SPA Risk

Reconnaissance Report

Aspects of the 11 March 2011 Eastern Japan Earthquake and Tsunami

Charles Scawthorn
Keith A. Porter

SPA Risk

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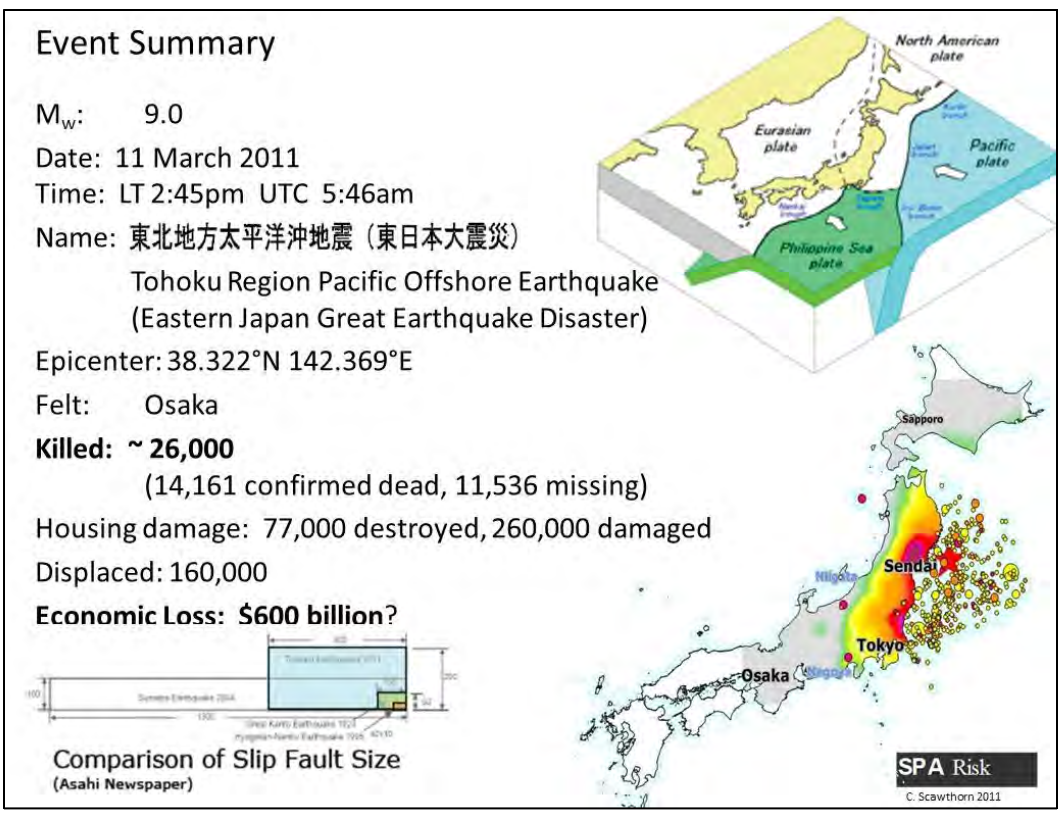
Executive Summary

The figure below summarizes the 11 March 2011 Eastern Japan Great Earthquake Disaster. It was caused by a Mw 9.0 earthquake occurring on portion of the earth's crust termed the Pacific plate, subducting beneath the Okhotsk plate (termed North American plate in the figure). The event occurred at 2:45pm local time, was felt through eastern and portions of western Japan, and resulted in very high peak ground accelerations throughout northeastern Japan. Shaking damage due to these ground motions was significant but paled by comparison with the damage caused by a massive tsunami that arrived approximately 30~40 minutes following the main shock. The shaking and primarily tsunami caused approximately 26,000 deaths and missing persons, and was followed by literally thousands of aftershocks, the largest of which was a Mw 7.9 relatively close to Tokyo. The event had massive impacts on Japan beyond the direct damage – Fukushima I nuclear power generating station was severely damaged by the tsunami, resulting in loss of coolant to several of its units and spent fuel pools, which resulted in massive secondary damage to the nuclear units and release of massive amounts of dangerous radionuclides. As a result, an area of approximately 30 km. radius has been semi-permanently quarantined. A number of other nuclear units were shut down immediately and/or remain shut down for various safety and political reasons, so that Japan has lost more than half its nuclear electric generation capacity for the midterm. The economic cost of the disaster is difficult to assess, but may approach USD 1 trillion when direct damage, global indirect losses, debris, rebuilding, nuclear cleanup and loss of real estate is fully accounted for. Beyond the actual damage, the extensive damage and impacts on Japan's economy has resulted in science, nuclear power and the government being questioned in Japan in an unprecedented manner.



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1. Introduction and Event Summary

This report documents selected aspects of the 11 March 2011 Eastern Japan Earthquake and Tsunami based on personal observation and selected references. No attempt is made to be comprehensive and, following a brief overview of the event, emphasis is on damage and performance of infrastructure, known within the earthquake community as ‗lifelines', with each section is structured in three parts:

- Observations and Performance
- Implications, for both Japan, and for other advanced economies
- Research Opportunities

1.1 Seismotectonic setting and historic seismicity

Figure 1 depicts the overall seismotectonic setting of Japan – Eastern Japan lies on the Okhotsk plate (shown in the figure as the North American plate – recent work has shown that the Okhotsk plate is distinct from the NA plate, which terminates further north along the Ulakhan Fault at the base of the Kamchatka peninsula), while Western Japan lies on the Eurasian Plate. The Pacific plate is subducting along the Japan Trench beneath Eastern Japan, while the Philippine Sea plate is subducting along the Nankai Trough beneath Western Japan. The Philippine Sea plate is subducting along the Sagami Trough beneath the North American plate. (vertical scale exaggerated). The Pacific plate is converging with and subducting beneath the Okhotsk plate at about 40 mm per year, resulting in frequent and large earthquakes. The Japan Trough has a long history of large events, including the 869 Mw 8.3 Jogan, 1896 Ms 7.2 Meiji Sanriku and 1933 Mw 8.4 Showa Sanriku events, all of which produced large destructive tsunamis.

Over the last decade, work has shown that the 869 Jogan event caused tsunami inundation far larger than the 1896 and 1933 events (which were themselves very large and damaging), and that extended at least 4 km inland (K. Minoura, 2001) In 2003 (Satake et al., 2007) rated the likelihood of this event at ―99%in the next 30 years".

1.2 Ground shaking

Figure 2 shows one depiction of the basis for Japan seismic hazard maps, taken from the J-SHIS website. Onshore is a depiction of seismic hazard, and offshore are historic subduction zone earthquakes (yellow) overlaid in some places by zones (green) where they may occur. The blue-highlighted zone is one of these (green) zones, in which a maximum Mw 8.2 event is postulated to occur about once every 575 years.

Figure 3 shows the main shock epicenter and aftershocks through 30 March, overlaid on the fault slip distribution as determined by Japan‗s National Research Institute for Earth Science and Disaster Prevention (NIED). Also shown are the smoothed contours of peak ground acceleration (PGA, g) as measured by K-NET. Very high accelerations were recorded all along coastal Eastern Japan, with especially high ground motions around Sendai.

Figure 4 compares the 2011 main shock with several other events, showing the very long duration of the 2011 main shock – approximately 150 seconds.

However, despite these very high long duration ground motions, surprisingly little building damage, landsliding, liquefaction or other effects normally associated with strong ground shaking were observed.

1.3 Tsunami runup

Figure 5 shows a detail of coastal Miyagi prefecture with land elevations colored – all colored areas are less than 6m above sea level, so will be inundated by a 6m tsunami. Figure 6 shows actual runup heights, which in the area in Figure 5 can be seen to have exceeded 10m. Figure 7 shows the port of Onagawa, with a runup height of approximately 11m.

2. Relevance for the US

The 11 March 2011 Eastern Japan Earthquake and Tsunami is extremely relevant to the US in that, after the US, Japan until recently has been the next largest economy in the world. In many ways it is the most similar economy to the US, with many commonalities in critical interconnected infrastructure, advanced technologies and density of capital investment. The combination of major seismicity and advanced economic development is perhaps unmatched anywhere else on earth. This has been recognized for a long time – indeed, over a quarter century ago, an EERI mission to Japan in regard to the ‗anticipated Tokai earthquake‘, concluded:

> *When the Tokai earthquake occurs, it will be a great earthquake in a large modern, heavily industrialized society. This is a phenomenon with which we have relatively little experience, but which is a very serious problem facing our society. There exist striking parallels between the situation in the Tokai region and the situation in the Los Angeles Basin, where a long term prediction of a great earthquake on the south central segment of the San Andreas fault has been made (FEMA, l98l). The Japanese are coping with a situation now that Southern California may have to cope with in the near future.* (EERI, 1984).

While these observations drew parallels between the anticipated mid-Japan Tokai event, and the Los Angeles basin, the parallels of the above observation are also aligned very closely for the 11 March mega thrust event, and the anticipated Cascadia subduction zone earthquake.

Indeed, the 11 March event and the anticipated Cascadia subduction zone earthquake are eerily similar. Figure 8 shows Japan and the aftershock pattern of the 11 March event overlaid on the Pacific coast of North America (Japan is at the same scale, but ‗flipped‘ about its N-S axis). The aftershock pattern of the 11 March event coincides almost exactly with the estimated rupture surface of the anticipated Cascadia subduction zone event.

The 11 March event is also relevant for the US in other ways:

- The damage to conventional and nuclear power plants has resulted in a loss of about 20% of the region‘s electric power generation capacity, which Japan is struggling with as the peak summer demand approaches. How Japan scrambles to meet its power shortfall can be very instructive for the US. The broader economic impacts of this electric power shortfall also illuminate the elasticity of our dependence on electric power.
- The global supply chain has been significantly disrupted by this event, with factories in Europe, Asia and North America idled due to the unavailability of key components, which may lead to a critical review and new lessons for the ‗just in time‘ supply model.
- The damage to two major oil refineries and related energy infrastructure in 11 March event resulted in gasoline shortages in the affected area for several weeks. A major Southern California earthquake could result in commensurately greater disruption to the gasoline supply in Southern California, obviously critically dependent on this crucial commodity, due to damage to the large number of oil refineries, tank farms, and related facilities in and around Long Beach. These facilities are responsible for half of California‘s gasoline and one third of the refined gasoline west of the Rockies.

Lastly, the on-going crises at the Fukushima Daiichi nuclear power plant are very relevant to the US, which has over 100 nuclear power plants, many of comparable design. The lessons to be drawn from the great difficulties in dealing with this disaster are of great value for the US, as well as the indication of the true cost of nuclear power.

3. Lifelines Aspects

This section discusses the performance of lifelines in the 11 March 2011 Eastern Japan Earthquake and Tsunami, with most emphasis placed on the effects of the tsunami. Lifeline sectors discussed are water and wastewater, transportation (roads, railroads, airports, ports and harbors) and energy (electric power, oil and liquid gas fuels). Each sector is discussed from three aspects – observations of the PEER-EERI team on the performance, the implications that can be drawn from this performance, and the research opportunities that arise therefrom.

3.1 Water and Wastewater

Observations and Performance: Water and wastewater was significantly affected by earthquake and tsunami, but recovered relatively quickly. The PEER-EERI team did not focus on this aspect, and no water or wastewater facilities were visited. Damage to buried water and wastewater pipes and appurtenances were as observed in previous earthquakes – in most cases due to permanent ground displacements and liquefaction, Figure 9. No information is available regarding damage to water intakes or treatment plants, and similarly no information is available regarding wastewater treatment plants, although some of the facilities were undoubtedly damaged by the tsunami, and should be researched in subsequent investigations. Figure 10 and Figure 11 show damage to buried pipe due to tsunami scour, and a destroyed stream crossing. Figure 12 to Figure 14 show affected areas and numbers or fractions of affected customers, while Figure 15 shows the recovery of water supply in the four prefectures (Iwate, Miyagi, Fukushima, and Ibaraki), where approximately 2.21million customers had service restored.

Implications: A large number of customers lost water supply, which was also not available for firefighting. Water supply was restored relatively quickly to many customers. Effects of the tsunami are as yet unclear but probably significant.

Research Opportunities: The damage to water pipes due to liquefaction and permanent ground displacements are probably a rich source of data for correlation and development of damage functions. This event offers in many ways the first opportunity to observe the effects of tsunami on modern water supply and waste water treatment plants. Impacts of the loss of water supply on post-event firefighting are unknown but may have been significant, and should be researched. The methods by which Japanese utilities quickly restored water should be documented.

3.2 Transportation

This section discusses four transportation modes: Roads (highways and bridges), Railroads, Airports and Ports and Harbors.

3.2.1 Roads

Observations and Performance: Shaking appears to not have caused significant damage to road bridges or tunnels. No damage was observed to tunnels (even when inundated by the tsunami) and very little damage was observed to bridges due to tsunami. Settlement at abutments, which is observed in virtually all such events, was observed at many crossings in this event. A few roads sustained damage due to landslips or liquefaction. In almost all cases, roads were quickly restored to service. The Tohoku Expressway is the major N-S transport and commercial artery connecting Northern Japan with the Kanto region and with numerous factories located along the route. Of a total length of 675 km, about 347 km was damaged in the earthquake on March 11 (virtually all due to shaking, not tsunami, but traffic restrictions were lifted on March 24th, following the completion of emergency restoration measures.

On the other hand, the tsunami destroyed a number of bridges. Figure 16 shows a bridge abutment that sustained massive scour and loss of the superstructure due to the tsunami, while Figure 17 shows massive damage to a multi-span river crossing. Figure 18 shows Sections of a through truss steel bridge swept away by tsunami on the Kitakami River, about 5 km upstream from river mouth. Other sections survived, and had debris on the downstream truss faces, and it is surmised the destroyed sections accumulated greater debris, with resulting greater drag and lateral force from the incoming tsunami. Figure 19 shows massive scour to a lower lying section of coastal road. Repairs had not yet begun on the bridge shown in Figure 18 as of June 2, which was surprising as the bridge was an important bridge and its loss caused a major time consuming detour and congestion.

Implications: Road bridges appear to have generally sustained shaking without damage, but the tsunami caused the failure of a significant number of bridges. Coast roads are vulnerable to tsunami scour, and disruption due to failed bridges.

Research Opportunities: The following research opportunities exist:

- Selected case studies of tsunami forces on bridges, and their survival or failure, would be useful for development of bridge tsunami fragility functions. Such studies might also lead to improved methods for avoidance of debris-related drag forces.
- Scouring of pavement was observed at several locations, and should be studied to understand the fundamental mechanisms and ways for reducing this damage.
- Economic impact due to loss of road facilities will be a fruitful area of research – much theory but little real data exists in this area, and the extensive road network and major economic infrastructure of the region is an ideal opportunity.

3.2.2 Railroads

Observations and Performance: Compared with roads and highways, rail structures sustained very significant shaking damage as well as massive tsunami damage. Figure 20 shows the rail network in the region, overlaid on peak ground acceleration. There are four major north-south rail lines – two coast lines (Pacific coast, on eastern side of Honshu; and Sea of Japan line, on western coast) and two major interior lines. Only two of these lines were significantly affected – the Pacific coast line was destroyed in many locations due to tsunami, and the easterly interior N-S line (the Tohoku shinkansen route) was damaged in many locations due to shaking. Figure 21 shows typical shaking damage to viaduct frames, and to overhead electrical catenary structures (respectively depicted as green and orange ―X"s in the map). The structural shaking damage is discussed elsewhere in this report, and portions of the shinkansen line were restored to service on April 12th , an impressive achievement (due in part to significant experience in repairing such structures in several earthquakes since the 1995 Kobe event). None of the 26 trains operating at the time of the earthquake derailed, nor was there any serious damage to the Shinkansen elevated bridges and stations, or collapse of tunnels. The entire Tohoku Shinkansen resumed operation on April 29th.

The coastal route on the other hand sustained major damage at a number of locations, Figure 22 to Figure 25. A number of rail bridges were swept away, road bed destroyed by scour and stations destroyed by the tsunami. Reportedly, all trains received warning of the approaching shaking and stopped and disembarked passengers who fled to higher ground, so that no passengers are reported to have been injured in this event, an impressive achievement. Some trains were undamaged but stranded due to damage to the rail lines in front and behind the section where they stopped.

On 27 April, JR East announced decrease in operating revenue of JY 59 billion (JY 42 billion due to transportation, remainder due to other operations), equivalent to about USD 7.5 billion, and damage costs also of JY 58.7 billion (USD 7.5 billion).

Implications and Research Opportunities include:

- As with roads, selected case studies of tsunami forces on rail bridges, scouring of track and signaling and the economic impact due to loss of rail lines are all fruitful areas of research.
- The Shinkansen was damaged, even though it had been retroffited in some locations. The line dates from the 1970s and its vulnerability was generally understood. The rapidity of repair as impressive and might offer lessons for other operators.
- The coastal route has suffered major damage, and repaires will take longer. Interim service will probably be accomplished with buses, but the costs of such disruption will be useful data from an economic modeling perspective.
- Study of this event and the 2004 Indian Ocean tsunami may provide a useful data set for identification of tsunami vulnerability and susceptible routes.

3.2.3 Airports

Observations and Performance: Two commercial and one military airport were affected by the tsunami. The larger of the commercial airports, Sendai International, had opened four years earlier, and sustained about 2 meters of tsunami runup, Figure 26. Military assets were employed to restore operations, with the runway operational on 28 March and the airport resuming commercial operations on 13 April.

Implications and Research Opportunities: Japan‘s national air traffic was disrupted, both by damage to several airports as well as diversion of flights from Narita (Tokyo‘s main airport) as a precaution. While air traffic was restored quickly, the procedures and possible problems associated with this disruption are worthwhile documenting. More useful perhaps would be full documentation of selected case studies of tsunami effects on air terminals, hangers, signaling and appurtenances, an improved understanding of scouring effects on the runway pavement and other facilities, and capturing of economic impact data due to the loss of air transport.

3.2.4 Ports and harbors

Observations and Performance: Ports and Harbors were of course heavily impacted by the tsunami. Figure 27 shows the affected ports which represent about 7% of Japan‘s port capacity, while Figure 29and Figure 31 show damage to commercial facilities. About 500,000 tons of large vessel tonnage were grounded or otherwise damaged by the tsunami, Table 1.

Also heavily affected was the Eastern Japan fishing fleet, which had about 19,000 fishing boats destroyed, Figure 28, representing more than one third of the entire fleet.

While quays of all ports were reportedly usable by 24 March, the ports of Soma and Onagawa were deadly quiet when visited on 2 June, and many quays and other facilities sustained significant permanent ground displacements and other damage that will take months or longer for repair. The port of Sendai, however, while sustaining major damage was partially back in operation.

Implications and Research opportunities: The major damage to ports, warehouses, fishing fleet and other capital facilities is very significant, and worth documenting from a fragility perspective. Even more valuable is the data collection and understanding of the loss of marine transport on the regional economy, particularly with regard to the ‗just in time‘ economic model employed in Japan.

3.3 Electric Power

Damage to the power system and resulting consequences were one of the most important results of the earthquake and tsunami. This section first provides a summary description Japan‘s electric power system, then reviews performance in the event, and concludes with Implications and Research Opportunities.

Overview: Japan‘s electric power is furnished by ten electric power companies, whose service areas are shown in Figure 32. Only two of the companies sustained significant direct damage as a result of the earthquake and tsunami, Tokyo Electric Power Co. (―TEPCO") and Tohoku Electric Power Co. (―Tohoku"). Data on the companies‘ size is shown in Table 2 and Table 3, from which it can be seen that TEPCO supplies 32% of all power in Japan, while Tohoku supplies about 9%.

Electric power is generated by virtually all prevailing technologies. However, as seen in Table 4, 90% of all power comes from only two sources: thermal (67%) and nuclear (27%k see Figure 42), with hydropower (7%) making up the next largest source.

Power is transmitted over an extensive network of extra high voltage (EHV) overhead transmission lines, Figure 33. Japan is unusual in having a 60 Hz system in the west and 50 Hz system in the east with three frequency converter stations linking the two systems (Higashi-Shimizu, Shin Shinano and Sakuma) with a total transmission capacity of 1 GW, Figure 34. That is, eastern Japan (i.e., the TEPCO, Tohoku only, we exclude the Hokkaido service area) have about 40% of the generation capacity (81 GW of 204 GW nationally, and 42% of the consumption, but can only be linked to western Japan via the three frequency converter stations, which have a combined capacity of 1 GW. Additionally, the Kitahon Interconnection Facility links northern Honshu to Hokkaido, with a capacity of 600 MW. In essence, the TEPCO/Tohoku network is almost entirely self-contained, with a maximum input from other networks of 1.6 GW, or 2% of its own generation capacity.

Regarding peak demand, Tohoku indicates its 2009 August demand was 14.9 GW at which time it had a capacity of 16.7 GW, or a reserve of 11.9%, while TEPCO's 2010 peak demand is 56.65 GW versus capacity of 61.3 GW, or a reserve of 8.3%.

Performance and Observations: Seven nuclear and three thermal power units were down for scheduled maintenance or inspection at the time of the earthquake. Together with th earthquake and tsunami, the total loss of generation capacity declined from a normal level of about 80 GW to about 30 GW, while demand was about 44 GW. The result was blackouts across a wide swath of Eastern Japan, Figure 35 and Figure 36. The most significant impact of course has been at Fukushima I power station, where three of the six units have experienced explosions and melted fuel to varying and still incompletely known degrees, as well as a spent fuel pool fire. Our team had no access to the power generation facilities, and have compiled the following from power company, Japanese government, news media and other sources:

- **Fukushima I:** The earthquake resulted in accelerations of 0.52 to 0.56 g, Figure 41, and triggered shutdown of the three active reactors, which has six units with a total generation capacity of 4,696 MW. Offsite power was lost due to a landslide taking out one transmission line, Figure 40 and bushing and other damage at the Shinfukushima substation, Figure 39. The tsunami that followed then stopped Fukushima I station's backup diesel generators, causing a station blackout. The subsequent lack of cooling led to explosions and partial meltdowns at the Fukushima I facility, with problems at three of the six reactors and one of the six spent fuel pools. No units have been restarted due to obvious damage, Figure 37. Damage has been attributed to the tsunami rather than earthquake shaking, but recent information indicates there may have been radiation leaks prior to the arrival of the tsunami[1].
- **Fukushima II:** The earthquake resulted in PGA of 0.21 to 0.28 and triggered shutdown of all four active reactors which have a total generation capacity of 4,400 MW.. Damage has been attributed to the tsunami rather with no suggestion that earthquake shaking caused any damage.
- **Onagawa**: while a fire occurred in the turbine room (non-nuclear portion of the plant), the extent of damage is unclear at this time. The plant appears to have been above, and undamaged by, the tsunami. Similar to the above observation, Onagawa is shut down at least for safety inspections.
- **Tokai**: The one unit (1100 MW) shut down automatically and remains shut down. It apparently has damage to cooling systems.
- **Higashidori**: this one unit is significantly farther from the earthquake, and does not appear to be have been affected by the tsunami. In any event, it was and remains now down for scheduled maintenance.
- **Kashiwazaki-Kariwa**: this is the world's largest power station, with seven units (total 8,212 MW). It is significantly farther from the earthquake, and did continued normal operation. In any event, units 2-4 (3,300 MW) were down (and remain so) for scheduled maintenance, while units 1,5,6,7 continue generation (4,912 MW).

The effects on nuclear generation are summarized in Figure 42. Generation at a number of thermal power stations has been lost, for varying period of time. The 2 GW coal-fired plant at Soma for example was inundated to perhaps 1 m by the tsunami, but will reportedly be shut down for a year. Generation at a number of hydro power stations was lost but restored relatively quickly. No detail on individual

1. Japan's Fukushima Reactor May Have Leaked Radiation Before Tsunami Struck *By* Yuji Okada, Tsuyoshi Inajima and Shunichi Ozasa - May 19, 2011 7:21 PM GMT+0900, http://www.bloomberg.com/news/2011-05-19/fukushima-may-have-leaked-radiation-before-quake.html

stations is available, and the advantage of pumped storage (i.e., off-peak energy storage) is partially negated by the lack of nuclear and thermal generation.

In summary, as compared with a pre-event generation capacity of 81 MW, the net effect on generation in the TEPCO-Tohoku service area was an initial loss of 51.9 GW (64% deficit) of generation following the event, with recovery by the next day to a deficit of 35 GW (43% deficit), and then gradual recovery so that by 20 April the deficit was 27 GW (33% deficit).

The 20 April remaining capacity (54 MW) is being supplemented by 1.6 GW of import via interties, as needed. As quickly as possible TEPCO is also bringing back on line several mothballed units and installing gas turbines, such that it will add several GW of capacity by August.

On 15 April, TEPCO issued the following announcement (note this applies only to the TEPCO service area):

> ―…the power supply capacity for this summer in TEPCO is estimated at around 46.50 million kW, far below the expected peak demand, 55.00 million kW (daily peak at generation end). The peak demand of last summer, which the temperature was considered to be extremely high, recorded 59.99 million kW (July 23, 2010) Thereafter, we have been concentrating our efforts in strengthening the capacity … to upwardly revise the capacity for power supply this summer, at around 50.70 million kW to 52.00 million kW. However, the power supply capacity for this summer is still expected to fall below the peak demand. Therefore, we will continue to exert utmost effort to strengthen the capacity for power supply, in order to continue avoiding the rolling blackouts. We would also like to ask our customers to cooperate in reducing electricity consumption in summer time….‖[2]

There are thousands of EHV transmission towers in the affected area – a few failed due to landslides or the tsunami. Substations were damaged both by shaking and tsunami. Detailed information is still to be compiled.

In summary, compared to the tsunami, shaking and associated effects (liquefaction, ground failure) had little effect on the overall electric system, but was still critical in isolating Fukushima I from offsite power. The tsunami affected some EHV substations and T&D, but its major impact was on generation stations on the coast, resulting in a sustained loss of about 11% of Japan‘s generation capacity (about twice this for the affected area, including Tokyo) that will result in stringent enforced and voluntary conservation and ‗rolling brownouts' this coming summer. Of course, the on-going crisis at Fukushima I is yet to be played out, but has already resulted in accelerated retirement of nuclear units in some countries, and may result in a longer term re-examination of nuclear power overall.

<u>Implications and Research Opportunities</u>: The event revealed the vulnerability of coastal power stations to tsunami, particularly nuclear power stations (due to their need for sustained cooling, and the catastrophic consequences if this is not provided). This alone calls for a review of nuclear and non-nuclear generation anywhere – Los Angeles for example has a significant amount of its thermal generation right on the coast. The performance of the Eastern Japan power grid is worthwhile documenting. Documentation of the specific effects of tsunami and seawater intrusion at power facilities is worthwhile understanding, as a first step towards tsunami ‗proofing' of waterside generating stations. The economic and social impacts, and social

[2] TEPCO Press Release 15 April 2011, Power Supply and Demand Outlook in This Summer and Measures (2nd Release)

adaptation/resilience, of the foreseeable electric power shortages this summer are worthwhile studying as they occur.

3.4 Gas and Liquid Fuels

Observations and Performance: Only sparse information is available on the performance of gas and liquid fuel systems in this event. A large number of oil refineries were in the affected area, mostly around Tokyo Bay, where they were not heavily shaken nor affected by the tsunami. However, one of these, at Chiba, did sustain a major tank fire, Figure 43. Further north, the ENEOS refinery at the Port of Sendai was inundated by the tsunami, resulting in a significant fire and spillage of rail gas tank cars, Figure 50 and Figure 51. Shortages of gasoline were endemic in Fukushima, Miyagi and Iwate prefectures for several weeks following the event.

Implications and Research Opportunities: The oil refinery performance has direct relevance to the concentrations of oil refineries in the San Francisco Bay Area and Los Angeles/Long Beach areas. The damage and non-damage in this event in the large number of oil refineries in the affected area should be documented, as well as the precise causes of the gasoline shortages.

3.5 Telecommunications

Observations and Performance: No specific investigation was made of the telecommunications performance in this event. Telecom seems to have functioned well, but this needs to be confirmed. One item of note was the real time earthquake warnings broadcast over cell phones, which at least twice alerted the team, once when they were in a damaged building (they evacuated quickly).

Implications and Research Opportunities: The apparent good performance of the Japanese telecom network is impressive and should be studied further. The US does not have a real time earthquake warning system. Why not?

4. Fire following earthquake

Observations and Performance: Approximately 345 fires were caused by the earthquake throughout the affected area, of which about 260 were ‗prompt' (ie, during or very soon after the event). Examples of a few of the fire sites observed by the team are shown in Figure 43, Figure 44, Figure 45 and Figure 50. The distribution of these fires is shown in Figure 47, Figure 48 and Figure 49, overlaid on peak ground acceleration and population density, respectively, and the correlation with both is seen to be strong. Sendai sustained about 60 fires, including one in the ENEOS oil refinery, Figure 50 and Figure 51, and a number in industrial facilities around the port, Figure 45. The ENEOS fire was most probably due to tsunami. An LNG tank at the refinery did not catch fire. Another major oil refinery occurred at the Cosmo oil refinery in Chiba, Figure 43, and was due to shaking not tsunami, while a number of other oil refineries around Tokyo Bay did not have fires. About 30 fires occurred in the Tokyo Metropolitan area – Tokyo has the largest fire department in the world, and these 30 ignitions did not pose a serious risk. Smaller towns that were heavily damaged by the tsunami, such as Kessenuma, Miyako and Onagawa, also had damage to their fire engines, Figure 46, and in some cases had significant conflagrations, Figure 44.

Implications and Research Opportunities: The approximately 345 fires that followed the earthquake were due to both shaking and tsunami and included several urban conflagrations, two major oil refinery fires (1 shaking, 1 tsunami), the destruction of a train of rail gas tank cars and over 60 fires in Sendai and 30 in Tokyo, show that fire following earthquake remains a very significant risk in selected urban locations, such as Japan and Western North America. The experience of the oil refineries in this event, both good and bad, undoubtedly contain useful lessons for the aggregation of oil and liquid gas facilities in and around San Francisco Bay and the Los Angeles / Long Beach areas. Research should be conducted to fully document the ignitions in this event, their spread and the damage to firefighting water supply and equipment.

5. Economic Impacts

The overall economic impacts of this event will not be known for a long time and depend to a significant extent on decisions made during the emergency response and recovery periods, which are still ongoing. The current estimate of direct damage to capital stocks is JY 16~25 trillion (USD 200~300 billion) (METI, 2011). The net effect on GDP over the next three years is expected to be positive (i.e., rebuilding adds to the economic activity) but only a fraction of the loss to capital stocks. The net loss to capital stocks is only about 1% of Japan's total capital stock, and the impact on GDP, while positive, is also only a small fraction of overall economic activity. About 60% of basic production facilities had restored production by the end of May, only 7% of Japan's steel production was impacted by the earthquake, and 10% of ethylene production. Toyota, Nissan and Honda factories that had been damaged had all resumed production by mid April.

The major economic unknown is the impacts of the damage to the Fukushima nuclear complex. Preliminary estimates of the cost of cleanup at Fukushima are approximately USD 250 billion (news media), or roughly the same as all other destruction. The political fallout is harder to estimate, but may result in many of Japan's nuclear power plants being closed before the end of their useful life – if this occurs, it would be another cost possibly attributable to the earthquake and tsunami.

Another cost not yet even discussed is the value of the land currently quarantined due to radiation. If a 50 km radius is assumed, the quarantined area is approximately 4,000 sq. km. – at USD 100 per sq. m. is used, the total value can be calculated as USD 400 billion.

Also not yet really addressed is the issue of compensation and livelihood for the persons displaced from the quarantined land, as well as the fishermen and others whose lives and livelihood have been, and continue to be, disrupted by the earthquake, tsunami and/or nuclear power problem. Even industries far removed from the affected area, such as the tourist industry across Japan, is being severely impacted, with less than 50% of foreign tourist arrivals in March and April.

Lastly, it is of interest to note the role of the insurance industry in this event. The Japanese insurance industry was strongly criticized following the 1995 Kobe earthquake, when insurance payments totaled less than 5% of the loss. In this event, private insurers appear to have sustained about USD 12 billion in personal lines claims and a gross commercial lines loss of about USD 7.4 billion (considering overseas reinsurance however, the net commercial lines loss is USD 2.6 billion), with mutual insurance companies (primarily Zenkyoren) sustaining about USD 10 billion (Ozawa, 2011). The gross claims paid by the insurance industry, of perhaps USD 30 billion, is perhaps 10% of the overall direct damage.

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Tables

Table 1 Large Vessels damaged by the tsunami

Name	DWT
Drilling ship Chikyu	27161
Coral Ring	75395
Shirouma	77739
Shiramizu	91439
C. S. Victory	32385
Chinasteel Integrity	175775
Asia Symphony	6175
Glovis Mercury	6901
Khrizolitoviy	523
Koshin Maru	1592
Emu Arrow	51800
Total tonnage	**546885**

Table 2 Japan Electric Power Company Data
(Source: *Electricity Review of Japan 2011*, The Federation of Electric Power Companies)

Company Data (Fiscal year ending March 31, 2010)

Company	Capital Stock (Million yen)	Total Assets (Million yen)	Generating Capacity (MW)	Electricity Supplied (GWh)	Electricity Sales (GWh)	Revenues from Electricity Sales (Million yen)	Number of Customers (Thousands)	Number of Employees
Hokkaido	114,291	1,536,430	7,418	35,448	31,451	526,422	3,957	5,631
Tohoku	251,441	3,589,252	16,550	86,894	78,992	1,497,103	7,688	12,639
Tokyo	676,434	12,643,034	64,487	304,456	280,167	4,733,288	28,599	38,117
Chubu	430,777	4,969,455	32,632	133,779	122,849	2,050,366	10,455	16,600
Hokuriku	117,641	1,382,606	7,963	30,175	27,175	458,624	2,084	4,716
Kansai	489,320	6,275,570	34,321	154,642	141,605	2,293,577	13,432	22,143
Chugoku	185,527	2,587,479	11,986	63,595	57,911	950,600	5,197	9,871
Shikoku	145,551	1,320,236	6,665	30,778	27,496	487,607	2,833	6,003
Kyushu	237,304	3,776,569	20,025	91,530	83,392	1,312,103	8,437	12,543
Okinawa	7,586	349,308	1,924	8,476	7,478	151,617	834	1,554
Total	**2,655,872**	**38,429,939**	**203,970**	**939,774**	**858,516**	**14,461,307**	**83,514**	**129,817**

Source: Handbook of Electric Power Industry

Table 3 Japan Electric Power Company Data

Company	**Generation Capacity (MW)**		**Electricity Supplied (GWh)**	
Hokkaido	7,418	4%	35,448	4%
Tohoku	**16,550**	**8%**	**86,894**	**9%**
Tokyo	**64,487**	**32%**	**304,456**	**32%**
Chubυ	32,632	16%	133,779	14%
Hokuriku	7,963	4%	30,175	3%
Kansai	34,321	17%	154,642	16%
Chugoku	11,986	6%	63,595	7%
Shikoku	6,665	3%	30,778	3%
Kyushu	20,025	10%	91,530	10%
Okinawa	1,924	1%	8,476	1%
Total	**203,971**	**100%**	**939,773**	**100%**
Total TEPCO and Tohoku only	**81,037**	**40%**	**391,350**	**42%**

Table 4 Electric Power Generation by Source, 2009

Power Source →	**Conventional Thermal**	**Nuclear**	**Hydroelectric**	**Biomass and Waste**	**Wind**	**Geothermal**	**Solar etc**	**Total**
2009	620	266	73.3	15.5	3.3	2.8	2.1	982
monthly	52	22	6	1.3	0.3	0.2	0.2	82
%	63%	27%	7%	2%	0.30%	0.30%	0.20 %	100%

Source: Compiled by Earth Policy Institute from U.S. Department of Energy, Energy Information Administration, International Energy Statistics, electronic database, at www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm , updated 31 October 2010.

Table 5 Tohoku and TEPCO Major Thermal Generation Plants

Name	Owner	MW	notes
Higashi Niigata	Tohoku	4600	LNG, Other Gas
Haramachi	Tohoku	2000	Coal
Akita	Tohoku	1300	Crude, Fuel Oil
Noshiro	Tohoku	1200	Coal
Futtsu	Tokyo	4534	LNG
Kashima	Tokyo	4400	Crude, Fuel Oil
Hirono	Tokyo	3800	Crude, Fuel Oil, Coal
Anegasaki	Tokyo	3600	Crude, Fuel Oil, LNG, LPG, NGL
Sodegaura	Tokyo	3600	LNG
Yokohama	Tokyo	3325	Crude, Fuel Oil, LNG, NGL
Chiba	Tokyo	2880	LNG
Yokosuka	Tokyo	2274	Crude, Fuel Oil, Other Gas, Disel Oil
Higashi Ogishima	Tokyo	2000	LNG
Goi	Tokyo	1886	LNG
Kawasaki	Tokyo	1500	LNG
Minami Yokohama	Tokyo	1150	LNG
Shinagawa	Tokyo	1140	LNG
Ohi	Tokyo	1050	Crude
Hitachinaka	Tokyo	1000	Coal
		47239	**Total Generation Capacity (MW)**

Figures

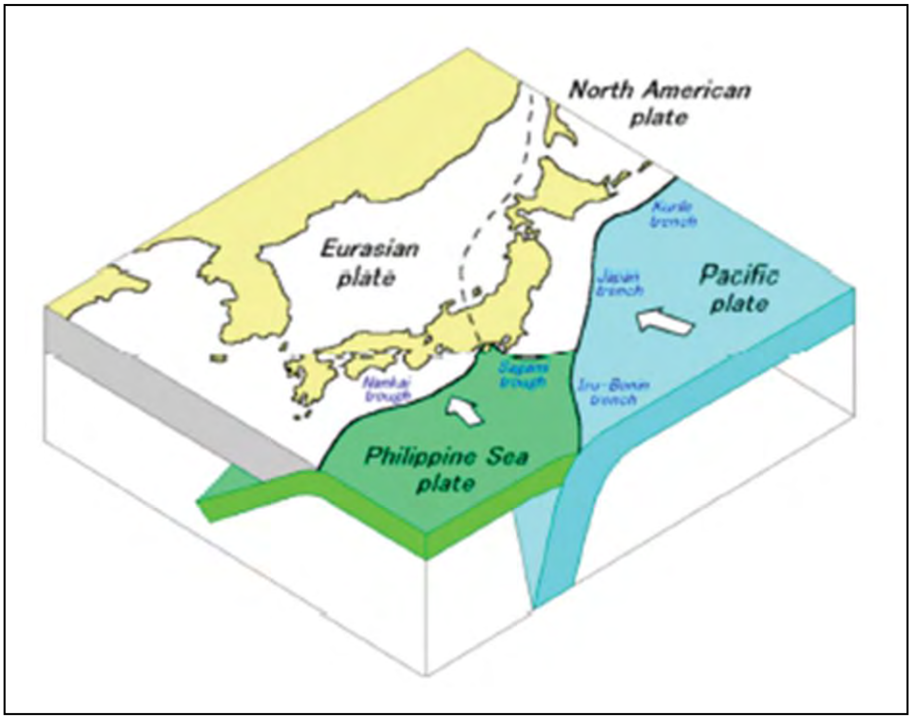


Figure 1 Japan seismotectonic setting – the Pacific plate is subducting beneath Eastern Japan, while the Philippine Sea plate is subducting beneath Western Japan.

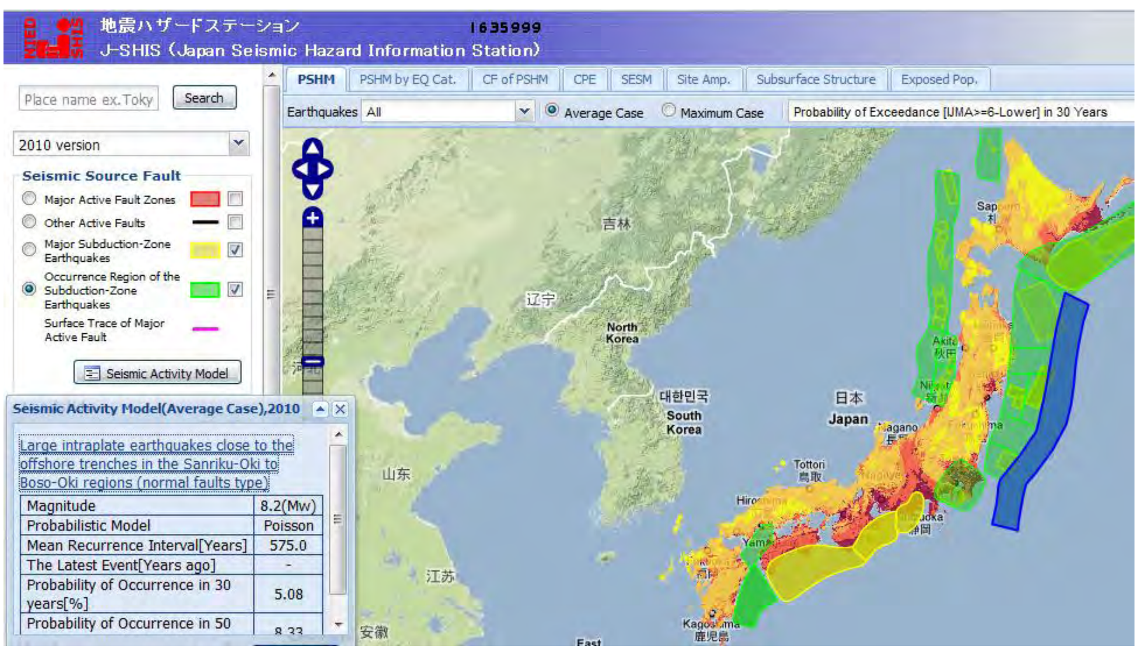


Figure 2 Basis for Japan seismic hazard maps – onshore is a depiction of seismic hazard, and offshore are historic subduction zone earthquakes (yellow) overlaid in some places by zones (green) where they may occur. The blue-highlighted zone is one of these (green) zones, in which a maximum Mw 8.2 event is postulated to occur about once every 575 years (see box at left) (http://www.j-shis.bosai.go.jp/?lang=en).

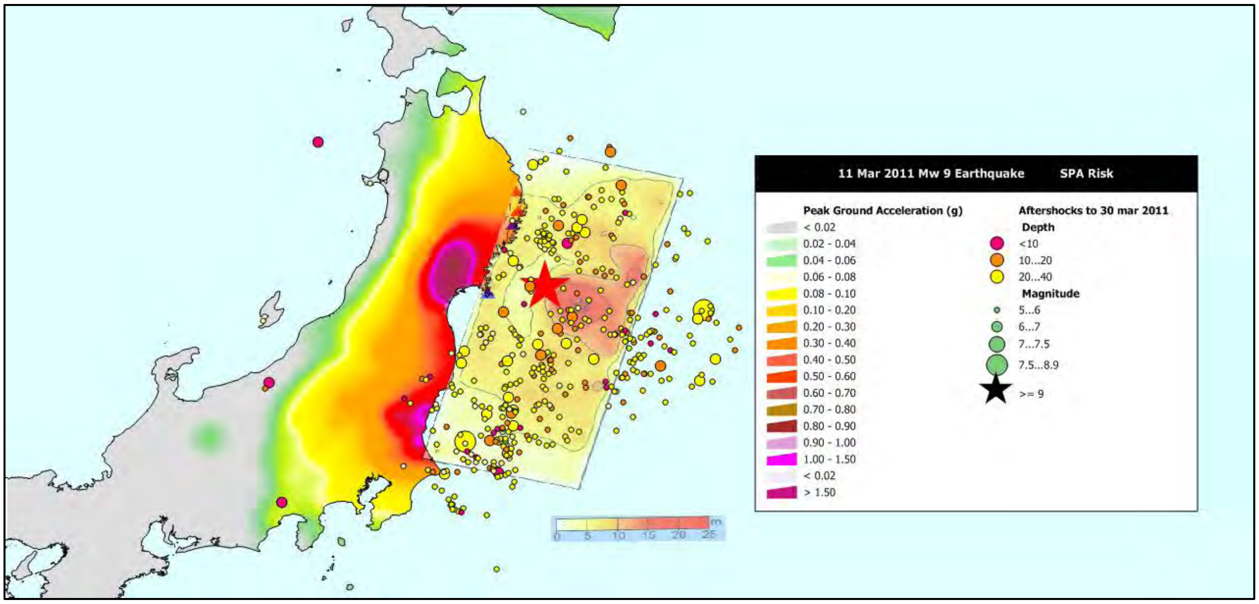


Figure 3 Main shock epicenter (red star) and aftershocks through 30 March, overlaid on slip distribution by NIED. Also shown are smoothed contours of peak ground acceleration (PGA, g) as recorded by K-NET.

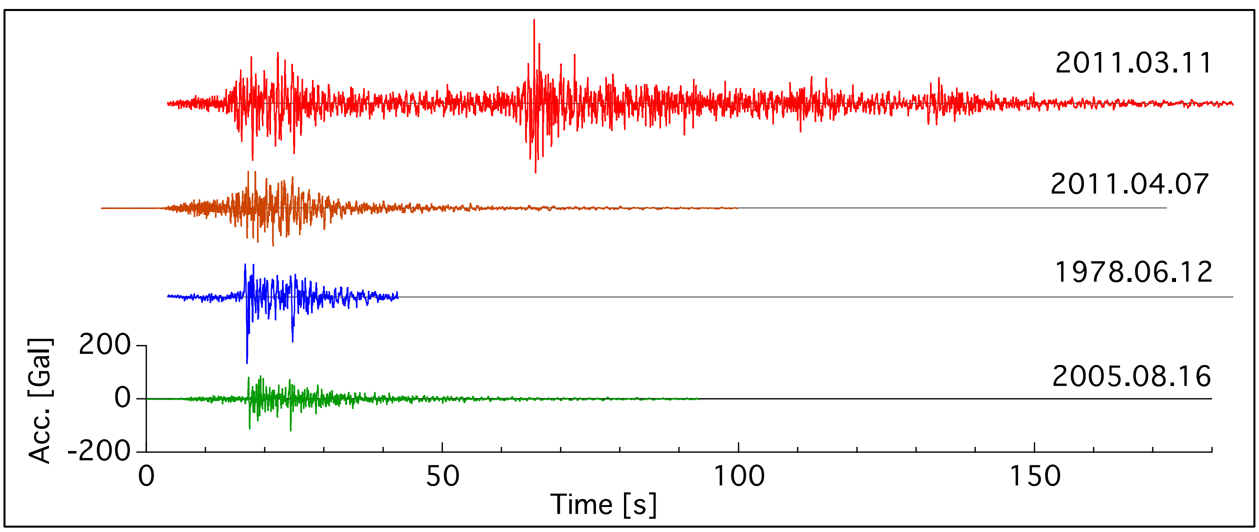


Figure 4 Recorded strong motions from 2011 events compared to 1978 Ms 7.7 and 2005 Mw 7.0 Miyagi-ken Oki earthquakes at Sumitomo Building (near Sendai Station). The duration of the 2011 main shock is approximately 150 seconds. (Credit: Prof. Motosaka, Tohoku University).

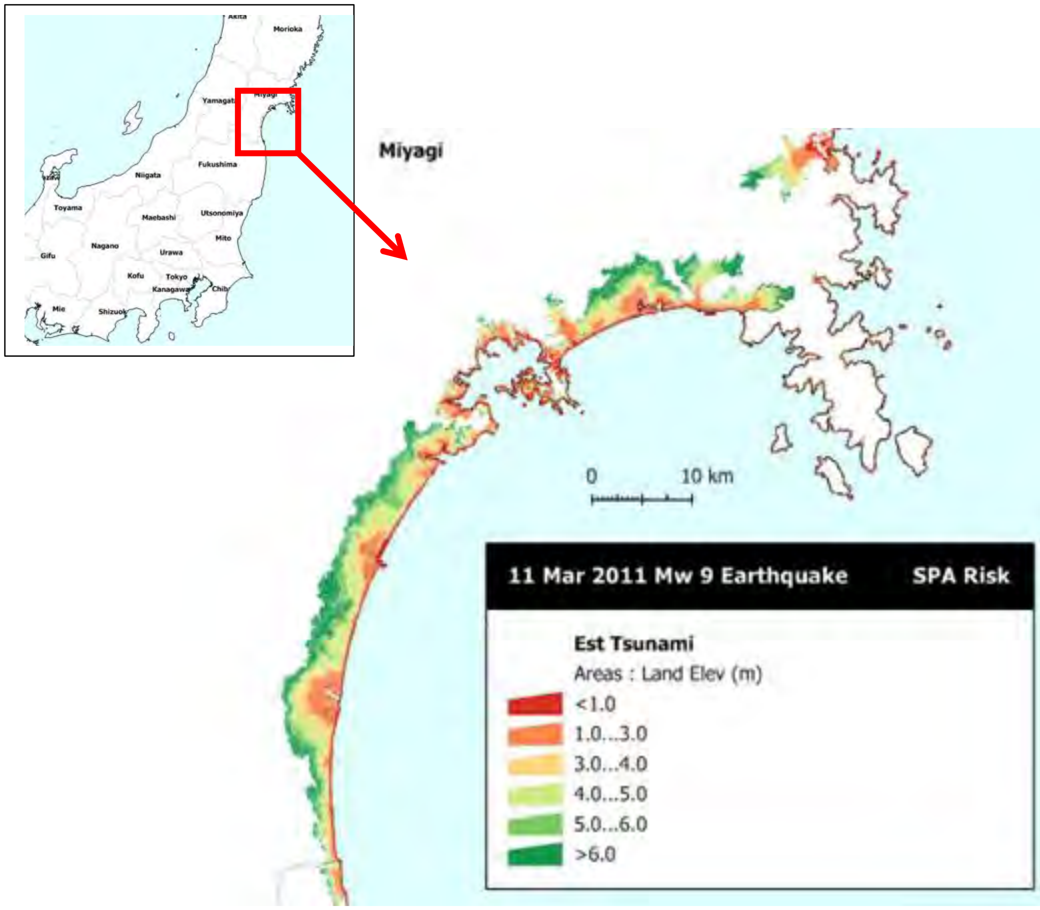


Figure 5 Detail of affected area, showing land elevation – red is less than 1 m above sea level, etc – a 6 m high tsunami runup will inundate all colored areas, extending inland in this region to more than 5 km. See next figure for actual tsunami runup heights, which in some areas exceeded 30 m.

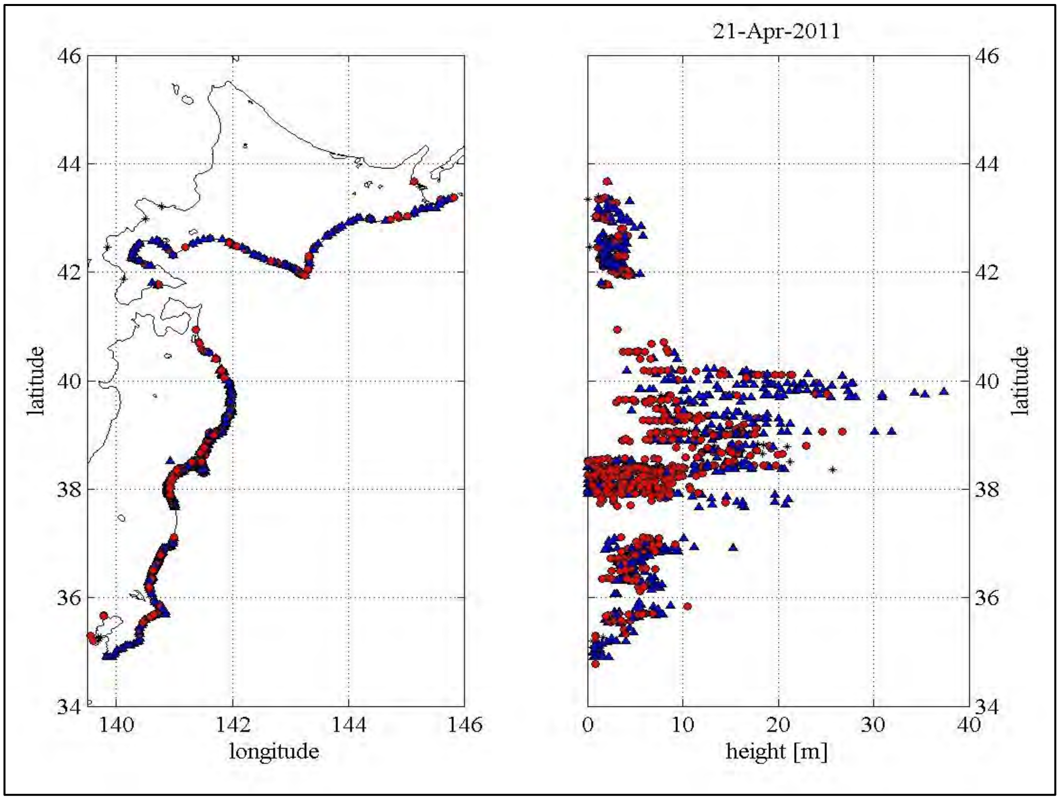


Figure 6 Tsunami runup heights and inundation heights, as recorded by Japanese investigators as of 21 April (Source: unattributed; not corrected for tidal variation)

Figure 7 Onagawa port – runup estimated approximately 11m.

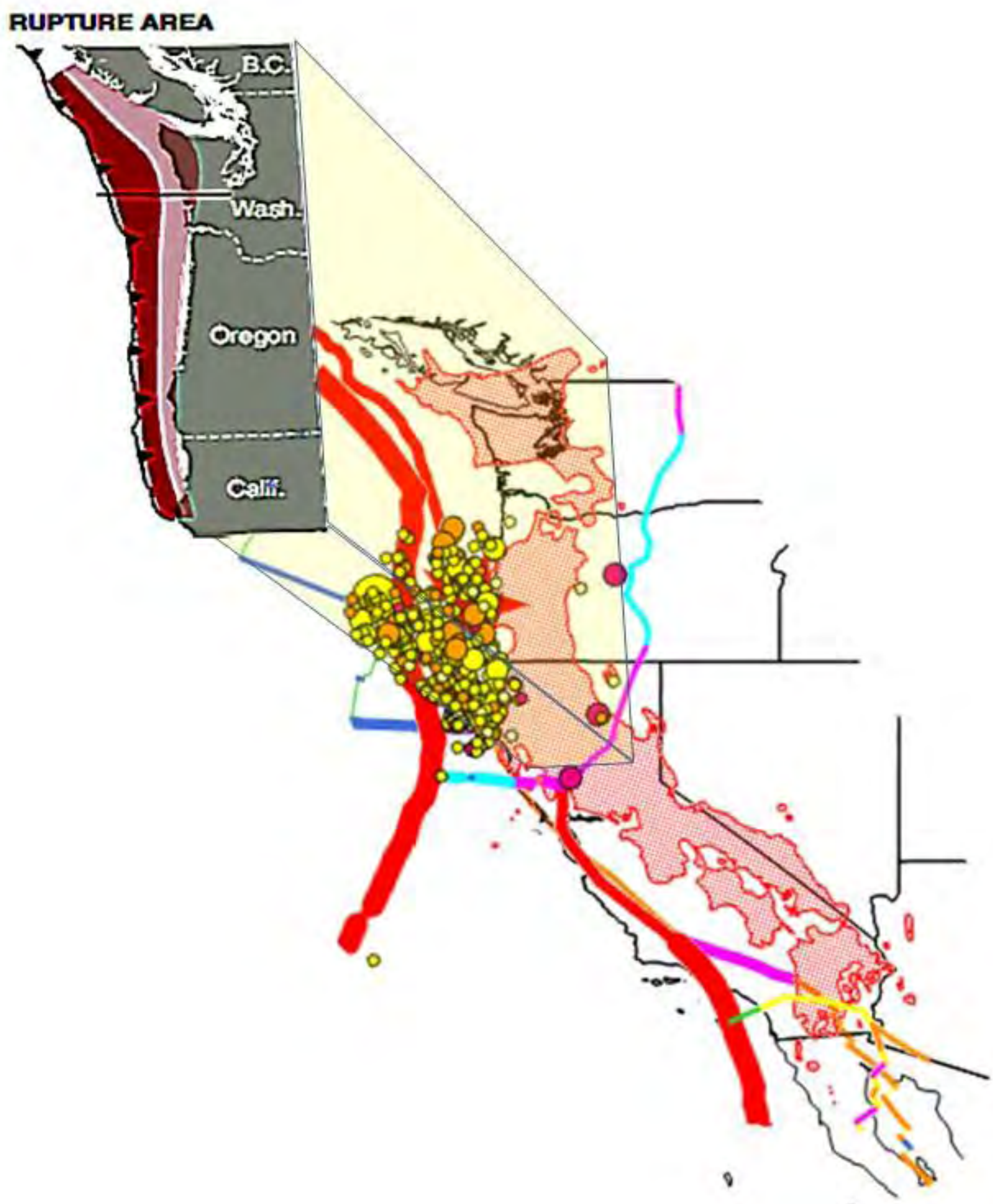


Figure 8 Japan at same scale, ‗flipped' about N-S axis and overlaid on Pacific coast of North America. Aftershock pattern of 11 March 2011 earthquake coincides precisely with anticipated location of Cascadia subduction zone event, as estimated by (Atwater et al., 2005).

Figure 9 Typical water supply system damage, observed in Chiba Prefecture (upper) floated manhole; (lower) repairs to water distribution main (Figures courtesy of Prof. S. Takada, Kobe University)

Figure 10 Tsunami scour around a building – note exposed blue tapes, which are buried above water supply pipe as a warning to excavators.

Figure 11 Water pipe trussed bridge swept away by tsunami.

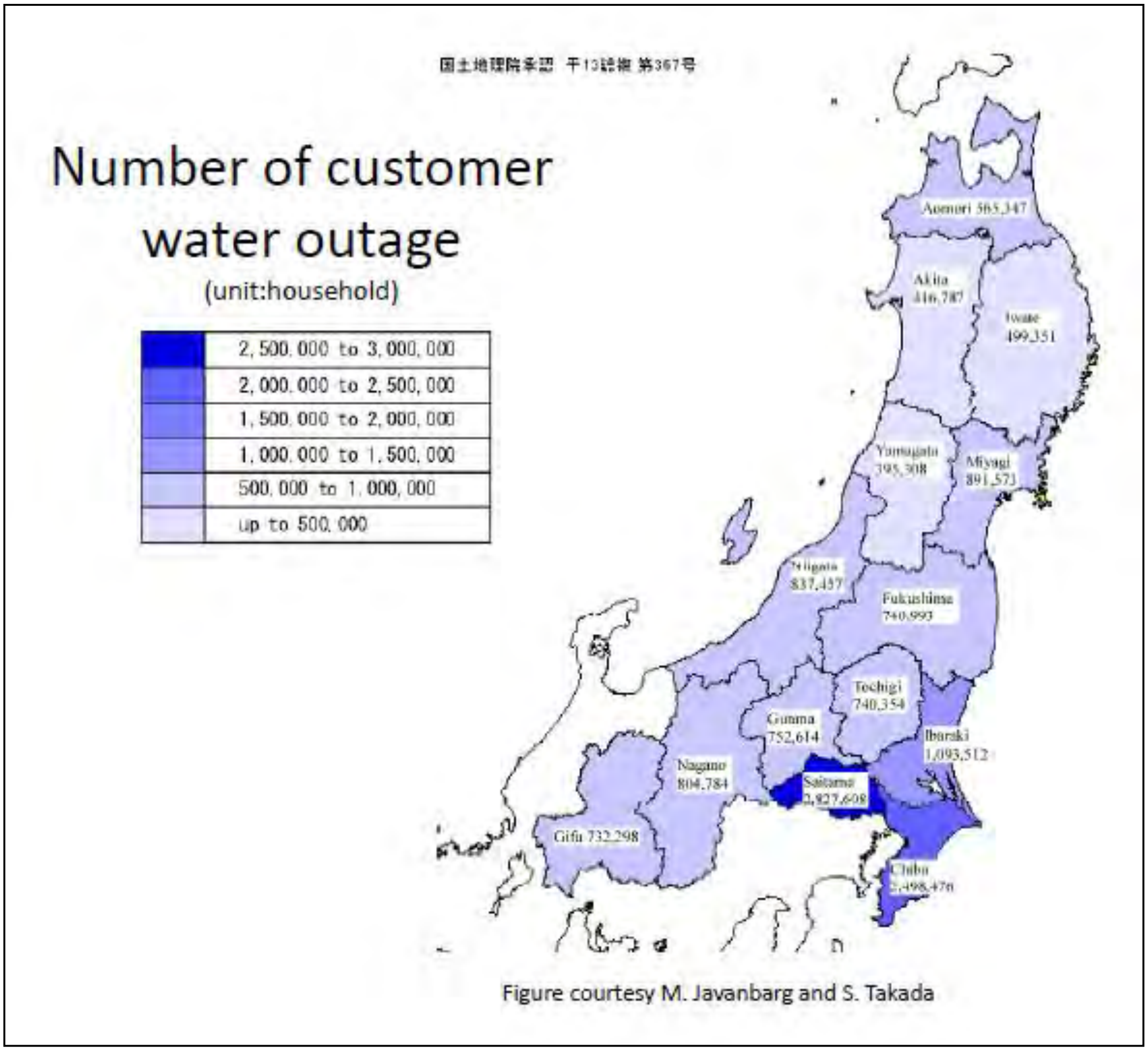
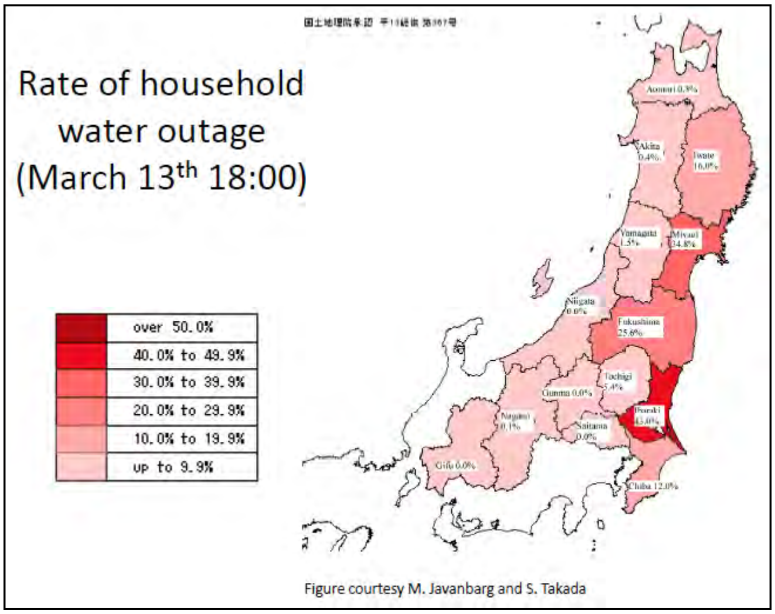


Figure 12 Number of customer water outages by prefecture immediately following the event (figure courtesy of Prof. S. Takada, Kobe University, and Dr. M. Javanbarg, Kyoto University).



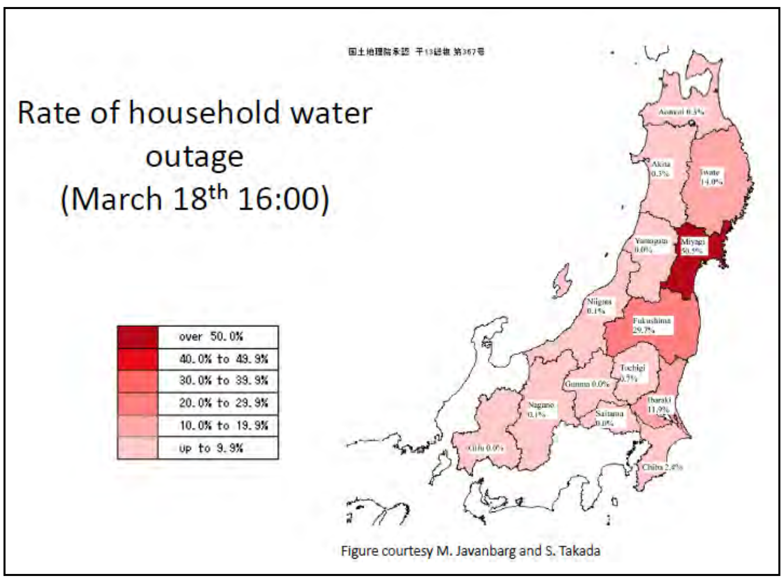
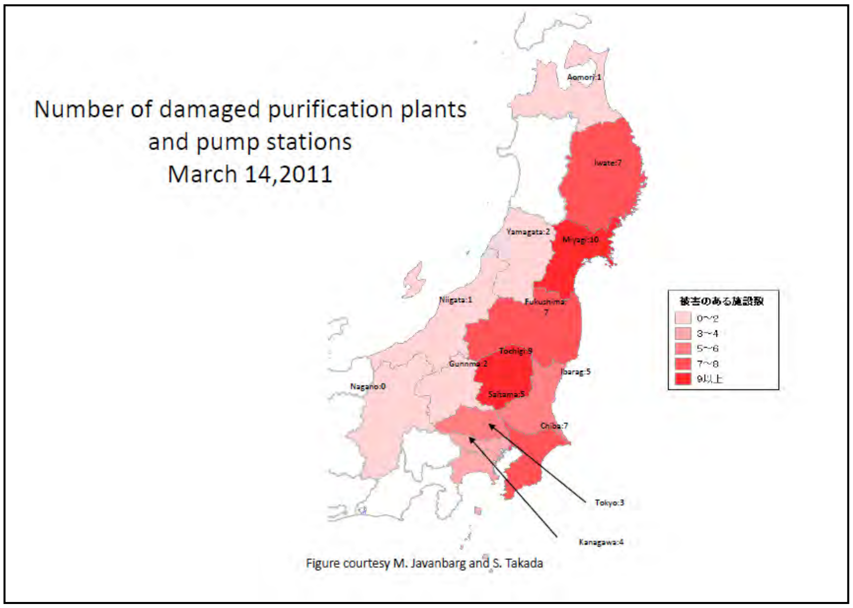


Figure 13 Household water outages on March 13 and March 18
(figure courtesy of Prof. S. Takada, Kobe University, and Dr. M. Javanbarg, Kyoto University).



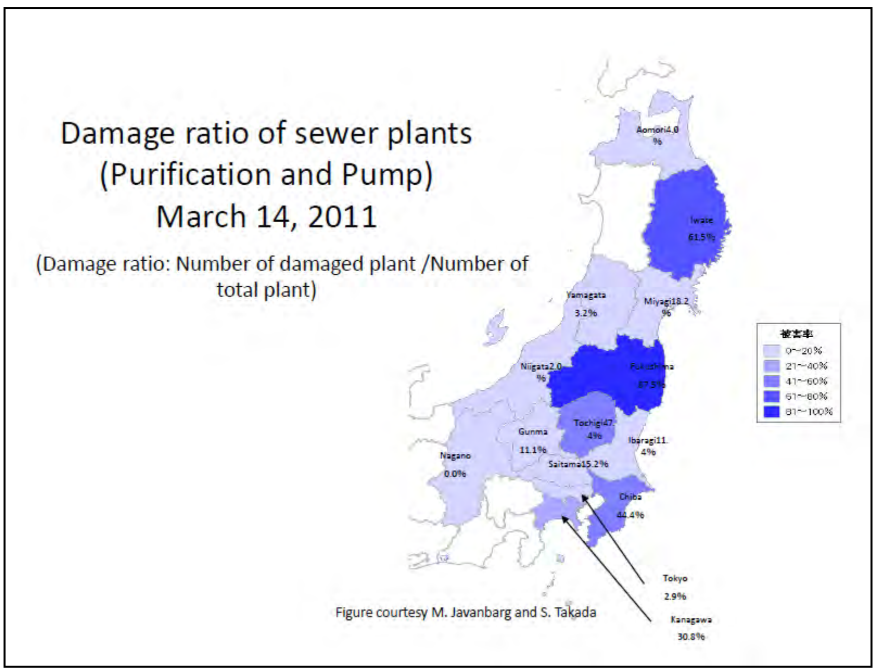


Figure 14 Damage to water and wastewater treatment plants
(figure courtesy of Prof. S. Takada, Kobe University, and Dr. M. Javanbarg, Kyoto University).

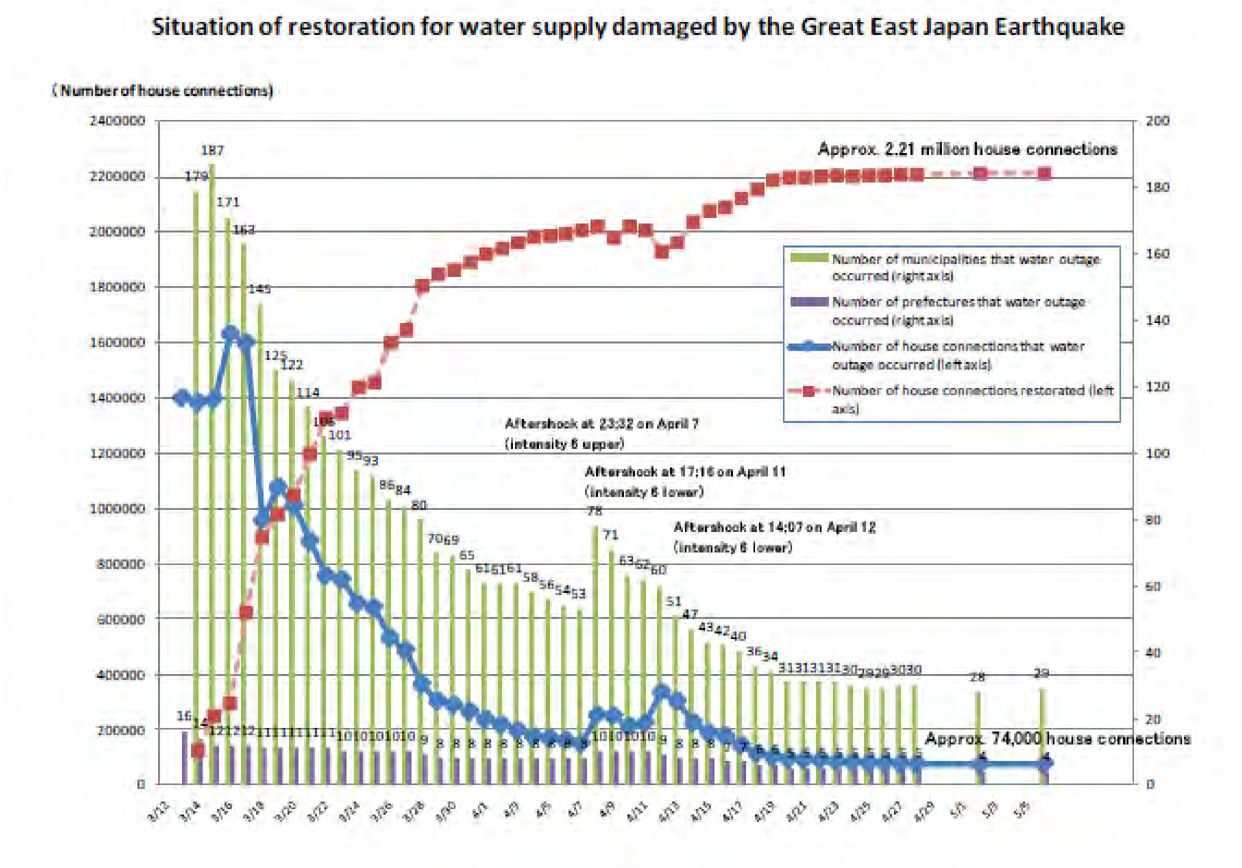


Figure 15 Recovery of water supply (Extracted from ―The damage situation of and measures taken against the Great East Japan Earthquake in 2011, 64th announcement, Ministry of Health, Labour and Welfare)

Figure 16 Scour at a road bridge

Figure 17 Damage to road bridges (figure courtesy of G. Deierlein, Stanford University).

Figure 18 Sections of steel truss bridge swept away by tsunami. Kitakami River, about 5 km upstream from river mouth. (Photo courtesy of Prof. Kawashima, Tokyo Institute of Technology).

Figure 19 Road damage due to scour.

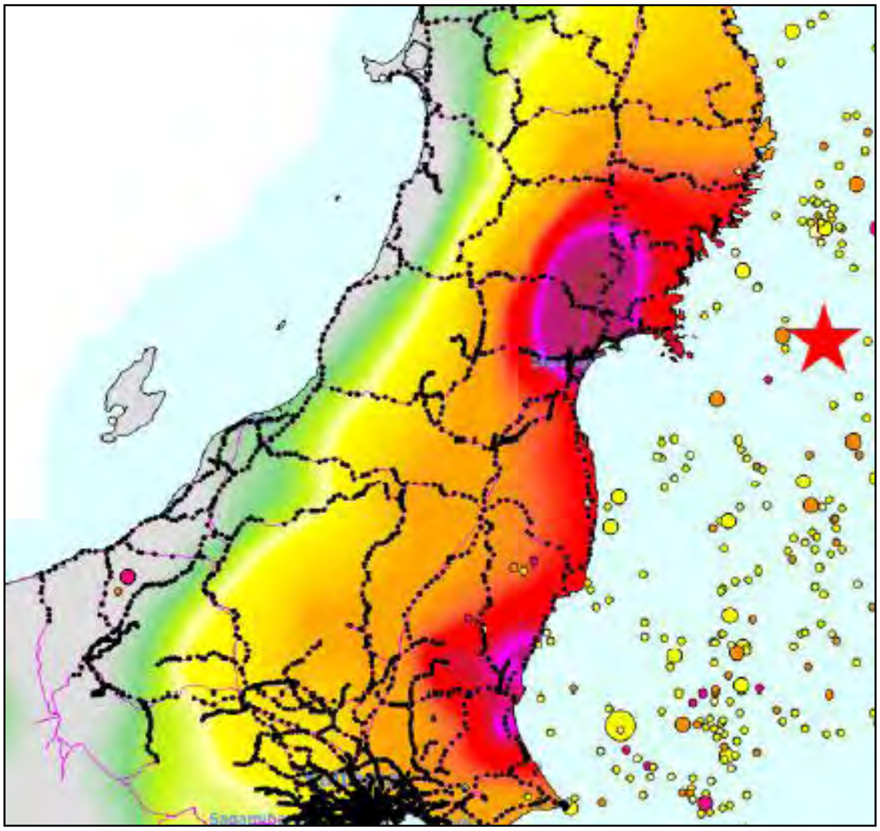


Figure 20 Railroad network overlaid on peak ground acceleration and aftershock pattern.

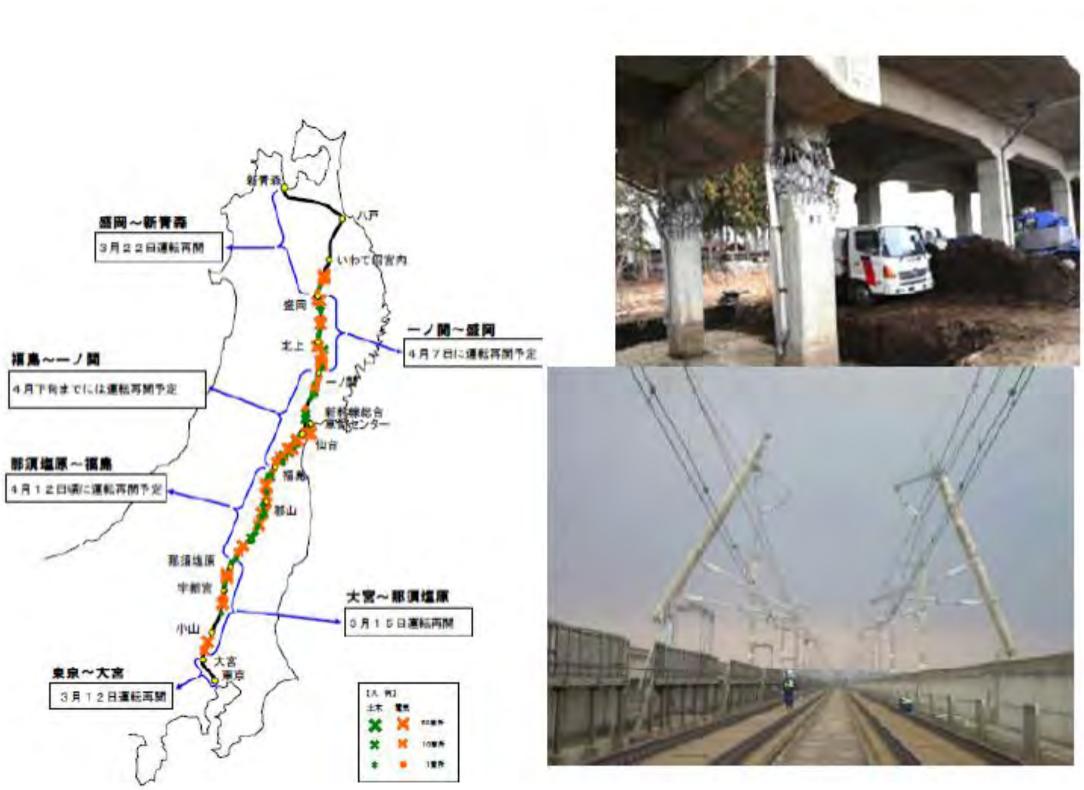


Figure 21 damage to Tohoku Shinkansen (Figures courtesy of Prof. S. Takahashi and JR East).

Figure 22 Shinchi station (track crossover structure in background, destroyed rail cars in foreground).

Figure 23 View of Shinchi station area.

Figure 24 swept away rail bridges (lower at Rikuzentakata)

Figure 25 stranded train

Figure 26 Sendai International Airport (upper figure from news media, lower figure courtesy of Asia Air Survey)

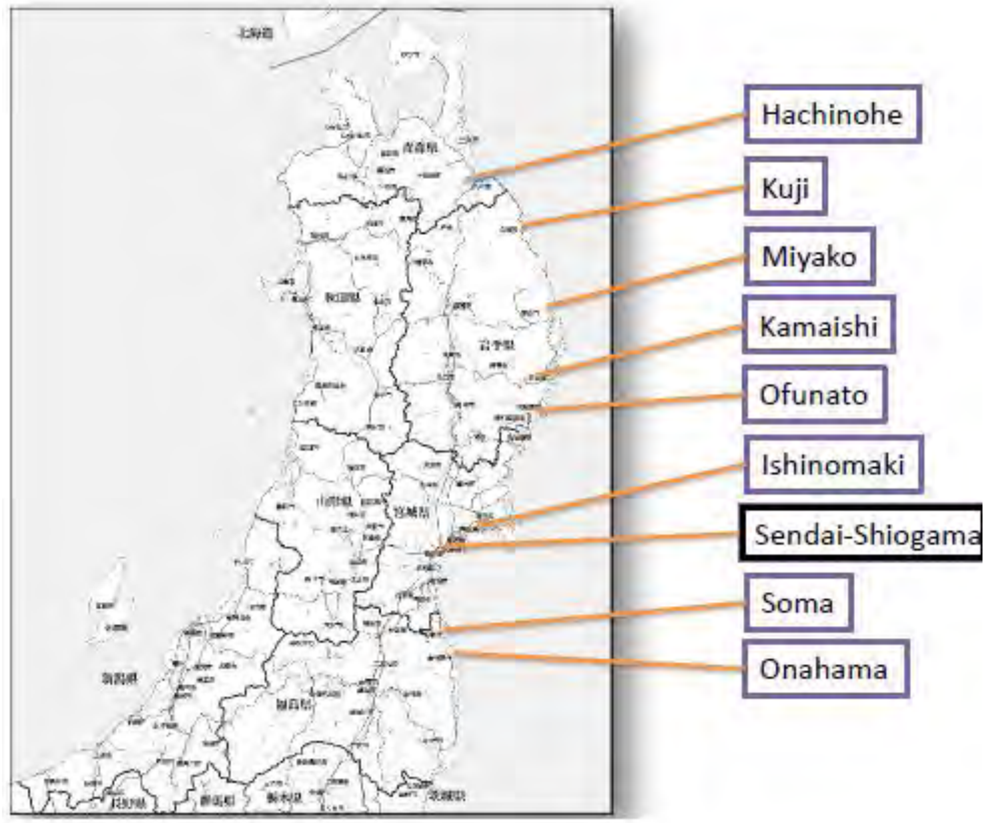


Figure 27 Major ports in the affected area

(Economic Impact of the Great East Japan Earthquake and Current Status of Recovery May 16, 2011Ministry of Economy, Trade and Industry, **http://www.meti.go.jp/english/earthquake/recovery/index.html**)

Figure 28 Fishing fleet damage

Figure 29 Damage to commercial port facilities.

Figure 30 Grounded bulk carrier, Port of Soma, and closeup of hull damage

Figure 31 scattered containers and equipment (photo news media)

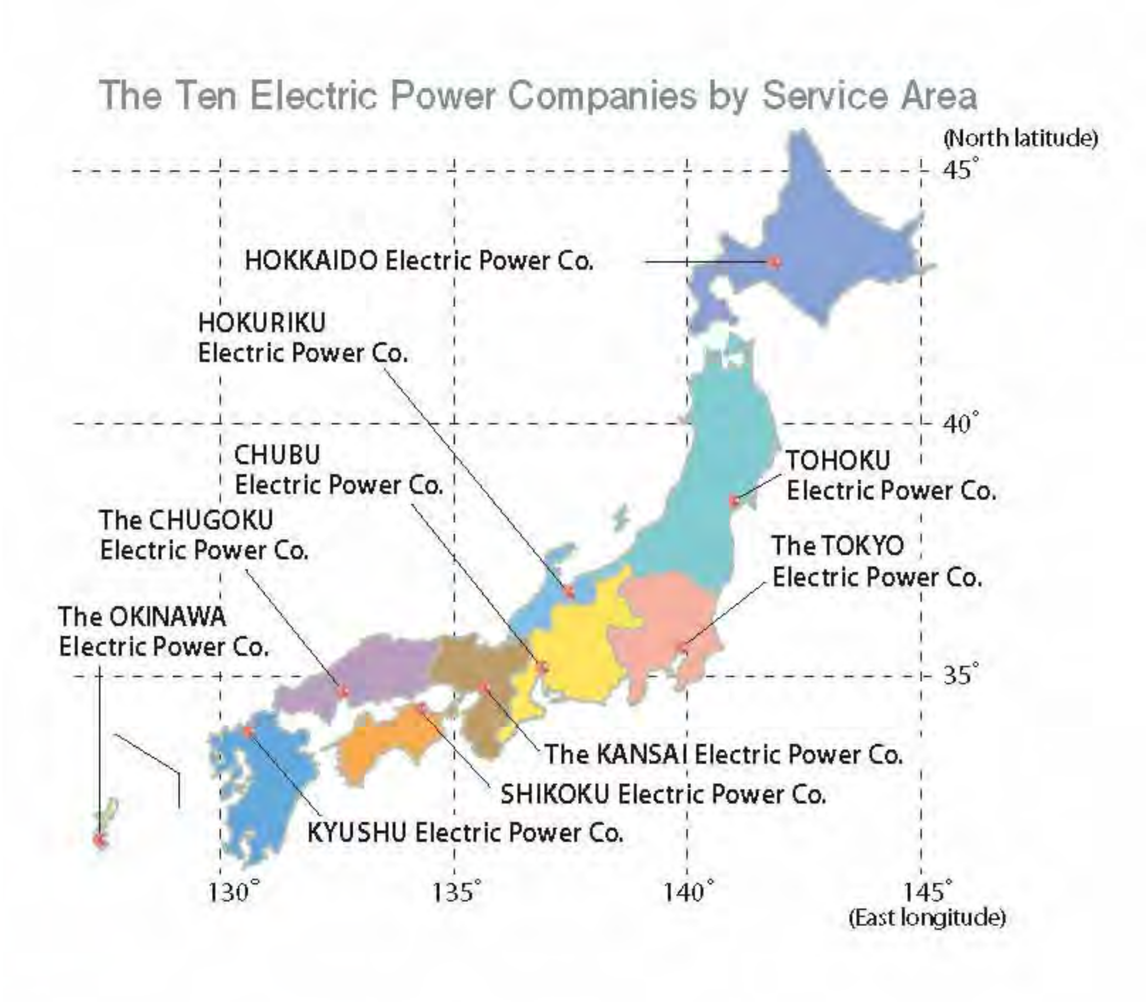


Figure 32 Electric power companies in Japan and their service areas

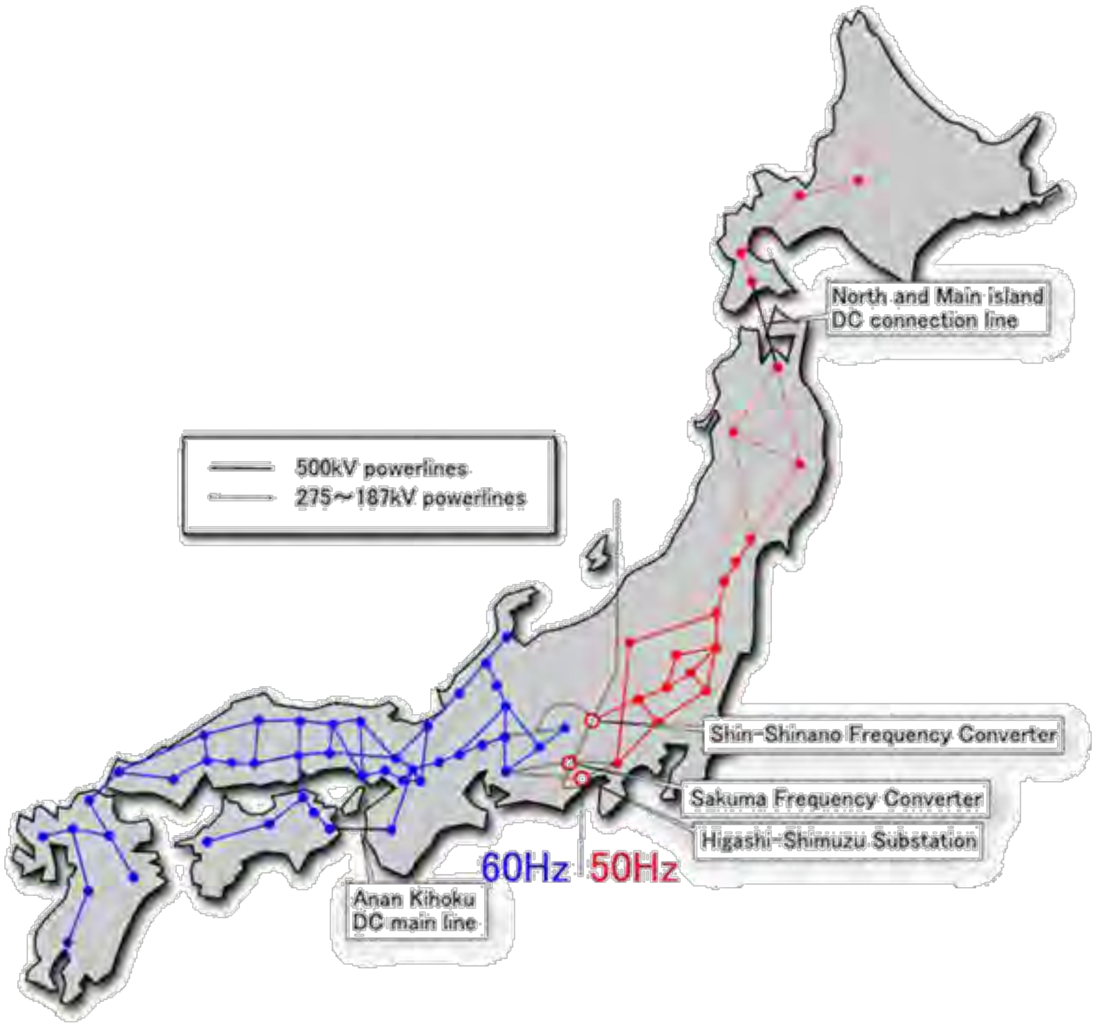


Figure 33 Schematic of Japan‘s electric power transmission and distribution network

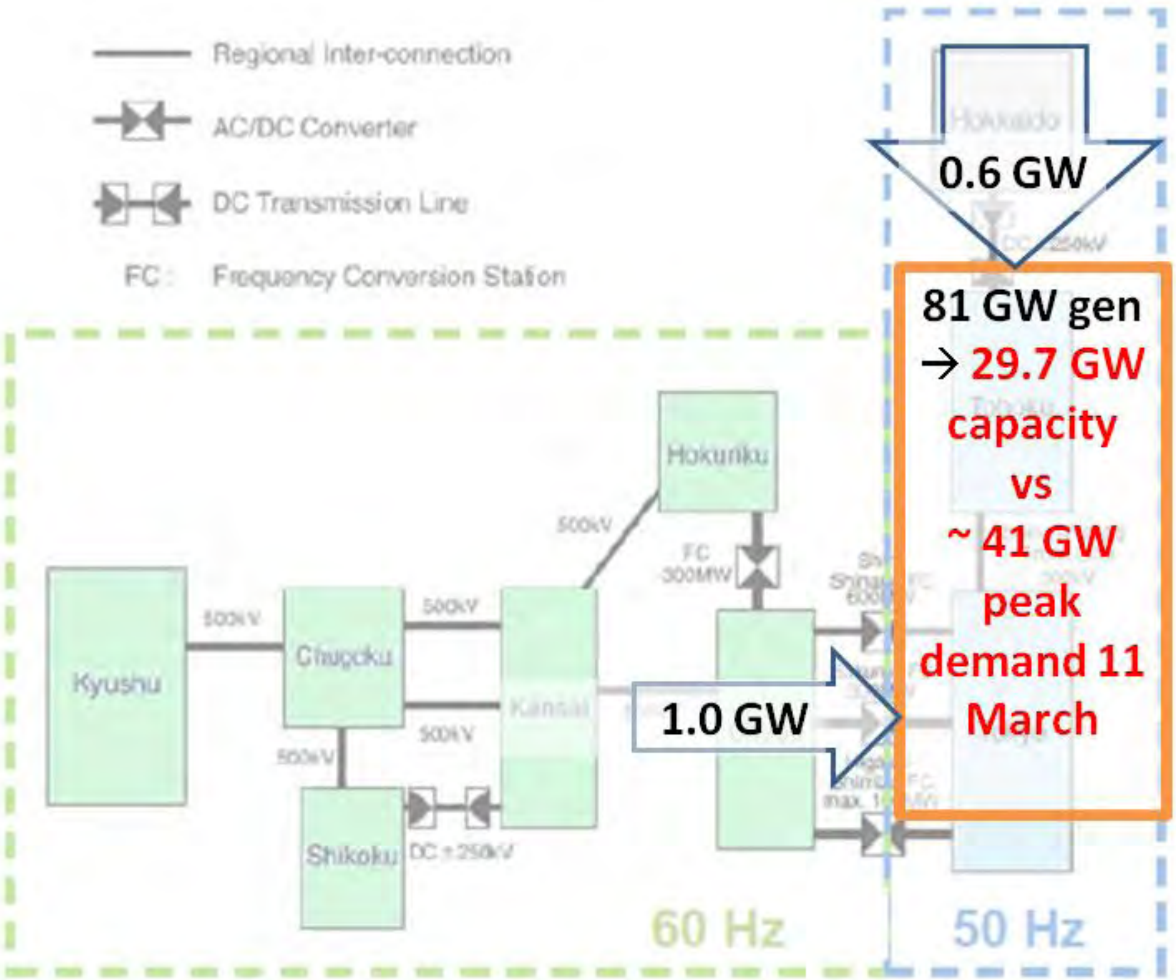


Figure 34 Schematic of Japan Electric Power System

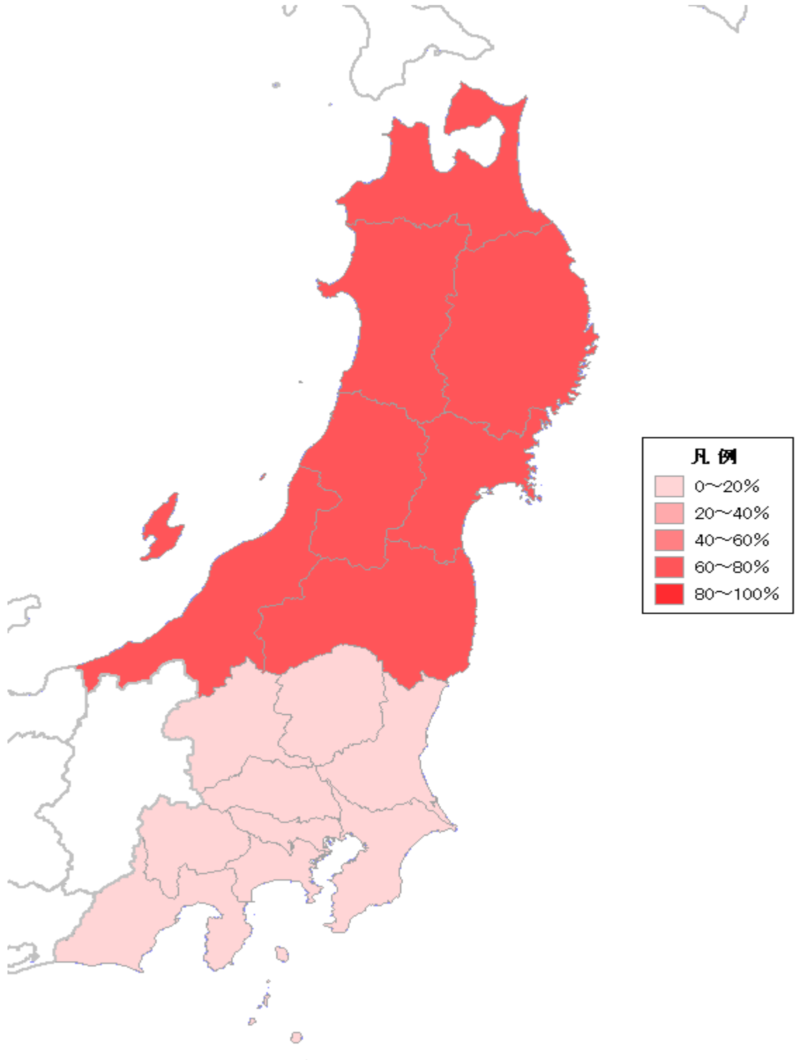


Figure 35 Ratio of power supply stoppage 15:24, March 11, 2011
(figure courtesy of Prof. S. Takada, Kobe University, and Dr. M. Javanbarg, Kyoto University).

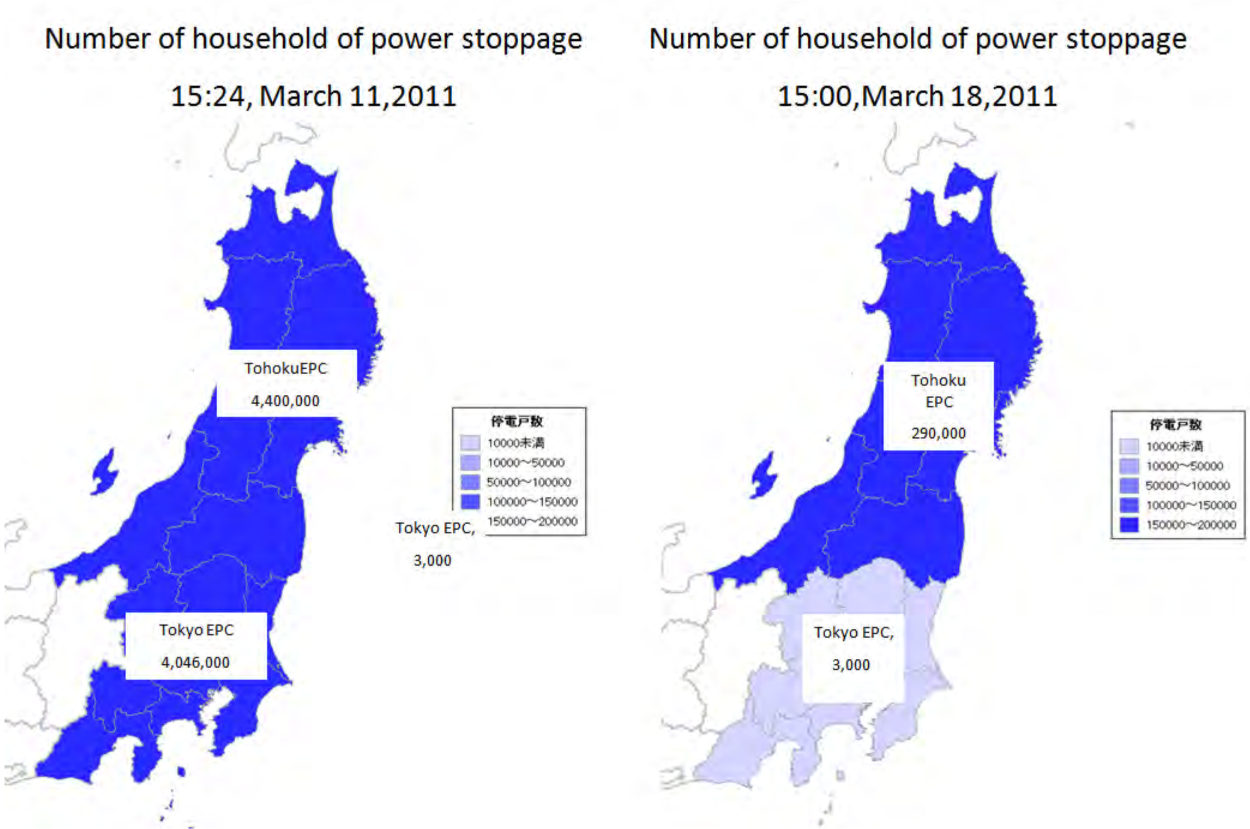


Figure 36 distribution of power outages, 11 and 18 March
(figure courtesy of Prof. S. Takada, Kobe University, and Dr. M. Javanbarg, Kyoto University).

Figure 37 Aerial view Fukushima I nuclear units 1 to 4.
(Photo news media)

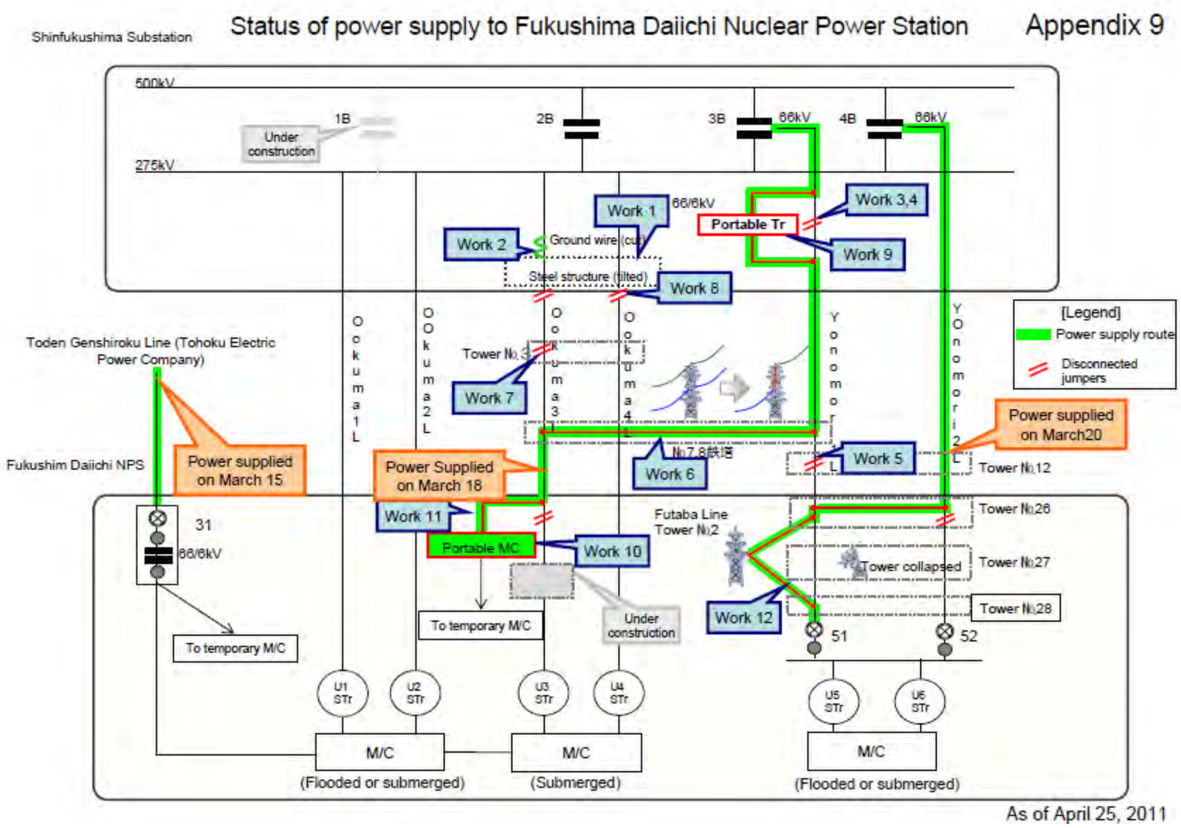


Figure 38 Schematic ShinFukushima substation showing damage (Source: Report regarding ―Collection of Reports pursuant to the Provisions of Article 106, Paragraph 3 of the Electricity Business Act" May 16th, 2011, Tokyo Electric Power Company)

Figure 39 Example of damage at ShinFukushima substation (Source: *ibid*).

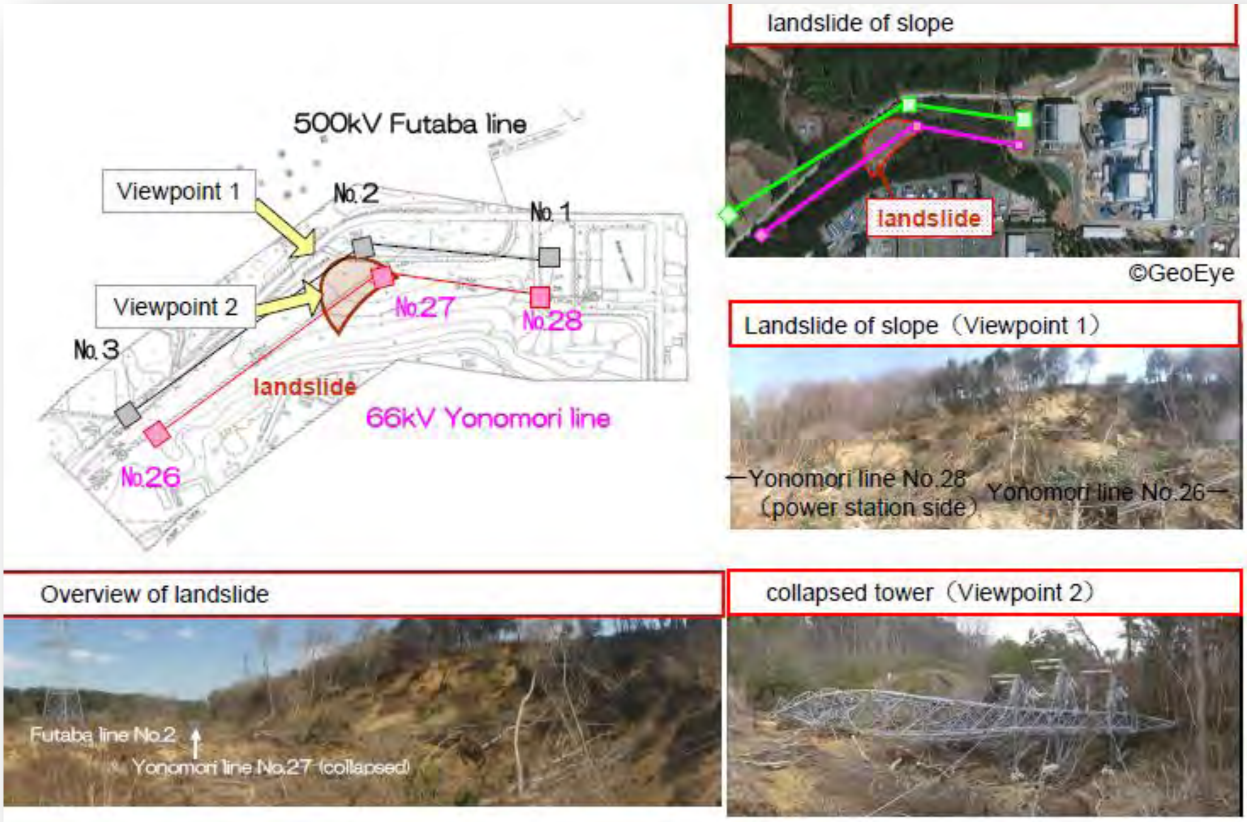


Figure 40 Damage to transmission lines feeding ShinFukushima substation (Source: *ibid*).

Summary TEPCO Fukushima recordings, 11 March 2011 Earthquake

(Source: Summary of the Report on the Analysis of Observed Seismic Data Collected at Fukushima Daiichi Nuclear Power Station and Fukushima Daini Nuclear Power Station pertaining to the Tohoku-Taiheiyou-Oki Earthquake May 16th, 2011, Tokyo Electric Power Company)

Observation Point (The base mat of reactor buildings)		Observed data Maximum Response Acceleration (gal)			Maximum Response Acceleration against Basic Earthquake Ground Motion Ss (gal)		
		Horizontal (N-S)	Horizontal (E-W)	Vertical	Horizontal (N-S)	Horizontal (E-W)	Vertical
Fukushima Daiichi	Unit 1	460※	447※	258※	487	489	412
	Unit 2	348※	550※	302※	441	438	420
	Unit 3	322※	507※	231※	449	441	429
	Unit 4	281※	319※	200※	447	445	422
	Unit 5	311※	548※	256※	452	452	427
	Unit 6	298※	444※	244	445	448	415
Fukushima Daini	Unit 1	254	230※	305	434	434	512
	Unit 2	243	196※	232※2	428	429	504
	Unit 3	277※	216※	208※	428	430	504
	Unit 4	210※	205※	288※	415	415	504

※ The recording time was about 130-150 seconds

Exceeds Basic Earthquake Ground Motion Ss (ie, design parameter)

Figure 41 Fukushima I and II recordings, 11 March 2011 main shock (Source: *ibid*)

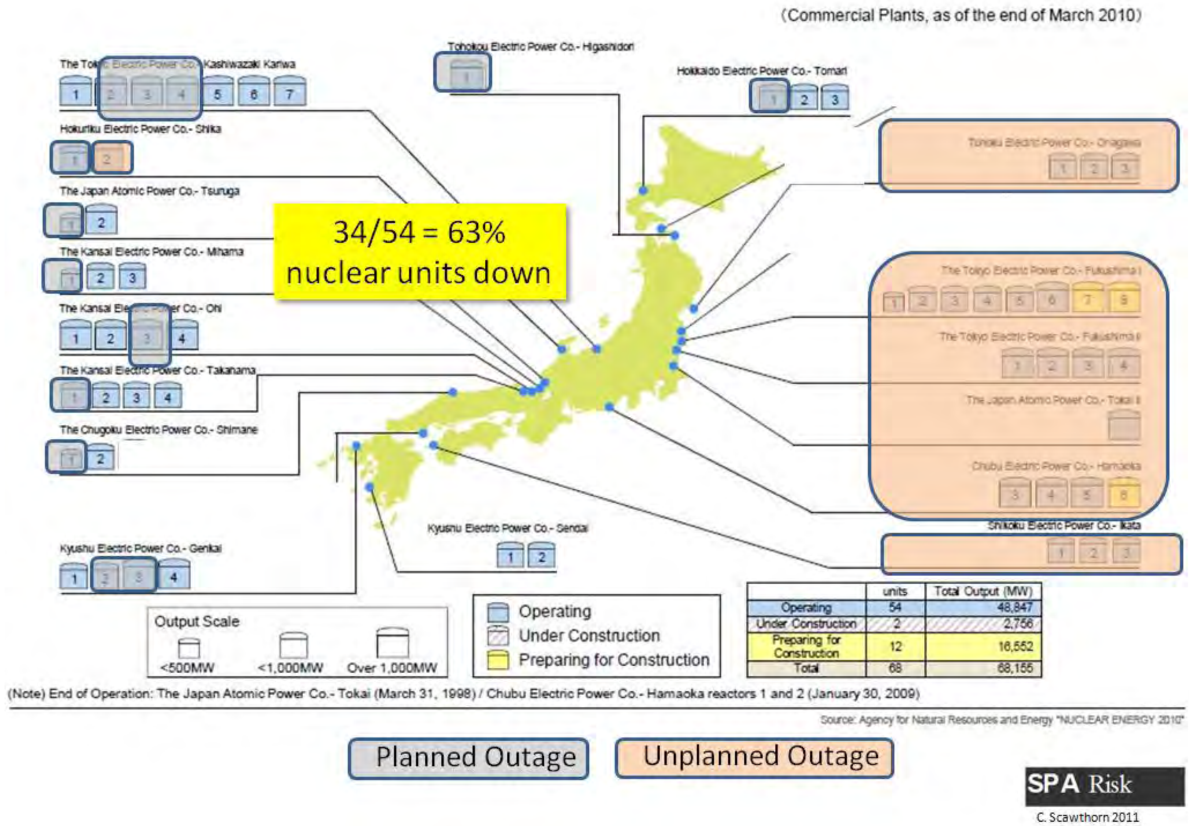


Figure 42 Commercial nuclear power units in Japan, indicating stations down for planned or unplanned outages.

Figure 43 Chiba oil refinery on fire and view from central Tokyo (photos news media)

Figure 44 Kessenuma conflagrations (Photo Asia Air Survey)

Figure 45 Warehouse fire, Port of Sendai

Figure 46 Destroyed fire engine, Onagawa

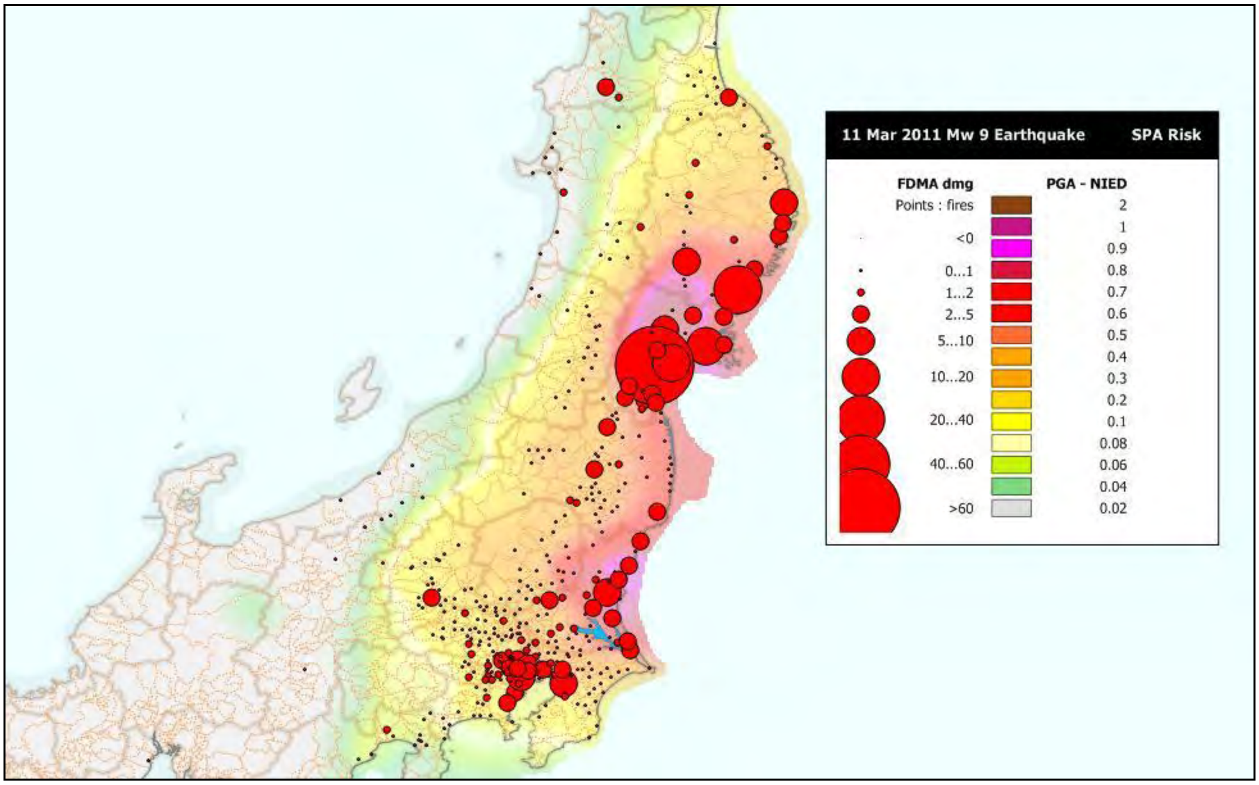


Figure 47 Distribution of fires overlaid on PGA

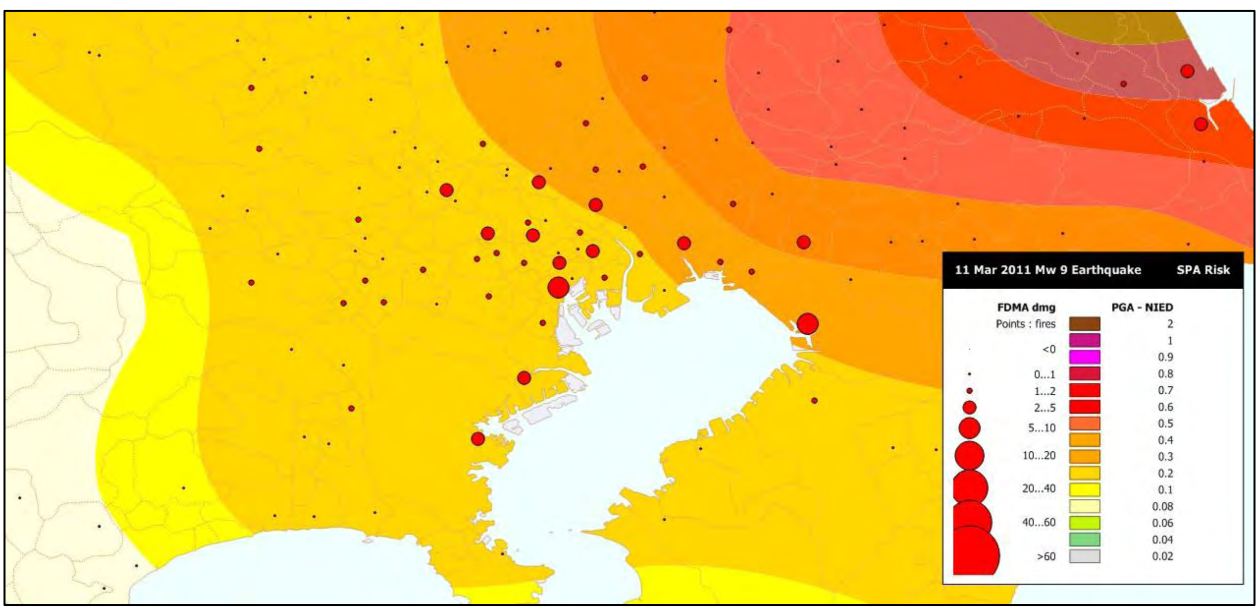


Figure 48 Fires in Tokyo area, overlaid on PGA

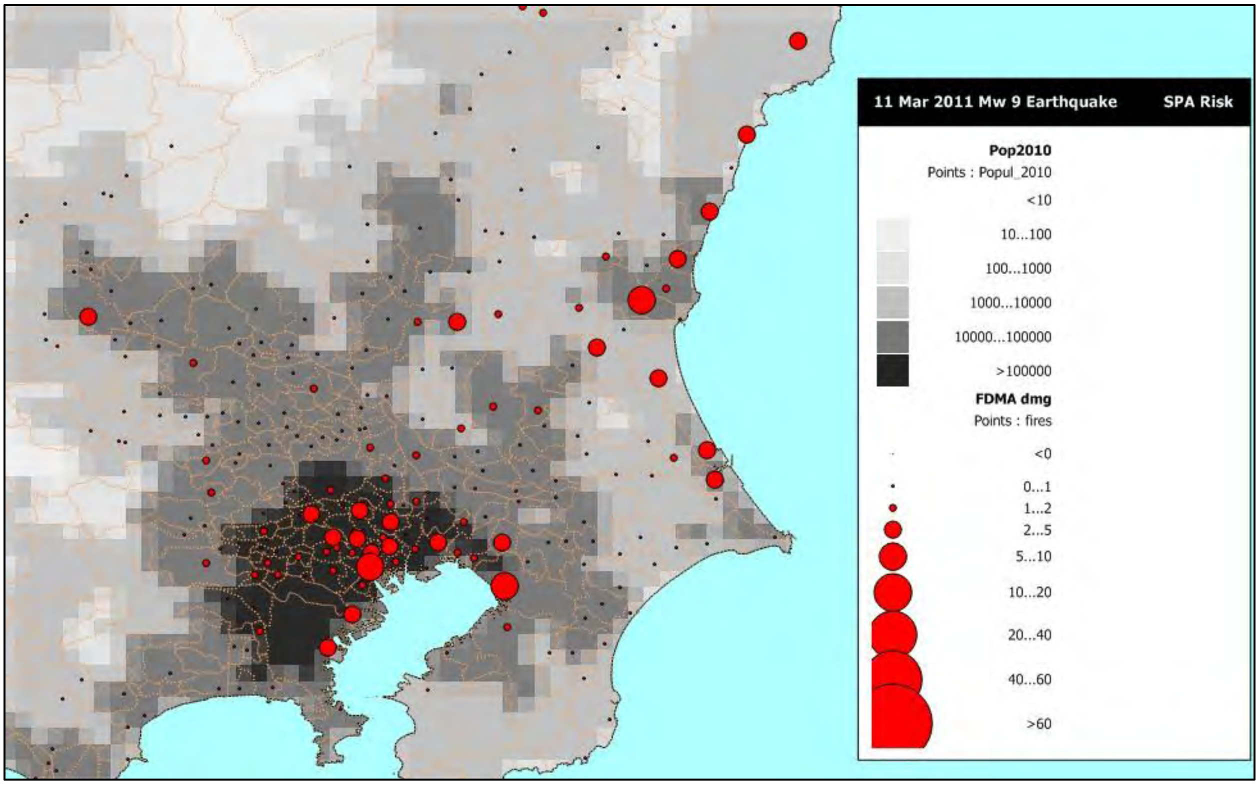


Figure 49 Distribution of fires overlaid on population density

Figure 50 Eneos Oil Refinery, Port of Sendai (see next figure for detail)

Figure 51 Details of Enneos Oil refinery (u) area of tank fire; (l) gas tank cars displaced by the tsunami.