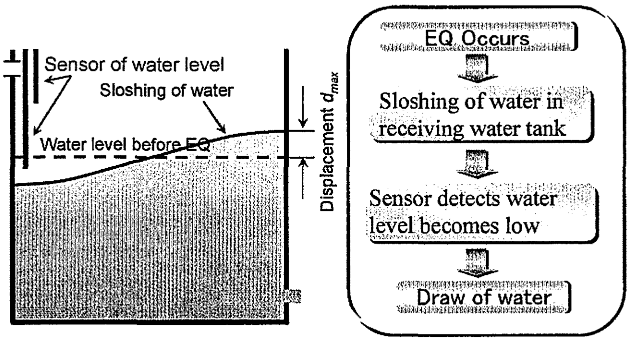

Figure 8 Mechanism of draw of water from distribution pipe to receiving tank by sloshing during earthquake.

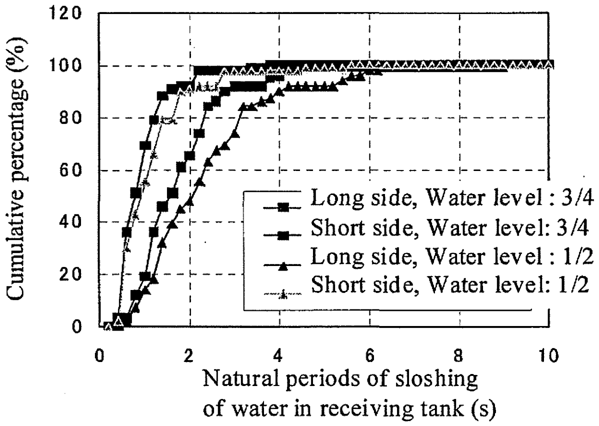

Figure 9 Cumulative percentage of natural period of water in receiving water tank

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. 8. 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. 9 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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2011 年東日本大震災における水道施設の地震被害の特徴

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東日本大震災においては、地震直後の断水人口が約 23 万人に上るなど、水道施設にも甚大な被害が生じた。地震後約 1 か月の間に約 90%断水が解消されたが、地震動のみならず、津波による水道施設の浸水被害、流出被害などにより、ごく一部の地域であるが地震後 2 ヶ月が経っても応急給水に頼らざるおえない地域もあった。また、津波による浸水地域についてはまだ復興事業が始まっていないこともあり、水道管路の修繕が行われておらず、被害の実態が明らかになっていない。 しかし、津波による浸水地域以外については、徐々に被害の実態が明らかになってきている。そこで本論文では、それらの資料を基に、これまでに明らかになった今回の大震災における地震動による被害の特長について考察する。

Key Words : the 2011 Great East Japan Earthquake, Water supply system, Earthquake damage

1. はじめに

2011 年東日本大震災においては、マグニチュード 9.0 というわが国の観測史上最大の巨大地震による地震動のみならず、それにより引き起こされた液状化と、東北地方から関東地方の海岸を襲った津波により、上下水道をはじめとするライフライン施設に甚大な被害が生じた。この巨大地震によって引き起こされたライフライン被害の影響因子は、長周期、長継続時間地震動、津波、広域液状化、人工改変地の地盤変状に大別することができる。それぞれの要因が被害にどのように影響しているのかは、今後の詳細な被害とその関連の資料の収集によるところが大きいが、これまでに明らかにされた、津波浸水地域を除く水道施設被害資料と著者が行った水道事業体に行ったアンケート調査結果に基づき、今回の大震災による水道施設被害の特長について考察する。

2. 仙台市における被害の特徴

(1) 仙台市の水道施設の概要

仙台市においては津波浸水地域を除く水道管路の被害データが整理されているので、本論文では仙台市の水道管路被害を例に、今回の大震災の水道被害の特徴を検討する。

仙台市の人口は約 104 万人であり、1 日の平均供給水量は約 336,000m³ である。導、送、配水本管からなる幹線管路の敷設延長距離は約 472km である。管種は約 74%が*ダクタイル*鉄管、約 24%が鋼管である。

(2) 被害の特徴

仙台市における導、送、配水本管の被害箇所数が 10 箇所であるのに対し、消火栓や弁類などの属具被害は 43 箇所に上っている。

まず、管路被害の内訳については、*ダクタイル*鉄管の K 型継手で 4 箇所、A 型継手で 4 箇所、T 型継手で 1 箇所、鋼管で 1 箇所の被害が発生した。導、送、配水本管の被害箇所数を敷設延長距離で除して被害率を求めると 0.02 箇所/km となる。なお、耐震継手では被害は生じていない。

一方、属具被害の内訳は空気弁が 41 箇所、仕切弁が 1 箇所、消火栓が 1 箇所となっており、空気弁の被害が際立っている。兵庫県南部地震の際にも空気弁の被害が注目されたが、このときは地震動により経年劣化した箇所に被害が生じたものがほとんどであったが、今回の被害形態はそれとは異なっているということである。仙台市の上水道に限らず、工業用水などでも同様な被害が多発しているようであり、今回の大震災における被害の特徴のひとつと考えられる。これらの被害原因の究明が急がれるところである。

配水支管まで含めた導、送、配水管全ての敷設延長距離は 3,761km であり、被害箇所数は 264 箇所であった。ただし、津波浸水地域は含まれてい

ない。導、送、配水管の被害率は 0.07 箇所/km となる。この被害率を近年の被害地震における他の都市の値と比較すると図１のようになる。図１には 1995 年兵庫県南部地震における神戸市、芦屋市、西宮市、2004 年新潟県中越地震における長岡市、2007 年能登半島地震における旧門前町、2007 年新潟県中越沖地震における柏崎市の被害率が示されている。それぞれの都市における最大加速度や震度が異なっているので、この図を単純に比較することはできないが、図１によれば、仙台市の導、送、配水管の被害率は、近年の被害地震における他都市の被害率と比較して最も小さい値であることがわかる。

この理由としては、1978 年宮城県沖地震以降、幾度かの被害地震に襲われ、耐震化が促進されてきたことが考えられる。仙台市の水道管路の耐震化率は 50%を越えており、全国平均（約 14%）よりもはるかに高い。しかし、その一方で、海岸付近の比較的軟弱な地域の被害データが、津波浸水地域ということで未だ含まれていないことにも注意を要する。津波浸水地域はより地震断層に近く地震動が大きかった可能性があること、液状化発生の可能性も高いことから、復興事業が進められた際の被害データの収集が極めて重要であると考えられる。

図２は管種別の被害率を、図３は管径別の被害率を示している。これまでの被害地震による被害と同様に、硬質塩化ビニル管の被害率が最も高く、鋼管、ダクタイル鉄管の順で被害率が小さくなっている。また、管径が小さいほど、被害率が大きくなる傾向も、これまでの被害地震と調和的である。

３．地震直後に発生する配水システムの異常挙動

(1) 異常挙動の概要

地震が発生した直後に、管路被害が発生していなくても急激な流量増加と水圧低下が発生するという異常挙動は、過去の地震においてしばしば観測されている。2008 年岩手宮城内陸地震においても仙台市水道局で異常挙動が観測され、急激な流量増加と水圧低下が地震後約 10 分間継続した。流量は仙台市総配水量で平常時の 45.5%増加し、水圧は最大で平常時の 28.6%低下した。この地震では同様の現象が新潟市水道局でも見られた。しかしながら、異常挙動の継続時間が短かったことから市民生活に影響を及ぼすことはなかった。

(2) 大阪市における過去の地震による異常挙動

表1は大阪市における過去の地震発生直後の異常挙動について示している1)。**表1**によれば、京都府南部での地震では震度３で異常挙動が発生しなかった反面、芸予地震のように震度２でも発生しており、地震直後の水供給システムの異常挙動に

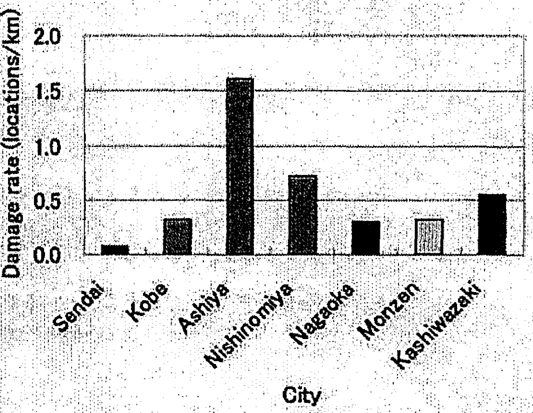

図１ 管路被害率の比較

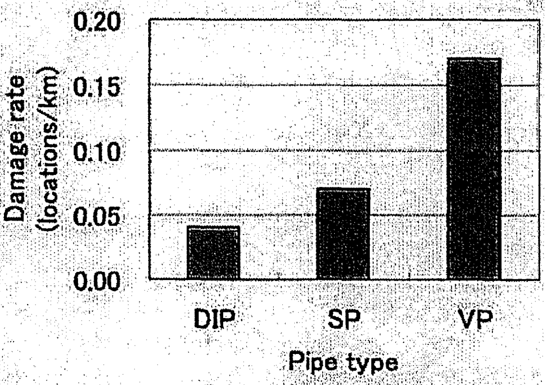

図２ 管路被害率と管種との関係

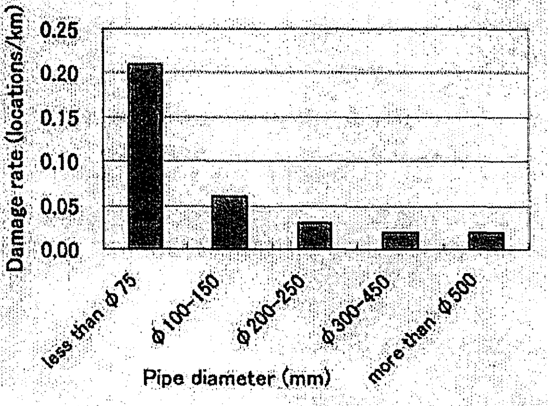

図３ 管路被害率と管径との関係

は、地震動の強さだけでなく、地震動の振動特性も寄与しているのではないかと考えられる。そこで、表1で挙げられている各地震の速度応答スペクトルに注目した。図4に各地震の速度応答スペクトルを示す。異常挙動の発生が確認されている鳥取県西部地震、芸予地震および紀伊半島南東沖の地震において、1秒以上のやや長周期の振動成分が卓越している。一方、異常挙動の発生が確認されなかった京都府南部を震源とする地震については、1秒以下の振動成分が卓越しており、他の地震に比べ卓越周期帯が短いことが明らかとなった。これらの速度応答スペクトルから、地震発生直後に発生する水道供給システムの異常挙動は、ある周期の地震動、すなわちやや長周期の地震動が間接的に水供給システムに影響を及ぼしていると推測される。

表 1 過去の地震履歴と異常挙動の関係

	鳥取県西部	芸予	京都府南部	紀伊半島沖(1)	紀伊半島沖(2)
発生日	2000/10/6	2001/3/24	2001/8/25	2004/9/5	
発生時刻	13時30分	15時28分	22時21分	19時07分	23時57分
震源	鳥取県西部	安芸灘	京都府南部	紀伊半島南東沖	
マグニチュード	7.3	6.7	5.3	6.9	7.4
大阪市における震度	震度4	震度2	震度3	震度4	震度4
異常挙動発生	あり	あり	なし	あり	あり

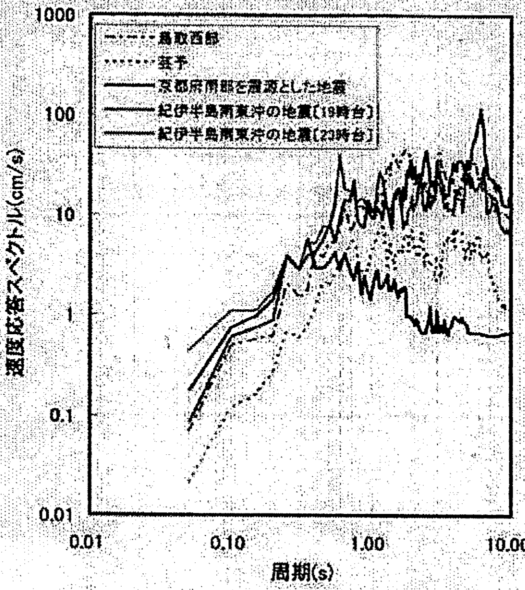

図 4 各地震における速度応答スペクトル

(3) 東日本大震災における異常挙動

東日本大震災においても同様な現象が発生していないかを確かめるために、東北地方のみならず西日本の一部も含めた 20 の水道事業体に対して配水システムの異常挙動に関するアンケート調査を行った、異常挙動の発生の有無と気象庁から発表されている震度を表 2 に示す。18 事業体から回答を得たが、その中の 7 つの水道事業体で異常挙動が観測されていた。表 2 によれば、東北、関東地方のみならず、名古屋市や大阪市などの遠方においても異常挙動が観測されている。また、これまでの事例と同様に、震度 5 弱以上でも異常挙動が発生していない水道事業体があるのに対して、震度 3, 4 でも異常挙動が発生している事業体がある。これらの水道事業体においては異常挙動の継続時間が短かったことから市民生活に影響を及ぼすことはなかったが、仙台市においては管路被害も生じているので、このような異常挙動が与えた影響についても明らかにする必要がある。

(4) 受水槽のスロッシングと異常挙動

受水槽は内部の水が一定水位以下になると、近傍の配水管から引水する構造になっている。したがって、地震時にスロシングが発生すると、水面が一時的に低下し、一斉に引水をはじめることにより、異常挙動が発生したと考えることができる。そこで、表 1 に示した各地震の大阪市における観測記録を用いてスロッシング変位量を計算した [1]。図 5 は、大阪市咲洲地区において行った受水層の実態調査に基づいて集計した各受水槽について、Housner の計算式 [2] を用いて計算したスロッシング量を累積度数で示した図である。解析結果から明らかなように、芸予地震を除き、異常挙動が発生した鳥取県西部地震、紀伊半島南東沖の地震は、受水槽の有効水位の 1/2 の時に約半数以上で 0.1m以上の変位が発生しており、最大変位についても

表 2 東日本大震災における異常挙動

自治体名称	水道事業体名	異常挙動の有無	震度
札幌市	札幌市水道局	無	3
青森市	青森市企業局上下水道部	無	4
盛岡市	盛岡市水道部	無	5強
秋田市	秋田市上下水道局	無	5強
仙台市	仙台市水道局	有	6弱
山形市	山形市水道部	有	4
新潟市	新潟市水道局	無	4
水戸市	水戸市水道部	無	6弱
宇都宮市	宇都宮市上下水道局	有	5強
東京都	東京都水道局	有	5弱
さいたま市	さいたま市水道局	有	5強
横浜市	横浜市水道局	無	5強
甲府市	甲府市水道局	無	5弱
名古屋市	名古屋市上下水道局	有	4
金沢市	金沢市企業局	無	3
大阪市	大阪市水道局	有	3
神戸市	神戸市水道局	無	2
広島市	広島市水道局	無	1

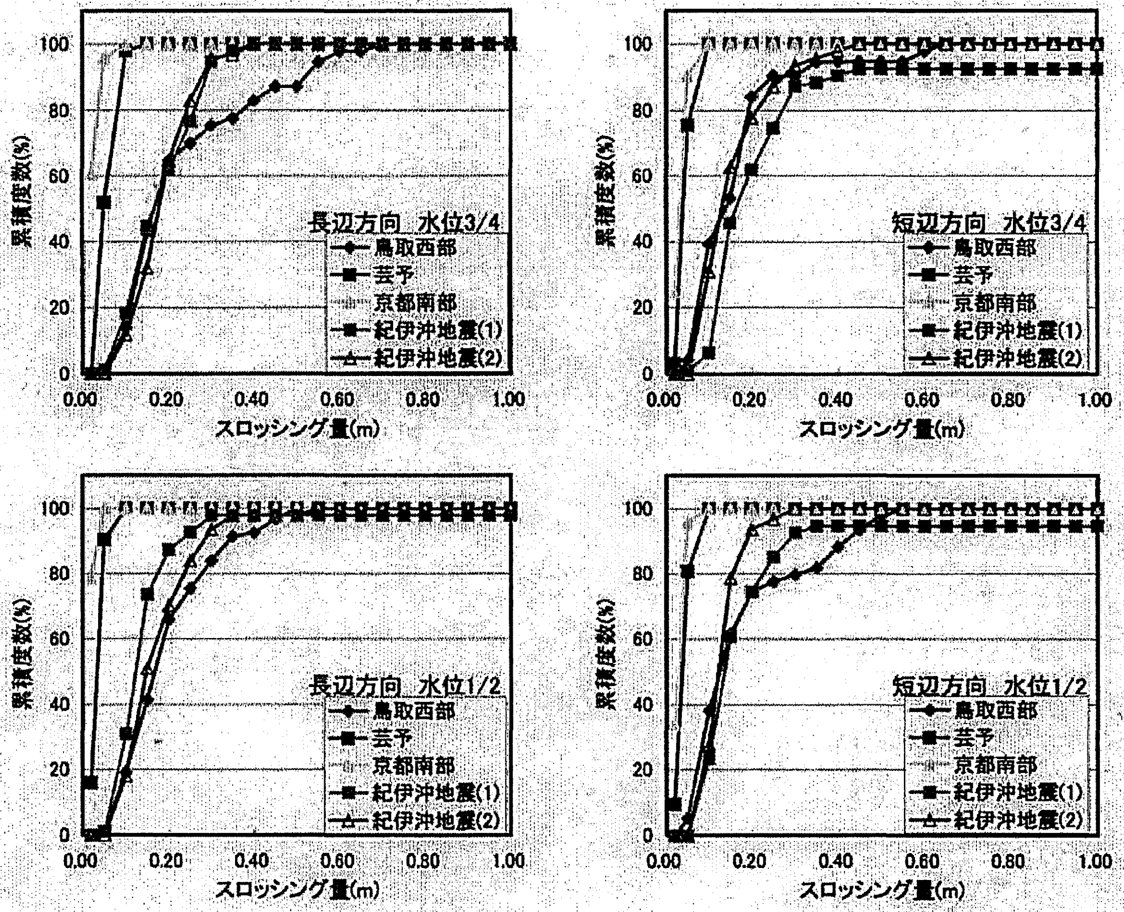

図5 各地震におけるスロッシング量

0.5m を超える変位が発生する。一方、異常挙動が確認出来なかった京都府南部を震源とした地震では、異常挙動が確認できた芸予地震よりもスロッシング量が低く、90%以上が 0.05m 以下のスロッシング量となっており、ほとんどの受水槽において、地震によるスロッシングが発生しないといよう。このことから、やや長周期の地震動による受水槽のスロッシング現象が水供給システムの異常挙動に深く関与していることがわかる。

今後は東北、関東地方をはじめ、当該地域の強震記録を収集し、同様の分析を行う予定である。

4．結論

本論文は、2011年東日本大震災における水道施設被害の特長について考察したものである。大震災から8ヶ月以上を経過した時点でこれまでに明らかにされた、津波浸水地域を除く水道施設被害資料と著者が行った水道事業体に行ったアンケート調査結果に基づき検討した結果、以下の特徴を明らかにした。

1．仙台市水道局を始め弁類や消火栓といった属具の被害が、顕著である。属具被害も断水に直接関係するので、被害原因の究明が急がれる。

2．仙台市水道局の導、送、配水管の被害率は 0.07 箇所/km となるり、この被害率を近年の被害地震における他の都市の値と比較すると極めて低い値であった。この理由としては、1978 年宮城県沖地震以降、幾度かの被害地震に襲われ、耐震化が促進されてきたことが考えられる。しかし、その一方で、海岸付近の比較的軟弱な地域の被害データが、津波浸水地域ということで未だ含まれていないことにも注意を要する。復興事業が進められた際の被害データの収集が極めて重要であると考えられる。

3．地震が発生した直後に、管路被害が発生していなくても急激な流量増加と水圧低下が発生するという異常挙動が、東北、関東地方のみならず、名古屋市や大阪市などの遠方においても異常挙動が観測されていた。このような異常挙動は、やや長周期の地震動が間接的

に水供給システムに影響を及ぼしていると推測されておりので、今後、当該地域の強震記録を用いた分析を行う必要がある。

謝辞

本論文では2011年5月の行われた厚生労働省水道課による地震被害現地調査に参加させて頂いた際に収集した資料の一部を用いている。訪問先の水道事業体の関係各位、厚生労働省はじめ調査団の皆様に深謝します。また、本研究の一部が文部科学省科学研究費（基盤研究（B） No.20310108 研究代表者：宮島昌克）の補助を受けていることを記して，謝意を表します。

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CHARACTERISTICS OF DAMAGE TO WATER SUPPLY FACILITIES IN THE 2001 GREAT EAST JAPAN EARTHQUAKE

Masakatsu MIYAJIMA

This paper deals with characteristics of damage to water supply facilities induced by the 2011 Great East Japan Earthquake. 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 coast of the main island of Japan. The earthquake and tsunami caused about 20,000 deaths and missing and injured about 6,000 people. A suspension of water supply was also occurred at about 2,300,000 houses in east Japan just after the earthquake. An outline of damage to water supply facilities is given and the characteristics of damage by the earthquake is discussed.

Damage to Water Supply Facilities during the 2011 Great East Japan Earthquake and Tsunami

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Abstract. This paper is focusing on 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 coast of the main island of Japan. The earthquake and tsunami caused about 20,000 deaths and missing and injured about 6,000 people. A suspension of water supply was also occurred at about 2,300,000 houses in east Japan just after the earthquake. An outline of damage to water supply facilities is given and lessons learned from the earthquake and tsunami is discussed.

Keywords. Earthquake damage, water supply facilities, 2011 great east Japan earthquake

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 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, Japanese Government). The major cause of death was the tsunami. The completely collapsed houses numbered 118,480 (As of October 4, Japanese Government).

The 2011 great east Japan earthquake and tsunami also caused extensive damage to drinking water facilities. Strengthening of the earthquake resistance of drinking water facilities has become a major issue for drinking water utilities, along with the renovation of aging facilities. An outline of damage to water supply facilities is given and lessons learned from the earthquake and tsunami is discussed.

2. Outline of the Earthquake and Tsunami

Figure 1 illustrates epicenters of main shock and aftershocks[1)]. According to the distribution of the epicenters of the aftershocks, the earthquake successively ruptures over an area of approximately 450km x 200km.

Figures 2 and 3 show a distribution of the peak ground acceleration (PGA) and peak ground velocity (PGV) [2)]. Maximum PGA was recorded at K-NET Tsukidate observation station in Kurihara City, Miyagi Prefecture. Large PGA and PGV were recorded not only at Tohoku region but also at Kanto region.

Table 1 lists observation sites where large PGA recorded. PGA and PGV listed here were vectorial summation of three components. The maximum PGA was 2,933 (cm /s/s) at K-NET Tsukidate station and the maximum PGV also recoded at K-NET Tsukidate station. More than 1G (= 980 cm/s/s) of PGA was observed at the nineteen observation stations of K-NET and KiK-NET observation stations.

Figure 4 shows inundation and run-up heights in Hokkaido, Tohoku and Kanto regions surveyed by Tohoku Earthquake Tsunami Joint Survey Group[3)]. Tsunami terminology is given by Figure 5[4)]. According to their survey, the maximum run-up height was 39.7m at Miyako City. The maximum inundation height at the Sendai Plain was 19.5m and the mean inundation height near the shoreline was about 10m[4)]. It has been estimated from areal and satellite photography that almost 535 km^2 of land were inundated in according to the Ministry of Land, Infrastructure, Transport and Tourism[5)]. The tremendous tsunami caused a catastrophic destruction in Tohoku region.

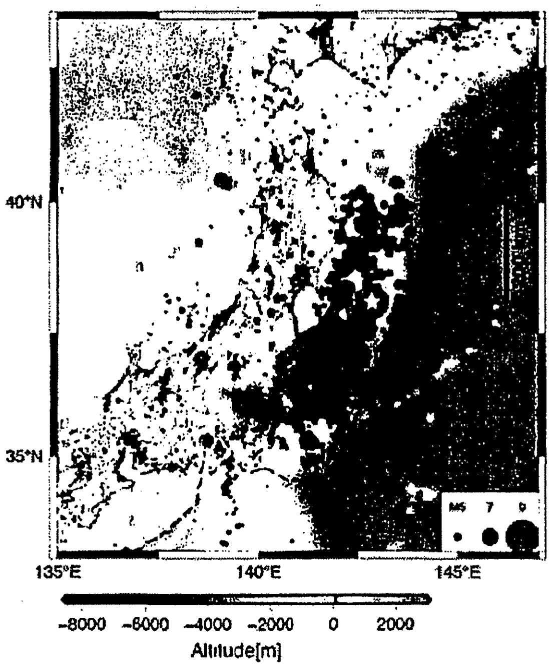
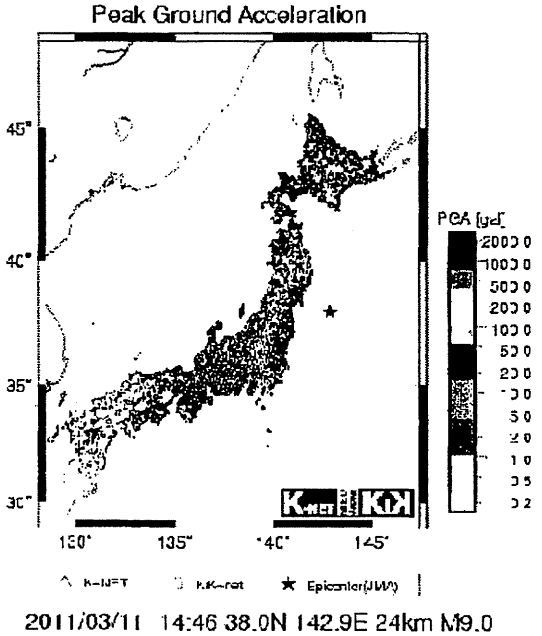


Figure 1 Distribution of epicenters of main shock and aftershocks (2011. 3.11-3.27)[1].

Table 1 Large PGA observed sites[2].

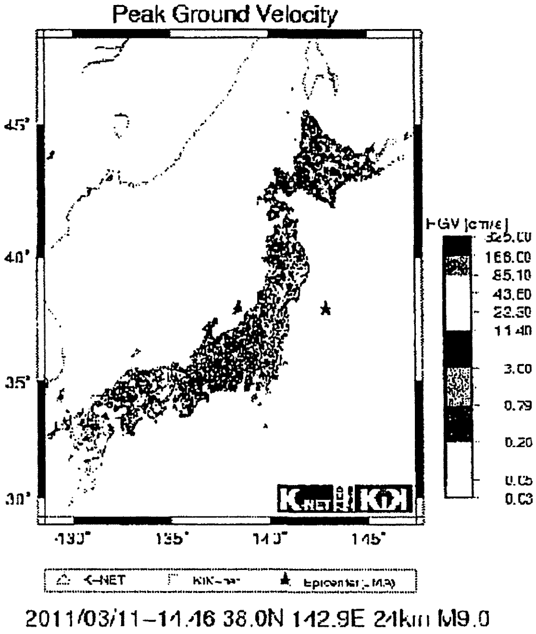
	Site Name	Site Code	PGA (cm/s/s)	PGV (cm/s)
1	K-NET Tsukidate	MYG004	2,933	106
2	K-NET Siogama	MYG012	2,019	64
3	K-NET Hitachi	IBR003	1,845	74
4	K-NET Sendai	MYG013	1,808	83
5	K-NET Hokota	IBR013	1,762	71
6	K-NET Imaichi	TCG009	1,444	48
7	K-NET Shirakawa	FKS016	1,425	63
8	KiK-net Nishigou	FKSH10	1,335	41
9	K-NET Oomiya	IBR004	1,312	47
10	KiK-net Haga	TCGH16	1,305	82

PGA and PGV : Vectorial Summation of 3 Components
Bandpass filter to calculate velocity waveform : 0.1-15Hz


Peak Ground Acceleration

2011/03/11 14:46 38.0N 142.9E 24km M9.0

Figure 2 Distribution of peak ground acceleration[2].


Peak Ground Velocity

2011/03/11-14:46 38.0N 142.9E 24km M9.0

Figure 3 Distribution of peak ground velocity[2]

3. Damage to Water Supply Facilities Suspension of water supply

A suspension of water supply was occurred at about 2,300,000 houses 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.

Causes of damage to facilities

The damage caused by the earthquake and tsunami is 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. Photo 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. Photo 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. Photo 3 shows damage to water pipe bridge by tsunami. The water pipe bridge was completely washed away. Photo 4 shows damage to pipeline. The pipe appeared above ground after tsunami because of scouring caused by tsunami. The mechanism of damage to pipe, that is, how much force acts on a pipe is not sure. The mechanism of this kind of damage must be clarified in future.

Damage to pipeline

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.

Since the damage to pipeline of Sendai City is 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). 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).

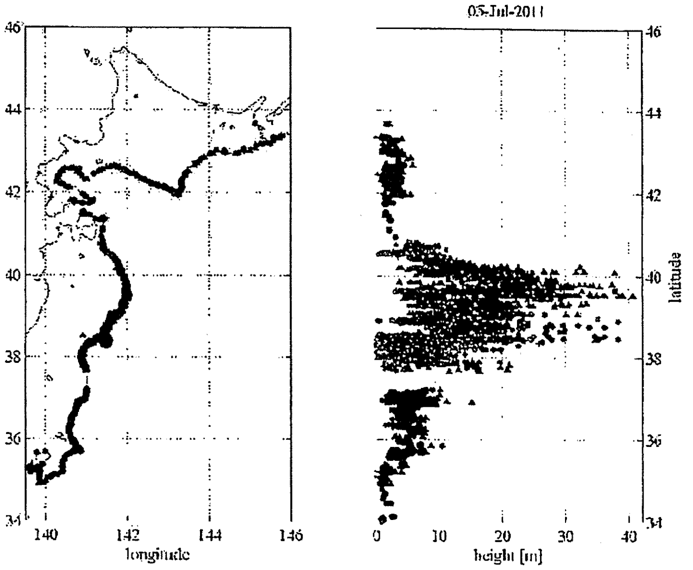


Figure 4 Inundation and run up heights of tsunami[3].
(red circle: inundation height, blue circle; run-up height)

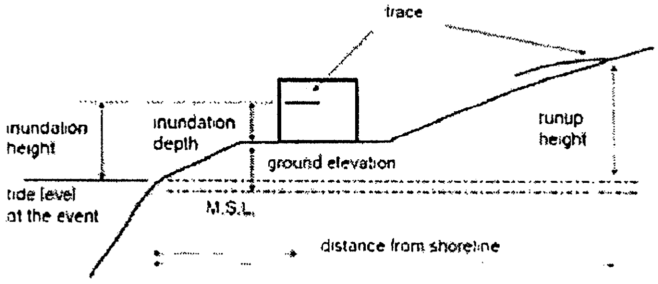


Figure 5 Tsunami terminology[4]

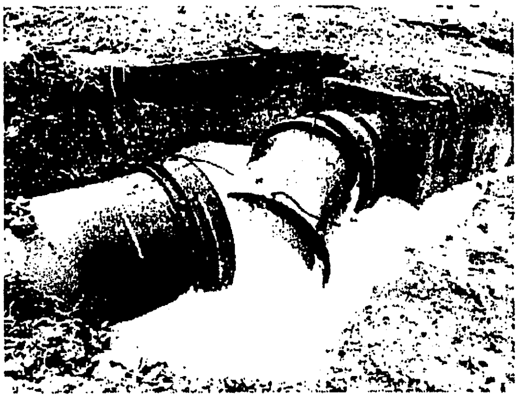


Photo 1 Damage to steel pipe with 2400mm diameter (Miyagi Pref.)[6].

Photo 2 Uplift of underground water tank (Chiba Pref.)[7].

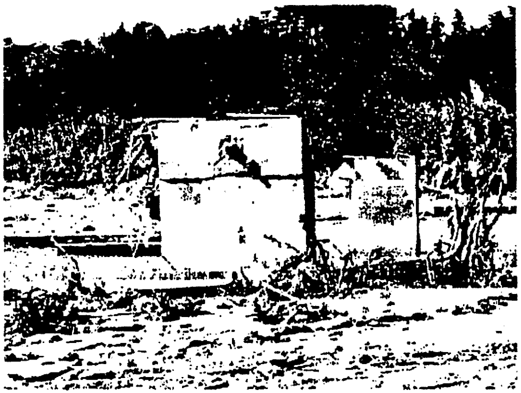


Photo 3 Damage to water pipe bridge (Miyagi Pref.).

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

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 Figures 6 and 7, respectively. Figure 6 indicates that the damage rate of polyvinyl chloride pipe (VP) is high. Figure 7 reveals that the smaller the pipe diameter is, the higher the damage rate.

Figure 8 illustrates a comparison of damage rate of Sendai City with those of other cities suffered damage to pipeline in the past earthquakes. 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 was different. PGA of K-NET Sendai observation station was, however, not small; 1,808 (cm/c/c) according to Table1. This value is higher than most of cities listed in Figure 8. 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%.

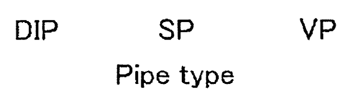


Figure 6 Damage rate related to pipe type.

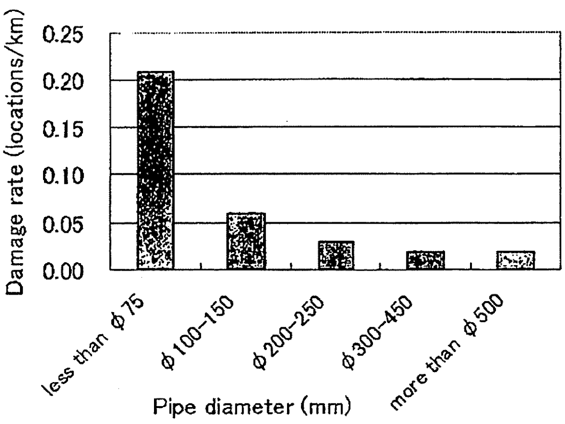


Figure 7 Damage rate related to pipe diameter.

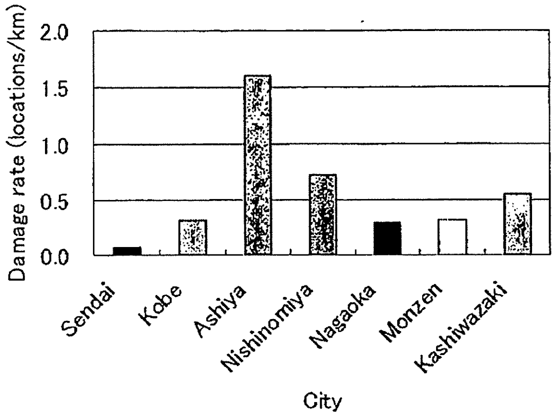


Figure 8 Comparison of damage rate.

Figure 9 illustrates the relation between the earthquake-proofing rate and damage rate suffered damage in the 2011 great east Japan earthquake. The damage rate hown 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 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 and welded steel pipe. Effect of earthquake-proofing pipe was, therefore, verified by the earthquake.

4. Concluding remarks

An outline of the earthquake and damage to water supply facilities from the 2011 great eat Japan earthquake and tsunami was presented and the damage rate of pipeline was discussed. The following conclusions may be drawn based on the present study.

1) The affected area was very large because of great earthquake and tsunami. Situation of emergency response and support from other cities must be reviewed.
2) 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.
3) Effect of earthquake-proofing for pipeline was verified. We must accelerate the earthquake proofing, especially for aged facilities.
4) Force of tsunami acted on a buried pipe is not clear. The effect of tsunami must be studied soon.

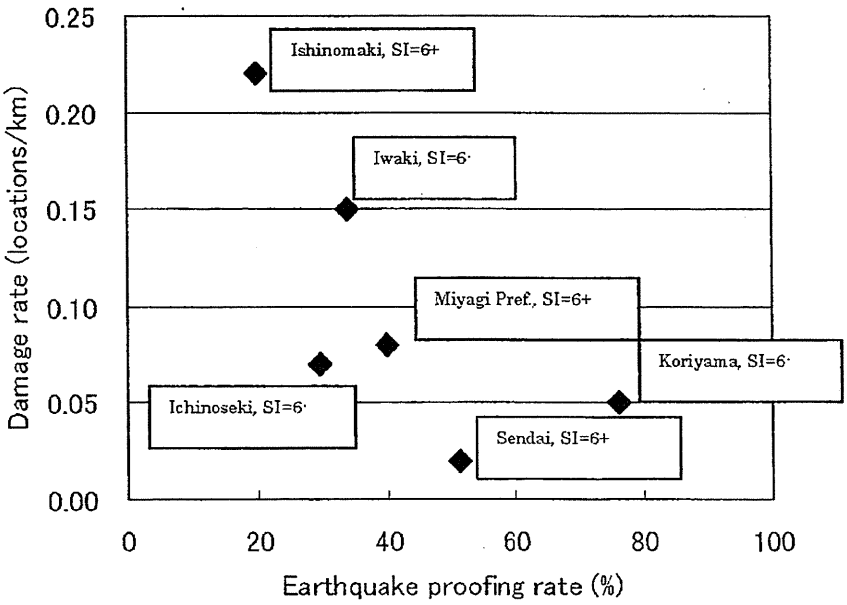


Figure 9 Relation between earthquake proofing rate and damage rate.

Acknowledgments

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Experimental evaluations of water treatment systems using a pilot-scale plant for adaptations to a sharp increase in raw-water turbidity caused by climate change

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Abstract
One effect of climate change on the water supply systems in Japan may be a sharp increase in the raw-water turbidity following heavy rain. The objective of this study was to evaluate water treatment performance with a sharp increase in raw-water turbidity. This evaluation was carried out from the perspective of turbidity response by a pilot-scale plant using sand filtration and membrane filtration with coagulation-sedimentation pretreatment. Two coagulants were used; namely, polyaluminum chloride with a basicity of either 72% (PACl-72%) or 51% (PACl-51%). Raw-water turbidity was increased from 5 TU to 300 TU by adding kaolin suspension. In the case of sand filtration, the filtered-water turbidity increased during the filter ripening period. An increase in the coagulant dosage produced a more rapid decrease in the filtered-water turbidity and shortened the filter ripening period. The filtered-water turbidity decreased more rapidly for PACl-72% than for PACl-51%. In the case of membrane filtration, an increase in the raw-water turbidity caused no significant increase in the filtered-water turbidity or the transmembrane pressure difference. These results demonstrated that, although neither filtration technique completely failed, membrane filtration was more robust than sand filtration against a sharp increase in raw-water turbidity.

Keywords
Climate change; Coagulant; Membrane filtration; Pilot-scale plant; Sand filtration; Turbidity

INTRODUCTION

It is essential for a water supply system to supply safe water continuously, which is indispensable for comfortable civil life and urban activity (Water Supply Division, Ministry of Health, Labour and Welfare, Japan, 2008). In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change described how "warming of the climate system is unequivocal" and concluded that "even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation essential, particularly in addressing near-term impacts" (IPCC, 2007). The scenarios in "Climate Change and Its Impacts in Japan" project that the average temperature increase between the end of the 20th century (1980–1999) and the end of the 21st century (2090–2099) will be in the range from 2.1°C to 4.0°C (Ministry of Education, Culture, Sports, Science and Technology et al., Japan, 2009). Therefore, it is essential to study adaptation measures for climate change in addition to mitigation measures such as reducing greenhouse gas emissions from water supply systems.

The influences of climate change on the water environment and resources in Japan are predicted to consist of increases in the following: drought risk; the frequency of short-term heavy rainfall; the temperatures of rivers, lakes, and groundwater; and the probabilities of blue-green algae and saline groundwater due to sea level rise (Ministry of the Environment, Japan, 2008). Heavy rainfall of more than 50 mm/h has occurred 1.5 times as often in recent years (1998–2007) as compared to 30 years ago (1976–1987) and that of more than 100 mm/h has occurred 2.1 times as often (River Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2008). Since 73.2% of the raw water in 2006 was dependent on surface water in the water supply system (Japan Water Works Association, 2008), an increase in river water turbidity caused by heavy rainfall is a concern in Japan. After one heavy rainfall in 2007, the raw-water turbidity in the city of Kitami reached nearly 15,000 kaolin turbidity units (TU), which resulted in a stoppage of the water supply in the area for 4 days (Ebie *et al.*, 2007), while the average raw-water turbidity in Japan was approximately 4.4 TU. Treated-water turbidity is one of the most important indices used to evaluate the performance of any water treatment system. Filtered-water turbidity must be kept at less than 0.1 TU in Japan to prevent contamination of treated water by *cryptosporidium* oocysts (Water Supply Division, Ministry of Health, Labour and Welfare, Japan, 2007). The filtered-water turbidity should be carefully controlled by, for example, discarding the filtered water over a filter ripening period after backwashing is done. Therefore, it is necessary to consider adaptation measures in the water treatment system to protect against any sharp increase in raw-water turbidity.

The objective of this study is to evaluate the turbidity removal performance of a pilot plant that operates a rapid filtration system or membrane filtration system and deals with a sharp increase in raw-water turbidity. While rapid filtration systems are commonly used for water treatment in Japan, the number of membrane filtration systems has increased in recent years. Polyaluminum chloride (PACl), which is an aluminum-based coagulant, makes up approximately 90% of the coagulant used in the country (Japan Water Works Association, 2008). A limit of 0.1 mg/L was set in 2009 for aluminum, which became a new Complementary Item under the quality standards for drinking water in Japan, and there is a tendency to require even lower aluminum concentrations in drinking water. In this study, we evaluate turbidity removal performance not only for water treated with conventional PACl, but also for water treated with 72%-basicity PACl, which is produced experimentally to reduce aluminum concentration.

METHODS

Outline of pilot-scale plant and operating conditions

Experimental tests were performed in the National Institute of Public Health (NIPH), Japan, using a pilot-scale plant that has sand filtration and membrane filtration with coagulation-sedimentation pretreatment. Figure 1 shows the experimental flow through the pilot-scale plant. Table 1 lists the specifications and operating conditions of the experimental plant, which has two lines the same. Each line has a capacity of 15 m^3/day, owing to a raw-water adjustment tank, a coagulation-sedimentation tank, two sand filtration towers, and a membrane filtration device. After the sedimentation process, the water is divided and fed separately into the sand filtration towers and the membrane filtration device. Groundwater from a deep well was used as experimental raw water. We added a high-concentration kaolin suspension to the raw water via a tubing pump and thus controlled the raw-water turbidity. The undiluted coagulant and a pH adjuster (sulphuric acid) were added in a pipe between the raw-water mixing tank and the coagulation tank. The coagulation pH was set at 7.0 and was automatically controlled with feedback from a pH meter in the rapid mixing tank. The G-value of the rapid mixing was set at 450 and that of the slow mixing was set at 12, based on the results from preliminary jar tests. Settled water was fed to both the sand filtration process and the membrane filtration process by pumping. The sand filtration rate was set at 120 m/day, which is the standard rate for such filtration nationally. In this study, the backwash interval of the sand filtration units was 24 h. The backwash process included air-washing for 330 s, air-washing and water backwashing in parallel for 70 s, and water backwashing for 400 s. The membrane filtration device was operated by dead-end ultrafiltration, with a filtration flux of 1.8 m^3/m^2/day. The membrane material was cellulose acetate, and the molecular weight cut-off was at 150,000. After each 179 min of filtering operation, the membrane was backwashed for 1 min, with a backwashing flux of 8.6 m^3/m^2/day. No chemical such as sodium hypochlorite was used for backwashing.

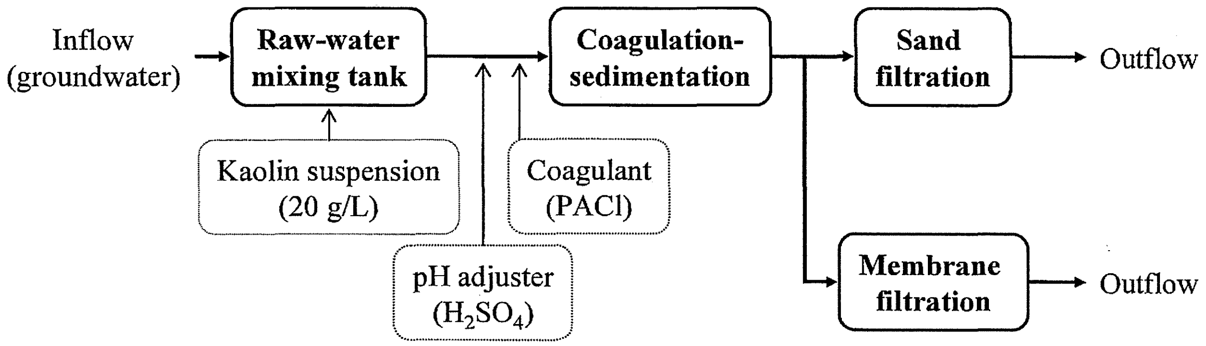

Figure 1. Schematic of treatment flow through the pilot-scale plant.

Table 1. Specifications and operating conditions of the pilot-scale plant.

Treatment process	Specifications		Operating conditions
Coagulation-sedimentation	Rapid mixing tank	Effective capacity: 0.055 m^3	Residence time: 5.5 min, Coagulation pH: 7.0 G-value: 450 s^{-1}
	Slow mixing tank	Effective capacity: 0.338 m^3	Residence time: 33.8 min GT-value: 24,000
	Sedimentation tank	Effective capacity: 0.900 m^3	Residence time: 90 min
Sand filtration	Thickness of sand layer: 60 cm Effective diameter: 0.6 mm Uniformity coefficient: 1.5		Filtration rate: 120 m/day Backwash interval: 24 hour
Membrane filtration	Cellulose acetate ultrafiltration membrane Molecular weight cut-off: 150,000 Membrane filtration area: 2.5 m^2		Flux:1.8 m^3/m^2/day System: dead-end filtration Backwash interval: 180 min

Conditions

The raw-water turbidity was pre-set at three levels: low turbidity of 5 TU, medium turbidity of 30 TU, and high turbidity of 300 TU. According to the results of a former project that included research on the raw-water quality of 36 Japanese water purification plants over 3 years (Japan Water Research Centre, 2005), the 5 TU level was at the 50th percentile of the cumulative frequency of all turbidity data and the 30 TU level was at the 95th percentile. Further, the 300 TU level was at the 95th percentile of the cumulative frequency of turbidity data in which 30 TU was exceeded for 5 days. Based on these result, it was assumed that 5 TU was the usual turbidity of the surface water, 30 TU was the usual turbidity in rainfall, and 300 TU was the peak turbidity in heavy rainfall. A popular PACl with 51% basicity (51%-PACl) and a high-basicity variant (72%-PACl) were used as coagulants. The basicity of PACl can be shown to obey the following equation:

$$\text{Basicity of PACl } [Al_2(OH)_nCl_{6-n}] = (n/6) \times 100\% \qquad (1)$$

It has been reported that the basicity of PACl can vary with aluminum speciation (Yang *et al.*, 2008): the PACl of higher basicity has less of the monomeric species (Al_a) but more of the medium polymeric species (Al_b) and colloidal species (Al_c). Moreover, it has been shown that PACl with higher Al_a content has a tendency to increase the residual aluminum concentration of the treated water (Yang *et al.*, 2007). The coagulant dosage in the experiments using raw water of 5 TU or 30 TU was 36 mg/L and that for 300 TU was 36 mg/L or 72 mg/L. These dosages were set on the basis of results from preliminary jar tests.

Analytical methods

Turbidity, pH, and transmembrane pressure difference (TMP) were continuously monitored by instruments installed within the pilot-scale plant. The turbidity of the raw water at the raw-water mixing tanks and that of the settled water in the sedimentation tanks were monitored using surface scatter turbidity meters. The turbidity of water treated by sand filtration or membrane filtration was monitored using a super-sensitive laser turbidity meter. The pH was monitored at both the raw-water mixing tanks and the rapid mixing tanks. The TMP, which is the difference between secondary pressure and primary pressure, was monitored with pressure meters. Metals were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS) after the addition of nitric acid to samples as 1%. Dissolved metals were analyzed in the filtered water by using a membrane filter with a pore size of 0.45 μm. Electrical conductivity (EC) was measured using meters. Alkalinity was calculated from the consumption of sulphuric acid to reach pH 4.8 using an automatic titration instrument.

Raw-water quality

Table 2 lists the average quality of raw water after the addition of kaolin suspension for each turbidity level. Due to the addition of kaolin, high total concentrations of Al and Fe were measured in the high-turbidity raw water.

Table 2. Average quality of raw water under the turbidity conditions.

	Unit	Pre-set raw-water turbidity		
		5 TU	30 TU	300 TU
pH	(-)	6.9	6.8	6.8
Turbidity	(TU*)	7.9	36	360
Water temperature	(°C)	17.5	17.2	17.3
Alkalinity	(mg/L)	91.0	90.8	90.9
Electrical conductivity	(µS/cm)	379	379	379
Total Al	(µg/L)	35.0	202	1070
Dissolved Al	(µg/L)	< 0.1	< 0.1	< 0.1
Total Mn	(µg/L)	0.1	0.1	0.2
Dissolved Mn	(µg/L)	0.1	0.1	0.1
Total Fe	(µg/L)	3.0	7.1	42.4
Dissolved Fe	(µg/L)	0.3	0.2	0.1

* The traditional Japanese turbidity unit is the kaolin turbidity unit.

RESULTS AND DISCUSSION

Figure 2 shows the turbidity trends for raw water, settled water (after using 51%-PACl), sand filtered water, and membrane filtered water. Each average value of the adjusted raw-water turbidity was higher than its pre-set value, as shown in Table 2. Specifically, with a pre-set raw-water turbidity of 5 TU, 30 TU, or 300 TU the average value was 7.9 TU, 36 TU, or 360 TU, respectively. For a coagulant dosage of 36 mg/L, and with the same three pre-set values of raw-water turbidity, the settled-water turbidity was approximately 1.0 TU, 3 TU, or 10 TU, respectively. Because the settled-water turbidity reached 10 TU when the pre-set raw-water turbidity was 300 TU, a coagulant dosage of 72 mg/L was applied, resulting in a settled-water turbidity decrease to about 6 TU. Hence, the settled-water turbidity was increased by the increase in raw-water turbidity but was decreased by the increase in coagulant dosage.

The rise in raw-water turbidity tended to produce a rise in the turbidity of the sand filtered water after each backwash. With a 36 mg/L coagulant dosage, the turbidity increase of the raw water from 5 TU to 300 TU led to that of the post-backwash sand filtered water from 0.01 TU to 0.05 TU. However, the highest finished-water turbidity was 0.05 TU, which exceeded neither the 2 TU limit required by the Japanese drinking water quality standard nor the 0.1 TU limit required by the "guidelines for *cryptosporidium* treatment in waterworks." The authorities can be reassured that sand filtration with adequate control, such as through coagulant dosage, is effective for turbidity removal even under the condition of a high raw-water turbidity, such as 300 TU.

The increase of raw-water turbidity resulted in slower reduction of the filtered-water turbidity and extension of the filter ripening period. Conversely, the increase of coagulant dosage both accelerated the filtered-water turbidity decrease and shortened the filter ripening period. For a rapid filtration system, these results indicate that a sharp rise in raw-water turbidity extends the cut-off time of start-up water and makes it essential to operate the coagulation-sedimentation process adaptively.

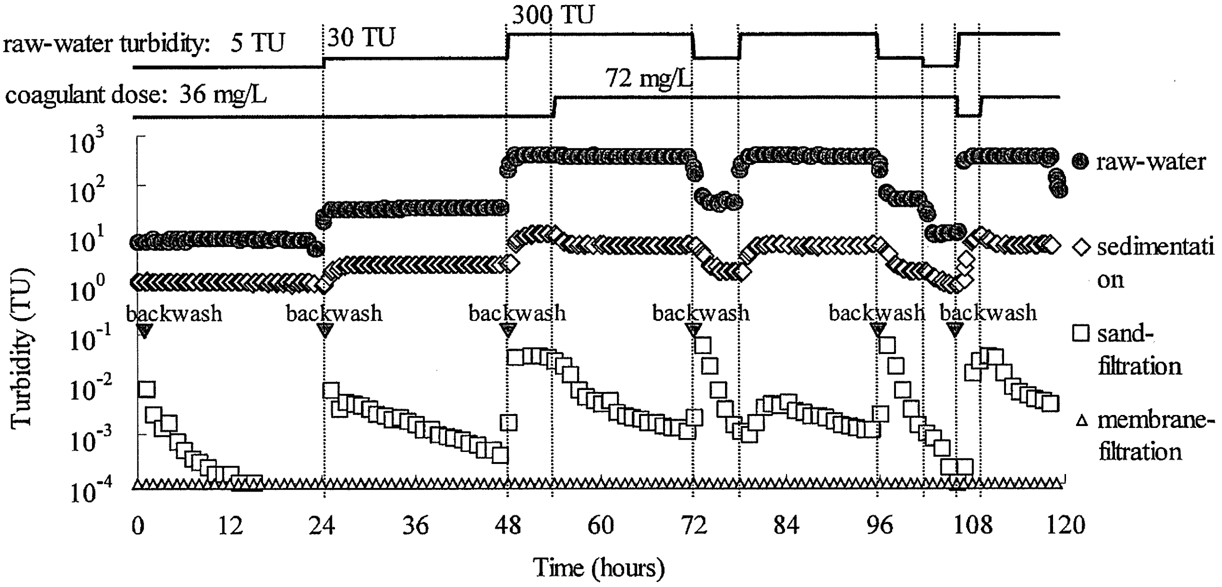

Figure 2. Turbidity of water in the pilot-scale plant when raw, after coagulation-sedimentation with 51%-PACl, after sand filtration, and after membrane filtration.

Figure 3 shows a comparison of the turbidity trends for 51%-PACl and 72%-PACl. No significant difference between the pair of coagulants was observed in the turbidity of the raw water or settled water. In the case of sand filtration, the filtered-water turbidity decrease was quicker and the filter ripening period was shorter when using 72%-PACl instead of 51%-PACl. These results were due to characteristics of the flock, which had greater particle size and higher zeta potential for 72%-PACl than for 51%-PACl (Kobayashi *et al.*, 2011). This suggested that using 72%-PACl as the coagulant would shorten the cut-off time of start-up water and would be a useful option to help manage a sudden rise in raw-water turbidity.

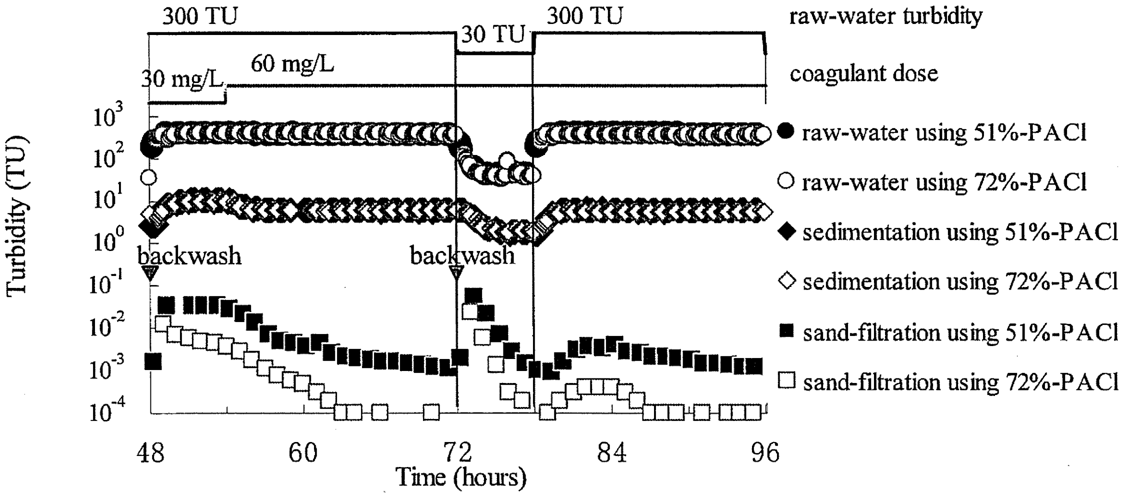

Figure 3. Comparison of turbidity trends for 51%-PACl and 72%-PACl.

In the case of membrane filtration of settled water between 1 TU and 10 TU, the turbidity of the filtered water was under the minimum (0.0001 TU) detection limit of the super-sensitive laser turbidity meter, as shown in Figure 2.

Figure 4 shows the trends in the TMP (adjusted to 25°C) when using 51%-PACl as the coagulant. In this experiment, neither the raw-water turbidity nor the 51%-PACl coagulant dosage affected the TMP significantly. Moreover, there was no significant difference between the pair of coagulants. With the membrane filtration system, it became clear that the sharp rise in raw-water turbidity would not affect the turbidity removal or the TMP in this short-term experiment of 5 days. These results indicated that the membrane filtration system would be safer and more stable than the rapid filtration system in the event of a rise in raw-water turbidity.

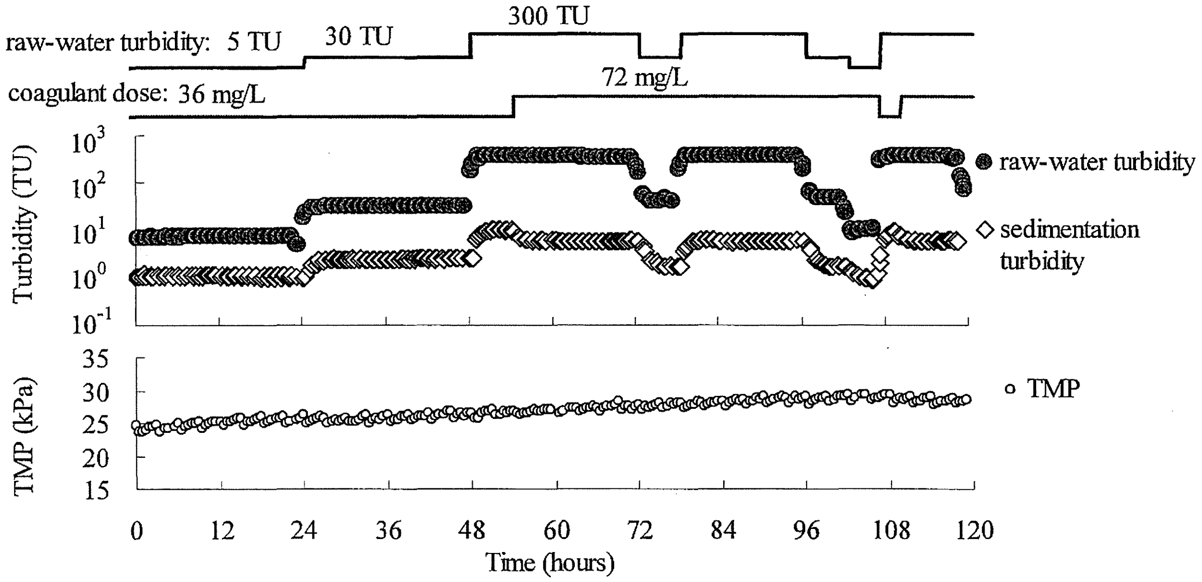

Figure 4. Trends in TMP when using 51%-PACl.

CONCLUSIONS

This study evaluated the turbidity removal by water treatment systems that had a rapid filtration system or membrane filtration system with a coagulation-sedimentation process for pretreatment. In particular, the adaptation to a sharp increase in raw-water turbidity caused by climate change was studied using a pilot-scale plant and artificial raw water. The results were as follows:

1. In the case of the rapid filtration system, the increase in raw-water turbidity resulted in a settled-water turbidity rise. The increase in raw-water turbidity also resulted in a slower filtered-water turbidity decrease and a longer filter ripening period. These results indicated that the rise in raw-water turbidity would extend the cut-off time of start-up water. Adequate control of coagulant dosage would be needed to diminish influences such as the extended cut-off time of start-up water due to the slower decrease of filtered-water turbidity. Using high-basicity (72%) PACl as the coagulant reduced both the turbidity of sand filtered water and the filter ripening period.
2. In the case of the membrane filtration system, no significant influence of the rise in raw-water turbidity was observed in either the filtered-water turbidity or the TMP.
3. The membrane filtration system obtained lower turbidity in the finished water, suggesting that rapid filtration systems are less robust against sharp increases in raw-water turbidity. However, under