Damage Analysis of Water Supply Facilities in the 2011 Great East Japan Earthquake and Tsunami

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SUMMARY:
This study is focusing on damage to water supply facilities during the 2011 great east Japan earthquake and tsunami. At first, an outline of damage to water supply facilities is given and the damage to water supply pipelines of Sendai City is analyzed. An abrupt increase in flow rate and a decrease in water pressure of water distribution system were occurred in spite of no damage to pipeline just after the earthquake. We clarified the situation through a questionnaire survey to waterworks bureaus. The relation of response velocity spectra of the earthquake ground motion to the unusual phenomena was investigated and the causes of the unusual phenomena are discussed.

Keywords: Great east Japan earthquake, water supply system, earthquake damage, sloshing of water in receiving tank

1. INTRODUCTION

The present paper deals with damage to water supply facilities during the 2011 great east Japan earthquake and tsunami. An earthquake with a magnitude of 9.0 occurred off the coast of northeast Japan on March 11, 2011 at 14:46 on local time. The earthquake generated a tsunami of unprecedented height and special extent along the Pacific coast of east Japan. The earthquake and tsunami caused about 20,000 deaths and missing and injured about 6,000 people. This earthquake and tsunami also caused extensive damage to water supply facilities. A suspension of water supply was occurred at about 2,300,000 households in east Japan just after the earthquake. Since residents in the flooded areas by tsunami have not lived there after the event, most of damaged pipelines in the flooded areas are not repair yet. So, we cannot collect the entire data of damage to water supply pipelines yet, but the damage data except flooded areas are analyzed in this paper.

At first, an outline of damage to water supply facilities is given and the damage to water supply pipelines of Sendai City is analyzed. Then an unusual phenomenon of distribution system is focused. An abrupt increase in flow rate and a decrease in water pressure of water distribution system were occurred in spite of no damage to pipeline just after the earthquake. A questionnaire survey to waterworks bureaus was conducted and situation of the unusual phenomena is revealed. The relation of response velocity spectra of the earthquake ground motion to the unusual phenomena was investigated and the causes of the unusual phenomena are discussed. Finally, lessons learned from the earthquake and tsunami is considered.

2. OUTLINE OF DAMAGE TO WATER SUPPLY FACILITIES

2.1. Suspension of water supply

A suspension of water supply was occurred at about 2,300,000 households in the wide area from Tohoku to Kanto regions just after the earthquake. About 90% of water outrage was recovered after one month from the event except flooded areas by the tsunami. Newly damage, however, occurred by the strong aftershocks happed in the middle of April.

2.2. Causes of damage to facilities

The damage caused by the earthquake and tsunami seems to be classified into five categories. Firstly the causes of damage are divided by earthquake and tsunami. Causes of damage by earthquake are classified into ground shaking itself and ground failure such as liquefaction, slope failure and etc. Fig. 1 shows damage to expansion joint of steel pipe with 2400mm diameter. This damage seems to be caused by ground shaking and/or ground deformation. Fig. 2 shows an uplift of underground water tank induced by liquefaction.

Causes of damage by tsunami are classified into three categories; inundation, washing away and scouring of surface ground. Some intake facilities were inundated by tsunami and became malfunction for long time because of high density of calcium chloride in water. Fig. 3 shows damage to a water pipe bridge by tsunami. The water pipe bridge was completely washed away. Fig. 4 shows damage to a buried pipeline. The pipeline appeared above ground after tsunami because of scouring caused by tsunami. The mechanism of damage to pipeline, that is, how much force acts on a pipeline is not sure. The mechanism of this kind of damage must be clarified in the future.

Figure 1. Damage to steel pipe with 2400mm diamete (Miyagi Pref.).
(http://www.pref.miyagi.jp/kigyo/)

Figure 2. Uplift of underground water tank (Chiba Pref.).

Figure 3. Damage to water pipe bridge (Miyagi Pref.).

Figure 4. Damage to pipe by scouring of tsunami (Miyagi Pref.) .

3. DAMAGE IN SENDAI CITY

3.1. Outline of water supply system of Sendai City

Since the damage to pipeline of Sendai City was obtained except the flooded area, damage rate of pipelines in Sendai City is discussed here. The water supply system of Sendai City has approximately 472,775m of transmission and distribution main pipelines. About 74% of the total piping length is made up of ductile cast iron pipe (DIP), 24% steel pipe (SP).

3.2. Damage to pipeline of Sendai City

The number of damage to transmission and distribution main pipelines was 10 and that of damage to air valve and hydrant was 43. The damage rate of pipelines, defined as the locations of damage divided by piping length, was 0.02 (locations/km).

The total number of damage to transmission main, distribution main and branch pipelines was 264 except the flooded areas, and the piping length is 3,761km. The damage rate of transmission main, distribution main and branch pipelines was, therefore, 0.07 (locations/km) The damage rate in relation to pipe type and pipe diameter is shown in Figs. 5 and 6, respectively. Fig. 5 indicates that the damage rate of polyvinyl chloride pipe (VP) is high. Fig. 6 reveals that the smaller the pipe diameter is, the higher the damage rate.

Fig. 7 illustrates a comparison of damage rate of Sendai City with those of other cities suffered damage to pipeline in the past earthquakes in Japan. Kobe, Ashiya and Nishinomiya Cities suffered damage to water supply pipeline in the 1995 Hyogo-ken Nambu Earthquake, Nagaoka City in the 2004 Niigata-ken Chuetsu Earthquake, Monzen Town in the 2007 Noto-hanto Earthquake and Kashiwazaki City in the 2007 Niigata-ken Chuetsu-oki Earthquake, respectively. This figure revels that the damage rate of Sendai City was very low in comparison with another cities. Magnitude of earthquake and seismic intensity in each city were different. PGA of K-NET Sendai observation station was, however, not small; 1,808 (cm/s/s). This value is higher than most of cities listed in Fig. 7. One of reasons of low damage rate in Sendai City seems to be high earthquake-proofing rate. The earthquake-proofing rate is defined as the piping length of ductile cast iron pipe with earthquake resistant joint and welded steel pipe divided by the total piping length. The earthquake-proofing rate of Sendai City is 51.2%.

Fig. 8 illustrates the relation between the earthquake-proofing rate and damage rate of each waterworks bureau suffered damage in the 2011 great east Japan earthquake. The damage rate shown in this figure is calculated by using the damage to transmission and distribution main pipeline, that is, distribution branch pipeline is not included. This figure shows JMA (Japan Meteorological Agency) seismic intensity scale in each area. This figure indicates that the higher the earthquake-proofing rate, the lower the damage rate is. There was no damage to the ductile cast iron pipe with earthquake resistant joint. Effect of earthquake-proofing pipe was, therefore, verified by the earthquake.

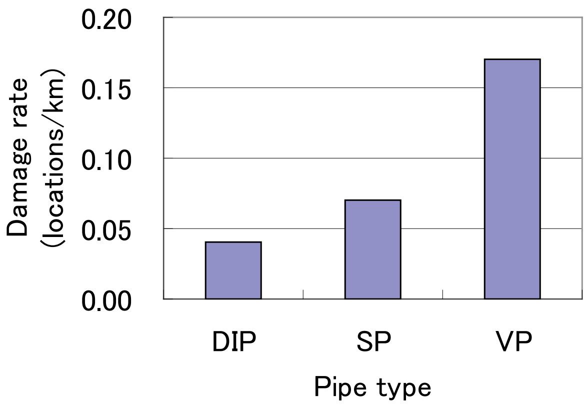

Figure 5. Damage rate related to pipe type.

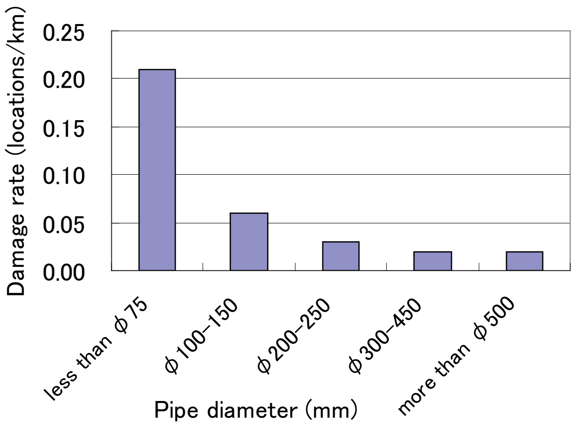

Figure 6. Damage rate related to pipe diameter.

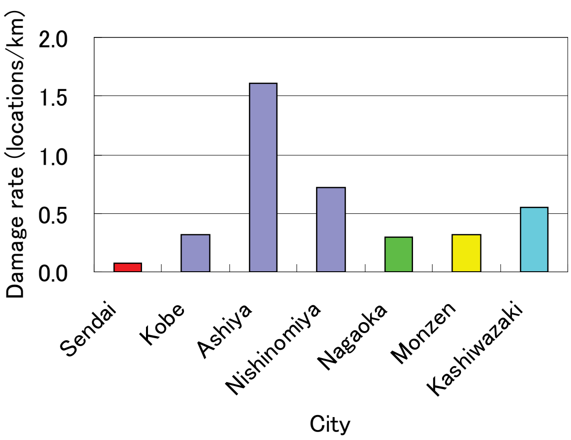

Figure 7. Comparison of damage rate.

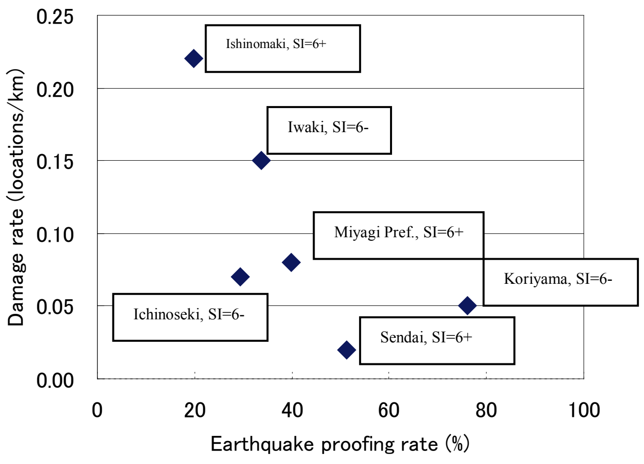

Figure 8. Relation between earthquake proofing rate and damage rate.

4. UNUSUAL PHENOMENA OF WATER DISTRIBUTION SYSTEM

Unusual phenomena such as an abrupt increase in flow rate and a decrease in water pressure of water distribution system in spite of no damage to pipeline was occurred in several cities during the great east Japan earthquake. Fig. 9 shows time histories of the flow rate and water pressure at a water distribution plant of the Bureau of Waterworks Tokyo Metropolitan Government. The flow rate increased and water pressure decreased rapidly just after the earthquake. The higher flow rate and lower water pressure were recovered after about 20 minutes. The similar phenomena were occurred again by the aftershock.

A questionnaire survey was conducted on the occurrence of the unusual phenomena of water distribution system after the great east Japan earthquake for twenty large scale waterworks bureaus not only in east Japan but also in west Japan. Table 1 lists the occurrence of the unusual phenomena of water distribution system in each waterworks bureau. The unusual phenomena occurred at even in the cities where JMA seismic intensity scale was less than 5, that is, Yamagata, Nagoya and Osaka Cities. Fig. 10 shows time histories of the flow rate and water pressure at a water distribution plant of the Osaka City Waterworks Bureau. This figure shows that the similar phenomena of the Bureau of Waterworks Tokyo Metropolitan Government occurred in Osaka City where JMA seismic intensity scale was 3. It suggests that the unusual phenomena depend on not only magnitude of ground shaking but also other factors such as frequency characteristics of ground shaking.

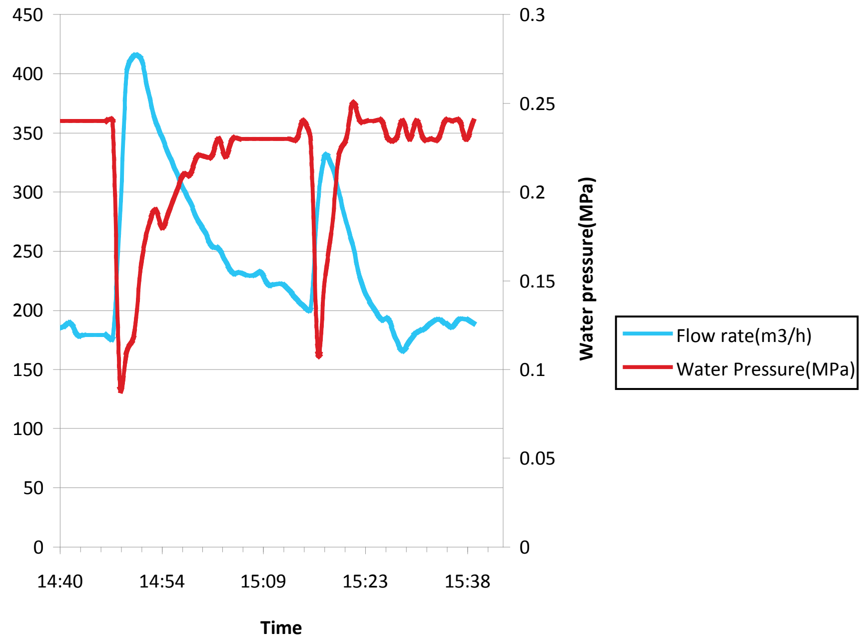

Figure 9. Time histories of the flow rate and water pressure at a water distribution plant of Tokyo.

Table 1. Occurrence of the unusual phenomena of water distribution system in each cities.

Name	Seismic Intensity	Occurrence
Sapporo City	3	N/A
Aomori City	4	N/A
Morioka City	5+	N/A
Akita City	5+	N/A
Sendai City	6−	Yes
Yamagata City	4	Yes
Niigata City	4	N/A
Mito City	6−	N/A
Utsunomiya City	5+	Yes
Chiba Prefecture	5+	Yes
Tokyo Metropolitan	5−	Yes
Saitama City	5+	Yes
Yokohama City	5+	N/A
Kofu City	5−	N/A
Nagoya City	4	Yes
Kanazawa City	3	N/A
Osaka City	3	Yes
Kobe City	2	N/A
Hiroshima City	1	N/A

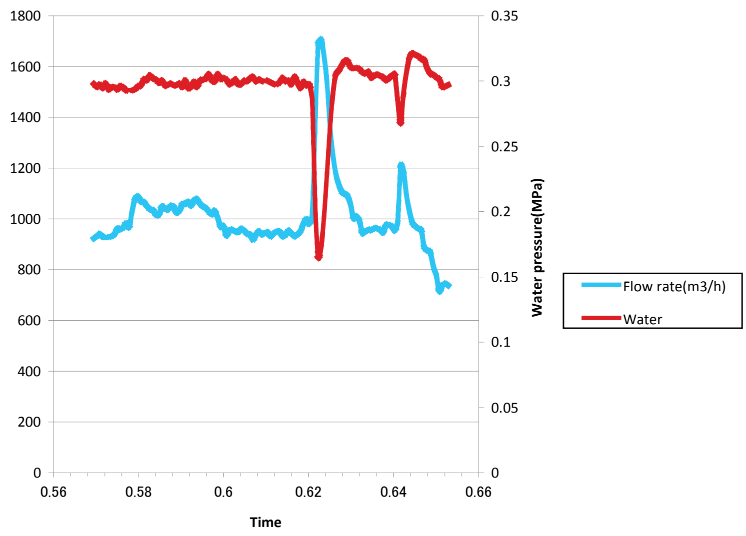

Figure 10. Time histories of the flow rate and water pressure at a water distribution plant of Osaka.

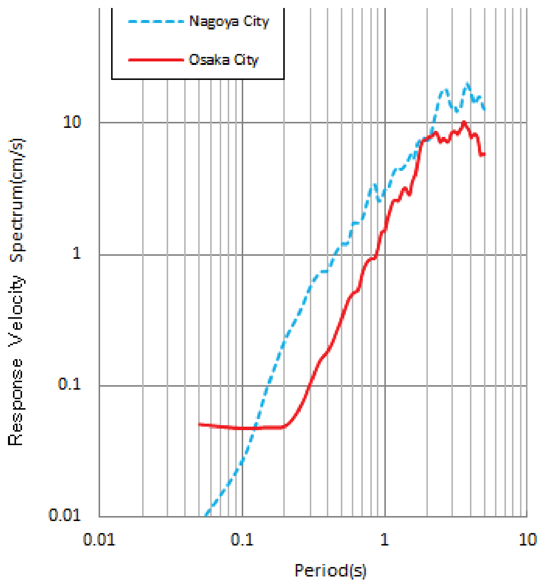

Figure 11. Response velocity spectra of recorded waveform at Nagoya City (K-NET AIC004) and Osaka City (K-NET OSK005).

Fig. 11 illustrates response velocity spectra of recorded waveforms of the great east Japan earthquake at Nagoya City (K-NET AIC004) and Osaka City (K-NET OSK005). This figure indicates that the predominant periods are more than one second.

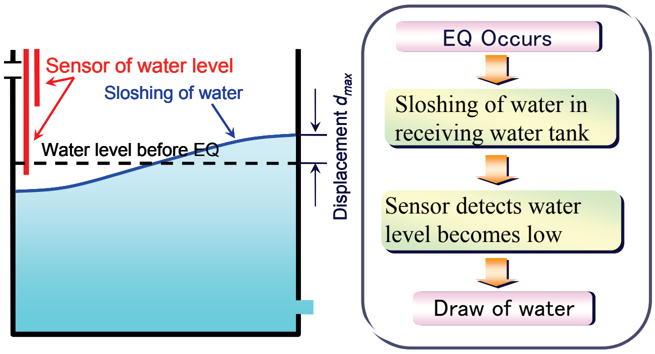

Figure 12. Mechanism of draw of water from distribution pipe to receiving tank by sloshing during earthquake.

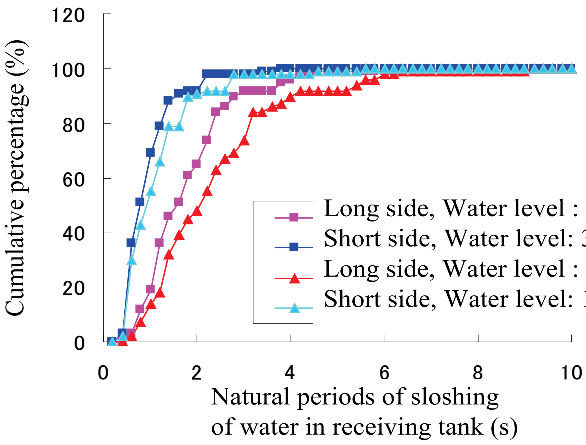

Figure 13. Cumulative percentage of natural period of water in receiving water tank

Murata and Miyajima have considered that one of the causes of the unusual phenomena seems to be sloshing of water in receiving water tank. If sloshing of water in receiving water tank is occurred by an earthquake, draw of water to receiving water tank from a distribution pipelines starts by error of a sensor of water level in the receiving water tank as shown in Fig. 12. If sloshing of water in many receiving water tanks occurred simultaneously, an abrupt increase in flow rate and a decrease in water pressure in the distribution pipeline may be occurred. Occurrence of sloshing of water in receiving water tank depends on the dimensions of receiving water tank and the height of water in the tank. Murata and Miyajima have investigated dimensions of receiving water tank in a water distribution block of Osaka City and estimated the natural period of sloshing of the water. Fig. 13 shows cumulative percentage of natural period of water in receiving water tank in case that the height of water is 3/4 and 1/2 of the height of water tank. The height of water is variable and depends on use of water. The natural period of sloshing is more than 1.0 second of more than 80% of the water tank in the direction of long side in the water distribution block in Osaka City. This is one example, but long period ground motion more than one second can be caused sloshing of water in receiving water tank. However, the further study is needed to clarify the cause of an abrupt increase in flow rate and a decrease in water pressure of water distribution system in spite of no damage to pipeline and its effects to emergence response just after large scale disaster.

5. CONCLUDING REMARKS

An outline of the damage to water supply facilities from the 2011 great eat Japan earthquake and tsunami was presented and the unusual phenomena of water distribution system just after the event was discussed. The following conclusions may be drawn based on the present study.

(1) The entire damage to water supply pipelines is not revealed, especially flooded areas by tsunami. We must collect all damage data and analyze it to learn the lessons from this disaster.
(2) Effect of earthquake-proofing for pipeline was verified. We must accelerate the earthquake proofing, especially for aged facilities.
(3) Force of tsunami acted on a buried pipe is not clear. The effect of tsunami must be studied soon.
(4) If sloshing of water in receiving water tank is occurred by an earthquake, draw of water to receiving water tank from pipeline starts by error of sensor of water level in the receiving water tank. Sloshing of water in receiving water tank, therefore, may be one of the causes of unusual phenomena.

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