Restoration Processes of Utility Lifelines in the Great East Japan Earthquake Disaster, 2011

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SUMMARY:
Restoration processes of utility lifelines including electric power supply, water supply, city gas supply systems and telecommunication systems are compiled on the basis of published data and press releases by the service providers and/or supervisory authorities. The scale and the duration of lifeline disruptions are compared with the Great Hanshin-Awaji Earthquake Disaster.

Keywords: The Great East Japan Earthquake Disaster, lifeline systems, restoration processes

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake, Japan (Mw=9.0) on March 11th, 2011 caused wide-spread catastrophic disaster to Tohoku and Kanto regions by tsunami, strong ground shaking and liquefaction and claimed 16,278 deaths and 2,994 missing persons as of March 13th, 2012. The aftermath was named as the Great East Japan Earthquake Disaster. Lifeline systems were severely damaged, causing significant social impacts on the affected areas as well as their surrounding areas. In this paper, restoration processes of lifelines including electric power supply, water supply, city gas supply, and telecommunication systems are compiled. Figure 1 shows the distribution of PGV on surface ground. Figure 2 shows the locations of relevant prefectures in Tohoku and Kanto regions.

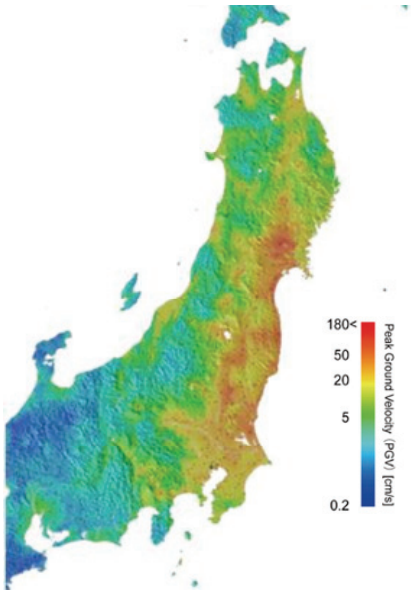


Figure 1. Peak ground velocity distribution on surface ground by the 2011 off the Pacific Coast of Tohoku Earthquake, Japan (AIST, 2011)

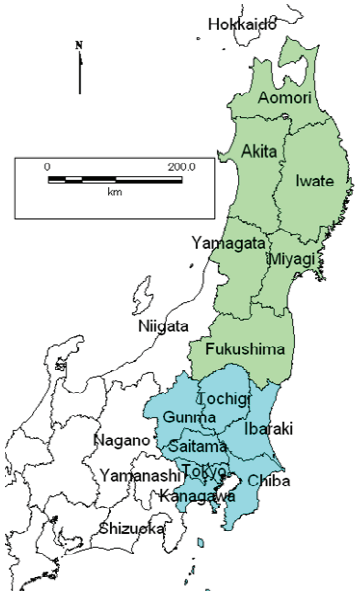


Figure 2. Prefectures in Tohoku region shaded green and Kanto region shaded blue

2. ELECTRIC POWER SUPPLY SYSTEMS

The initial outage of electric power supply was 8.91 million households in total. In the area of Tohoku Electric Power Company, 4.86 million households in six prefectures (Aomori, Iwate, Akita, Miyagi, Yamagata and Fukushima) suffered power outage. Figures 3 and 4 show the restoration processes of electric power supply in each prefecture. Relatively rapid restoration was accomplished at the early stage as a result of rerouting operations and prompt recovery works of hierarchically higher facilities such as transmission lines and substations. The aftershock on April 7th (M=7.2) affected 4 million households and that on April 11th (M=7.0) affected about 200 thousand households in Fukushima prefecture again, but the restoration was very rapid. Figure 5 shows the spatial restoration process of electric power supply in each local office of Tohoku Electric Power Company in terms of the number of households without service. Initial outage spread over almost the entire Tohoku region, but only data in Iwate, Miyagi and Fukushima prefectures were available and plotted herein. Obviously the coastal regions and Fukushima area took longer time for service recovery.

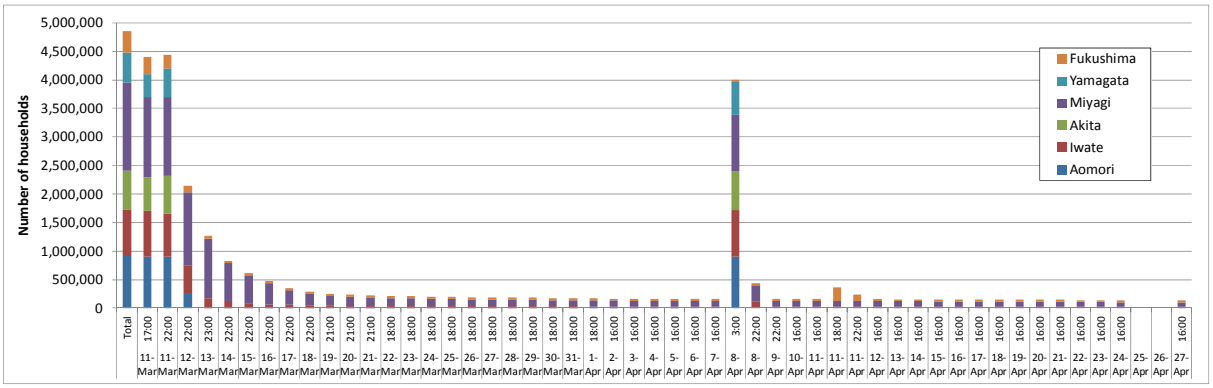


Figure 3. Number of households without electric power supply (Tohoku Electric Power Company, 2011)

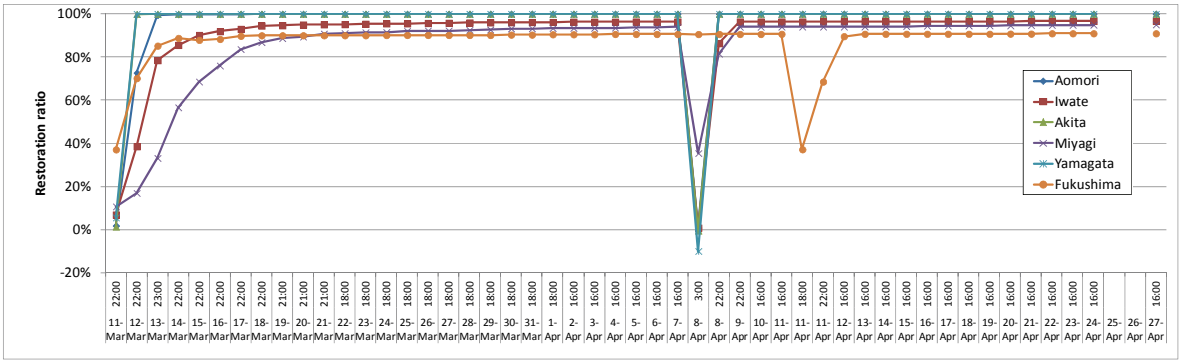


Figure 4. Restoration curves of electric power supply service in affected prefectures

Especially, the restoration in the tsunami-devastated area was extremely lengthy process. Figure 6 shows the number of household without electric power during about a month after March 21st. The causes are categorized into six: (1) public infrastructures and dwelling houses washed away by tsunami, (2) areas blocked by tsunami debris, (3) equipments inundated by tsunami and/or damaged by ground shaking, (4) no safety confirmation mainly due to absence of users, (5) ready to be restored but not yet, (6) no entry zones around the Fukushima Daiichi Nuclear Power Plant. Note that these categories had been recomposed during the period of time. As a whole, categories (1) and (6) were the predominant causes of recovery hindrance.

In the area of Tokyo Electric Power Company, 4.05 million households suffered power outage. Figure 7 shows the restoration processes in each prefecture. The restoration was rapid; almost all the affected customers in Tokyo, Kanagawa, Gunma, Yamanashi and Shizuoka prefectures were restored by the

next day of the earthquake. The completion of service recovery was on March 13th in Saitama prefecture, March 14th in Tochigi and Chiba prefectures, and March 19th in Ibaraki prefecture.

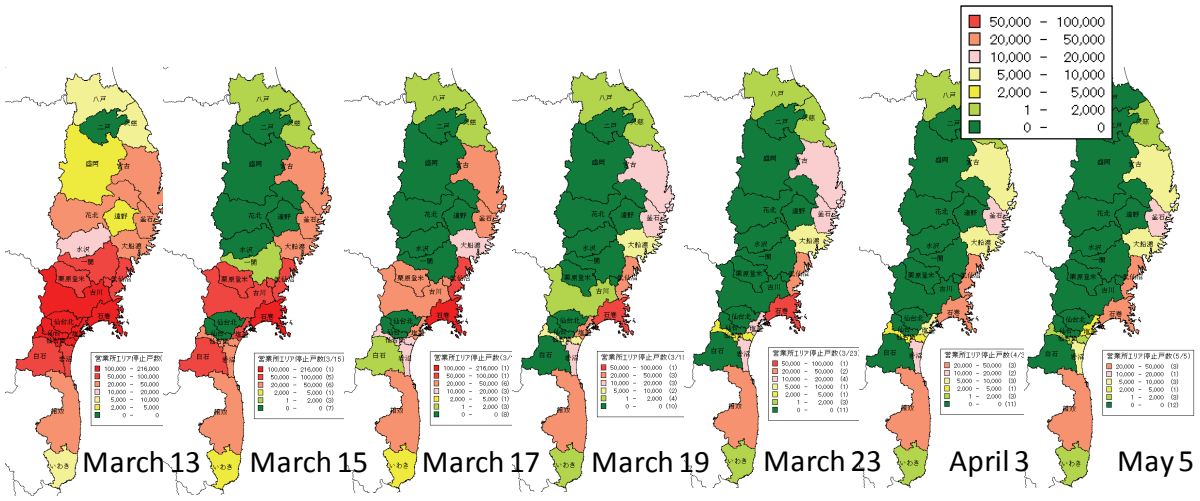


Figure 5. Spatial restoration process of electric power supply service (Number of households without service in local offices in Iwate, Miyagi and Fukushima prefectures)

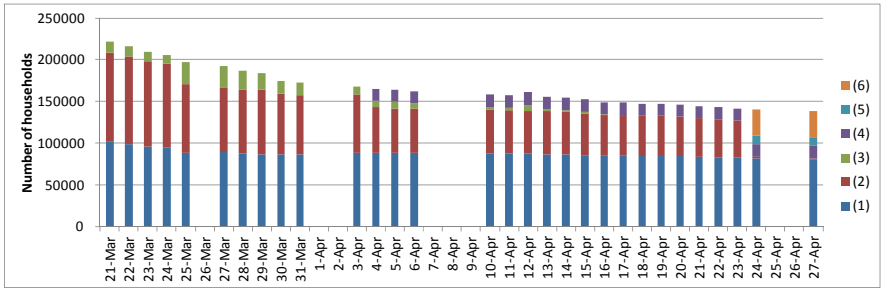


Figure 6. Number of households without electric power supply categorized into six causes (Tohoku Electric Power Company, 2011)

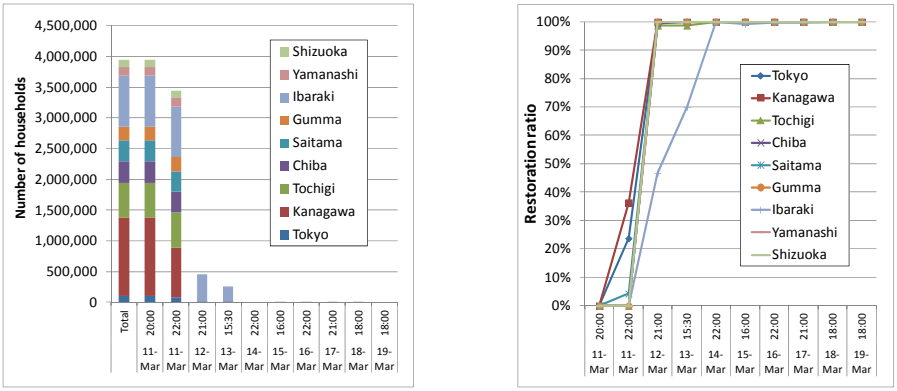


Figure 7. Number of households without electric power supply (left) and restoration curves of electric power supply service in affected prefectures (right) (Tokyo Electric Power Company, 2011)

3. WATER SUPPLY SYSTEMS

Water supply was disrupted at about 2.2 million households after the earthquake. Figures 8 and 9 show the restoration processes of water supply in each prefecture. Iwate, Miyagi and Fukushima prefectures have been most affected. Figure 10 shows the spatial restoration of water supply in each municipality

in terms of restoration ratio. Almost the eastern half of Tohoku and Kanto regions was affected. Similar to the electric power system, the coastal regions and Fukushima took longer time for restoration. Two major aftershocks on April 7th and 11th also drew back the restoration progress especially in Iwate, Miyagi and Fukushima prefectures.

In Iwate Prefecture, restoration ratio as of ten days after the earthquake reached 50%, but the restored customers were limited to those in inland regions or northern coastal regions where tsunami disaster was none or relatively slight. Slow progresses of restoration thereafter reveal that recovery works in the tsunami devastated coastal regions were significantly hindered.

In Miyagi Prefecture, The Sennan-Senen regional water supply system takes water from Shichkasyuku Dam and Shiroishi River, and transmits to 17 municipalities in the central-south Miyagi prefecture. The Ohsaki regional water supply system takes water from Naruse River and Yoshida River, and transmits to 10 municipalities in central-nourth Miyagi prefecture. Large-diameter welded steel transmission pipelines of these trans-municipal water supply systems suffered major damage (16 and 51 breaks, respectively), which significantly hindered recovery work during a few weeks. The configurations of these water transmission networks are basically tree-like structures. Because of poor redundancy of tree networks, the downstream areas of the most upstream location of pipe failures lose water supply. Recovery works of the failed pipes had to be conducted from the upper part in order to restore connection between water sources to users. Therefore, remote areas from the water source experienced longer disruption of water. Two independent lines, currently serving high- and low-elevation areas independently, are planned to be connected and looped to enhance redundancy and improve reliability in case of disaster (Miyagi Prefectural Government, 2011).

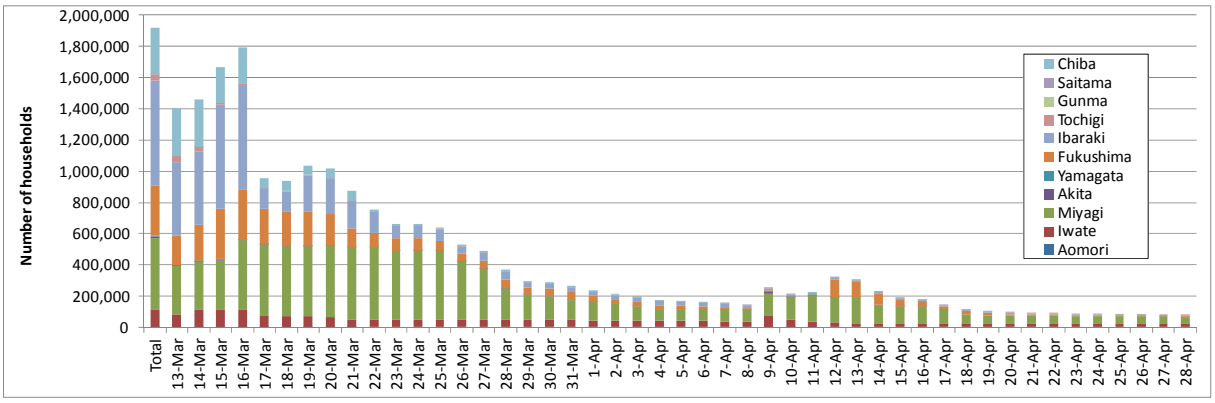


Figure 8. Number of households without water supply (Ministry of Health, Labour and Welfare, 2011)

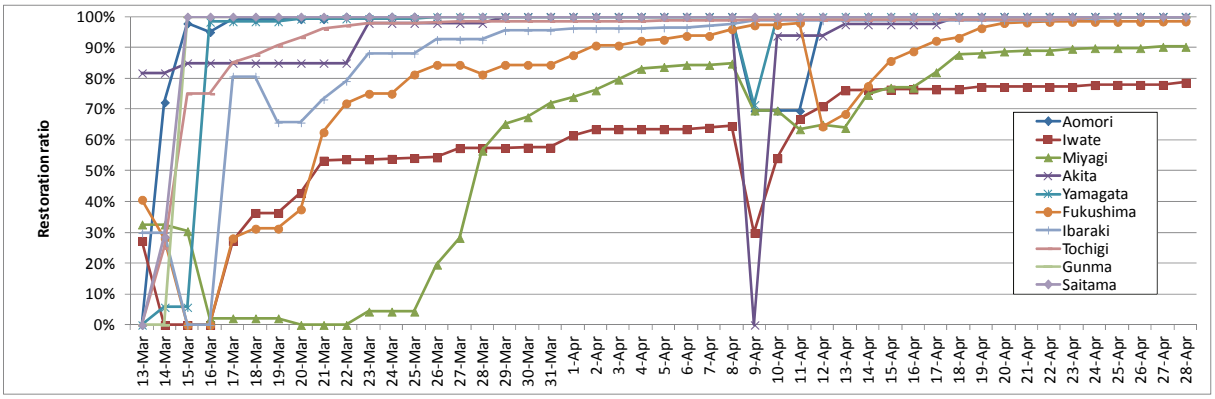


Figure 9. Restoration curves of water supply service in affected prefectures

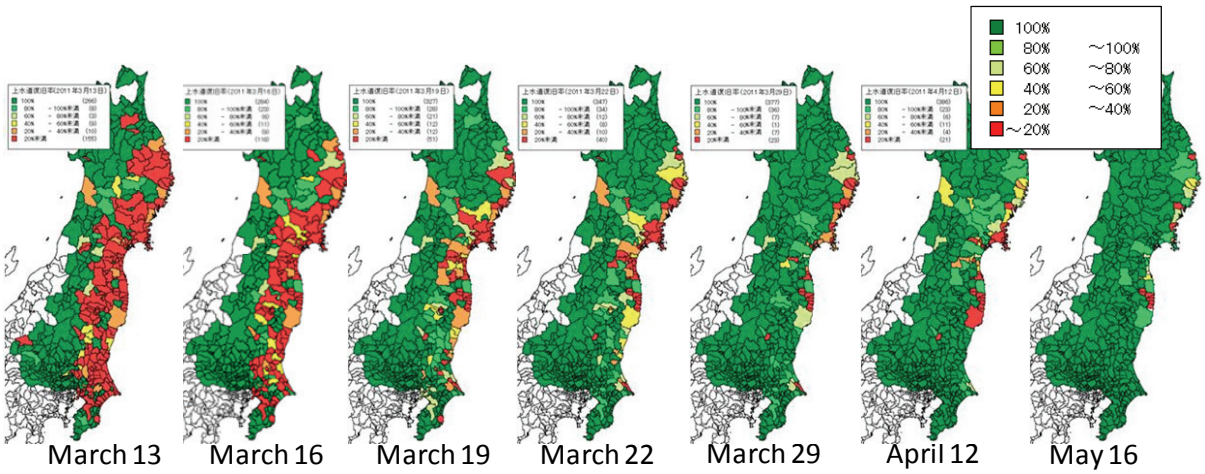


Figure 10. Spatial restoration process of water supply service (Restoration ratio in municipalities)

4. CITY GAS SUPPLY SYSTEMS

In Tohoku and Kanto regions, 16 city gas suppliers sustained suffered damage and the initial outage was 459 thousand households in total. Figures 11 and 12 show the restoration processes of city gas supply in each prefecture. In city gas supply systems, unlike electric power supply and water supply systems, the effect of the two aftershocks was not so significant. Figure 13 shows spatial restoration processes of city gas supply systems in each municipality in terms of restoration ratio. The service areas of city gas supply are limited to urbanized regions in Tohoku. In four Prefectures where city gas supply service was severely affected, the average penetration ratio of city gas supply via pipeline networks is only 25.9%. The breakdown of this ratio is 14.7% in Iwate, 44.2% in Miyagi, 20.3% in Fukushima and 19.4% in Ibaraki.

In Saitama, Kanagawa, Aomori and Ibaraki prefectures, restoration processes were relatively rapid; temporary restorations were achieved on March 12th, 13th, 16th and 24th, respectively. However, this accounts for only 10.3% on the number of customers' basis. In Chiba prefecture, pipelines of Keiyo Gas Corp. suffered severe damage in Urayasu City due to intensive liquefaction, and temporary restoration was completed on March 30th. In Iwate, Fukushima and Miyagi prefectures, completion days were April 11th, 15th and 25th, respectively.

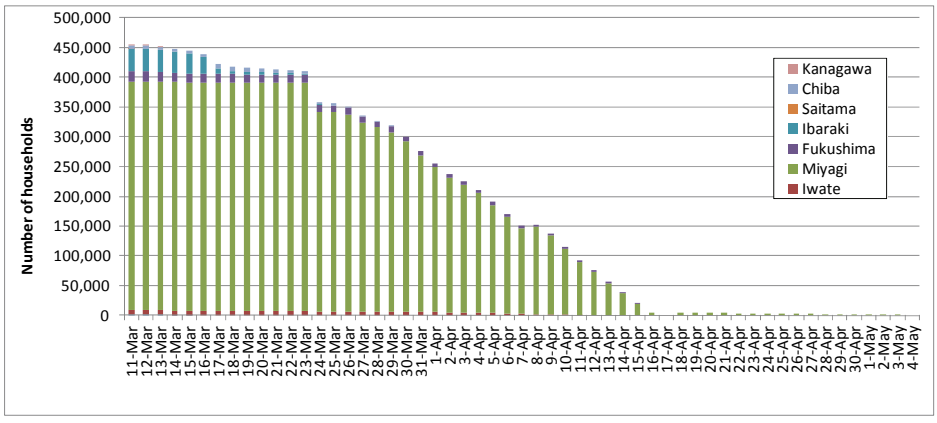


Figure 11. Number of households without city gas supply (The Japan Gas Association, 2011)

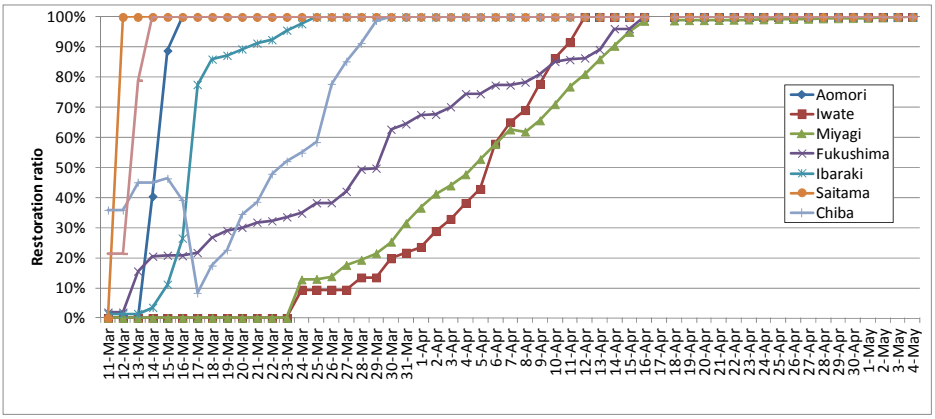


Figure 12. Restoration curves of city gas supply service in affected prefectures

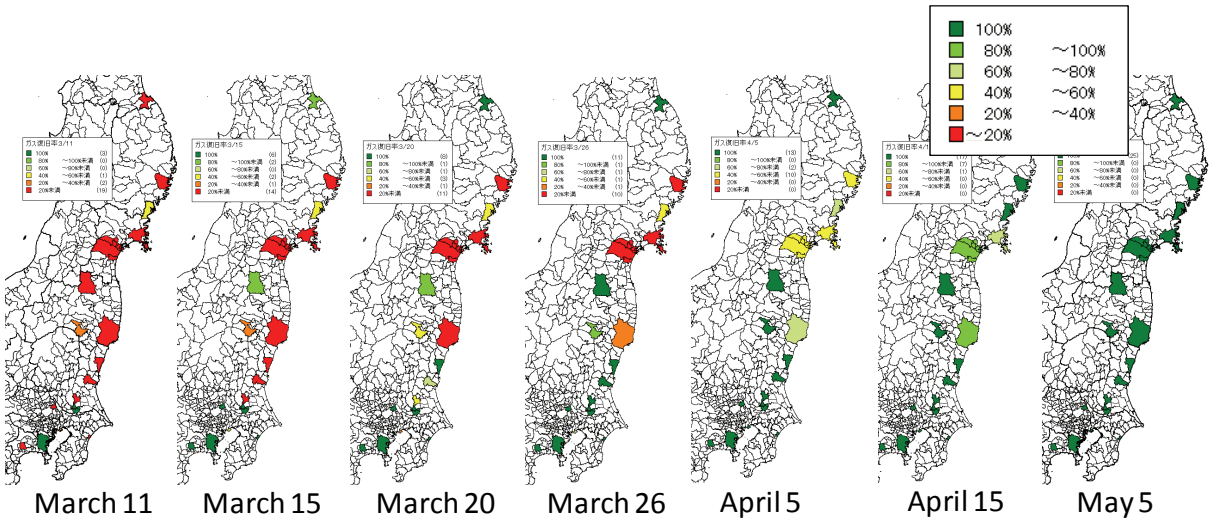


Figure 13. Spatial restoration process of city gas supply service (Restoration ratio in municipalities)

The most affected supplier was the Gas Bureau of City of Sendai. The Minato LNG plant was devastated by tsunami, which was the main cause of the city gas outage at 359 thousand households (78.2% of the total outage). Fortunately, long-distance high-pressure pipeline network transmitting natural gas from Niigata Prefecture to Sendai performed well. Transmission of natural gas was shut off immediately after the earthquake at Shiroishi junction valve station. However, after completing safety inspection along the transmission line to Sendai including 15 valve stations the network system restarted its operation on March 23th, contributing to rapid recovery thereafter. Thanks to this operation, two disaster base hospitals in Sendai City were prioritized and immediately restored. Without the natural gas transport via high-pressure pipeline, service recovery of city gas supply in Sendai City could have been much later.

5. TELEPHONE AND TELECOMMUNICATION SYSTEMS

Figure 14 shows the restoration processes of telephone and telecommunication lines. Affected telephone and telecommunication lines peaked on March 13, i.e., two days after the earthquake, because of exhausted back up generators and batteries. About 1.52 million lines were out of service. The 90% and 95% restoration took 14 days and 25 days, respectively. About 70,000 lines were affected again on April 8th mainly due to power loss caused by the major aftershock on April 7th.

As for cellular phones, more than 13,000 base stations of three major service providers lost functions. Figures 15 and 16 show the restoration processes of base stations of three major cellular phone

companies. The 90% and 95% restoration were achieved in 19 days and 46 days, respectively. The rapid recovery of base stations at the early stage is congruent with that of electric power supply, which is a typical aspect of lifeline system interactions. Many base stations for cellular phones were damaged mainly because electric power supply units were inundated and/or washed away by tsunami, significantly hindering progress of recovery.

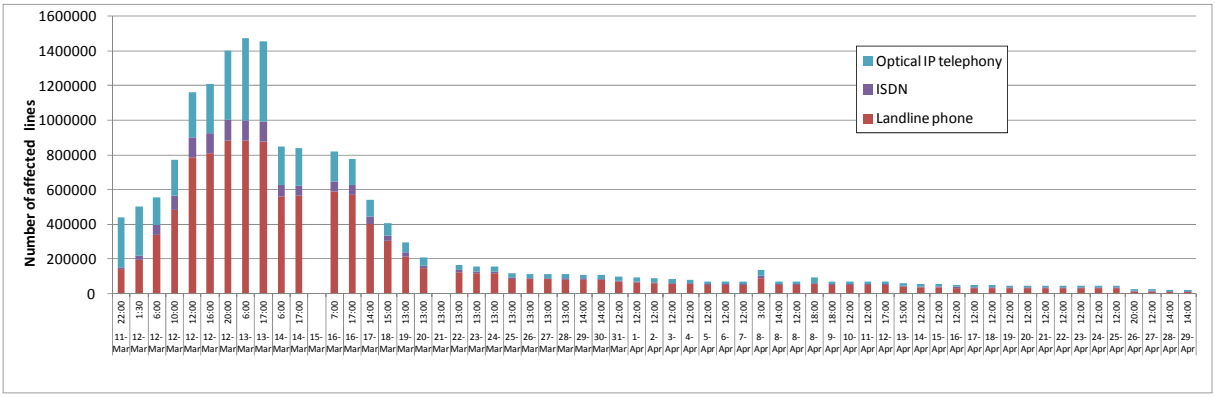


Figure 14. Number of affected telephone lines (NTT East Corp., 2011)

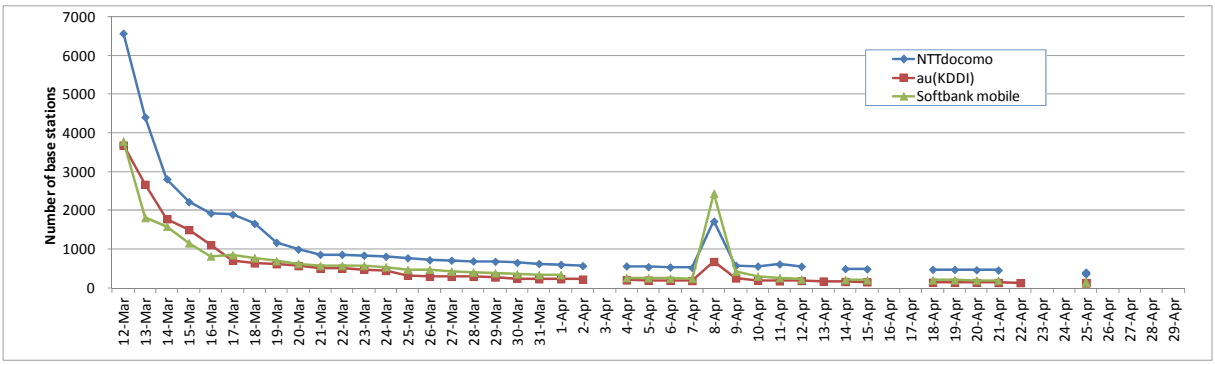


Figure 15. Number of affected base stations for mobile phones in three providers (Ministry of Internal Affairs and Communications, 2011)

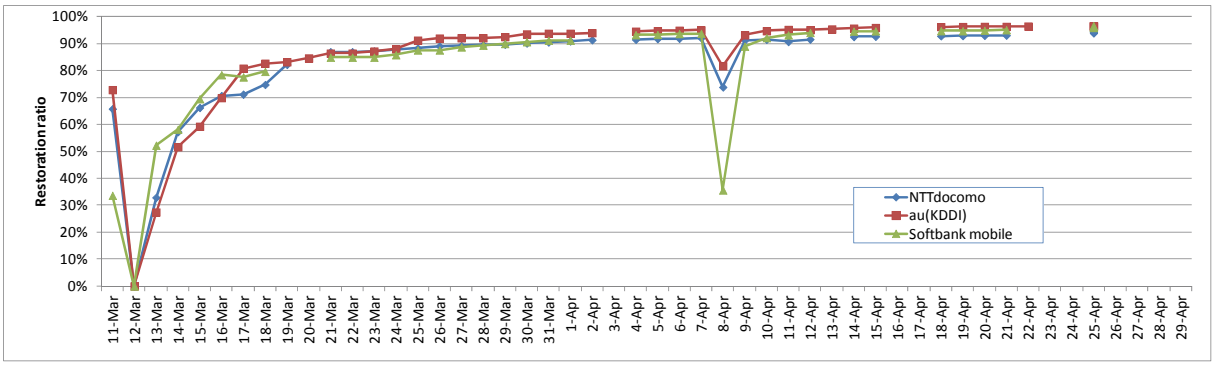


Figure 16. Restoration curves of base stations for mobile phones in three providers

6. COMPARISON WITH THE GREAT HANSHIN-AWAJI EARTHQUAKE DISASTER, 1995

The 1995 Great Hanshin-Awaji Earthquake Disaster, Japan was caused by the 1995 Hyogoken-Nambu Earthquake which was an inland crustal earthquake of M=7.3 with a fault rupture zone of approximately 40 km by 15 km. The 2011 Great East Japan Earthquake Disaster was caused by the 2011 off the Pacific Coast of Tohoku Earthquake, Japan (Mw=9.0) which was an off-shore

mega-thrust earthquake of Mw=9.0 with a gigantic fault rupture zone of approximately 500 km by 200 km. Although these two events (referred to as the 1995 event and the 2011 event, respectively) are quite different in the characteristics and spatial extent of strong motions and tsunami, lifeline systems were severely damaged in both earthquake disasters, resulting in long-term disruption of lifeline services.

In the 2011 event, as previously mentioned, 8.91 million (4.86 million in Tohoku EPCO + 4.05 million in Tokyo EPCO) lost electric power, over 2.2 million lost water supply and 0.86 million lost water supply. The number of the inundated houses is reported as about 0.21 million as of April 25th, 2011 (Statistics Bureau, Ministry of Internal Affairs and Communications, 2011), which is much less than the initial outage listed here. Although tsunami damage was catastrophic in this disaster, tsunami was just a part of the causes of damage as far as lifelines are concerned.

Table 1 and Figure 18 compares the initial outage in terms of the number of households without three kinds of utility lifelines (*E*: electric power, *W*: water and *G*: city gas). In the 1995 event, 2.6 million households lost electric power, 1.26 million lost water supply and 0.86 million lost city gas supply. It is common that the scale of initial outrages are in the order of *E*, *W* and *G*. The Ratios of initial outage (2011/1995) are 342% (187% if Tokyo Electric Power Company is excluded), for *E*, over 180% for *W* and 54% for *G*. The fact that spatial extents of initial damages are in the order of *E*, *W* and *G* is also common to the two disasters.

Table 1. Comparison of initial outage of lifeline services
(The 2011 Great Eastern Japan EQD and the 1995 Great Hanshin-Awaji EQD)

Lifeline	2011 off the Pacific Coast of Tohoku EQ (The Great Eastern Japan EQ Disaster)	1995 Hyogoken-Nambu EQ (The Great Hanshin-Awaji EQ Disaster)	Ratio (2011/1995)
Electric power supply	8.91 million (4.86 million in Tohoku)	2.6 million	342% (187% in Tohoku)
Water supply	Over 2.2million	1.26 million (in Hyogo Prefecture only)	Over 180%
City gas supply	0.46 million	0.86 million	53%

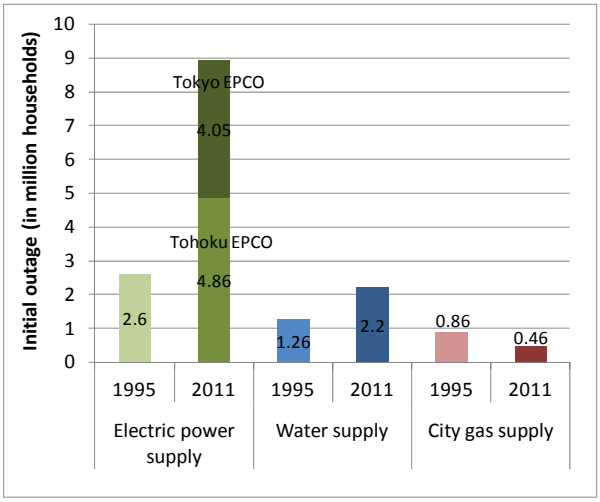


Figure 17. Comparison of initial outage of lifeline services (The 2011 Great Eastern Japan EQD and the 1995 Great Hanshin-Awaji EQD)

Figure 18 compares the decreasing process of the number of households without *E*, *W* and *G* in the two earthquake disasters. Figure 19 compares the associated restoration curves representing percent number of households restored, in other words, the ratio of the number of restored households to the maximum outage in each lifeline. As for electric power in the Great East Japan Earthquake disaster in

both figures, Tokyo Electric Power Company is excluded from the data. It is common that the rapidness of service recoveries is in the order of *E*, *W* and *G*. Moreover restoration curves in Figure 2 look similar.

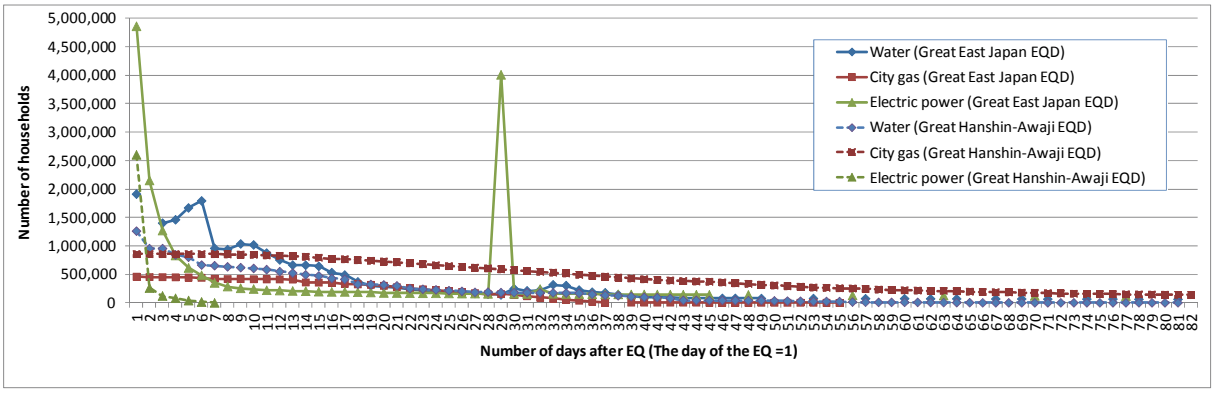


Figure 18. Comparison of number of households without lifeline services (The 2011 Great Eastern Japan EQD and the 1995 Great Hanshin-Awaji EQD)

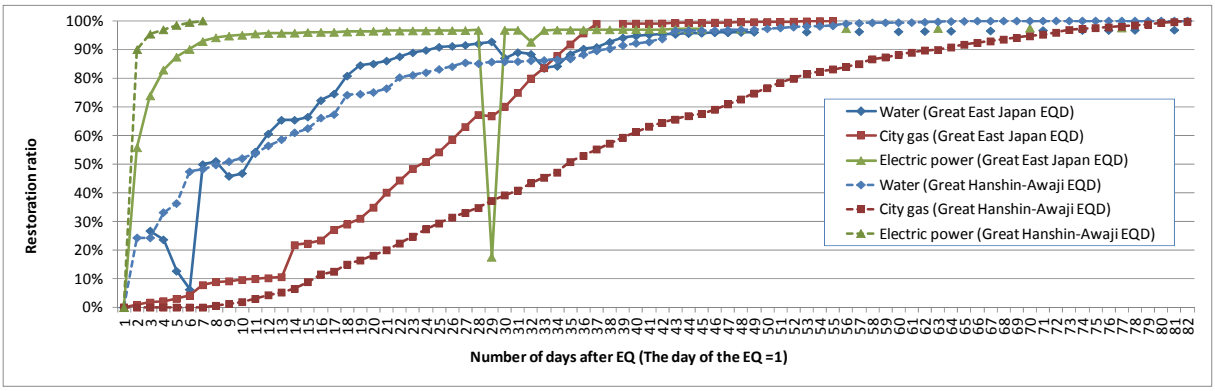


Figure 19. Comparison of restoration curves (The 2011 Great Eastern Japan EQD and the 1995 Great Hanshin-Awaji EQD)

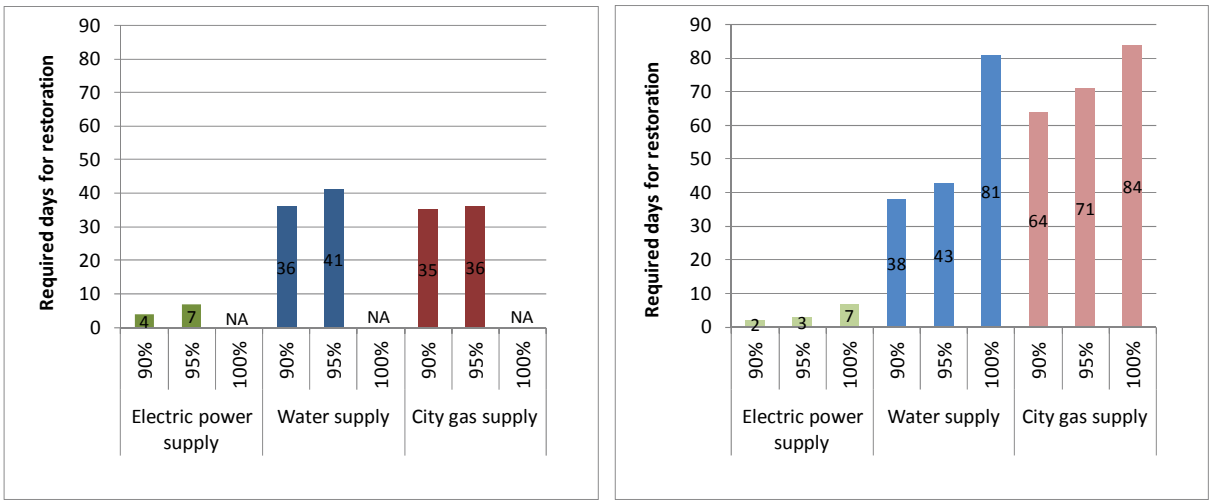
Table 2 and Figure 20 compare the time periods required for 90% and 95% level of restoration. In electric power systems, the 90% and 95% levels of restoration took six days and 10 days, respectively (four days and seven days including Tokyo Electric Power Company) in the 2011 event, which are longer than in the 1995 event, but much faster than water and city gas supply systems. In water supply systems, the 90% level was achieved once in 25 days. However, two major aftershocks drew back the restoration progress. Therefore, it required 36 days after all. The 95% restoration was achieved in 41 days. These are comparative with the 1995 event. In city gas supply systems, 35 days and 36 days were required, faster than in the 1995 event. However, about 12.3% of the affected customers were tentatively excluded from the emergency recovery plan. Therefore, 100% applies to the remaining 402 thousand customers.

In these two earthquakes disasters, quantities of damage are different, causes of damage are different, and spatial extents of damage are also different, however, the restoration curves are incidentally similar. One of the possible reasons is that social demands to lifelines for rapid recovery had become very strong since the 1995 event and the restoration process at that time are considered to be a recovery target in catastrophic disaster. Therefore, organizational assistance came from all over Japan to complete the restoration as soon as possible. However, the restoration of tsunami-devastated areas was very slow. The recovery works are still in going on in association with regional disaster recovery plans, which will require years of time period to complete the restoration.

Table 2. Comparison of required days for 90%, 95% and 100% restoration
(The 2011 Great Eastern Japan EQD and the 1995 Great Hanshin-Awaji EQD)

Lifeline	Level of restoration	2011 off the Pacific Coast of Tohoku EQ (The Great East Japan EQ Disaster)	1995 Hyogoken-Nambu EQ (The Great Hanshin-Awaji EQ Disaster)
Electric power supply	90% 95% 100%	4 days (6 days in Tohoku) 7 days (10 days in Tohoku) N.A.	2 days 3 days 7 days
Water supply	90% 95% 100%	25 days (36 days *) 41 days N.A.	38 days 43 days 81 days
City gas supply	90% 95% 100%	35 days # 36 days # N.A.	64 days 71 days 84 days

* After two aftershocks of April 7th and 11th, 90% restoration was achieved again on April 15th.
# 56,588 (12.3%) customers severely affected by tsunami were tentatively excluded from the emergency recovery plan. The remaining 401,976 customers (89.7%) is renormalized to 100%.



(a) The 2011 Great Eastern Japan EQD (b) The 1995 Great Hanshin-Awaji EQD

Figure 19. Comparison of required days for 90%, 95% and 100% restoration

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