Comparison of Functional Damage and Restoration Processes of Utility Lifelines in the 2016 Kumamoto Earthquake, Japan with Two Great Earthquake Disasters in 1995 and 2011

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Key Facts
- Hazard Type: Earthquake
- Date of the disaster: April 14th and 16th, 2016
- Location of the survey: Kumamoto Prefecture
- Date of the field survey: April 15th through June 7th, when needed.
- Survey tools: Documents published via press release or related websites, Interviews
- Key findings: 1) Population exposures to JMA seismic intensity were compared and characterized.
  2) Initial outages were roughly in proportion to population exposure at certain levels of intensities.
  3) Restoration processes were relatively rapid in the Kumamoto Earthquake.
  4) Substantial organizational efforts contributed to rapid recovery in the Kumamoto Earthquake.

Key Words : *The 2016 Kumamoto Earthquake, the 1995 Great Hanshin-Awaji Earthquake Disaster, the 2011 Great East Japan Earthquake Disaster, utility lifelines, functional damage, initial outage, restoration process, organizational efforts*

1. INTRODUCTION

The 2016 Kumamoto Earthquake[1)], a series of earthquakes, including two events which occurred on April 14 21:26 (M_{JMA}=6.5) and April 16 1:25 (M_{JMA}=7.3) marked JMA seismic intensity I_{JMA}=7, caused major damage to lifelines in central Kyushu region, mainly in Kumamoto Prefecture. In the previous paper[2)] by the authors, functional damage and restoration processes of utility lifelines including electric power supply, water supply, city gas supply were compiled.

In this paper, population exposure to JMA seismic intensity I_{JMA}, initial outage, functional restoration processes and organizational efforts for disaster response in the 2016 Kumamoto Earthquake are compared with those in the 1995 Great Hanshin-Awaji Earthquake Disaster and the 2011 Great East Japan Earthquake Disaster[3)-5)]. The former was caused by the 1995 Hyogoken-Nambu Earthquake, Japan which is an inland crustal earthquake of JMA magnitude M_{JMA}=7.3. The latter was caused by the 2011 off the Pacific Coast of Tohoku Earthquake, Japan which is an off-shore mega-thrust earthquake of moment magnitude M_w=9.0. The three earthquake events are referred to as follows hereafter.

The 1995 event: The Great Hanshin-Awaji Earthquake Disaster, 1995
The 2011 event: The Great East Japan Earthquake Disaster, 2011
The 2016 event: The 2016 Kumamoto Earthquake

The following abbreviations are also used.

E : Electric power supply
W : Water supply
G : City gas supply

Damage statistics in these three events are listed in Table 1[6)-8)].

Table 1 Damage statistics in the three earthquake disaster[6)-8)].

	The 1995 Great Hanshin-Awaji Earthquake Disaster	The 2011 Great East Japan Earthquake Disaster	The 2016 Kumamoto Earthquake
Date and time (JST)	January 17, 5:46, 1995	March 11, 14:46, 2011	April 14, 21:46 andApril 16, 1:35, 2016
Magnitude	M_{JMA}=7.3	M_w=9.0	M_{JMA}=6.8 and 7.3
Highest I_{JMA}	7	7	7
Human damage	-	-	-
Deaths	6,434	19,418	95 (45)*
Missing	3	2,592	0
Injured	43,792	6,220	1,806
Building damage	639,686	1,144,495	171,111
Collapse (households)	104,906 (186,175)	121,809	8,142
Partial collapse (households)	144,274 (274,182)	278,496	28,671
Minor damage	309,506	744,190	134,298

* Number of deaths due to indirect causes related to the earthquake (included in the total).

For the explanation of JMA seismic intensity I_{JMA}, refer to Appendix A in the previous paper[2)].

2. POPULATION EXPOSURE TO JMA SEISMIC INTENSITY

(1) Definition and calculation of population exposure to seismic intensity

Population exposure to seismic intensity (PEX) is evaluated as an aggregation of spatially distributed population exposed to a certain level of seismic intensity. The PEX represents the overlapped effect of two major contributors to the impact of seismic disaster: the distribution of seismic intensity as a natural factor, and that of population as a social factor[9),11)]. For the 1995 event, PEX was evaluated using the distribution map of I_{JMA} inversely estimated based on building damage[9)]. For 2011 event, the I_{JMA} distribution map provided by QuiQuake[10),11)] (Quick Estimation System for Earthquake Maps Triggered by Observation Records) was used. QuiQuake is operated by Advanced Industrial Science and Technology (AIST) taking advantage of data collected via strong-motion seismograph networks (K-NET and KiK-net)[12)] operated by National Research Institute for Earth Science and Disaster Prevention (NIED). Also for the 2016 event, the I_{JMA} distribution map provided by QuiQuake has been used[4)]. Population exposure to tsunami is not considered in this study.

(2) Population exposure using all population

Figure 1(a) compares population exposure to JMA seismic intensity I_{JMA}=5L+ (5 lower or greater), 5U+ (5 upper or greater), 6L+ (6 lower or greater), 6U+ (6 upper or greater) and 7, using all population.

For all ranges, the 2016 event gives the least values of the three earthquake events. The 1995 event gives the largest value for PEX(I_{JMA}=7). The 1995 and 2011 events are comparative for PEX (I_{JMA}=6U+).

The 2011 event gives the largest values for less intensive intensity ranges (I_{JMA}=5L+, 5U+ and 6L+) because of the extremely large dimension of fault rupture, large magnitude thereby, relatively long distance from the source region to densely populated area involving Tokyo metropolitan area.

Although M_{JMA}=7.3 is coincidentally identical in the 1995 event and the 2016 event (on April 16), population exposures are considerably different, since the former involved Kobe metropolitan area in its hardest-hit area.

(3) Population exposure for city gas supply

While the penetration ratios of *E* and *W* can be considered as almost 100%, that of *G* strongly depends on the locality. Therefore population exposure PEX_G has been evaluated using population served by city gas supply systems[13)]. Figure 1(b) compares the results.

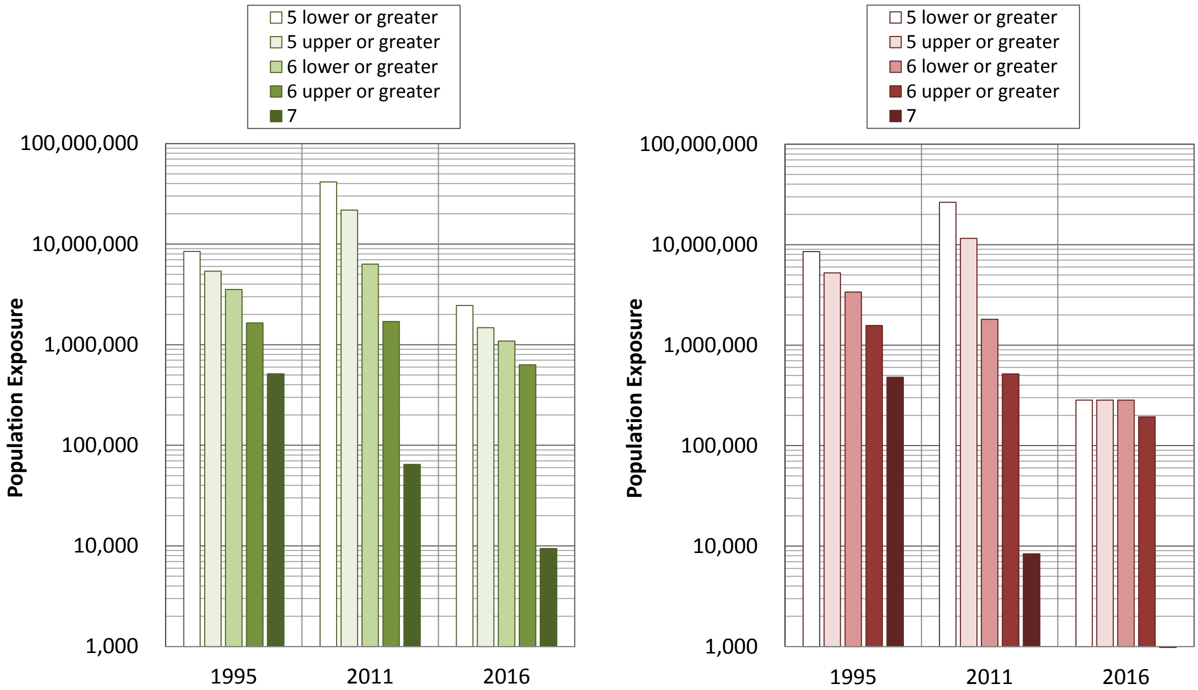
The high seismic intensity area in the 1995 event was Kobe and Osaka metropolitan area where penetration ratio of city gas was around 98%. The difference between PEX and PEX_G in Figure 1(a) and (b) is small for all intensity range. On the contrary, for the 2011 event, PEX_G(I_{JMA}=6L+) and PEX_G (I_{JMA}=6U+) are approximately 30% of their corresponding PEX. In the 2016 event, almost the entire area of city gas service was exposed to I_{JMA}=6L or greater. PEX_G(I_{JMA}=6L+) and PEX_G (I_{JMA}=6U+) are also approximately 30% of their corresponding PEX, whereas almost none was exposed to the highest seismic intensity level I_{JMA}=7.

3. INITIAL OUTAGE

(1) Comparison of initial outage

Figure 2 compares initial outages[2),3)] in terms of the number of customers without *E* and those of households without *W* and *G*. The largest outage of *E* and *W* occurred in the 2011 event, and that of *G* occurred in the 1995 event.

In each earthquake disaster, it is commonly seen



(a) All population (b) Population served with city gas

Fig.1 Comparison of population exposure to seismic intensity.

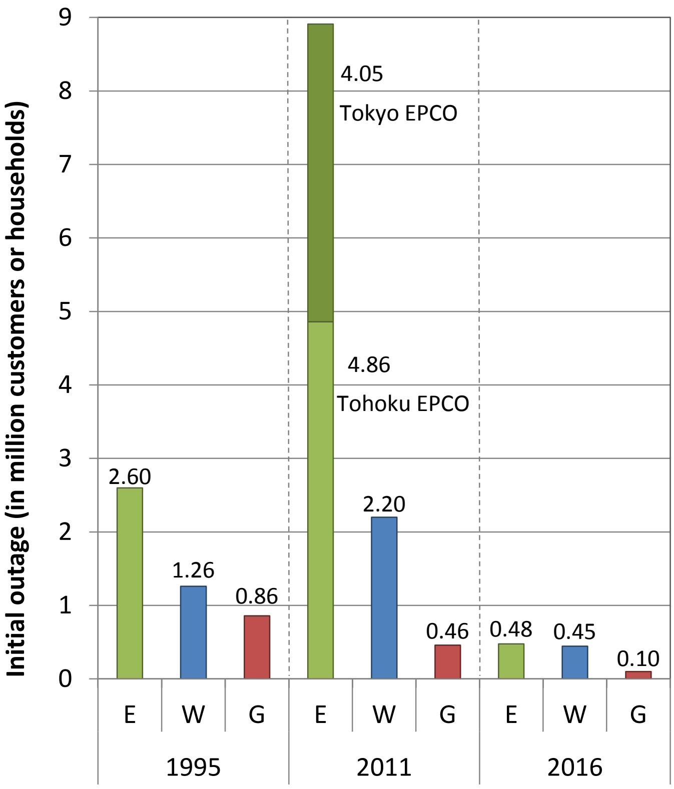
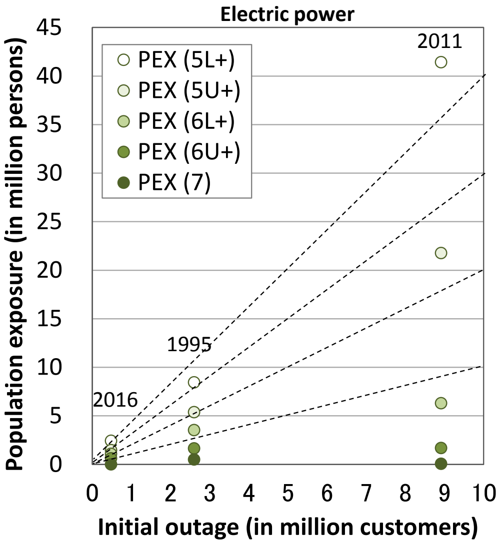


Fig.2 Comparison of initial outage of lifeline services.

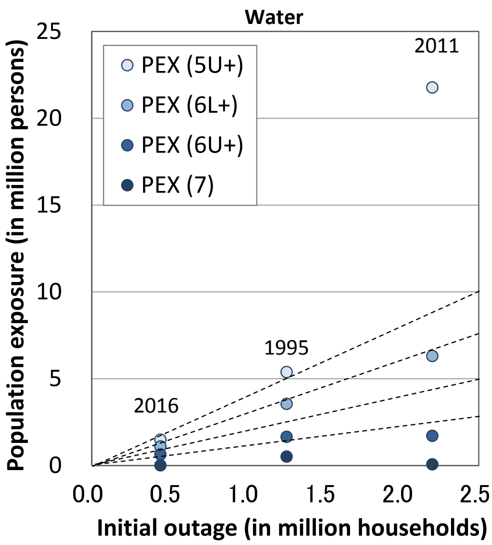
that the scale of initial outage is in the order of *E*, *W* and *G*. In general, functional fragility relations of lifelines suggest that lifeline serviceability is susceptible to ground shaking in the order of *E*, *W* and *G*. However, the difference between *E* and *W* is much smaller in the 2016 event than in the other two events, which implies that the spatial extent of power outage was relatively limited to high seismic intensity area.

(2) Relationship between initial outage and population exposure

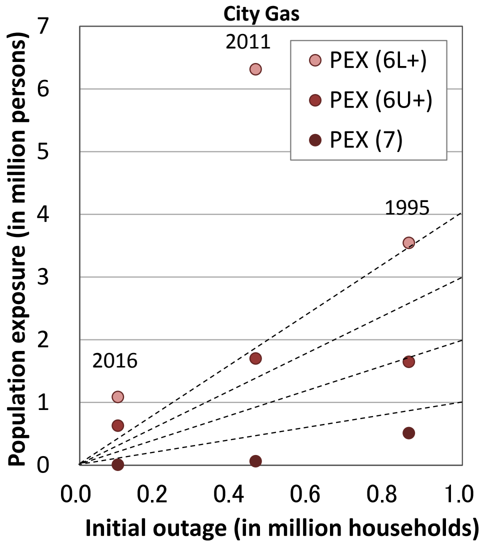
The relationships between PEX for various inten-



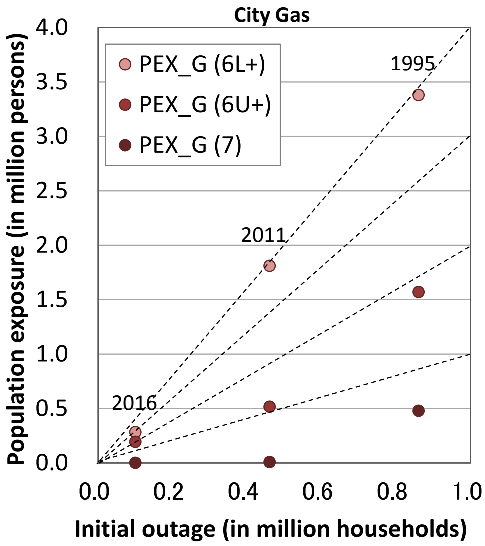
(a) Electric power supply (all population)



(b) Water supply (all population)



(c) City gas supply (all population)



(d) City gas supply (population served by city gas systems)

Fig.3 Relationships between population exposure to five ranges of seismic intensity and initial outage. (Four dashed lines correspond to 1:1, 1:2, 1:3 and 1:4 proportional lines from the bottom to the top.)

sity ranges (Fig.1(a)) and initial outage of *E*, *W* and *G* (Fig.2) are shown in Fig.3(a)-(c). Four dashed lines correspond to 1:1, 1:2, 1:3 and 1:4 proportional lines from the bottom to the top.

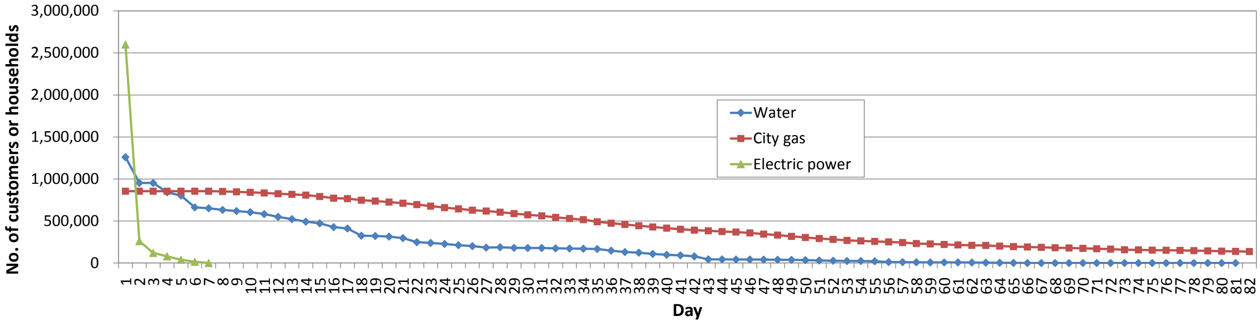
Initial outage of customers of *E* is roughly a half to one third of PEX(I_{JMA}=5U+). Initial outage of *W* is approximately one third of PEX(I_{JMA}=6L+). As for *G*, such relationship with PEX for any range is unclear because of the difference in penetration ratio. Instead, as shown in Fig.3(d), initial outage of *G* is highly correlated with PEX_G(I_{JMA}=6L+) shown in Fig.1(b). A half to 100% of PEX_G(I_{JMA}=6U+) can also agree with initial outage of *G*. It can be said that population exposure to seismic intensity shown in Fig.1, in conjunction with the penetration ratio stated above, accounts for the initial outage to some extent.

4. FUNCTIONAL RESTORATION PROCESSES

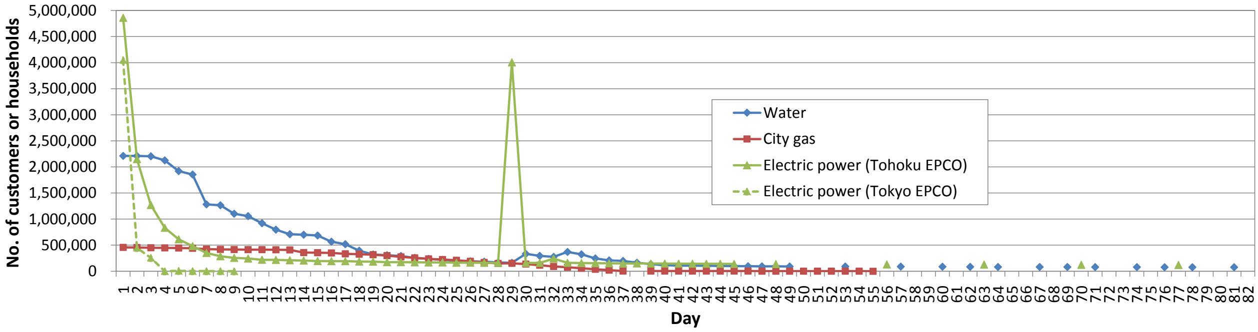
(1) Restoration processes

Figure 4 shows the decreasing processes of the number of customers without *E* and those of households without *W* and *G*[2),3)]. The first day of the horizontal axis is set to the day of occurrence of each earthquake: January 17 of 1995, March 11 of 2011 and April 16 of 2016, respectively. The effects of the first event on April 14 of 2016 is omitted herein. As to electric power in the 2011 event, Tohoku and Tokyo Electric Power Co., Inc. are separately represented.

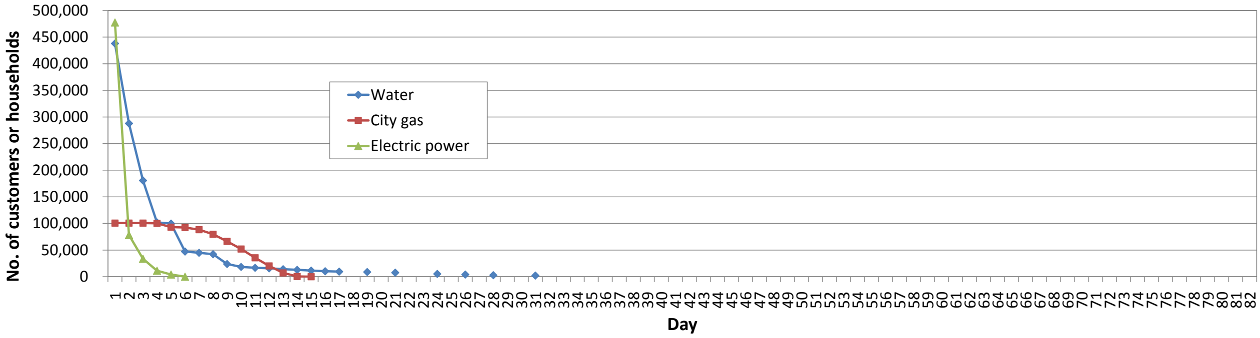
Figure 5 shows the associated restoration curves representing percent number of customers or



(a) The 1995 Great Hanshin-Awaji Earthquake Disaster (First day: January 17, 1996)



(b) The 2011 Great East Japan Earthquake Disaster (First day: March 11, 2011)



(c) The 2016 Kumamoto Earthquake (First day: April 16, 2016)

Fig.4 Comparison of decreasing processes of number of customers of households without lifeline services. (The first day of horizontal axis is set to the day of occurrence of each earthquake.)

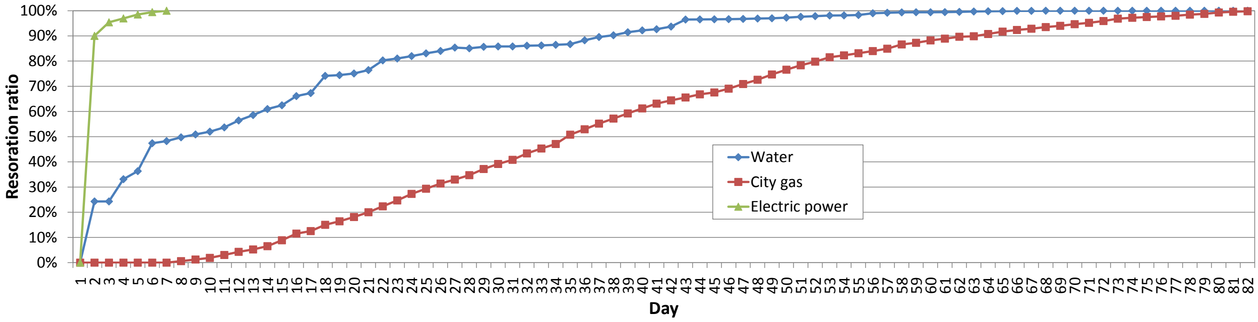
households restored, in other words, the ratio of the number of restored ones to the maximum outage in each lifeline.

Relative configurations of restoration curves are similar in the three events. It is commonly seen that the rapidness of service recoveries is in the order of *E*, *W* and *G*. In general, provisional restoration works of overhead facilities such as electric power distribution lines and utility poles are much more rapid than restoration works of buried pipelines. Restoration works of water pipelines allow water leaks to find damage locations, while those of city gas pipelines must follow strict safety measures that never allow gas leaks.

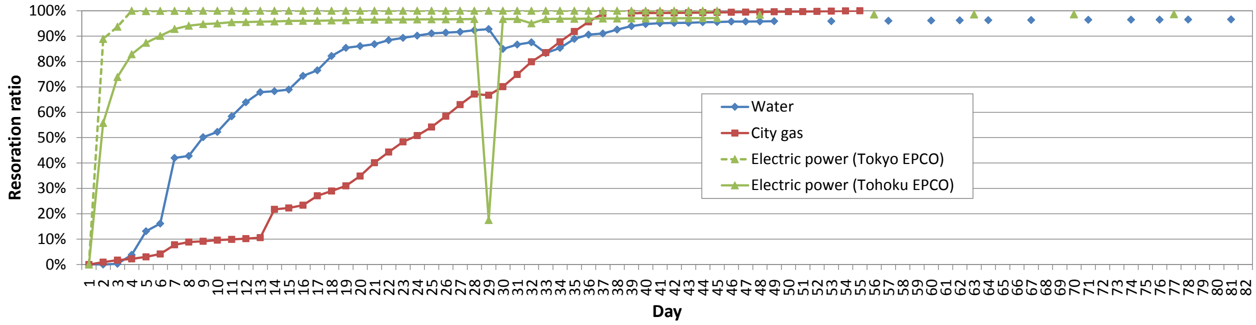
(2) Time periods required for restoration

As opposed to the similarities in relative configurations of restoration curves, absolute configurations in the three events are different from each other. Figure 6 compares the time periods in terms of the number of days required for 50%, 90%, 95% and 100% level of restoration.

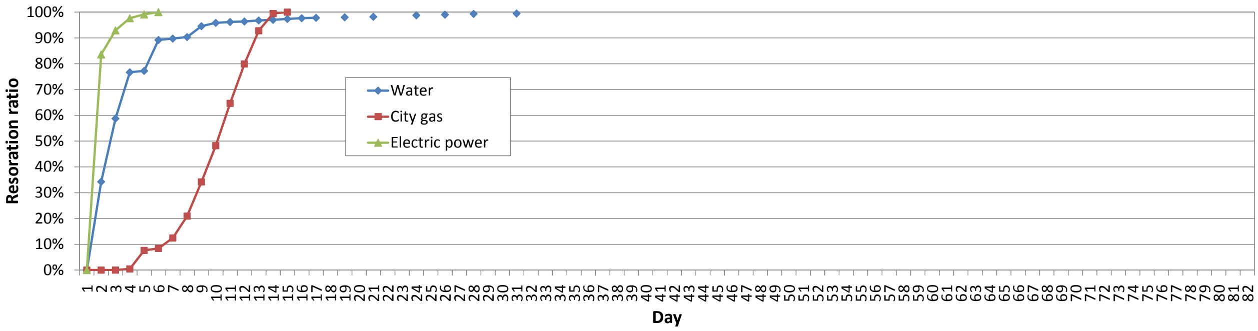
With regard to *E*, restoration curves are similar in the three events, except for delay in completion of restoration in tsunami-devastated areas and the effects of two major aftershocks on April 7 and 11, 2011. Even in catastrophic disaster, restoration of electric power supply within one week is considered to be social demands, conceivably establishing a recovery target for service providers. On the contrary, as for *W* and *G*, the restoration processes in the 2016 event are much more rapid than in the other two events.



(a) The 1995 Great Hanshin-Awaji Earthquake Disaster (First day: January 17, 1996)

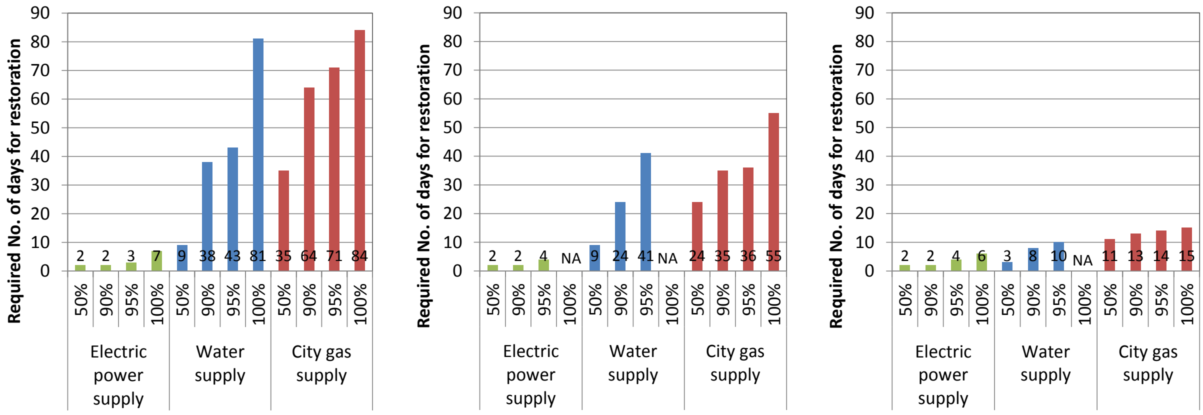


(b) The 2011 Great East Japan Earthquake Disaster (First day: March 11, 2011)



(c) The 2016 Kumamoto Earthquake (First day: April 16, 2016)

Fig.5 Comparison of restoration curves representing increasing process of restoration ratios.
(The first day of horizontal axis is set to the day of occurrence of each earthquake.)



(a) The 1995 Great Hanshin-Awaji EQD (b) The 2011 Great East Japan EQD (c) The 2016 Kumamoto Earthquake

Fig.6 Comparison of required days for 50%, 90%, 95% and 100% restoration.

Although the spatial extents and quantities of physical/functional damage in the 2016 event were relatively small compared to the 1995 and 2011 events, considerable organizational assistance by related associations was devoted aiming at rapid completion of functional restoration. The next chapter sheds light on such aspects of disaster response.

5. ORGANIZATIONAL EFFORTS FOR DISASTER RESPONSE

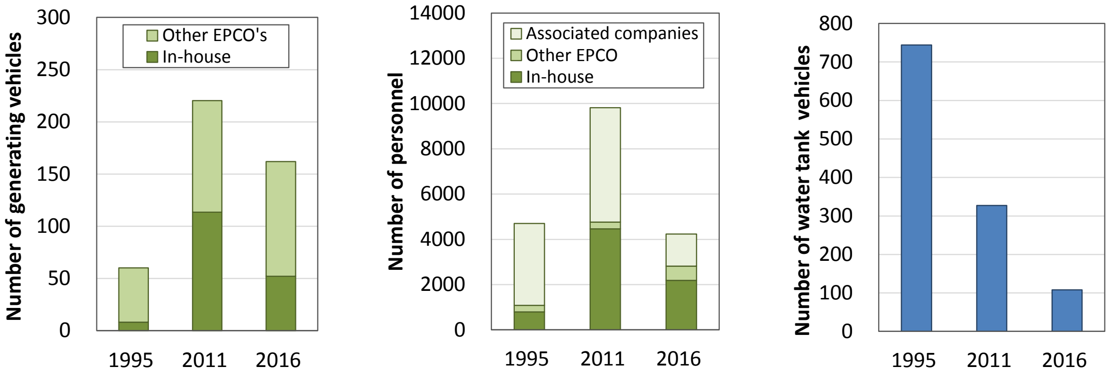
In this chapter, organizational efforts for disaster response are compared in the light of restoration works and emergency supply. All the numbers shown in Fig.7 are the peak values in each time history.

(1) Electric power supply system

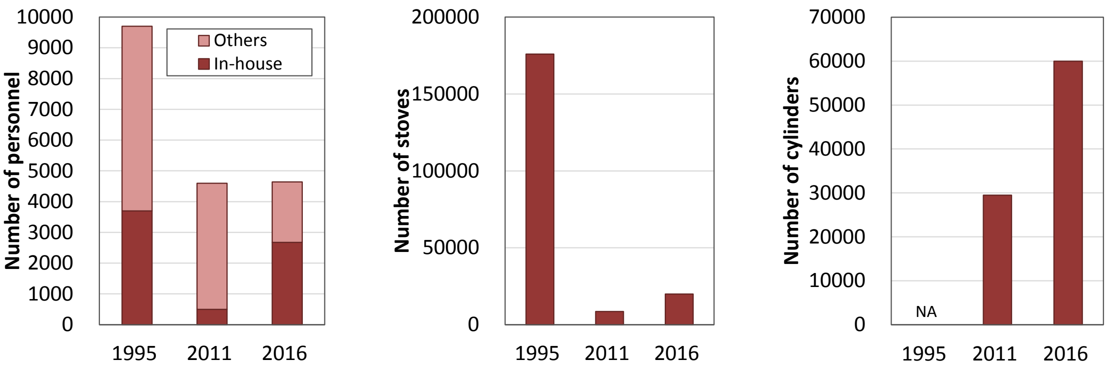
Figure 7(a) shows the number of high-voltage electric power generating vehicles[14)-18)] deployed to the areas isolated from normal electric power supply routes due to various causes such as intensive building damages and large scale landslide. The numbers are classified into two: in-house vehicles and those provided by other electric power companies for emergency assistance. For the 2011 event, the numbers of in-house vehicles were unknown; therefore those numbers were estimated by assuming 90% of each stock were deployed: 58 out of 64 vehicles in Tohoku Electric Power Co., Inc. and 56 out of 62 vehicles in Tokyo Electric Power Co., Inc.

Considering the relative scale of disaster, it can be said that 162 vehicles in the 2016 event significantly contributed rapid completion of functional recovery as described in Fig.4 in the previous paper[2)]. On the other hand, the total number of high-voltage electric power generating vehicles owned by the ten electric power companies is 380 vehicles[18)] as of 2014. In the 2011 and 2016 events, 58% and 43% of the total were utilized, respectively. It is concerned that shortage of power generating vehicles will occur in future huge earthquake disaster.

The numbers of personnel engaged in restoration of power distribution lines[14)-18)] are compared in Fig.7(b). In addition to the two categories above, associated companies for construction works are included. Although the number for the 2016 event is the least of the three, it is comparable to the 1995 event.



(a) High-voltage electric power generating vehicles (The number of in-house vehicles in the 2011 event was estimated as 90% of the stock.) (b) Personnel for power distribution division (c) Water tank vehicles



(d) Personnel for gas restoration works (e) Portable cooking stoves (f) Cassette gas cylinders

Fig.7 Comparison of organizational efforts for disaster response in terms of number of personnel and emergency supply.

(2) Water supply system

The numbers of water tank vehicles deployed for emergency water supply[19)-21)] are shown in Fig.7(c). The total number of water tank vehicles owned by 1,496 water suppliers is 1,148 vehicles[22)] as of 2013. The number in the 2016 event is far less than in the other two events. The ratio to the total vehicles was 9%. Relatively small initial outage as well as relatively rapid recovery mitigated the emergency demands.

(3) City gas supply system

The numbers of personnel for recovery works of city gas supply[23)-25)] are compared in Fig.7(d). Although the number in the 2016 event is a little less than half of that in the 1995 event, it is slightly more than that in the 2011 event. In addition to substantial number of in-house personnel of Saibu Gas Co., Ltd., inter-organizational assistance was organized by Japan Gas Association. Rapid recovery of city gas supply shown in Figs.4 and 5 was supported by such organizational efforts.

Figures 7(e) and (f) show the numbers of portable cooking stoves and cassette gas cylinders distributed by gas companies[23)-25)], respectively. Those gas apparatuses were provided for alternative heat sources for boiling water and cooking during the period of city gas supply disruption. Both numbers in the 2016 event are twice as many as those in the 2011 event despite of lesser initial outage and shorter duration of disruption.

6. CONCLUDING REMARKS

In this paper, functional damage and restoration processes of three utility lifelines were compared among the 1995 Great Hanshin-Awaji Earthquake Disaster, the 2011 Great East Japan Earthquake Disaster and the 2016 Kumamoto Earthquake. Major findings derived from this study are listed below.

1) Population exposure to JMA seismic intensity was compared using all population and population served with city gas supply. The results were characterized by the differences in magnitude, population density and penetration ratio of city gas supply.
2) Initial outage among the three events was compared in conjunction with population exposure. Initial outages of electric power supply, water supply and city gas supply were found to be roughly in proportion to population exposure to I_{JMA}=5U+, 6L+ and 6U+, respectively, implying the differences in functional fragility relationships.
3) The numbers of customers or households without lifeline services and associated restoration curves in corresponding areas of each lifeline damage were graphically compared. Although relative configurations of restoration curves are similar in the three events, restoration processes in the 2016 event were much more rapid than the other two events.
4) Organizational efforts for disaster response were compared. Considering the scale of disaster, much efforts were devoted aiming at rapid functional recovery in the 2016 event. Such tendency can be markedly seen in deployment of restoration personnel and emergency supply measures in electric power supply and city gas supply.

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