blades. The Unit 3 turbine components had been sent to the manufacturer for repair; possibly needed a few more months before the turbine could be re-used.

- The normal plant staffing at the three unit plant was reported as about 500 people. When we visited in March 2012, there were about 2,500 people on site, and all three units were shutdown. the extra 2,000 people were doing various repair efforts to get the three unit plant ready for re-start.

- Efforts were underway to raise the level of the earthen sea-wall berm by about 3 meters (to over 17 meters).

- The roof of the Unit 3 turbine building has buckled members. Onegawa staff reported that there were plans to rebuild the roof with a concrete diaphragm.

- The Former Administration Building at the site had previously been seismically upgraded using an external braced steel frame.

- The New Administration Building at the site was recently constructed, using base isolation rubber bearing pads. The maximum pad movements during this earthquake were about 12 inches, about half their design capacity.

- There was some damage to the site tower; repairs were underway when we visited.

- The access roads to the site were all damaged by either landslides or tsunami inundation by the earthquake. It took several days to re-open access via road. In the interim, many local residents (non-plant staff) went to the site to gain shelter. Helicopter airlifts of commodities (food, water) were brought in.

When queried about the original tsunami height design basis, plant staff reported to us that the original basis for Unit 1 (1980, based on historic review of tsunami heights) had been 3 meters, then increased to 9.1 meters for Unit 2 (1990), and the earthen sea wall actually built to 14.8 meters. Exactly who was to take credit for the extra-high sea water berm remains unknown, and what role the cut-fill considerations for original plant construction lead to the ultimate height of 14.8 meters remains unclear. In any case, it was fortunate that the sea wall was actually that height, otherwise the sea wall cooling motors would have been inundated; but still unfortunate that in the 2007-vintage seismic re-evaluation, the potential for a higher-than-design basis tsunami had not been thoroughly evaluated and mitigated.

It was clear to us that Tohoku EPCO was investing major amounts of resources (money, people, materiel) at Onegawa, even one year after the earthquake, with the intent to restart the plant. As of the time of writing this report (June 2012), the plant is still not restarted, as is the case for essentially all of the nuclear power plants in Japan. As an investor-owned utility, there is considerable financial risk in making this ongoing investment, if the plant will not be allowed to restart; if the plant is ultimately not allowed to restart, then it will become a large stranded asset. Given the shortage of electric generation available to the country, as well as other factors (global warming, CO2 emissions, rate payer costs for electricity, the impact of planned brownouts for the summer of 2012, etc.), it will be interesting to see the ultimate outcome….

4.3 Performance of TEPCo Electric Power Facilities

4.3.1 System Overview

Tokyo Electric Power company (TEPCo) is the largest electricity company in Japan. Figure 4-74 shows the major components of the TEPCo system.

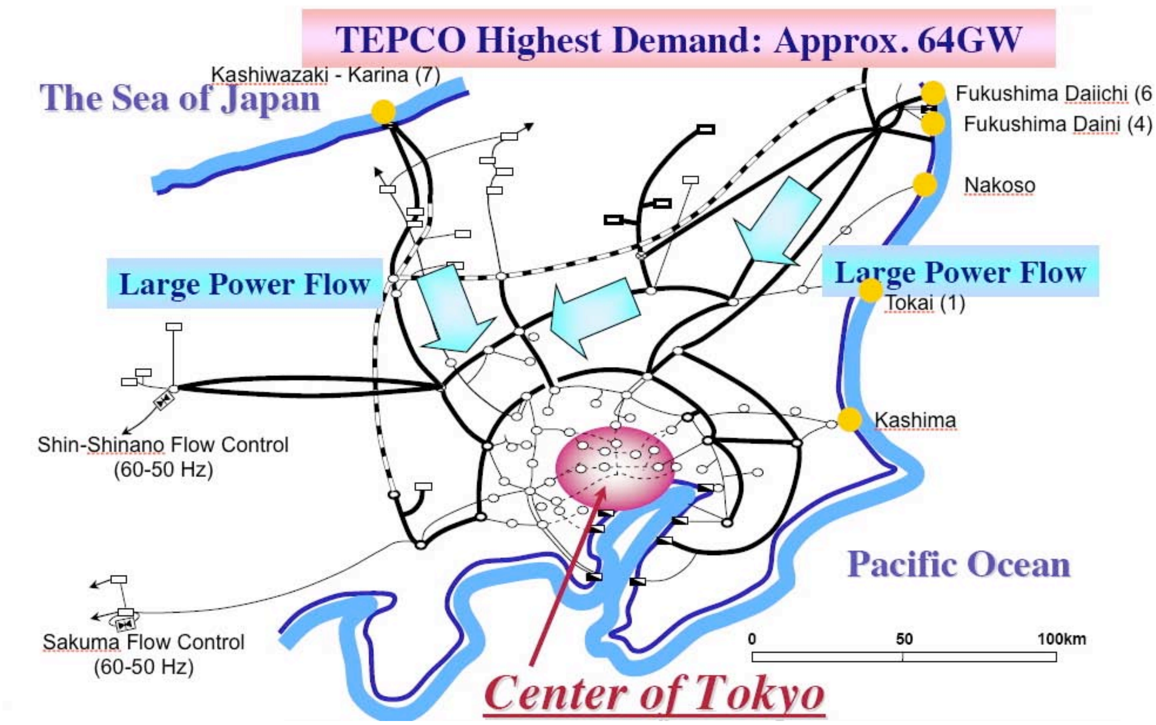

Figure 4-74 TEPCo Grid

As noted in Figure 4-1, Japan's electric grid runs on 50 Hz (TEPCo and Tohoku, eastern Honshu Island) or 60 Hz (western Honshu Island). There are two flow control (60-50Hz converter stations) that allow interchange of power between the two systems. As of March 12, 2011, TEPCo was importing 1,000 MW from western Japan via these flow control stations.

4.3.2 Power Outages

After the earthquake, Prof. Shoji and his students, of the University of Tsukuba, performed a survey of the various towns and cities in and around Tokyo (TEPCo service area), to determine the actual power outages. Figure 4-75 shows the underlying basemap used to establish the JMA intensity for each town and city; these are somewhat different from the values in Figure 2-6, but perhaps reflect more interpretation available to Prof. Shoji.

In total, the dataset included 107 cities and towns that reported no power outages, and 195 cities and towns that did report a power outage. After adjusting for population of each reporting town/city, Figure 4-76 shows the corresponding chance that a particular locale had a power outage, with respect to JMA intensity.

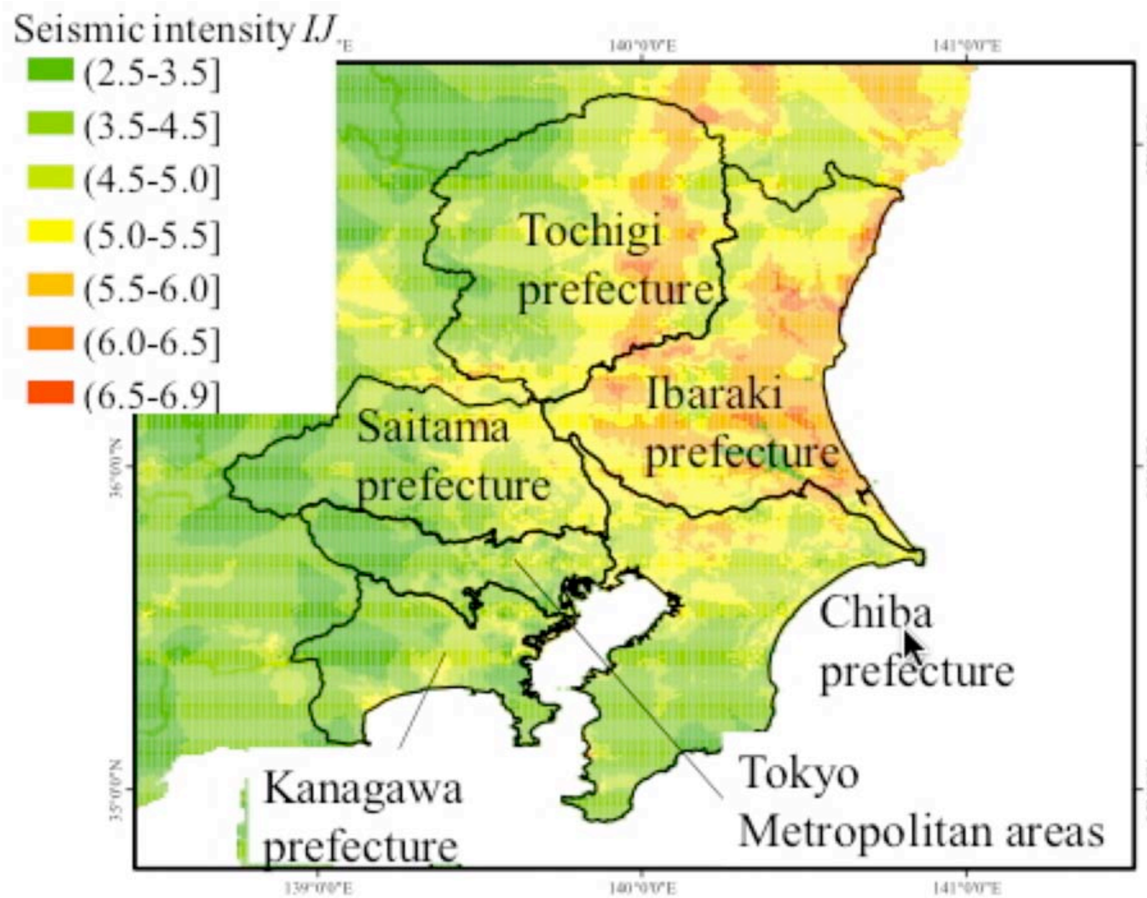

Figure 4-75. JMA Intensities Near Tokyo

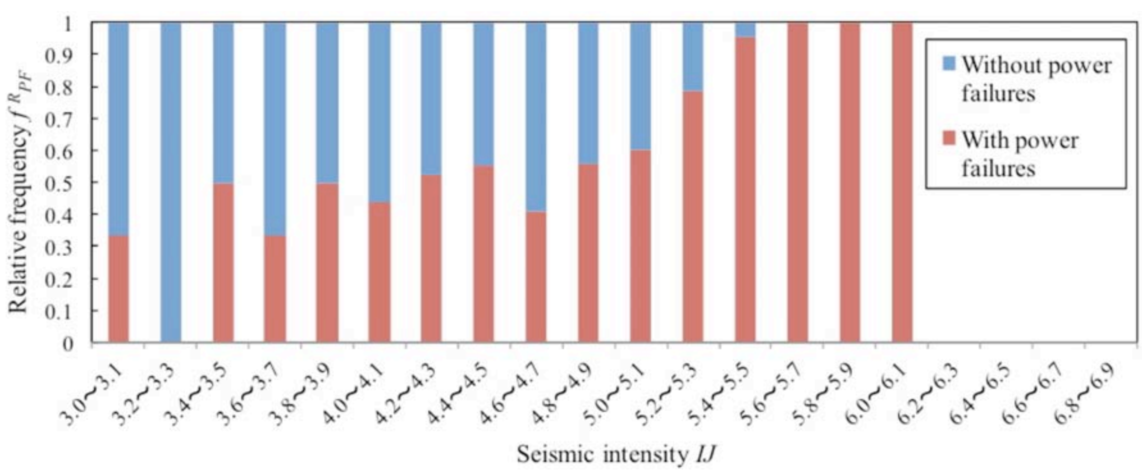

Figure 4-76. Chance of Power Outages Versus JMA Intensity, Near Tokyo

For each locale that had a power outage, (and excluding any that had tsunami impacts), the duration of that outage was recorded. This is tabulated in Figure 4-77.

Restoration period D_{RP} (days)	Frequency(Seismic intensity IJ)				
	IJ=7	IJ=6 higher	IJ=6 lower	IJ=5 higher	≤IJ=4.9
0～0.25	0	0	8	42	59
0.25～0.5	0	1	7	19	16
0.51～1.0	0	3	12	0	1
1.01～1.5	1	2	4	4	0
1.51～2.0	0	6	10	4	0
2.01～2.5	0	1	0	0	0
2.51～3.0	0	10	1	0	0
3.01～3.5	0	0	0	0	0
3.51～4.0	0	7	3	0	0
4.01～4.5	0	0	0	0	0
4.51～5.0	4	1	1	0	0
5.01～5.5	0	0	0	0	0
5.51～6.0	0	2	0	0	0
6.01～6.5	0	0	0	0	0
6.51～7.0	0	1	0	0	0
Summation	5	34	46	69	76

Figure 4-77. Duration of Power Outages Versus JMA Intensity, Near Tokyo

Using the data in Figure 4-77, once can construct "fragility curves" (damage functions) with respect to power outages, and this is shown in Figure 4-78.

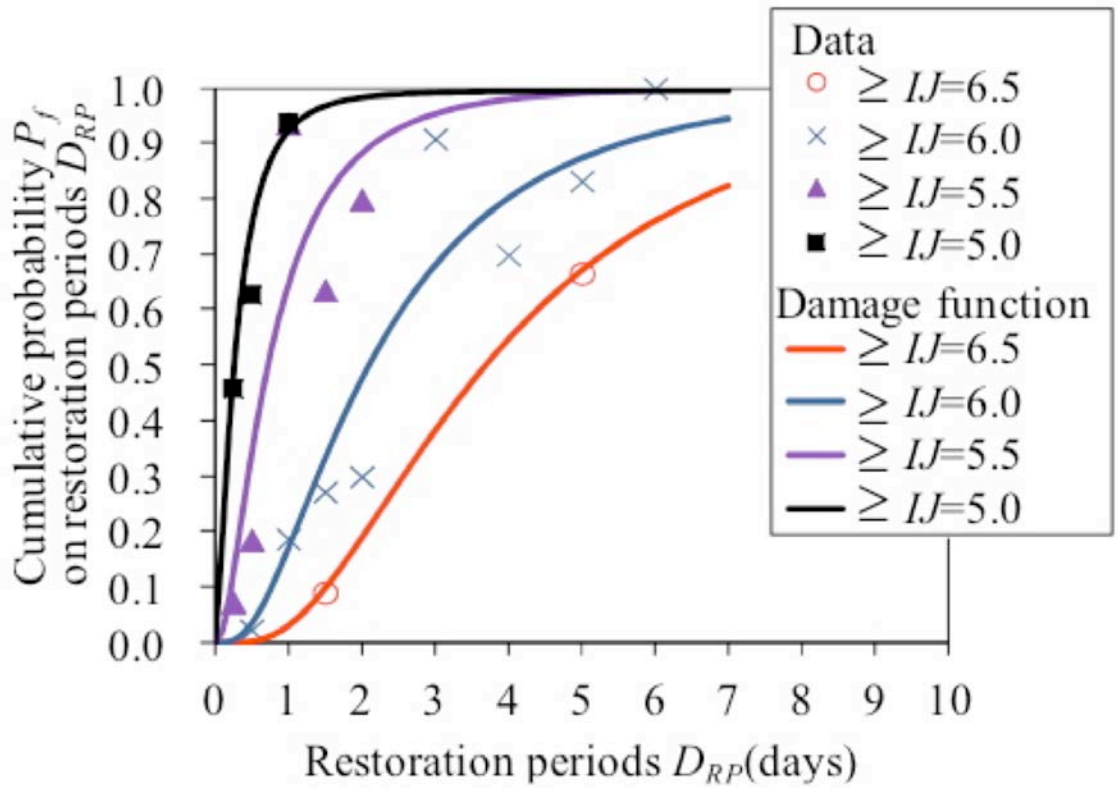

Figure 4-78. Fragility Curves for Duration of Power Outages Versus JMA Intensity, Near Tokyo

The data in Figures 4-75 to 4-78 provide an excellent review of how end users perceive the actual power outages. While this is of great interest, the underlying questions as to "what caused" the power outages, and "what did TEPCo actually do to respond" are not answered by this data. For example, what were the contributions to the outages due to:

- System imbalances after the earthquake
- Loss of generation due to damaged power plants
- Loss of transmission due to damaged substation components
- Loss of transmission due to damaged transmission circuits
- Loss of distribution
- Effects of strong ground shaking
- Effects of permanent ground deformations due to liquefaction or landslide
- The ramp-up of TEPCo staff to make repairs

- The issue of no-go zone in and around the Fukushima nuclear power plant due to radiation

- The efficacy of the Japanese (or IEEE) seismic qualification methods for substation equipment (see Figures 4-2 and 4-3)

4.3.3 Damage at Substations

Figure 4-79 shows damage to a 275 kV bushing. The gasket has been extruded where the porcelain bushing is attached to the forged metal support. This failure mode has been commonly observed in past earthquakes. This type of damage can lead to oil leaks, and while the utility can choose to continue to operate the transformer, there is heightened risk of fire.

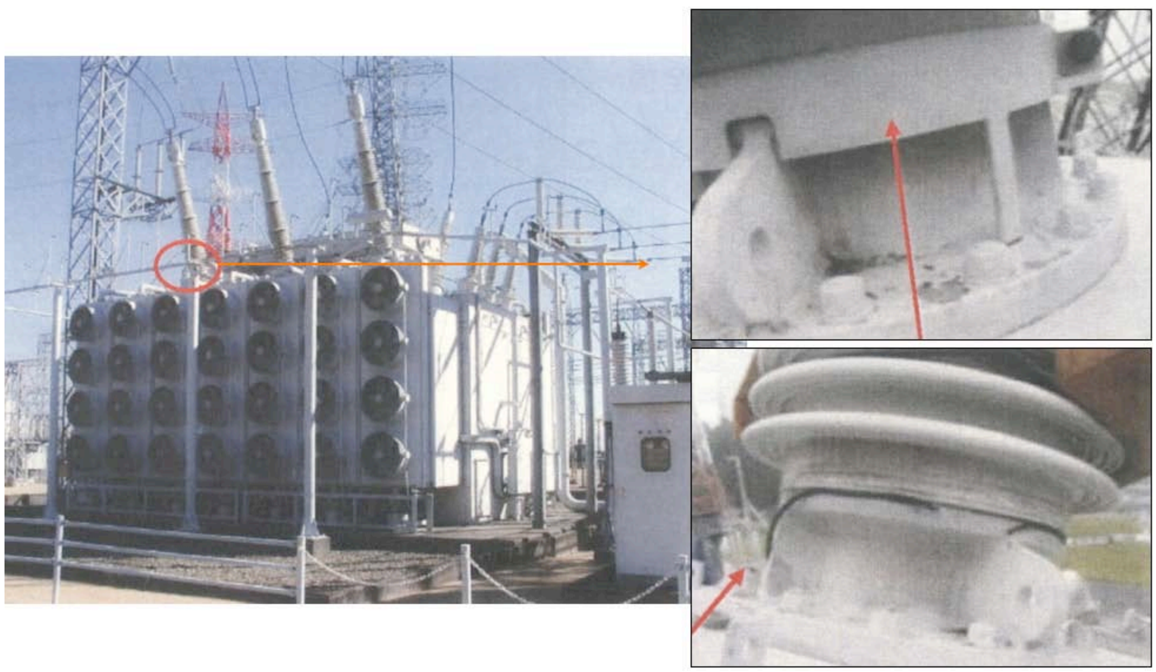

Figure 4-79. Damage to a 275 kV Bushing

Figure 4-80 shows ground settlement adjacent to a 154 kV cable termination device (pothead). It is unknown if the settlement damaged the buried cables.

Figure 4-80. Ground Deformations Near a 154 kV Pothead

Figure 4-81 shows damage to an instrument transformer.

Figure 4-81. Damaged 154 kV Instrument Transformer

Figure 4-82 shows damage to a 275 kV disconnect switch, at the Shin Fukushima substation, located about 7 km west of the Fukushima Daiichi nuclear power plant. Possibly, the damage is due to the rocking of the dead end tower, leading to cable pull on the switch, Figures 4-83, 4-84.

Figure 4-82. Damaged 275 kV Disconnect Switch

Figure 4-83. Damaged 275 kV Disconnect Switch

Figure 4-84. Damaged 275 kV Disconnect Switch

Figure 4-85 shows damage to V-type insulations supporting a double conductor circuit. These insulators are composed of four post segments, and the failure mode appears to have occurred due to high bending along the assembly. the effect of cable dynamics, coupled with amplified motions at the top of the towers, should be investigated.

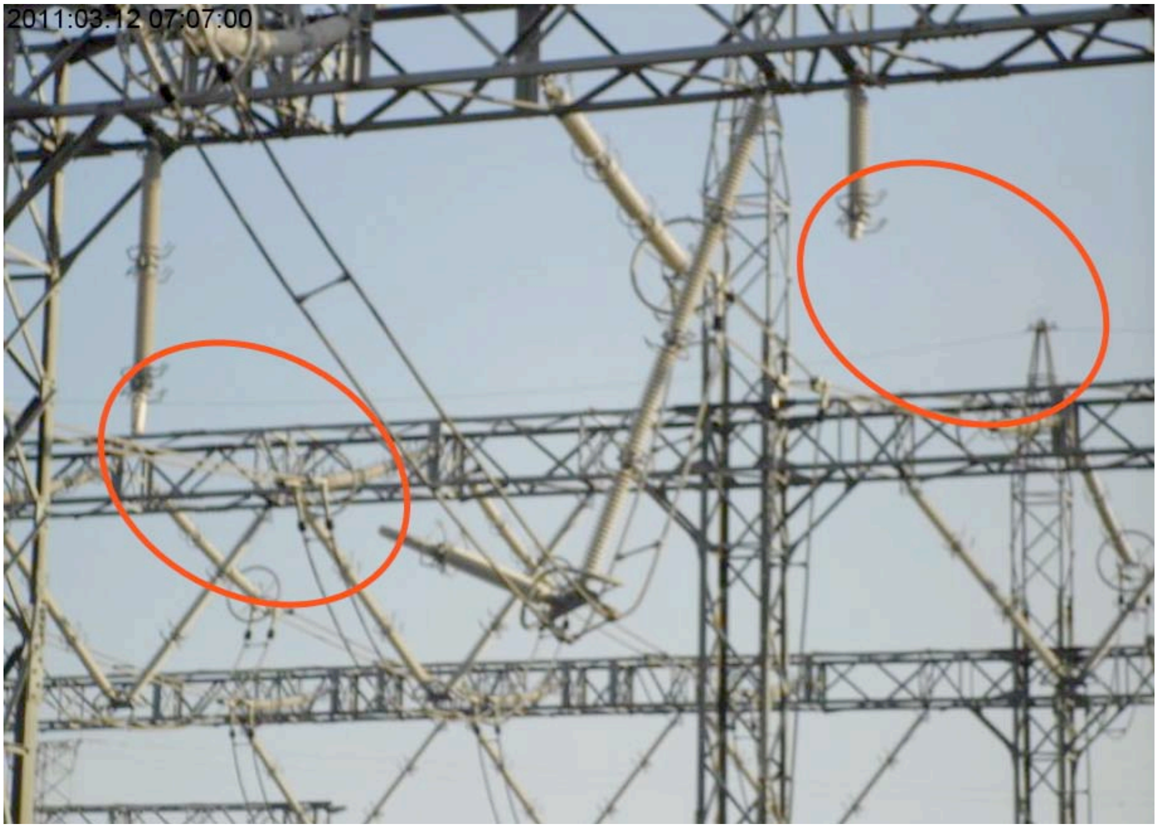

Figure 4-85. V-Type Insulator

Figures 4-86 and 4-87 show damaged 275 kV live tank circuit breakers at the Shin Fukushima substation. These breakers had reportedly been seismically qualified, but failed to possible higher-than-assumed ground shaking at this substation.

Figure 4-86. 275 kV Live Tank Circuit Breakers

Figure 4-87. 275 kV Current Transformers and Live Tank Circuit Breakers

Figures 4-88, 4-89, 4-90 show failed 500 kV disconnect switches at the Shin Fukushima substation. Figure 4-89 shows the failure of the switch post, even though the three "tripod" lateral supports remain intact. Figure 4-90 shows the failure of the one of the tripod legs, even though the central switch post remains intact.

Figure 4-88. 500 kV Disconnect Switch

Figure 4-89. 500 kV Disconnect Switch

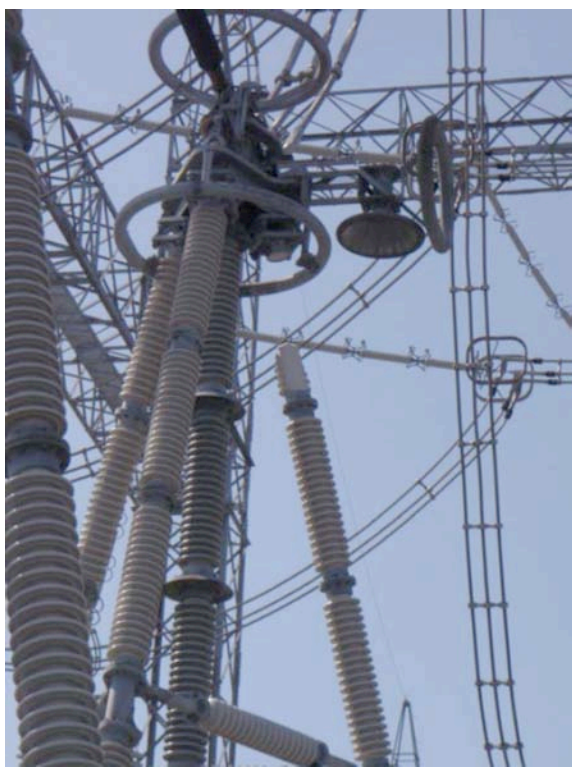

Figure 4-90. 500 kV Disconnect Switch

There was damage to two positions of 275 kV circuit breakers at the Hitachi substation.

4.3.4 Transmission Lines

There was damage to the insulator strings at several towers along a 275 kV transmission line, Figure 4-91. Figure 4-92 suggests the possible failure modes.

Figure 4-91. Damage to 275 kV Transmission Line

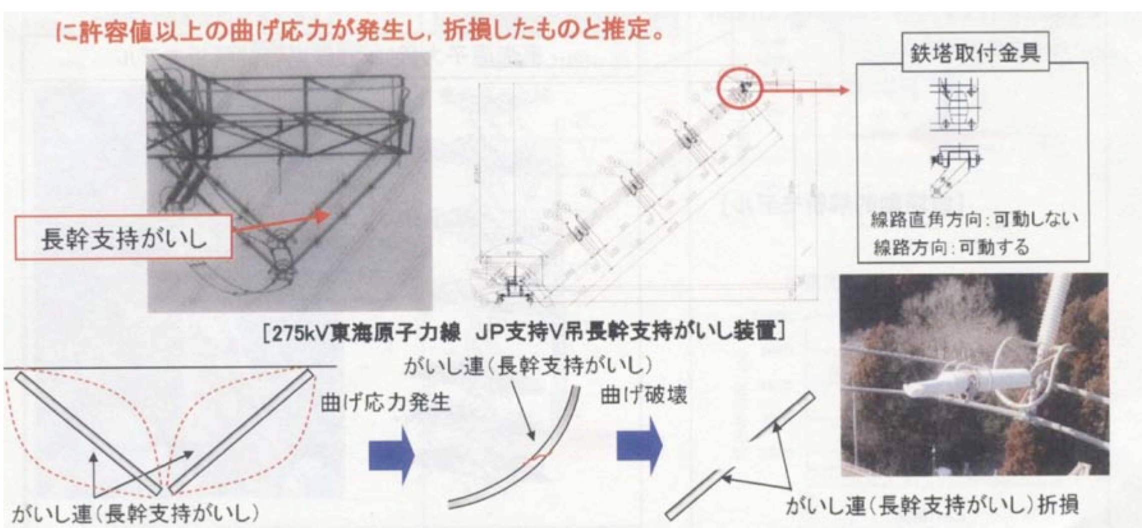

Figure 4-92. Possible Failure Modes to 275 kV Transmission Line

4.3.5 Fukushima Daiichi Nuclear Power Plant

Figures 4-93 and 4-94 show the Fukushima Daiichi nuclear power plant.

Figure 4-93. Fukushima Daiichi Nuclear Power Plant (Before the earthquake)

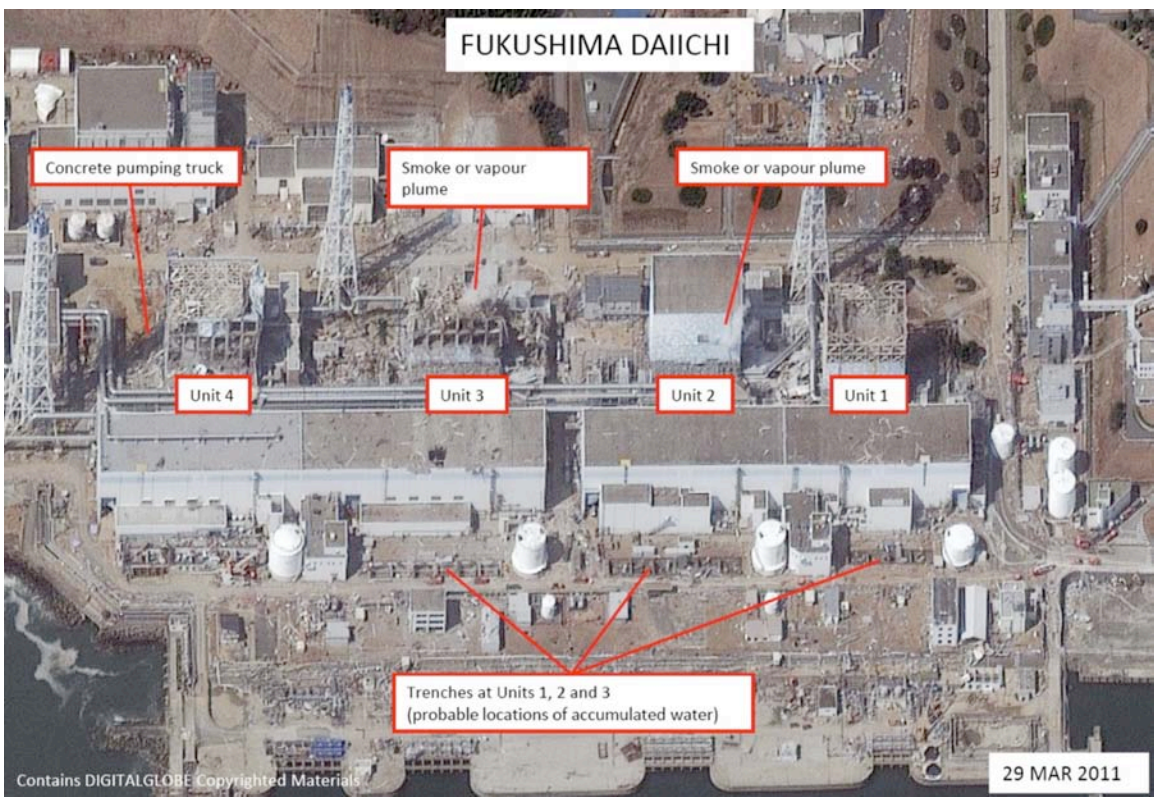

Figure 4-94. Fukushima Daiichi Nuclear Power Plant (After the earthquake and tsunami)

Table 4-16 lists the recorded motions at Fukushima Daiichi, all at the reactor building basemat. The original Unit 1 plant seismic design basis (late 1960s) was PGA = 0.18g, assuming a rock site, and with base shears established using normalized El Centro NS 1970 and Taft EW 1952 ground motions. Since 2007, TEPCo had been re-evaluating the buildings for much stronger ground motions, assuming a deeply embedded structure within a soil site. TEPCo had analyses that that showed that the base and interstory shears from modern analyses (albeit without any limitation on radiation damping) were not much different from those from the original fixed base analyses at PGA = 0.18g.

Unit	NS	EW	Vertical
Fukushima Daiichi 1	460	447	258
Fukushima Daiichi 2	348	550	302
Fukushima Daiichi 3	322	507	231
Fukushima Daiichi 4	281	319	200
Fukushima Daiichi 5	311	548	256
Fukushima Daiichi 6	298	444	244

Table 4-16. Recorded Motions – Fukushima Daiichi (Gal)

Figure 4-95 shows a schematic of the tsunami inundation of Fukushima Daiichi, Units 1 to 4. The site elevation for Units 1-4 is 10 meters above sea level; for Units 5-6 is 13 meters above sea level. The assumed tsunami height had been 5.7 meters in 2002. In the 2011 event, the first big wave (41 minutes after the earthquake) was at 4 meter height; 8 minutes later, the gages broke, but the height of the follow-on wave was estimated at 10 meters. This second wave went over the top of the breakwater and flooded the sea water pumps, making them useless, and then flooded the emergency generators located in the turbine buildings (elevation 0 to +5.8 meters), making all but one of them useless, Figure 4-96 (one emergency generator for Unit 6 was above the inundation level, and worked). The actual water run-up level was 14 meters.

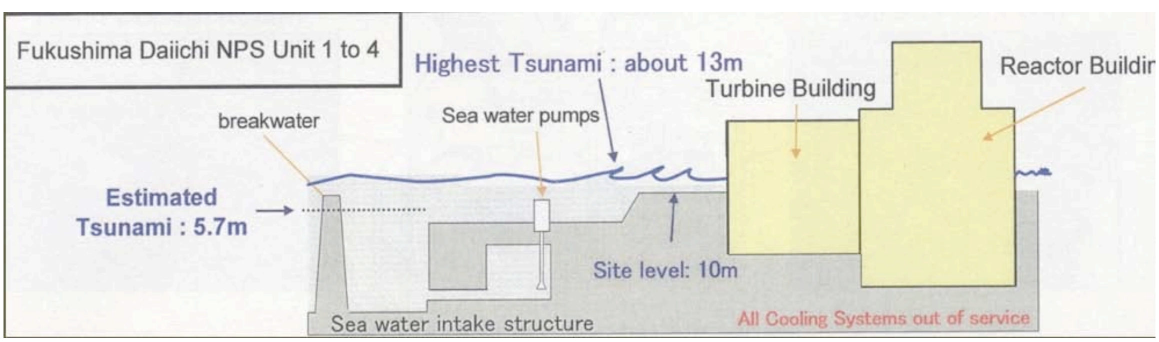

Figure 4-95. Fukushima Daiichi Tsunami Inundation

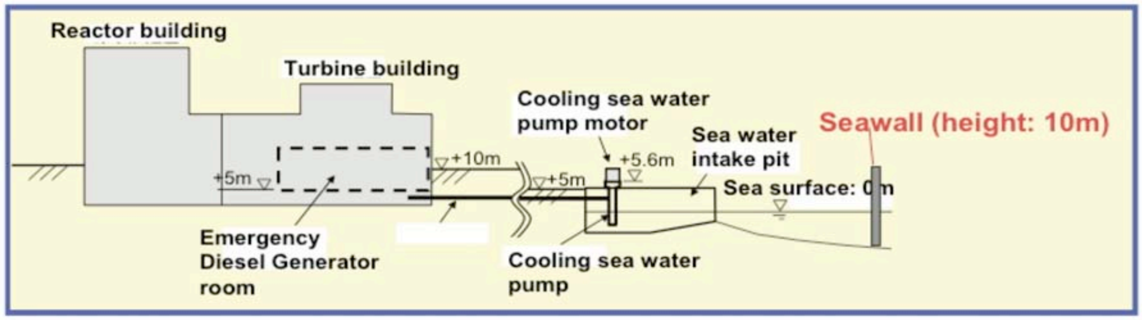

Figure 4-96. Fukushima Daiichi Tsunami Inundation

Figures 4-97 to 4-99 show the tsunami approaching and impacting Fukushima Daiichi.

Figure 4-97. Tsunami Approaching Fukushima Daiichi (photo credit John Luxat McMaster)

Figure 4-98.Tsunami Impacting Fukushima Daiichi (photo credit John Luxat McMaster)

Figure 4-99. Tsunami Flooding the Salt Water Pump Pits at Fukushima Daiichi (photo credit John Luxat McMaster)

4.3.5 TEPCo Supply and Demand

Figure 4-99 shows the actual supply and demand for TEPCo for the year following the earthquake. Due to loss of supply (damaged power plants and forced shutdowns of undamaged nuclear power plants), there was power restrictions put in place for the summer of 2011. This may have to be repeated for the summer of 2012.

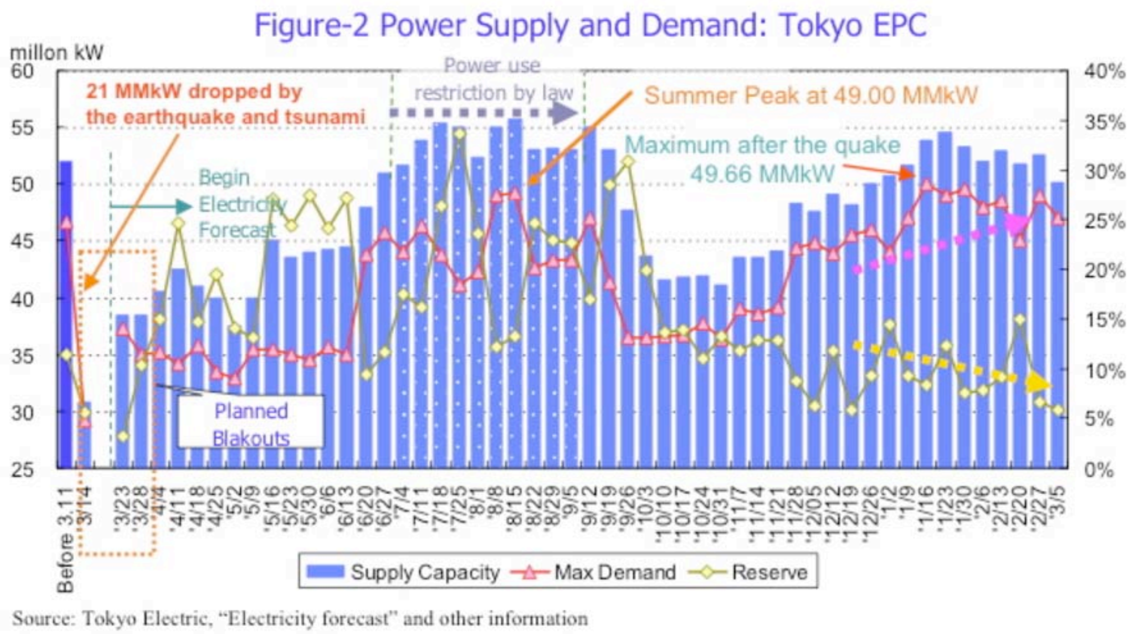

Figure 4-99. TEPCo Power Supply and Demand, March 2011 – March 2012

4.4 Major Observations and Recommendations

The tsunami inundation of power plants along the Pacific coast resulted in major damage to nuclear and non-nuclear power plants. The tsunami heights were larger than originally considered, even for the most recently constructed power plants. Given the geography of Japan, it makes sense to place power plants along the coastline, where they can easily obtain fuel (gas, coal oil), and be provided with ample cooling water. However, given the limited understanding of tsunami heights, event after consideration of past subduction zone earthquakes such as the M 9.2 event in Chile (1960), the design provision for tsunamis was inadequate.

Inertial damage at ground motions typically about PGA = 0.5g and PGV = 20 inches per second, along the coastline, was rather limited. This reflects a high level of seismic design practice in Japan. It would be prudent if US power companies considered similarly high levels of ground shaking, along with very low allowance for post-yielding action; repeatedly, when "code allowed" "R" values are applied, the distortions implied into the buildings result in excessive damage, and especially to critical commodities such as pipes attached to hanging boilers, should uplift of columns actually occur.

Inertial damage at high voltage substation equipment occurred in this earthquake, as it has in essentially every major earthquake around the world. While the Japanese have adopted seismic qualification measures for substation equipment, not all of it worked as intended, either due to higher-than-assumed ground motions, or damage to older, non-qualified equipment.

Inertial damage to insulators on transmission towers occurred. While the total quantity of such damage was small (perhaps under 100 locations out of perhaps 150,000 towers), such damage on circuits leading to/from nuclear power plants can have contributed to unintended increase risk at those plants. the issue of cable dynamics needs to be further considered for circuits to essential (nuclear) installations.

The failure to start of "seismically qualified" emergency generators (such as at Onegawa) demonstrates that qualification by analysis remains somewhat unreliable, even when coupled with good operating / testing practices for emergency generators. A "defense in depth" strategy would seem a prudent approach for providing backup power at nuclear power plants (multiple emergency generators, plus seismically-qualified transmission to offsite reliable sources).

4.5 Acknowledgements

Unless otherwise specified in annotations, all figures and tables belong to John Eidinger and Alex Tang.

Staff of Tohoku Electric Power Company allowed access to three power plants and one substation, and provided overview summaries as to their performance as a whole. Information about TEPCo was collected from various sources; no information was collected directly from TEPCo.

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