Influence to Water Outage due to Damage to Regional Water Supply during the 2011 off the Pacific Coast of Tohoku Earthquake

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SUMMARY
The 2011 off the Pacific coast of Tohoku earthquake, which occurred on March 11, 2011, caused water-supply outages to 2.2 million households in 187 cities and towns. There were long-term disruptions of regional water supplies, long-term electric power outages, extensive liquefaction damage, and the damage caused by the tsunami. These multiple factors made the damage pattern complex, and water-supply restoration was delayed even though the seismic ground motion was moderate. This study attempts to elucidate the factors that caused water-supply restoration to be delayed following the earthquake and to measure the earthquake impact on water-supply outages due to damage of regional water supply. As a result, the long restoration time for the water supply following the Tohoku earthquake could be explained by a combination of above factors. The residents in Miyagi Prefecture were affected by the regional water-supply outage rather than other suffered areas.

Keywords: water supply outage, the Tohoku earthquake, factor analysis, regional water supply

1. INSTRUCTION

The 2011 off the Pacific coast of Tohoku earthquake (hereinafter referred to as the Tohoku earthquake) caused wide-area earthquake disaster, a tsunami, and a nuclear disaster in the stricken area. While this earthquake affected a wide area in Eastern Japan, damage to houses and civil structures was minor or moderate, considering the observed seismic ground motion. Damage to water supply facilities and pipelines was also less than or equal to the amount of damage caused by previous earthquakes, if damage due to the severe tsunami and liquefaction is excluded. Nevertheless, it took a long time to restore the water supply. The water-supply outage caused by this earthquake and the following earthquakes in the Niigata and Nagano Prefectures affected up to 187 cities and towns and about 2.25 million households. The number decreased from 2.25 million to 1.2 million, 0.6 million, and 0.31 million by the 1st, 2nd, and 3rd weeks of the earthquake, respectively. Some prefectures reduced the number of households affected by the water-supply outage by half in a week, whereas others were still affected by the long-term disruption of the water supply.

Several natural and social events caused the prolongation of the water-supply outage. They were different for different water-supply district. Referring to the reconnaissance report on the damage to the water-supply system just after the earthquake (JSCE, 2011), the main factor for delayed restoration was said to be the damage of the regional water-supply system, which supplies water to the local water-supply districts via large-diameter pipelines. The main factor is still not clear because several factors can be considered to have affected the water-supply outage.

This study attempts to elucidate and evaluate the factors that delayed water-supply restoration after the Tohoku earthquake, including the damage to regional water-supply systems. First, earthquake damage and emergency response to the disaster are investigated at the water-supply authorities that had delayed restoration owing to cuts in the regional water-supply and other factors. Then, these factors that prolonged the water-supply outage are summarized qualitatively and analyzed in terms of the number of days until service could be restored, hereafter referred to as restoration time in day, compared with the experienced restoration time that can be calculated by the pipeline repair rate.

2. FACTORS AFFECTING THE PROLONGATION OF WATER-SUPPLY OUTAGES

2.1 Selection of Prolongation Factors

The Tohoku earthquake caused water-supply outages to about 2.25 million households at its peak, as mentioned above. Many water-supply districts in which service was restored more than two weeks after the earthquake were not only affected by the tsunami but were located inland. In order to clarify the factors that delayed water-supply restoration, water-supply authorities in 19 affected cities and towns in four prefectures were interviewed; in most cases, two interviews were conducted. The first interview was conducted approximately one month after the earthquake, and the second interview was conducted approximately six months after the earthquake. Based on the earthquake and tsunami damage, emergency response, and statistical data provided by the water-supply authorities, five factors were selected. The reasons for the long-term water-supply outages are described in the following sections. The detailed numbers and activities of the authorities are omitted in this paper.

2.1.1. Factor 1: Lack and delay of restoration resources in a wide-area disaster
Although many restoration resources such as assistance personnel and machines were urgently required by the 187 affected water-supply districts in the Tohoku and Kanto region, it took four days to gather information and dispatch a steady number of water trucks. By March 15, 300 vehicles had been dispatched from outside the affected water-supply authorities under the disaster assistance framework of the Japan Water Works Association (JWWA). In addition, because most of the stricken water-supply authorities were in rural areas, engineering staff for overseeing the water-supply repair work was limited. Moreover, it took time to restore roads and transport fuel to the stricken areas. One of the factors for the prolongation of the water-supply outage was the delay and lack of restoration resources including personnel, machines, and fuel.

2.1.2. Factor 2: Long-term power-supply outages
Large areas from the North Kanto to the Tohoku region could not get electric power for at least a few days after the earthquakes. The water-supply authorities could not respond to the power-supply outages for more than one day even though they were prepared with private generators. The water-supply authorities that could restart water processing using private generators were the ones with small facilities. Treated water was available for emergency water delivery but there was not enough to supply the entire area by pipeline. Moreover, the remote monitoring system that was used to manage the water-supply operation had difficulty confirming the extent of damage due to the electricity black out. Most of the water-supply authorities in the north of the Miyagi Prefecture could not begin repair work for two weeks after the earthquake because electric power was out for almost a week.

2.1.3. Factor 3: Damage to regional water-supply systems
The regional water-supply systems are installed not only in the stricken area of this earthquake but all over Japan. The regional water-supply system has been developed and enlarged by prefectures and regional water-supply authorities to provide a steady water resource to meet the increased demand for water in high-growth period of the Japanese economy. The regional water-supply system is increasingly being extended to include small water-supply authority for more efficient business management purposes. The extended system, however, has low redundancy.

In this earthquake, ten regional water-supply authorities suffered outages for at least one week. Fig. 1 shows the restoration time for the water supply in the local water-supply authorities. Similarly, Fig. 2 indicates the restoration time for the regional water-supply in ten authorities. Large parts of the Miyagi and Ibaraki Prefectures were affected by the regional water-supply outage. It corresponds to the restoration time in Fig. 1. One cause for the delay in restoring regional water-supply systems was power outages. The blackout, which lasted for at least three days after the earthquake from the North Kanto to the Tohoku region, caused the water transmission system to malfunction. After the power supply was restored, it took several days to fill the empty reservoir and large-diameter pipeline with water. The regional water-supply system could not be quickly restored. The second cause was leakage and separation of the large-diameter pipe. Because the regional water-supply system has low redundancy, one location of damage caused a complete outage of the water supply to downstream authorities. Moreover, repairing the large-diameter pipeline was difficult immediately after the earthquake owing to the nature of the work itself as well as the problem of procuring a special replacement pipe.

For instance, the Sennan-Senen Regional Water-supply Authority which supplies water to the local authorities in the south of the Miyagi Prefecture was affected and as a result caused damage to a large-diameter pipeline at 14 locations. This system has two trunk lines for the north and south districts. The trunk line to the north districts had breaks at a flexible joint of pipeline with a diameter 2400 mm at the upstream end of the system, which required 11 days for repair. The water supply to Matsushima and Shiogama Cities at the far end of the pipeline was not able to be restored until March 31, whereas the water supply in the trunk line for the south district was restored by March 15. Because most of the local water-supply authorities depend on the regional water-supply for more than half of their water demand, they cannot provide an adequate supply of water from their own resources. As the other case, the Wanigawa water treatment plant, which is managed by the Rokko Regional Water-supply Authority in the Ibaraki Prefecture, was severely damaged owing to liquefaction, which resulted in its being out of service for a month.

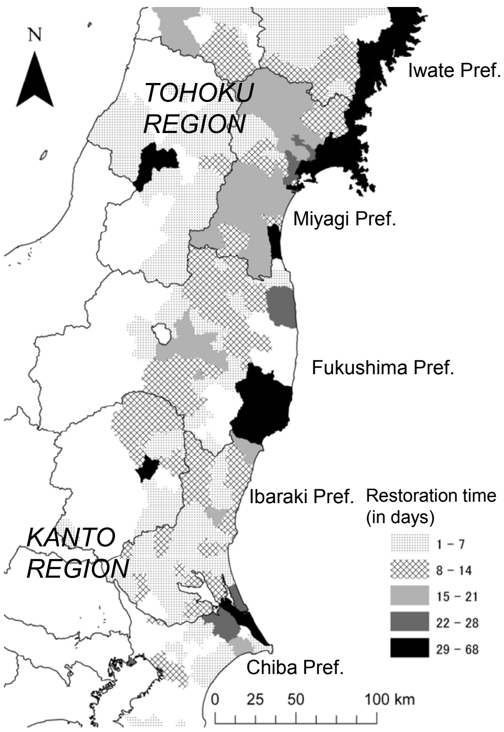


Figure 1. Restoration time for water-supply system in water-supply districts following the Tohoku earthquake

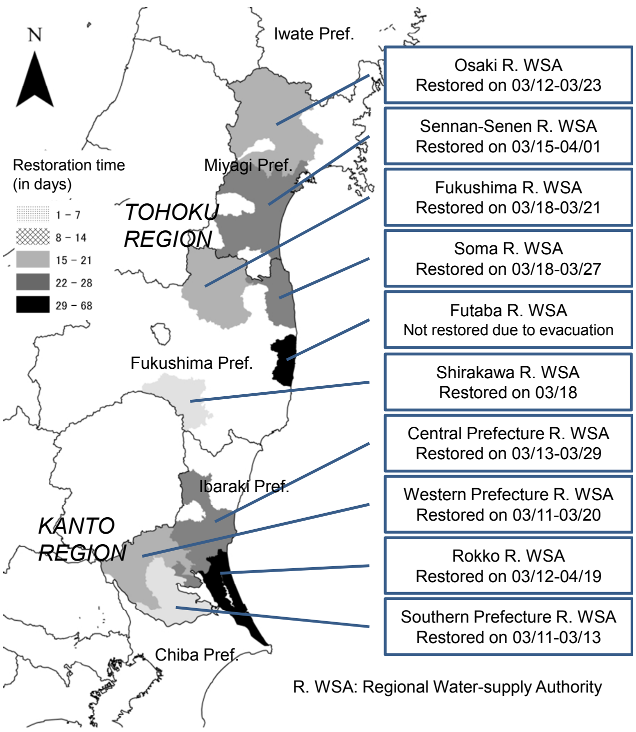


Figure 2. Restoration time for the regional water-supply systems following the Tohoku earthquake

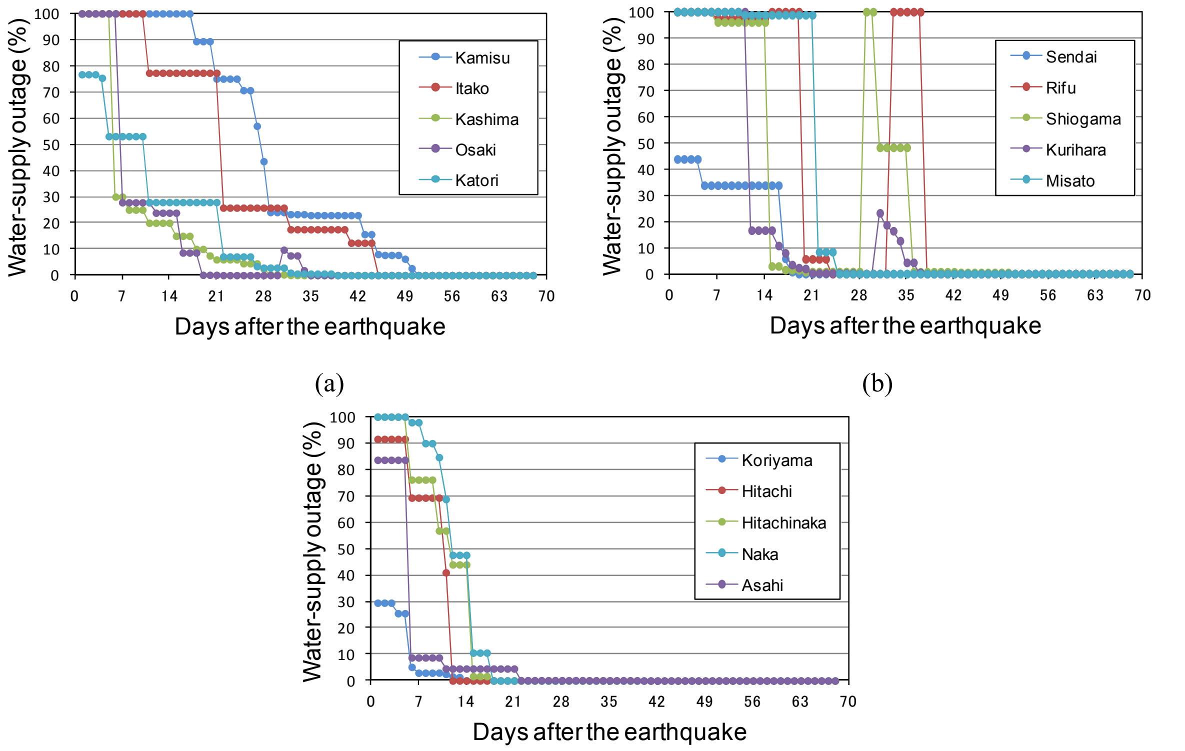
2.1.4. Factor 4: Pipeline repair in large areas of liquefaction

There was extensive pipeline damage due to liquefaction around the coast of the Tokyo Bay and the valley of the Tonegawa River in the Kanto region, for instance, in Urayasu, Katori, and Asahi Cities in the Chiba Prefecture and Kamisu, Itako, and Kashima Cites in the Ibaraki Prefecture. The liquefied area corresponds to 10 to 20 % of the entire water-supplied area. The water-supply pipelines as well as housing lots and roadways were damaged in the liquefied area, which was as large as a residential block.

2.1.5. Factor 5: Restoration in the tsunami-affected area
While water-supply facilities and pipelines are mostly installed underground, water-pipe bridges and pipelines hanging on river bridges may be damaged by the tsunami running up the river. In the Miyagi and Iwate Prefectures, the office and water treatment plant were flooded by the tsunami following this earthquake. There was salt-water damage to the shallow water well after flooding by the tsunami in the Iwate Prefecture. In the tsunami-flooded areas, reconstruction of residential settlements is given a higher priority than pipeline repair by previous specifications. Its restoration process is substantially different from the process for repairing damage due to the other factors mentioned above. We do not deal with this factor as being the same as the other factors in the following analysis.

2.2 Water-supply Restoration Process in Water-Supply Authorities

The water-supply restoration process in the water-supply authorities that were the most severely affected due to the regional water-supply outages and due to the liquefaction is compared to the restoration process in the authority which were not affected by special factors, as shown in Fig. 3.
In the local water-supply authorities where the regional water supply was cut for a long time, a high rate of water-supply outages continues for a while after the earthquake and then the rate rapidly decreases after the restoration of the regional water supply, as shown in Fig. 3(a). The restoration of the regional water supply is a prerequisite for the restoration of the water-supply in the local authority. The increase in the outage rate at around 30 days after the earthquake was due to the damage of the regional water supply by the aftershock on April 7. The water-supply authorities affected by large-area liquefaction shows a gradual decrease of water-supply outages at first and then remarkably slow restoration of the remaining 30% or less of outages, as shown in Fig. 3(b). Such delays appear to be due to problems in procuring temporary pipes and construction difficulties in the liquefied area. The water-supply authorities that were not affected by special factors tended to have complete outages for the first few days owing to power outages and then gradual decreases in outages until approximately 90 % of the outage were restored. The remaining 10 % of the outages were restored more slowly, as shown in Fig. 3(c). The restoration process of the water supply can be characterized by the prolongation factor of the water-supply outage.



(a) (b) (c)

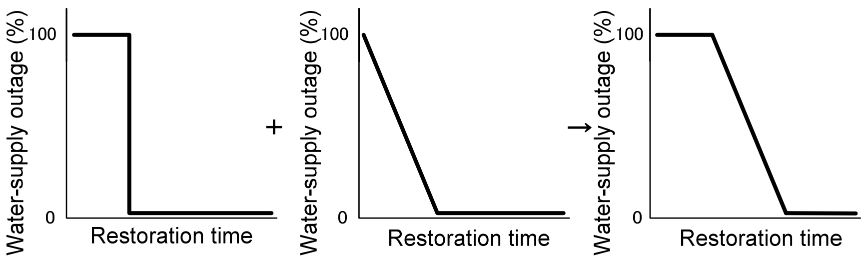
Figure 3. Restoration process of the water supply: (a) Water-supply authorities affected by the regional water-supply outage, (b) Water-supply authorities affected by large-area liquefaction, and (c) Water-supply authorities not affected by special factors.

3. ANALYSIS OF THE FACTORS THAT PROLONGED THE WATER-SUPPLY OUTAGE

3.1 Concept of Restoration Model

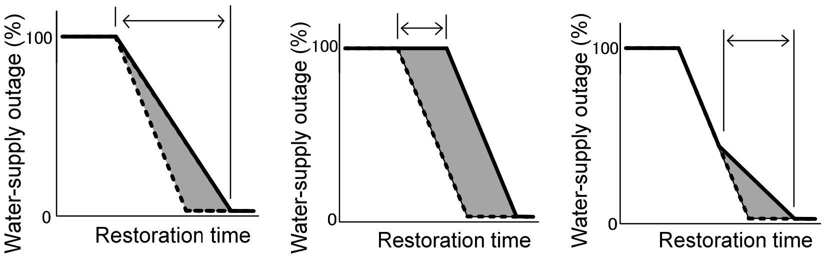
When the system of water-supply facilities and pipelines is considered, the relation between the restoration time and the water-supply outage rate is shown in Fig. 4. The functions of water-intake and water-treatment facilities after an earthquake determine whether the system itself can function, as shown in Fig. 4(a). Meanwhile, the function of pipelines is explained by the restoration rate in supplied areas, as shown in Fig. 4(b). The supplied area increases from upstream to downstream of pipelines because water is required in the pipeline to locate the damage. The water-supply outage rate on the customer side is, therefore, expressed as in Fig. 4(c) because the repair of the pipeline damage begins only after the upstream facilities are repaired.

Here, when the prolongation factors of the water-supply outage are considered, the delay of pipeline restoration due to the lack of restoration resources (Factor 1) affects the rate of pipeline restoration, as shown in Fig. 5(a). The power outage at a water purification facility in a water-supply authorities (Factor 2) and the cut of the regional water-supply (Factor 3) have the same effect as an outage of the water-treatment facility: either 100% or 0% in the rate of water-supply outage (see as Fig. 5(b)). In addition, the restoration rate of pipelines in a liquefaction area (Factor 4) rapidly decreases for the few remaining water-supply outages, as shown in Fig. 3(b). The model can be drawn as Fig. 5(c).



(a) (b) (c)

Figure 4. Schematic chart of water-supply restoration: (a) Facility, (b) Pipeline, and(c) Entire system



(a) (b) (c)

Figure 5. Concept of restoration time due to the following factors: (1) Delay in pipeline restoration, (2) Power-supply outage at the water facility and/or outage of the regional water-supply, (3) Delay due to pipeline repair in a liquefaction area

This study proposes a model to estimate the restoration time for the water supply, using a basic restoration model based on pipeline damage as well as the restoration time due to power outages, regional water-supply outages, and pipeline repair in liquefaction areas.

3.2 Restoration Model Based on Pipeline Damage

The basic model to estimate restoration time until 90% completion, $T_{p90,}$ is proposed by the relationship of the pipeline repair rate (hereafter, *RR* (repair number/km)) and the customer density (the number of water-supplied households per length of pipeline, (hereafter, *d* (households/km)) during the Kobe earthquake (Takada et al., 2003) as follows:

$$T_{p90} = 0.38d^{0.86}RR^{0.59} \tag{3.1}$$

When the restoration is 90% complete, the restoration rate for the remaining outages in the area varies according to the individual damage and condition. Therefore, the model adopts the restoration up to 90%, in which the restoration rate is almost constant.

In the case of the Kobe earthquake, damage to the water supply facilities was reported to be on pipeline (Kobe City, Water Supply Bureau, 1996). Kobe City had received water from the regional water-supply systems, the Hanshin Regional Water-supply Authority. The water transmission was cut just after the earthquake, but resumed by the end of the day. Although there was power-supply outage at 37 facilities, 35 facilities were restored in 12 hours. The remains were not important facilities in the whole system. Their power-supply outage was little influence to water-supply. The percentage of liquefaction in Kobe City was less than 10% in terms of liquefied area to the water-distributed area based on the liquefaction map (Wakamatsu, 2011). The influence of liquefaction during the Kobe earthquake was little. Thus, the 90% restoration time shown in Eq. (3.1) is not affected by the prolongation factors mention above and it can say that the equation is the based on restoration of the pipeline damage. This study deals with the 90% restoration time in Eq. (3.1) as the 90% restoration time for the pipeline damage.

The restoration time based on pipeline damage in this earthquake is estimated for the 19 water-supply authorities. The number of pipe repairs was obtained by the interviews. The pipe repair rate, *RR*, is calculated using statistics obtained from water-supply businesses (JWWA, 2007). The 90% restoration time in day are obtained from the report of the Ministry of Health, Labor and Welfare (2011). The pipe repair rate in number per km ranged from 0.04 to 0.67. The pipe repair rate exceeded 0.3 in the strong ground-motion area in the north of the Miyagi Prefecture and in the liquefaction area in the Ibaraki Prefecture. This damage was equal to the damage in the recent inland earthquakes in Japan. All the cities and towns, however, were not damaged at such a high level. Most of the cities and towns had little damage.

Fig. 6 shows the relationship between 90% pipe restoration time, T_{p90}, and actual 90% restoration time (hereafter, T_{obs}). The estimated restoration times are fewer than the actual restoration times among all the authorities. The restoration times are more than twice the estimated 90% restoration time based on the pipeline damage. Although the restoration seems to have been delayed because repair personnel and resources were not dispatched quickly enough, it is evident that restoration time cannot be explained only by the pipeline damage.

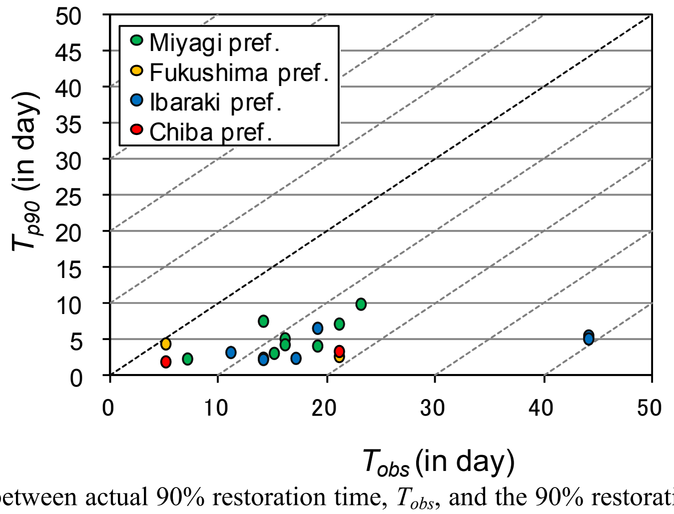


Figure 6. Relationship between actual 90% restoration time, T_{obs}, and the 90% restoration time estimated by the pipe repair rate, T_{p90}, for 19 affected water-supply authorities

3.3 Enhancement of Restoration Model

In order to improve the estimation model, the restoration time for the power supply, T_e, regional water supply, T_t, and the pipeline in the liquefaction area, T_l, are added to the estimated restoration time for pipeline damage as prolongation factors for restoring the water-supply following this earthquake. If the rate of water demand from the regional water supply to the entire water demand of the local water-supply authority is defined as r, the estimation model for the restoration time can be enhanced by Eq. (3.2). Each coefficient can be obtained by the multi-regression analysis.

$$T_{est} = k_1 T_{p90} + k_2 (1-r) T_e + k_3 r T_t + k_4 T_l \tag{3.2}$$

where, T_{p90} is time until 90% restoration based on pipeline repair, T_e is restoration time for the power supply at the facility, T_t is the restoration time for the regional water-supply, T_l is the time awaiting pipeline repair in a liquefaction area.

Table 1 shows correlation matrix of terms in Eq.(3.2). The highest correlation coefficient is -0.36 of T_l and T_e (1-r). Thus, each term is independent to the others.

Table 1. Correlation matrix in terms of Equation (3.2)

Term	T_{p90}	$(1-r)T_e$	rT_t	T_l
T_{p90}	1.00			
$(1-r)T_e$	-0.02	1.00		
rT_t	0.29	-0.35	1.00	
T_l	0.13	-0.36	0.14	1.00

The restoration of the power supply has two aspects; restoration to the water treatment facility and restoration to the supplied area. This study focuses on the power supply at the facility that produces and distributes water. If the water-supply authority prepared a private generator and continued water processing on the day of the earthquake, the restoration time of the power supply is regarded as 0 even though the power supplied to the area was cut. The restoration time for the regional water supply is taken from the reports from the Miyagi Prefecture (2011) and the Ibaraki Prefecture (2011). When a water-supply authority receives water at several points from a regional water-supply system, the average of the restoration times is used. As for liquefaction, the time from the restoration rate 70% to 90% completed only when restoration rate rapidly decreases is used as the delayed time due to pipeline repair in the liquefaction area. Although the tsunami is considered as one factor, the number of households destroyed by the tsunami is less than 2% of the households in all the authorities in this study. The tsunami factor does not affect this model.

As the result of multiple regression analysis, the coefficient of correlation has a good correlation as $R^2 = 0.92$. The regression coefficient of each parameter is listed in Table 3. Fig. 7 shows relationship between actual 90% restoration time, T_{obs}, and the 90% restoration time estimated by the enhanced model, T_{est}. Regression coefficients in the 2nd, 3rd and 4th terms are values roughly close to 1.0. Factors such as power-supply outages, regional water-supply outages, and liquefaction introduced in this study have a strong effect on the actual restoration time for the water supply. It can be said that they are predominant factors for the prolongation of the water supply outages. The value of the regression coefficient of the parameter in the 1st term for pipeline damage is calculated as 1.75. Briefly, the 90% restoration time calculated by the pipeline damage underestimates the restoration time of this earthquake. The pipeline repair in this earthquake can be understood to be twice as hard as that in previous earthquakes.

Table 3. Coefficient of regression analysis

Term		Coefficient	Explanatory variable	Value of coefficient
1	Pipeline repair	k_1	T_{p90}	1.75
2	Power-supply	k_2	$(1 - r)T_e$	0.86
3	Regional water-supply	k_3	rT_t	0.81
4	Liquefaction	k_4	T_l	1.17

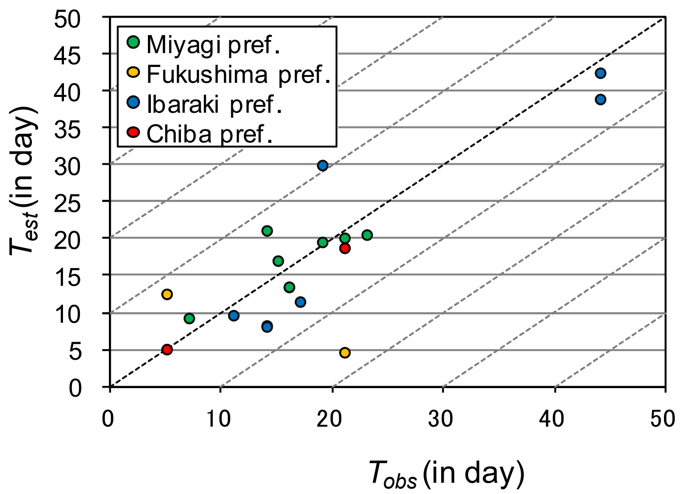


Figure 7. Relationship between actual 90% restoration time, T_{obs}, and the 90% restoration time estimated by the enhanced model, T_{est}, for 19 affected water-supply authorities

4. EVALUATION OF HOUSEHOLDS AFFECTED BY REGIONAL WATER-SUPPLY OUTAGES

This study focuses on the earthquake impact due to regional water-supply outage. Fig. 8 shows the number of household with water outage in the Miyagi Prefecture following the earthquake. The number of households affected by regional water-supply outage is accounted by the entire households of municipalities multiplied by the rate of demand from regional water-supply. As it can be seen, the slow restoration rate of the Miyagi Prefecture in the first two weeks has same trend with that due to the regional water-supply outage. The reason why the restoration rate in the Miyagi Prefecture was slow is that the regional water-supply outage depends strongly. The total number of households affected by the regional water-supply outages accounts 2.3 millions.

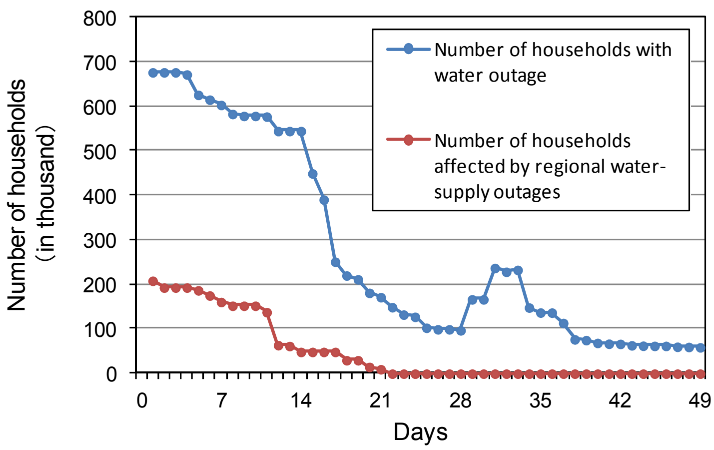


Figure 8. Number of households with water outage following the Tohoku earthquake in Miyagi Prefecture.

The earthquake impact due to the prolongation factors for water-supply outages can be evaluated by the model of Eq. (3.2). The estimated restoration time for the water supply affected by the regional water-supply outageis shown in Fig. 9 by each term of Eq. (3.2). The rate of restoration time due to the regional water-supply outage was as high as 62% in Rifu Town, which receives a large amount of water from the regional water supply. The impact of the regional water-supply outage did not strongly affect Kurihara City because the rate of water demand was low in spite of the long period of the regional water-supply outage. For Kurihara City, the power-supply outage was more serious than the regional water-supply outage.

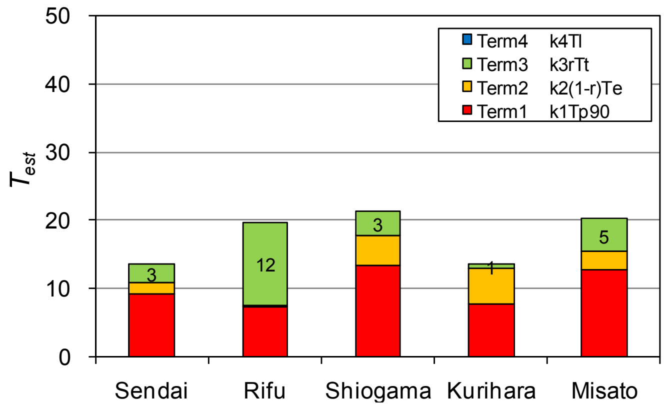


Figure 9. Estimated restoration times for the water supply with composition for restoration times due to regional water-supply outage

The earthquake impact on regional water-supply outages can be explained as the number of households with water-supply outages in terms of the estimated restoration times for the regional water-supply outage multiplied by the total number of households in the water-supply authority. This accounts for the color-filled area in Fig. 5(b) multiplied by the total number of households. The number of households with water-supply outages due to a regional water-supply outage is shown in Fig. 10 for 19 targeted water-supply authorities.

The number of affected households with water-supply outages due to a regional water-supply outage is 1.4 million in the targeted water-supply authorities. Among them, Sendai City, in the Miyagi Prefecture had 0.6 million households, and Kamisu City, Ibaraki Prefecture had 0.4 million households. Both of the cities have a large number of water-supplied households affected by long-term regional water-supply outages. The water to the affected households corresponds to the water delivered by 1050 water trucks, assuming a water truck with 4 m^3 capacity delivers three liters per person per day.

The prolongation of the water-supply outage during the Tohoku earthquake is attributed to two factors: the wide-area earthquake disaster and the inter-plate earthquake. The wide-area earthquake disaster caused a shortage of restoration resources and a malfunction of the lifeline system in the wide area. The inter-plate earthquake provoked long-period and long-duration of ground shaking resulting in severe liquefaction. The factors of power-supply and regional water-supply outages and liquefaction were significant, and they can explain the restoration time for the water supply by summation, besides doubling the number of restoration time due to pipeline repair. Especially the regional water-supply outage affected much in the Miyagi Prefecture and it accounts 2.3 million households in total.

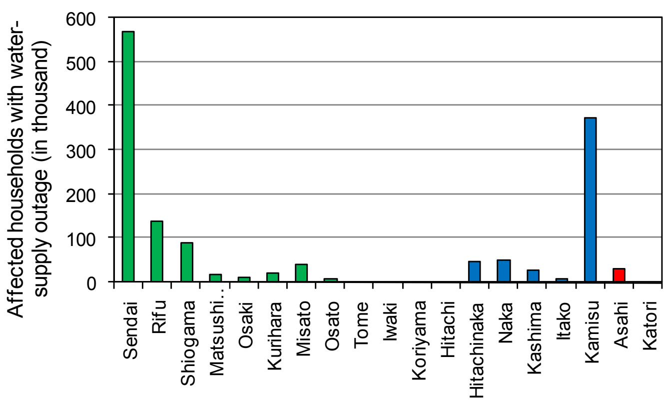


Figure 10. Affected households with water-supply outages by factors in the water-supply authorities due to cuts in the regional water supply

5. CONCLUSIONS

This study attempted to evaluate the prolongation factors in water-supply outages during the Tohoku earthquake and their impact due to regional water-supply outage. This study can be summarized as follows.

- The restoration time for the water-supply following the Tohoku earthquake can be explained by a combination of the restoration times for the power-supply and the regional water-supply, and pipeline repair in liquefaction areas in addition to the restoration time for pipeline repair experienced in the past earthquake.
- Pipeline repair took twice as long compared with past earthquakes because of the wide area of the earthquake disaster.
- The restoration time in day caused by regional water-supply outages was 62% at the maximum according to the enhanced model to estimate restoration time.
- In terms of the number of households affected by water-supply outages, the earthquake impact due to regional water-supply outages was high in Sendai City, Miyagi Prefecture, and Kamisu City, Ibaraki Prefecture, and the total number of households affected by the regional water-supply outage accounts 2.3 million in the Miyagi Prefecture.

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