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THE DAMAGE OF SEWAGE TREATMENT SYSTEMS CAUSED BY THE GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The Great East Japan Earthquake severely damaged sewage treatment systems over a wide area from the Tohoku Region to the Kanto Region. At the many sewage treatments, the systems were shut down by the tsunami, numerous building structures were toppled by the wave force of the tsunami and electrical and mechanical machines were damaged by submersion. The many pipelines damaged by liquefaction throughout the region lost their ability to carry sewage as a result of plugging by sand after the occurrence of the earthquake.

Key Words: Great East Japan Earthquake, tsunami, liquefaction, sewage treatment systems, sewage systems, and pipes

INTRODUCTION

At 2:46 p.m. on March 11, 2011, an earthquake with magnitude of 9.0 (seismic intensity of 7 at Kurihara City in Miyagi Prefecture), which was the most powerful earthquake ever observed in Japan, occurred with its hypocenter offshore from the Sanriku Coast (below referred to as, “Great East Japan Earthquake”). This disastrous earthquake claimed many precious human lives and property at the same time as it shut down urban and industrial activities by, for example, disrupting transportation networks and cutting off communications, severely impacting Japan socially and economically. And public infrastructures which must support and protect the life of the people were also severely damaged at the same time as questions were raised about how such infrastructure should be provided in the future.

Sewage treatment systems, which are important infrastructure, also suffered serious damage, forcing the lengthy shut down of sewage treatment services. Japan, which is known as an

“Archipelago of Disasters”, has been struck by many massive earthquakes in recent years, but two new phenomena caused by the Great East Japan Earthquake are considered to be characteristics of damage to sewage treatment systems.

One is catastrophic damage to sewage treatment systems caused by tsunami. Sewage treatment plants and pumping stations located along the coastlines of the prefectures of Iwate, Miyagi, and Fukushima which were struck by giant tsunami lost their sewage treatment functions because their electrical and mechanical equipment malfunctioned as a result of submersion, and their civil engineering structures were destroyed by powerful wave forces. It has been estimated that it will take more than one year to restore these severely damaged treatment plants.

The other characteristic is that widespread severe liquefaction occurred in the Kanto, which is far from the hypocenter. Every day, news broadcasts and newspapers reported leaning power poles, settlement of homes, and waves on road surfaces severely obstructing not only vehicle traffic, but pedestrian use. Damage of these kinds was seen frequently in regions where the land had been artificially improved. In Urayasu City, liquefied soil flowed into pipelines, plugging them and preventing their use as part of the sewage treatment systems for long periods of 1 to 2 months. Some manholes were uplifted more than 1m or displaced sideways, and in Itako City, buried pipes appeared above the ground.

In Japan, this “Archipelago of Disasters”, it is still necessary to take advance measures to increase earthquake resistance in preparation for disasters. On the other hand, many challenges remain to be overcome to implement disaster countermeasures. For example, responding to the rapidly changing global environment, preparing for earthquakes exceeding the scale previously hypothesized, and overcoming the financial challenges caused by the recent deterioration of the finances of the national government and of regional governments.

It is said that sewage treatment systems are irreplaceable facilities. To this extent, adequate measures to prepare for disasters must be taken promptly. We also have to devote all our resources to quickly building sewage treatment systems capable of responding to future disasters such as the predicted Tokai-Nankai Earthquake.

This paper reports on the damage to sewage treatment systems by the Great East Japan Earthquake, the response of the Ministry of Land, Infrastructure, Transport and Tourism, and its approach to future earthquake resistance measures.

STATE OF DAMAGE TO SEWAGE TREATMENT SYSTEMS

Damage to sewage treatment systems

Sewage treatment systems generally use the natural flow method, so treatment plants are constructed on low-lying ground near a public body of water. Therefore, in cities along the Pacific Ocean coastline, treatment plants have been unavoidably constructed at relatively low places along the coast, where they were directly impacted by the tsunami damage. In the area inundated by the tsunami, electrical equipment and machines were destroyed. And at sewage treatment plants not isolated from the coastline by structures or other obstructions, the destruction of civil engineering structures by powerful wave forces, and other unprecedented severe damage to sewage treatment systems occurred.

Distribution of damaged sewage treatment plants

Table 1 shows the state of damage to sewage treatment plants immediately after the Great East Japan Earthquake (March 16, 2011) and the present time (January 10, 2012). The Ministry of Land, Infrastructure, Transport and Tourism clarified and categorized information about damage to sewage treatment systems at one-week intervals beginning immediately after the earthquake. According to information provided two days after the earthquake, damage occurred at a total of 120 sewage treatment plants; 44 sewage treatment plants were shut down, facilities at 67 treatment plants were partially damaged, and the state of damage is unclear at 9 treatment plants.

As shown in Figure 1, damage has been confirmed over a wide area ranging from Iwate Prefecture to Kanagawa Prefecture, with sewage treatment plants along the coastlines of the prefectures of Iwate, Miyagi, and Fukushima suffering particularly severe tsunami damage, while even at inland sewage treatment plants which were spared tsunami damage, the earthquake motion either damaged or dislodged sludge scrapers.

Now that ten months have passed since the earthquake (Jan. 10, 2012), at 95 inland sewage treatment plants, normal treatment has been almost completely restored by early earthquake response, but at 15 treatment plants damaged by tsunami, simple treatment is now performed by primary treatment and chlorine sterilization as full-scale restoration activities continue.

Table 1. State of Damage to Sewage Treatment Systems Immediately After the Earthquake and at the Present Time

	March 16, 2011	January 10, 2012
Number of damaged treatment plants	120	120
Operation shut down*	44	15
Facility damaged※	67	96
Unclear (Nuclear plant area)	9	9
*Includes simple treatment		
※Includes almost all normal treatment		

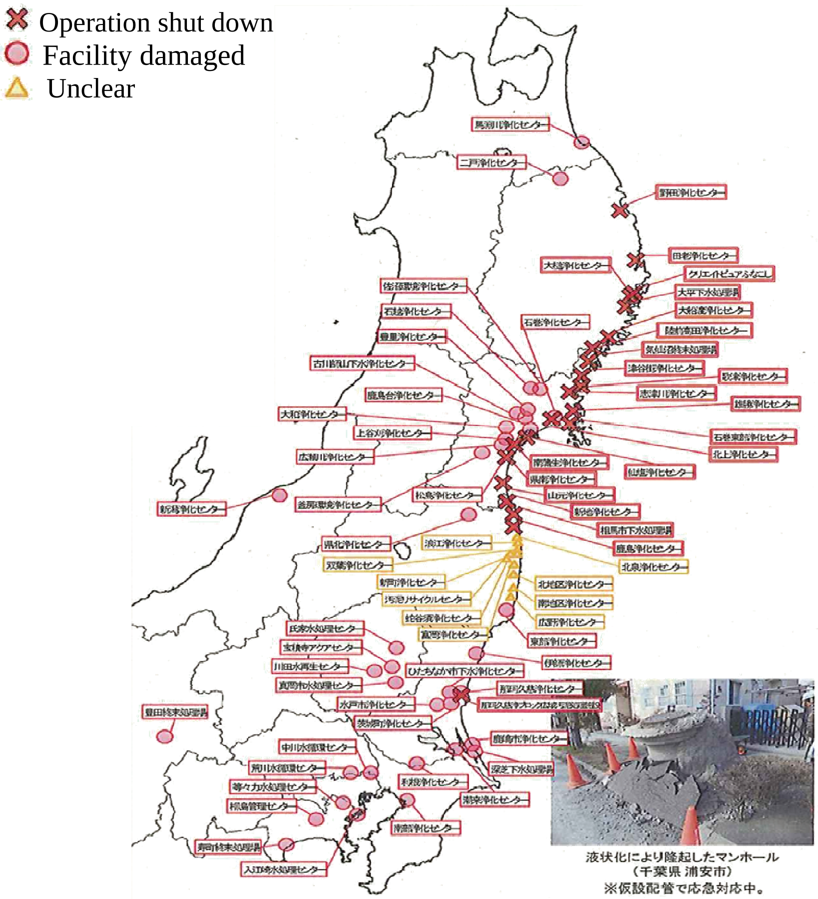

Figure 1. Damage to Sewage Treatment Systems by the Great East Japan Earthquake

Causes and characteristics of damage to sewage treatment plants

In order to clarify the causes of various kinds of damage at sewage treatment plants, a questionnaire survey (effective response rate: 69%) was carried out at local governments in regions where damage occurred.

The percentages of damage by cause of damage at individual facilities inside sewage treatment plants (divided into 23 facilities) (Fig. 2), were 54% caused by tsunami, followed by 41% by earthquake motion, and 4% by liquefaction.

Damage to sewage treatment systems caused by earthquake motion included derailment or breakage of flight chains and breakage of flight plates of sludge scrapers, or leakage caused by displacement of expansion joints of interior pipes, etc. (Fig. 3). But these kinds of damage were also caused by past earthquakes, and at the same time, at many damaged sewage treatment plants, countermeasures hypothesized on level 2 earthquake motion have not yet been taken, so it is predicted that similar damage will gradually decline in severity as earthquake resistance measures progress.

Damage caused by tsunami can be broadly categorized as two kinds: damage caused by the wave force of tsunami and damage caused by submersion.

It is reported that damage caused by the wave force of tsunami varied in its degree according to the distance from the coast and according to the layout of structures between the coast and the damaged facility *[1], but as shown in Figure 4 and Figure 5, on civil engineering structures and buildings inside treatment plants at locations without structures acting as barriers, damage such as the destruction of gates, windows, walls, or columns occurred often.

Submersion damage caused by tsunami occurred throughout the prefectures of Iwate, Miyagi, Fukushima, and Ibaraki. According to the results of the questionnaire survey, at some treatment plants, respondents answered that the maximum submersion depth (maximum traces of maximum submersion on each facility) was 10m or more, making this the most common cause of damage to sewage treatment plants by the Great East Japan Earthquake. Specific damage by submersion was, as shown by Figure 6, shutting down functions of electrical equipment and machines, deterioration of insulation, power failures or short-circuits, and the partial or complete halting of sewage treatment functions. In addition, large quantities of floating debris (rubble, automobiles, etc.) flowed into reaction tanks, creating conditions obstructing restoration.

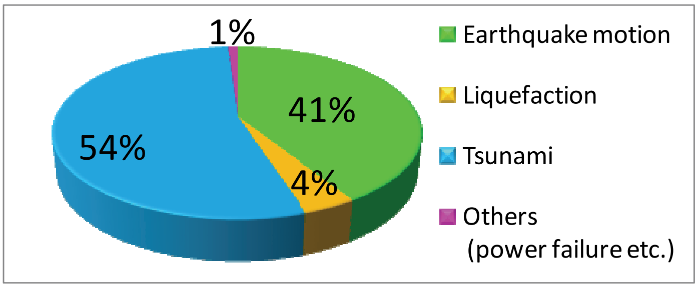

Figure 2. Causes of Damage to Sewage Treatment Plants

Figure 3. Earthquake Motion Damage to Sewage Treatment Plants (Leaks, flight panel displacement)

Figure 4. State of Damage to Walls and Columns of Structures by Wave Force

Figure 5. Damage to Doors and Windows by Wave Force

Figure 6. Damage to Electrical and Mechanical Equipment by Submersion

Restoration of sewage treatment functions

Figure 7 shows change over time of the number of sewage treatment plants which were shut down. At the time of the disaster, 48 sewage treatment plants were shut down (tsunami was the cause at 20 of these).

At treatment plants shut down by earthquake motion, normal operation was almost entirely restored by about half a month after the earthquake by prompt emergency restoration.

However, at 20 sewage treatment plants damaged by tsunami, while restoration activities were obstructed by fatal damage to entire facilities and by rubble etc., in order to prevent untreated water from flowing into city streets and conserve public waters, beginning about three and one-half months after the earthquake, the plants began to perform simple treatment such as precipitation or sterilization, and on January 12 this year, emergency restoration work has been completed at all sewage treatment plants receiving inflowing polluted water. But it is predicted that it will take about two years to return these plants to normal operation, and it is believed necessary to take tsunami-resistance measures at sewage treatment facilities in the future.

The tsunami severely damaged many sewage treatment plants, but the sewage treatment function of a number of treatment plants has been quickly restored. So a survey was performed to learn the reasons why the functions of some sewage treatment plants could be restored rapidly. The present survey clarified characteristics such as installing concrete covers on reaction tanks and placing the control rooms used to control electrical and mechanical equipment on the second or higher floor of the building. For these reasons, future surveys will be carried out to obtain reference information to be applied to plan tsunami measures for future sewage treatment plants.

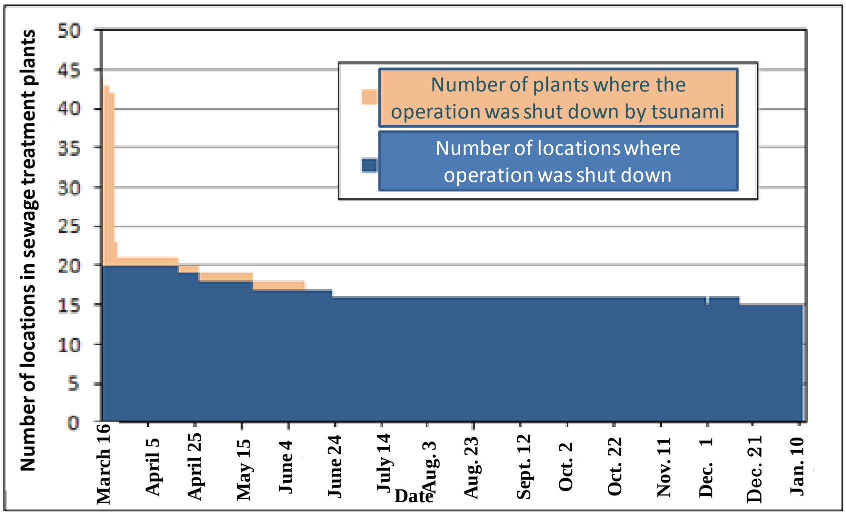

Figure 7. Change Over Time of the State of Operation of Treatment Plants by Cause of Damage

Damage to sewer mains and manholes

It has been reported that beginning with the Niigata Earthquake (1964), which increased people's familiarity with the word, "liquefaction phenomenon", the Hanshin-Awaji Earthquake, Kushiro Offshore Earthquake, and the more recent Niigata Prefecture Chuetsu Earthquake and the Noto Peninsula Earthquake, triggered liquefaction which damaged sewage treatment system pipes and facilities at the same time as it uplifted manholes high above road surfaces, obstructing the passage of automobiles.

Table 2 compares damage to sewage pipelines and facilities by the Great East Japan Earthquake with damage by past earthquakes (Noto Peninsula Earthquake and Niigata Chuetsu Earthquake).

The characteristics of earthquakes and characteristics of the ground differ so they cannot be correctly compared, but the total damaged length by this earthquake is about 10 times that of the Niigata Chuetsu Earthquake, which was marked by long damaged length. And because of the widespread damage by the Great East Japan Earthquake, the number of damaged organizations was also more than 50 times as large as that of past earthquakes. And when the damaged length was divided by the number of damaged organizations to compare this with past earthquake damage by regional governments, the values obtained showed that in addition to the prefectures of Miyagi, Fukushima, and Ibaraki, which are close to the hypocenter, an extremely high value was obtained for Chiba Prefecture where the shaking was relatively low.

Table 2. Lengths of Damage to Sewage Treatment Pipeline Systems by the Great East Japan Earthquake and Past Earthquakes

Prefecture Name	Number of Damaged Groups	Damage Length/total length	Damage rate	Damage length /number of Groups
Aomori	1	0.1km/113km	0.1%	0.1km
Iwate	11	12km/3526km	0.3%	1.1km
Miyagi	39	221km/9702km	2.3%	5.7km
Fukushima	22	120km/5110km	2.3%	5.5km
Ibaraki	36	129km/9509km	1.4%	3.5km
Tochigi	2	1km/266km	0.4%	0.5km
Saitama	1	0.006km/214km	0.003%	0.006km
Chiba	13	54km/8446km	0.6%	4.2km
Kanagawa	1	0.5km/11625km	0.004%	0.5km
Tokyo	1	12km/15793km	0.1%	12km
Niigata	2	1km/426km	0.2%	0.5km
Great East Japan Earthquake	129	550km/64730km	0.8%	4.3km
Noto Peninsula Earthquake	6	15km/652km	2.3%	0.4km
Niigata-ken Chuetsu Offshore Earthquake	5	50km/3072km	1.6%	10km

Distribution of damage to sewer pipes and manholes

Because damage to sewer pipes etc. was widespread, in order to clarify the characteristic of the forms of the damage regionally, a questionnaire survey of regional governments in damaged regions was carried out.

The survey organized the distribution of damaged locations by categorizing the form of damage as a), b), and c) below.

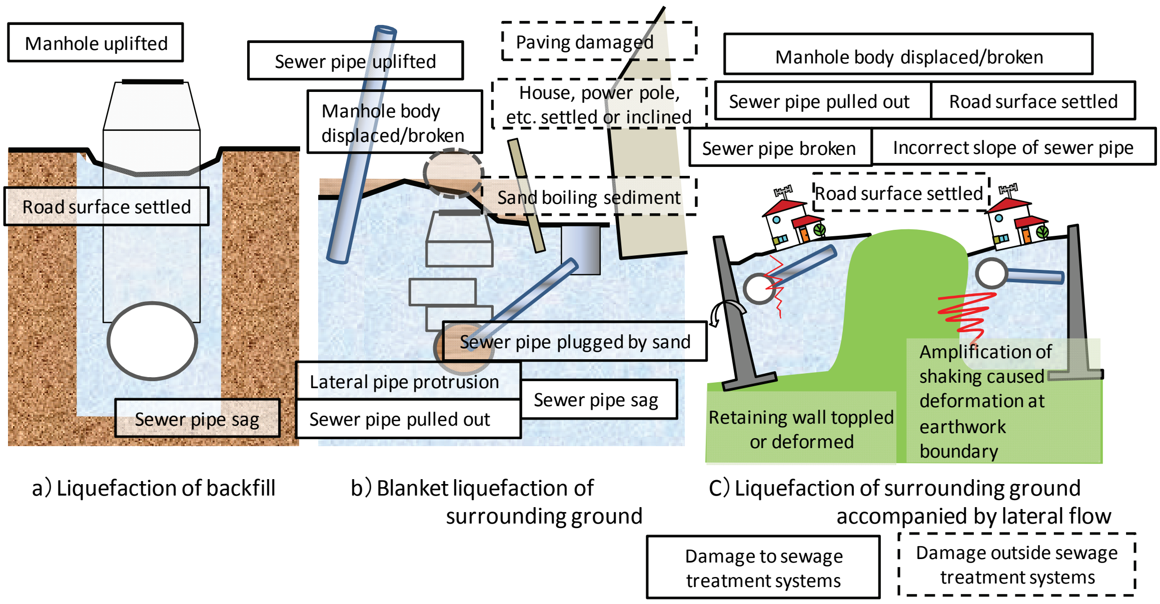

Figure 8. Categorization of Causes of Damage to Sewage Treatment Systems

a) Liquefaction of backfill

Case where only the backfill of sewer pipe facilities liquefied (a in Fig. 8)

b) Blanket liquefaction of the surrounding ground

Case where the surrounding ground entirely including the backfill liquefied (b in Fig. 8)

c) Deformation of the surrounding ground accompanied by lateral flow

Case where lateral flow was caused by liquefaction etc., including the surrounding ground (c in Fig. 8).

Figure 9 is a diagram showing the distribution of the causes of damage to sewer pipes.

It shows that damage to backfill by liquefaction was seen relatively often in the Tohoku Region, which includes the prefectures of Iwate, Miyagi, and Fukushima, and damage caused by liquefaction of all the surrounding ground was seen in Tokyo, Chiba Prefecture, Ibaraki Prefecture and other regions centered on the Kanto, which are far from the hypocenter and where the earthquake motion was smaller than in Tohoku.

And although not shown in the figure, in hilly regions of Sendai City and Shiroishi City in Miyagi Prefecture, or in Fukushima City in Fukushima Prefecture, liquefaction of the surrounding ground occurred accompanying large-scale lateral flow.

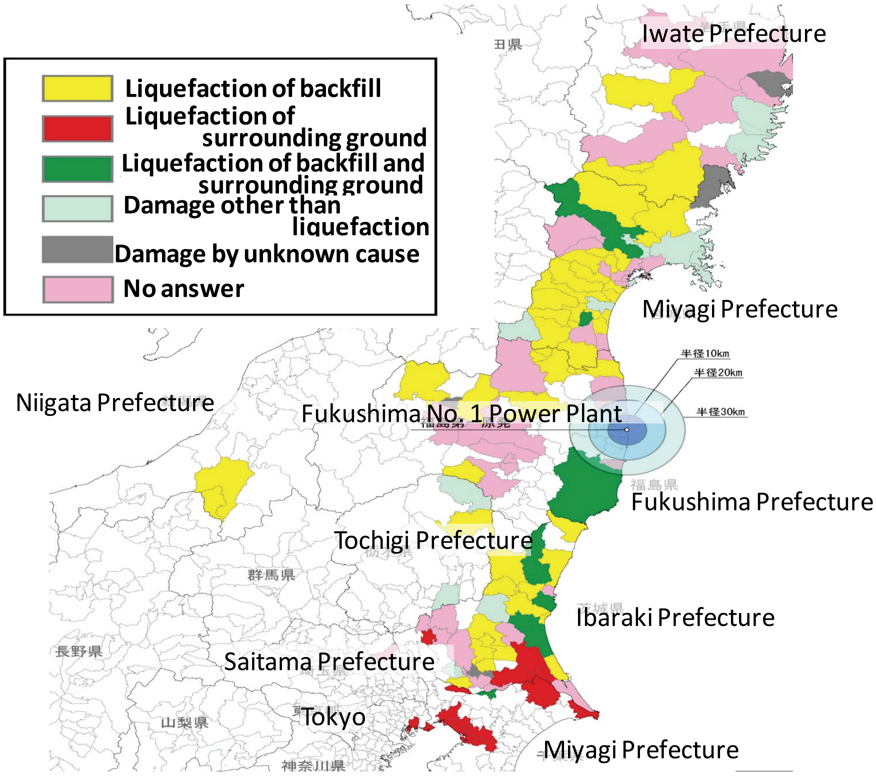

Figure 9. Distribution of Damage to Sewer Pipes

Damage to sewer pipes and manholes and its characteristics

(a) Damage to backfill caused by liquefaction and its characteristics

In the Tohoku Region close to the hypocenter, much of the liquefaction of backfill uplifted manholes above the ground or deformed the road surface at locations of pipeline backfill, which are types of damage similar to those caused by the past Niigata Prefecture Chuetsu Earthquake or the Noto Peninsula Earthquake. (Fig. 10) But on most of the damaged sewer pipes and manholes, earthquake resistance work had not been executed. And sewer pipes constructed by an execution method stipulated in present earthquake resistance design guidelines satisfied earthquake resistance performance although they were slightly damaged, so it is assumed that future strengthening of the earthquake resistance of sewer pipes and manholes will mitigate such damage.

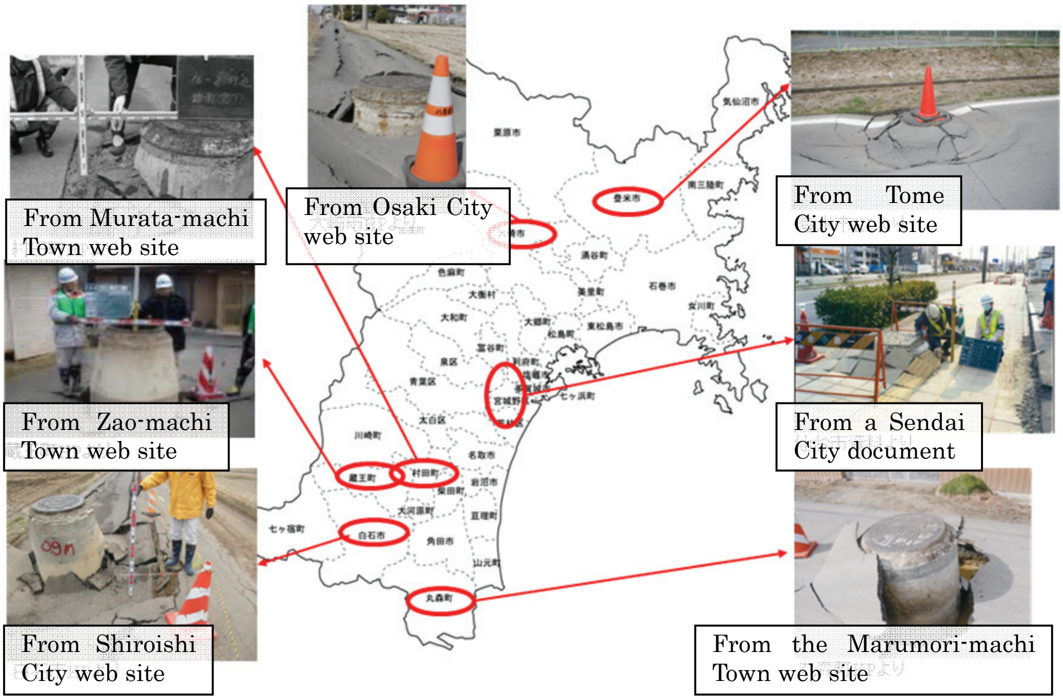

Figure 10. State of Damage to Sewage Treatment Pipeline Systems Caused by Liquefaction of Backfill in Miyagi Prefecture

(b) Damage caused by blanket liquefaction of the surrounding ground

The blanket liquefaction of the surrounding ground which was concentrated on the shore of Tokyo Bay and in the lower basin of the Tone River, which are far from the hypocenter, severely damaged road and houses etc. in addition to sewage treatment systems. Damage to sewage treatment systems was primarily meandering and sagging of sewer pipes, displacement of manhole bodies, and plugging by sand, etc., and cases where part of a sewer pipe was exposed above the ground surface was confirmed. (Fig. 11)

The causes of such large-scale liquefaction are believed to be the long duration of the earthquake motion, even where this motion was smaller than in the Tohoku Region, and the continuous occurrence of large after-shocks and induced earthquakes *[3]. Typical locations where these phenomena occurred were concentrated in Chiba Prefecture and Ibaraki Prefecture.

The districts shown in Table 3 share a common history: filling of seashores, old river courses, and marshes etc. to prepare land for residences or roads. In Urayasu City, where damage was particularly conspicuous, large scale seashore land reclamation was executed between the early 1970s and the early 1980s, but in the Imagawa District and Irifune District where the landfill was completed relatively early, main sewer pipes breaking or pulling out, displacement of manhole bodies and similar damage occurred at many locations. Because it was land reclaimed from the ocean and the layer above the engineering reference elevations of T.P. -40 to -50, was formed by loose sandy ground, its N-value was low, and according to location, ground improvement had been done by pre-loading as a soft ground countermeasure or sand compaction pile work as a liquefaction prevention measure, and it is assumed that the degree of damage varied greatly according to the landfill period, whether or not ground was improved, and the improvement method. The characteristics of the damage must be analyzed in detail to help hypothesize future damage, select countermeasure technologies.

Figure 11. Blanket Liquefaction Damage of Surrounding Ground (Sand plugging, sewer pipe exposure)

Table 3. Typical Locations of Large-scale Liquefaction

	Name of local government	District name	Land condition	Land use	Typical damage
Chiba Prefecture	Chiba City	Kaihin-makuhari	Beach	Housing land (reclaimed)	Main sewer – lateral pipe connection damaged, plugged by sand
	Urayasu City	Imagawa	Beach	Housing land (reclaimed)	Manhole side soil mass displaced, plugged by sand, road surface collapsed
	Abiko City	Fusa	Flood plain	Housing land (reclaimed)	Plugged by sand, sewer pipe sag
	Narashino City	Kasumi	Beach	Housing land (reclaimed)	Sewer pipe damaged, manhole damaged
Ibaraki Prefecture	Shimotsuma City	Kinu	Old river course	Housing land (reclaimed)	Manhole side soil mass displaced, manhole damaged, road surface collapsed
	Inashiki City	Nishishiro	Delta	Housing land (reclaimed)	Sewer pipe pulled out
	Itako City	Hinode	Delta	Housing land (reclaimed)	Sewer pipe uplifted (exposed above ground), blocked by sand
	Kamisu City	Horiwari	Marsh	Housing land (reclaimed)	Uplifting or opening of joints of storm drain, road surface collapsed

(Based on results of on-site survey and interview survey by the NILIM)

(C) Damage caused by deformation of the surrounding ground accompanied by lateral flow

In Aoba Ward and Taihaku Ward of Sendai City in Miyagi Prefecture and in Fukushima City etc. *[2], ground was deformed by lateral flow caused by liquefaction of the surrounding ground, causing damage such as meandering or pulling out of sewer pipes and breakage of sewer pipes. Damage by past earthquakes included localized lateral flow around seawalls and on prepared embankments, but at many places, the Great East Japan Earthquake caused large-scale ground deformation—fluidization of entire regions which had been artificially filled by embanking etc., a type of damage caused at some locations by the Hanshin-Awaji Earthquake.

Their causes will be studied by a future comparison of geological conditions, the bedrock surface, histories of past land preparation, and sewer pipe damage and other surrounding structural damage.

EFFORTS TAKEN TO RESTORE SEWAGE TREATMENT SYSTEMS

On April 12, the Sewerage and Wastewater Management Department, Water and Disaster Management Bureau, Ministry of Land, Infrastructure, Transport and Tourism, established the Sewage Treatment System Earthquake/Tsunami Countermeasure Technology Study Committee (Chairman: Professor Hamada Masanori of Waseda University) consisting of scholars etc., in cooperation with the Japan Sewage Works Association in order to carry out appropriate emergency restoration of sewage treatment facilities damaged by the Great East Japan Earthquake and to perform final restoration to prevent repeat damage.

The committee released the Emergency Technical Recommendations to Restore Sewage Treatment Systems (April 15), the Second Recommendation, Staged Emergency Restoration Methods (June 14), and the Third Recommendation, Final Restoration Methods for Sewage Treatment Systems Damaged by the Great East Japan Earthquake (August 15). These sequentially presented the current state of revised guidelines concerning the sewage treatment system BCP method, and methods of support during disasters. It is expected that based on these recommendations, efforts to carry out final restoration in the disaster regions will be accelerated.

Regional governments in regions where damage occurred presented their basic opinions on how to improve the level of treatment in stages through emergency restoration according to the time periods required until final restoration under the second recommendation, carried out staged emergency restoration while ensuring the quality of the discharged water in line with the basic opinions, and in response to the third recommendation, rapidly carried out restoration by presenting restoration methods permitting the adequate implementation of measures, not only to restore functions, but to prevent recurrence of damage.

To resolve problems with the post-earthquake response by sewage treatment system managers, the committee has presented a BCP procedure which considers the dominance of post-earthquake response based on the preparation of BCP and of tsunami etc., and a revision of the BCP manual based on this procedure is scheduled to be done in the future.

The NILIM is, as the secretariat of the committee, responsible for analysis of causes of the damage and for technological studies of restoration methods etc. It is scheduled to study sewage treatment system BCP and wide area support during disasters, and will continue to offer technical support.

CONCLUSIONS

In the future, efforts must be made to encourage earthquake resistance measures and tsunami protection measures for sewage treatment facilities. The following are concrete descriptions of such efforts.

First, based on lessons taught by the Great East Japan Earthquake and the recommendations of the Sewage Treatment System Earthquake/Tsunami Countermeasure Technology Study Committee, a pressing challenge is to conduct further damage analyses and studies of technological measures to establish required performance standards. And in particular, to deal with predicted large earthquakes in the maximum South Pacific Trough class *[4], technological response measures must be quickly and concretely proposed in order that measures for cities where damage is predicted be taken as quickly as possible.

The second is to establish countermeasure methods to reduce damage and to promote their wide introduction. Following the Great East Japan Earthquake, sanitary problems caused by polluted water overflowing into living environments and into public bodies of water attracted attention, so the need for sewage treatment system BCP was pointed out. It has been revealed that an effective way to rapidly collect damage information after an earthquake and to efficiently carry out emergency restoration is to introduce asset management. A large amount of knowledge has been obtained concerning effective ways to provide support during a wide-area disaster encompassing many cities.

In the future, it will be necessary to resolve disputes and technological challenges in order to aggressively enact sewage treatment system BCP measures and introduce asset management, and at the same time, carry out simulations and training, etc. in order to be able to rapidly build a disaster support system to deal with wide-area disasters.

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