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EFFECTS OF TSUNAMI ON WATER SUPPLY NETWORK IN CASE OF THE 2011 TOHOKU EARTHQUAKE IN JAPAN

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Abstract

This paper deals with damage to water supply system caused by tsunami in the 2011 Tohoku Earthquake in Japan and discusses effects of tsunami on water supply network. The 2011 Tohoku Earthquake generated a tsunami of unprecedented height and exceptional extent along the northeast coast of Japan. A water supply system suffered severe damage by strong ground motion, ground failure and tsunami. Interruption in water supply happened at about 2.57 million houses just after the earthquake and tsunami. In the majority of flooded areas, residents have not been able to return home after the event because most buildings and houses have been washed away. As a result, there has been no need to distribute water in these areas. Most of the damaged pipelines in the flooded areas, therefore, have been left unrepaired. However the lessons from this tremendous tsunami disaster should be learnt and prepare for the future disasters. This study focuses on the damage to water supply facilities and buried pipelines caused by tsunami. First, questionnaire survey was conducted for 186 waterworks bureaus in earthquake and tsunami hit-areas. Structural damage and functional damage to water purification plants were discussed in comparison with the damage in inundated and non-inundated areas. Next, a field survey was conducted to survived water supply pipe buried in tsunami hit areas and the performance of the pipeline was evaluated by using the data of the field survey. Finally we discussed the effects of tsunami on water supply facilities and buried pipelines.

Keywords: water supply system, tsunami, the 2011 Tohoku earthquake, damage

1. Introduction

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. Its epicenter was located at 38.1N, 142.9E. A JMA (Japan Meteorological Agency) seismic intensity of 7 that is the maximum was recorded at K-NET Tsukidate observation station in Kurihara City, Miyagi Prefecture. The earthquake generated a tsunami of unprecedented height and special extent along the coast of the main island of Japan. The earthquake and tsunami caused 15,821 deaths and 3,931 missing, and wounded 5,940 people (As of October 4, 2011, Japanese Government). The major cause of death was the tsunami. The completely collapsed houses numbered 118,480 (As of October 4, 2011, Japanese Government)

Water supply facilities were damaged severely and a suspension of water supply was occurred at about 2.57million houses in the wide area from Tohoku to Kanto regions just after the earthquake. In the majority of flooded areas, residents have not been able to return home after the event because most buildings and houses have been washed away. As a result, there has been no need to distribute wter in these areas. Most of the damaged pipelines in the flooded areas, therefore, have been left unrepaired. However the lessons from this tremendous tsunami disaster should be learnt and prepare for the future disasters.

First, a questionnaire survey was conducted for 186 waterworks bureaus in earthquake and tsunami-hit areas to clarify the functional damage induced by earthquake and tsunami. Then a field survey was conducted to survived earthquake resistant ductile pipe buried in tsunami hit areas, and the performance of the pipeline is discussed to learn the lessons from the disasters.

2. Questionnaire survey on functional damage to water supply system

A questionnaire survey was conducted for 186 waterworks bureaus in five prefectures, Iwate, Miyagi, Fukushima, Ibaragi and Chiba prefectures. The survey was done by using post mail in October 2013. Table 1 lists a number of questionnaire sheets sent to each prefectures and the collection rate. Ten waterworks bureaus had inundated area in their service area.

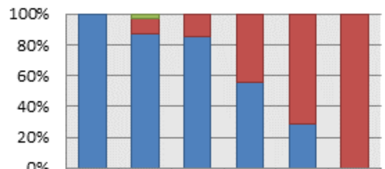
Fig. 1 shows numbers of waterworks bureaus caused water stoppage and its duration after the earthquake in relation to JMA seismic intensity. The water stoppage occurred at more than 50% of the waterworks bureaus in seismic intensity more than 5-. Number of waterworks bureaus that suffered water stoppage in more than one week rapidly increase in seismic intensity 5+. No waterworks bureau recovered within one day in seismic intensity 6+. The number of waterworks bureau that suffered water stoppage of more than four weeks does not depend on the seismic intensity. This means that long water stoppage was caused not only by strong ground motion but also by another cause.

Fig. 2 indicates causes of water stoppage in relation to JMA seismic intensity in multiple answers. Damage to pipelines and blackout were the main reasons in more than 70% of the non-inundated waterworks bureaus. On the other hand, the damage to pipelines was the main reason in less than 30% of the inundated waterworks bureaus except of 6+ of seismic intensity. This means that most of the damages to pipelines have been left unrepaired and the damages to pipelines in inundated areas were not clarified. Percentage of damage to facilities and equipment of inundated waterworks bureaus is twice of that of the non-inundated waterworks bureaus. These damages seem to affect the duration of water stoppage crucially.

Table 2 lists the maximum and average duration of water stoppage in relation to the causes. The duration of water stoppage is not big difference in inundated and non-inundated waterworks bureaus in case of the damage to pipelines and blackout as a cause. The duration of water stoppage in inundated waterworks bureaus was about five times in non-inundated ones if the damage to facilities and equipment are included in the causes.

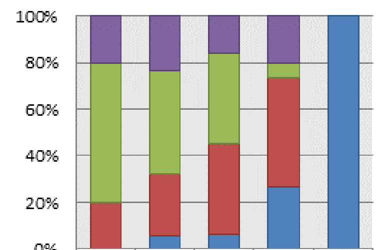
Table 1- Number of questionnaires and collection rate in each prefecture

Prefecture	Iwate	Miyagi	Fukushima	Ibaragi	Chiba	Total
Distribution	28	33	36	42	47	186
Collection	19	25	21	25	29	119
Rate(%)	67.9	75.8	58.3	59.5	61.7	64.0
Number of inundation	5	5	0	0	0	10



	6+	6-	5+	5-	4	3
N/A	0	1	0	0	0	0
No	0	4	5	12	5	1
Yes	10	34	30	15	2	0

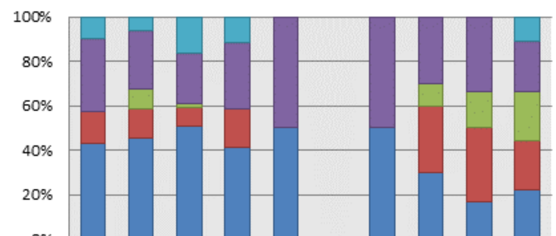
(1) Occurrence of water stoppage



	6+	6-	5+	5-	4
More than 29 days	2	8	5	3	0
8-28 days	6	15	12	1	0
2-7 days	2	9	12	7	0
Less than 1 day	0	2	2	4	2

(2) Duration of water stoppage

Fig. 1 - Occurrence of water stoppage and its duration in relation to seismic intensity

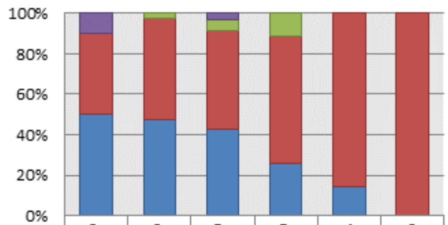


	6+	6-	5+	5-	4		6+	6-	5+	5-
Others	2	4	8	2	0		0	0	0	1
Blackout	7	18	11	5	1		1	3	2	2
Damage to equipment	0	6	1	0	0		0	1	1	2
Damage to fasilities	3	9	4	3	0		0	3	2	2
Damage to pipelines	9	31	25	7	1		1	3	1	2
	Non-inundation						Inundation			

Fig.2 - Causes of water stoppage in relation to JMA seismic intensity

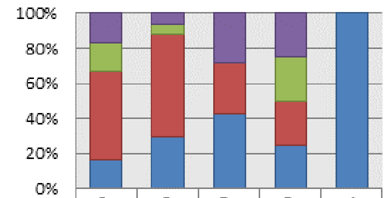
Table 2 - Maximum and average days of water stoppage

Unit: day		Damage to pipelines and Blackout	Damage to pipelines and facilities, and Blackout	Damage to pipelines, facilities and equipment, and Blackout
Non-inundation	Maximum	50	30	25
	Average	11.2	22.3	17.5
Inundation	Maximum	17	170	108
	Average	17	115	88
	Ratio	1.5	5.2	5.0



	6+	6-	5+	5-	4	3
No facility	1	0	1	0	0	0
N/A	0	1	2	3	0	0
No	4	19	17	17	6	1
Yes	5	18	15	7	1	0

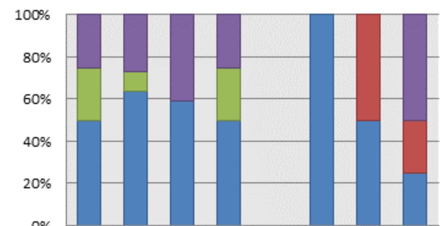
(1) Occurrence of intake stop



	6+	6-	5+	5-	4
More than 29 days	1	1	4	2	0
8-28 days以内	1	1	0	2	0
2-7 days	3	10	4	2	0
Less than 1 day	1	5	6	2	1

(2) Duration of intake stop

Fig. 3 - Occurrence of intake stop and its duration in relation to seismic intensity



	6+	6-	5+	5-		6-	5+	5-
Others	2	6	7	2		0	0	2
High turbidity	2	2	0	2		0	0	0
High sodium chloride	0	0	0	0		0	2	1
Blackout	4	14	10	4		1	2	1
	Non-inundation					Inoundation		

Fig. 4 - Causes of intake stop in relation to seismic intensity

Fig. 3 shows number of waterworks bureaus caused intake stop and its duration after the earthquake in relation to JMA seismic intensity. Most of waterworks bureaus reopened intake in less than one week in spite of seismic intensity. The number of waterworks bureau that suffered intake stop of more than one week does not depend on the seismic intensity. This means that long intake stop was caused not only by strong ground motion but also by another cause.

Fig. 4 indicates causes of intake stop in relation to seismic intensity in multiple answers. Blackout was the main reason in more than 50% of in the inundated and non-inundated waterworks bureaus except of 5- of the seismic intensity. High sodium chloride by tsunami is listed as a reason in inundated waterworks bureaus and high sodium chloride was observed not in river but in the water of shallow well. On the other hand, high turbidity is listed as a reason in non-inundated waterworks bureaus. It seems that landslide of a slope at upper stream of intake facility seems to be affected to the high turbidity.

3. Damage to water supply facilities and pipelines by tsunami

3.1 Damage characteristics by tsunami

Causes of damage by a tsunami are roughly classified into three categories: inundation, washing away and scouring of surface ground. Some intake facilities were inundated and had not functioned for a long time because of high concentration of sodium chloride in groundwater (Photo 1). Photo 2 shows damage to a water pipe bridge, which was completely washed away. It is unknown yet which caused this kind of damage, water pressure, floating wreckage or both. We should study the force acted on the water pipe bridge during the tsunami through a damage analysis. Photo 3 shows damage to buried pipeline. The pipe appeared as the covered soil had been scoured by the tsunami. The mechanism of damage to the pipe, that is, how much force was acted on the pipe in what way, is still unknown, waiting to be clarified in future.

Photo 1 - Inundated intake facilities (Sukedukuri No.2)

Photo 2 - Washed-away water pipe bridge

Photo 3 - Damage to pipe by tsunami-induced scouring

3.2 Field survey of surviving pipes in Ishinomaki City

The earthquake resistant joint ductile iron pipes (ERDIP) did not suffer damage at all in the 2011 Tohoku Earthquake. A field survey was conducted on surviving ERDIP buried in the tsunami-hit area at Ishinomaki City in Tohoku region. Photo 4 shows an ERDIP appeared above ground surface by scouring caused by the tsunami. The exposed pipelines were covered by debris of crushed wooden houses and a steel container as shown in Photo 5. This pipeline is ERDIP with NS joint with 300 mm of nominal diameter, installed in 2010. Deformation of pipeline, displacement and bending angle at each joint were measured for fourteen pipes as shown in Fig. 5 [1].

Fig. 6 illustrates a horizontal distance to a pipeline from the edge of a road before and after the earthquake. Because the road was not dislocated horizontally or deformed by the earthquake and tsunami, this figure indicates that the pipeline moved about 40 cm. Fig. 7 shows bending angles at joints measured at the field. The maximum bending angle is 7.5 degrees at the joint No. 11. It seems that the pipeline appeared above ground by the scouring, hit by a steel container and debris in undertow of the tsunami, and moved to the coastline. There was, however, no damage to ERDIP and water suspension did not occur.

Photo 4 - ERDI exposed above ground

Photo 5 - ERDIP covered by debris

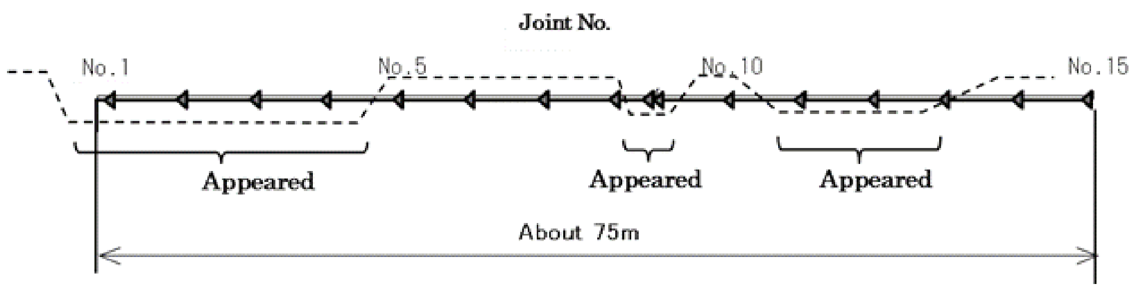


Fig. 5 - Profile of ERDIP with 300 mm of nominal diameter
(Dashed line indicates the level of ground surface after the

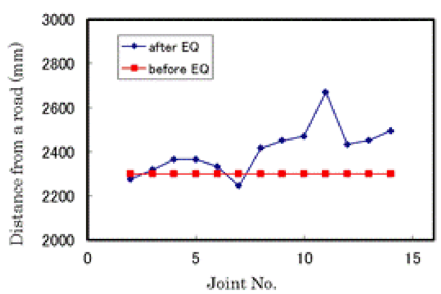


Fig. 6 - Distance of the pipeline from a road edge before and after the earthquake

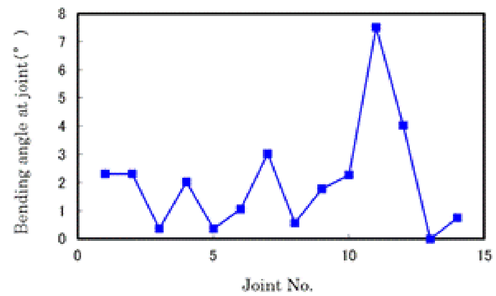


Fig. 7 - Bending angle at joint measured at the field

3.3 Field survey of surviving pipes in Sendai City

Performance of sueviving ERDIP burien in tsunami-hit area at the eastside of Sendai City was surveyed, where liquefaction also occurred. This area was about 2m flooded by the tsunami after the earthquake. Road was undulated, utility pole and traffic sign subsided about 1m by liquefaction as shown in Photo 6. Measured pipeline is ERDIP with SII type joint in the nominal diameter 300 mm. The behavior of the pipes of about 80m intervals was measured by TV camera inserted in the pipelines [1].

Settlement of the ground surface of the surveying site occurred about 0.3m in a section of about 50m from the threshold by the earthquake as shown in Fig. 8. The pipelines followed the ground displacement. Two consecutive joints near 70m point had been fully expanded nearly. The sum of amount of expansion and contraction of each joint is 240 mm; amount of expansion was equivalent to 0.3% of the pipe length. This amount was small enough compared with the capacity of 1 percent, expansion amount of the pipeline.

The measured pipelines could absorb ground displacement by expansion / contraction performance to allowance limit of some joints. Moreover, the behavior of joints has locally concentrated. It is considered that the ground strain was also concentrated locally because of ground uniformity. In such places, the pipelines had absorbed the large ground strain by expanding the adjacent joints, even if a joint expanded up to allowance limit. In other words, the effectiveness of the chain structure pipeline absorbed ground deformation has been demonstrated.

Photo 6 - Subsidence of utility pole induced by liquefaction in Sendai City

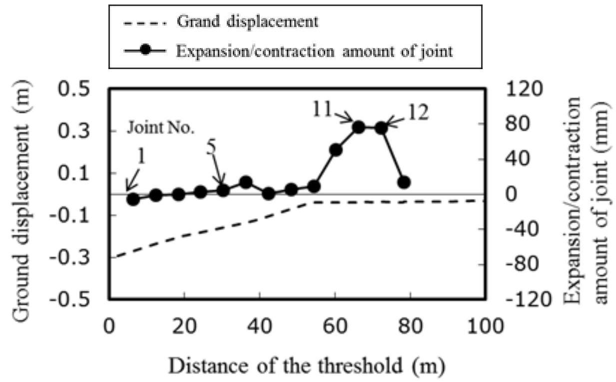


Fig. 8 - Expansion/contraction amount of joints and vertical displacement of ground surface

4. Concluding remarks

The present paper focused on a questionnaire survey conducted for 186 waterworks bureaus in earthquake and tsunami-hit areas to clarify the functional damage induced by earthquake and tsunami. And a field survey was conducted to survived earthquake resistant ductile pipe buried in tsunami-hit areas to learn the lessons from the disasters. The following conclusions may be drawn based on the present study.

(1) Percentage of damage to facilities and equipment of inundated waterworks bureaus is twice of that of the non-inundated waterworks bureaus as a cause of water stoppage. These damages seem to affect the duration of water stoppage crucially.

(2) The duration of water stoppage in inundated waterworks bureaus was about five times in non-inundated ones if the damage to facilities and equipment are included in the causes.

(3) Blackout was the main reason in more than 50% of in the inundated and non-inundated waterworks bureaus except of 5- of the seismic intensity. High sodium chloride by tsunami is listed as a reason in inundated waterworks bureaus. On the other hand, high turbidity is listed as a reason in induced in non-inundated waterworks bureaus.

(4) A field survey was conducted on surviving ERDIP buried in the tsunami-hit area at Ishinomaki City in Tohoku region. The pipeline exposed above ground by the scouring, hit by a steel container and debris in undertow of the tsunami, and moved to the coastline. There was, however, no damage to ERDIP and water suspension did not occur.

(5) The earthquake resistant ductile iron pipe had absorbed the large ground strain by expanding the adjacent joints in liquefaction area in Sendai City.

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