Development of a Simulation System for Water Failure Rate in the Event of Large Earthquakes - A Tool for Optimizing Water Pipe Replacement Projects

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Abstract: One of the largest risks which could cause serious damage to water supply systems is a large earthquake. Among various countermeasures, replacement of water pipes takes a long time and requires a huge cost. Therefore, strategic planning and effective implementation are needed. Tokyo Waterworks has developed a simulation system which calculates water failure rate for each district in the event of future earthquakes. By inputting the speed of ground movement caused by an earthquake, the system provides a result taking the latest pipe information and liquefaction potential of soil into account. This system enables water utilities to predict districts where water failure rate would be highest, to develop strategic plans and to evaluate the effectiveness of pipe replacement. By using this system, water utilities can show the effectiveness of replacement quantitatively to residents and relevant entities. This contributes to gaining their support for pipe replacement projects.

Keywords: Large Earthquakes, Water Failure Rate, Pipe Replacement

Introduction

The largest risk which could threaten a stable water supply in Japan is a large earthquake. The Great East Japan Earthquake which occurred on March 11, 2011 caused serious damage to water facilities, which resulted in cutting off water supply to more than 2 million households and disrupting urban activities (Ministry of Health, Labour and Welfare, 2013). Also, a lot of water facilities located along the coast were washed out by a massive tsunami.

In Tokyo, an earthquake occurring directly beneath the city of Tokyo has a 70% possibility of occurring within the next 30 years (Ministry of Education, Culture, Sports, Science and Technology, 2004). Therefore, Tokyo Waterworks implements a range of countermeasures such as replacing old pipes to earthquake-resistant pipes, enhancing the earthquake-resistance of water facilities, enhancing back-up functionality by reinforcing the transmission pipe network, securing alternative water supply measures by constructing emergency water supply stations, and securing power supply by expanding the capabilities of stand-alone power generation facilities.

Among these countermeasures, Tokyo Waterworks has been actively engaged in replacing water pipes, which account for about 70% of water infrastructures, with an aim to replace 5,000 km of old pipes to new ones with earthquake-resistant joints within 10 years. However, as the total length of distribution pipes reaches more than 26,700 km, replacing all pipes to earthquake-resistant ones requires a huge cost and much time (table 1). To implement pipe replacement effectively, identification of the districts where cost-effectiveness of pipe replacement is high, development of a strategic plan and periodical evaluation of implementation are needed.

In order to accomplish these tasks, Tokyo Waterworks has developed a simulation system which predicts water failure rate for each district in the event of future earthquakes. By inputting earthquake motion, the system provides a result taking the latest pipe information and potential of liquefaction into account.

Table 1 Overview of Tokyo Waterworks as of March, 2015

Population served	About 1.3 million
Service area	1,239 km^2
Total length of distribution pipes	26,774 km
Total capacity of purification plants	6.86 million m^3/day
Average distribution amount per day	4.17 million m^3/day

Materials and Methods

Detailed information of each pipe and other pipe-related equipment such as valves and fire hydrants are recorded with location information and managed in an electrical database. Through an online retrieval system, detailed data including material, diameter, installed year, length, and joint type can be viewed. An example of its operation screen is shown in Figure 1. If you click each pipe or equipment, its detailed information is shown on the right side of the screen.

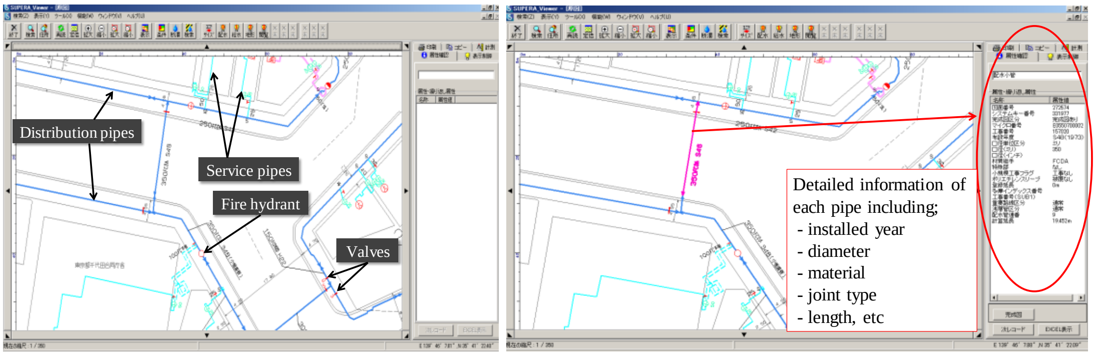

Figure 1 Operation screens of the online GIS database

Before developing the simulation system, GIS data are converted into 250 m x 250 m mesh data to calculate water failure rate in detail according to the following procedure shown in figure 2. Firstly, a segment data which is the smallest component of GIS data, composed of a single material with a straight-line shape is plotted on a mesh grid. Then, cross points of the mesh grid and segment line are determined. As a result, the segment is divided into smaller units called sub-segments. In this way, GIS data are converted into mesh data.

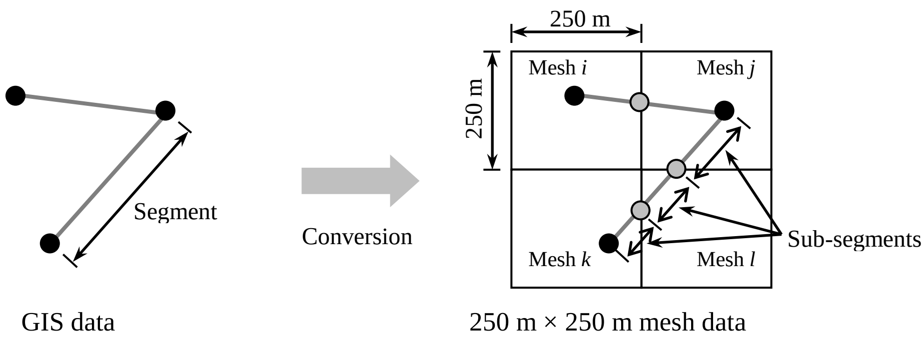

Figure 2 Conversion of GIS data to mesh data

As the magnitude of the Great East Japan Earthquake was the highest (M9.0) in recorded history in Japan, Tokyo Metropolitan Government reviewed the worst case scenarios caused by future large earthquakes based on the latest scientific findings.

Firstly, the latest earthquake model developed in a special project (Ministry of Education, Culture, Sports, Science and Technology, Earthquake Research Institute of the University of Tokyo, 2012) was adopted. Also, the method of calculating seismic intensity was modified by reducing the depth of Philippine Sea Plate based on the latest scientific findings. A distribution map of expected seismic intensity measured on the Japan Meteorological Agency seismic intensity scale of 7 in the case of the Northern Tokyo Bay Earthquake of M7.3 is shown in figure 3. This earthquake is considered to cause the largest amount of damage in the Tokyo Metropolitan Area.

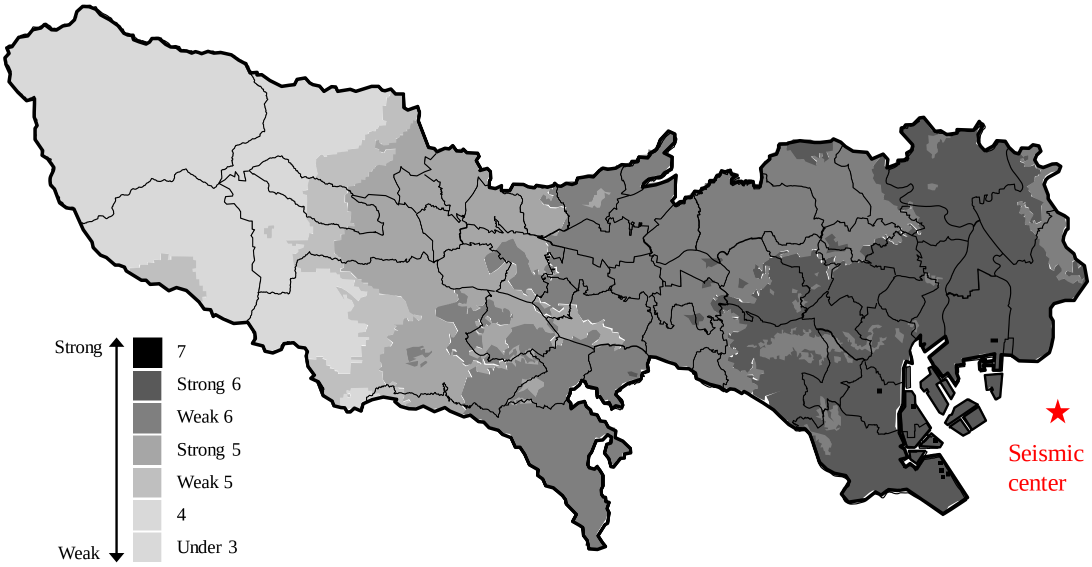

Figure 3 Distribution map of seismic intensity on the Japanese Meteorological Agency's scale of 7 in the event of the Northern Tokyo Bay Earthquake of M7.3

In the Great East Japan Earthquake, liquefaction was widely observed in the area having 650 km in the north-south direction including Tokyo which is located about 500 km away from the seismic center. About 27,000 houses were affected by the liquefaction (Ministry of Land, Infrastructure, Transport and Tourism, 2011). If liquefaction occurs, buried water pipes could lose earth pressure resulting in disjointing of pipes. In order to increase accuracy of the water failure rate forecast, it is important to evaluate the effects of liquefaction caused by an earthquake on water pipes.

Potential of liquefaction is evaluated by Liquefaction Potential Index (P_L) according to the method suggested by Yasuda et al (2009). P_L for each mesh is calculated based on the soil's resistance to lateral movement caused by an earthquake. A distribution map of P_L in the event of the Northern Tokyo Bay Earthquake of M7.3 is shown in figure 4.

In the calculation of water failure rate, correction factor (C_1) reflecting P_L is used (table 2). C_1 is determined based on the comparison of observed pipe failure rates between liquefied and non-liquefied area including the survey conducted after the Great East Japan Earthquake.

Table 2 Correction factors (C_1) for potentials of liquefaction (P_L)

P_L	0	$0 < P_L \leqq 5$	$5 < P_L \leqq 15$	$15 <$
C_1	1.0	1.8	3.2	8.8

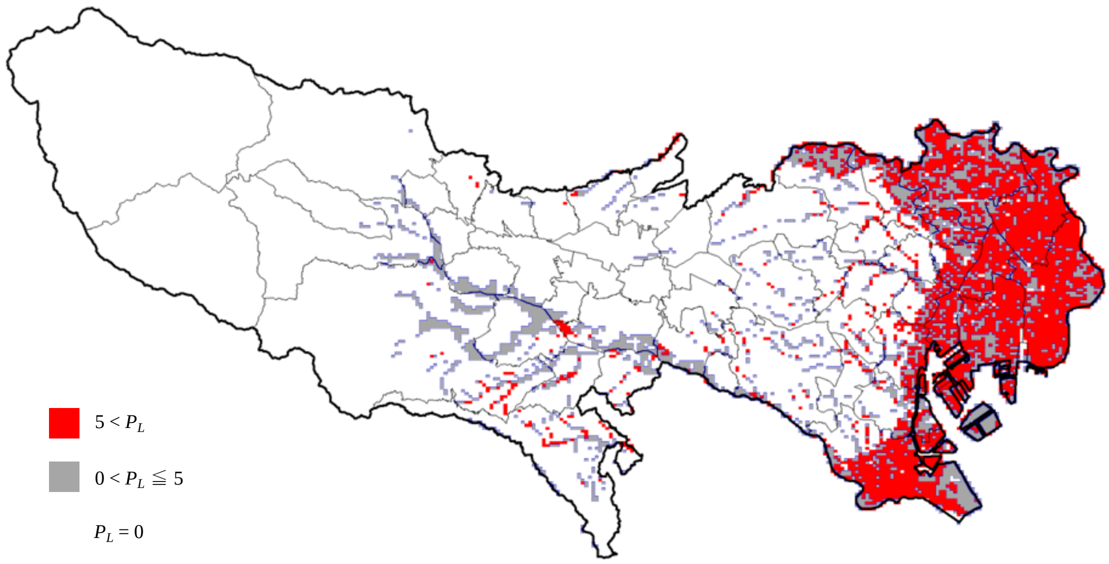

Figure 4 Distribution map of potential of liquefaction (P_L) in the event of the Northern Tokyo Bay Earthquake of M7.3

Water failure rate of each mesh is calculated by the following procedure. Firstly, the average incidence of water pipe breaks per km (R) in a mesh (i) is calculated according to the following formula which requires speed of ground movement (V) as input data. This formula was statistically derived based on pipe failure data collected from surveys on past large earthquakes in Japan (Tokyo Metropolitan Government, 1997).

$$R_i = 2.24 \times 10^{-3} \times (V_i - 20)^{1.51}$$

A correction factor (C_2) reflecting material, diameter and joint of each pipe (j), which was developed by the Japan Water Works Association (1996), is used in this study (Table 3). The average incidence (R_i) is adjusted by weighted average of C_{2i} which is calculated by multiplying C_{2j} by pipe length (L_j). R_i is also adjusted by correction factor (C_1) to reflect the effect of liquefaction. After these procedures, a specific incidence of water pipe breaks in a mesh (D_i) is determined.

$$D_i = R_i \times C_{1i} \times \sum_j C_{2j} \cdot L_j \div L_i$$

Table 3 Correction factor (C_2) for different types of pipe material diameter, and joint

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="5">Pipe diameter (mm)</td></tr>
<tr><td>≦ 75</td><td>100 - 250</td><td>300 - 450</td><td>500 - 900</td><td>1,000 ≦</td></tr>
<tr><td rowspan="4">Pipe material and joint type</td><td>DCIP[1] with seismic-resistant joints</td><td colspan="5">0.00</td></tr>
<tr><td>DCIP without seismic-resistant joints</td><td>0.60</td><td colspan="2">0.30</td><td>0.09</td><td>0.05</td></tr>
<tr><td>CIP[2]</td><td>1.70</td><td>1.20</td><td colspan="2">0.40</td><td>0.15</td></tr>
<tr><td>Steel</td><td>0.84</td><td>0.42</td><td colspan="3">0.24</td></tr>
</table>

1) DCIP stands for ductile cast iron pipe
2) CIP stands for cast iron pipe

Water failure rate (F) of each mesh is calculated by the following formula which is expressed as a function of D. This formula was invented statistically based on data collected from surveys on past large earthquakes in Japan (Kawakami, 1996).

$$F_i = 1/\{1 + 0.307 \times {D_i}^{-1.17}\}$$

The final output of the system is a distribution map of water failure rate for each administrative district. This is obtained by multiplying water failure rate by population and subsequently calculating weighted average.

More than 99% of water pipes owned and operated by Tokyo Waterworks are ductile cast iron pipes (DCIP). As DCIP is extremely strong as a material, it is unlikely that the pipe itself is damaged even by large earthquakes. Many water failures caused by recent large earthquakes in Japan resulted from the separation of pipes at joints (Japan Water Works Association, 1996 and 2012; Ministry of Health, Labour and Welfare, 2005). Therefore, Tokyo Waterworks has been actively engaged in replacing old pipes to new ones with seismic-resistant joints. The rate of DCIP with seismic-resistant joints in each administrative district as of FY 2014 is shown in figure 5.

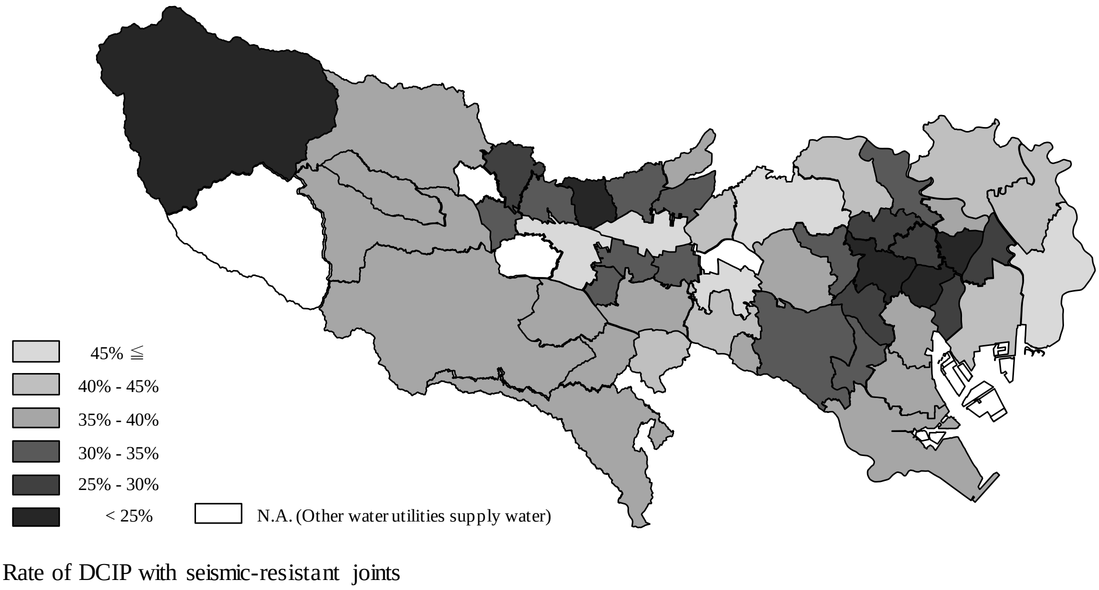

Figure 5 Rate of DCIP with seismic-resistant joint in each administrative district

In order to forecast water failure rate in each administrative district, not only current population but also expected population in the future are prepared in the simulation system. Also, total length of annual pipe replacement in a specific administrative district in the future can be chosen in the system to evaluate the effect of the replacement project on water failure rate quantitatively.

Results and Discussion

The simulation system has three components shown in figure 6. The first component which converts GIS data to 250 m x 250 m mesh data is automatically programmed. Therefore, an operator just runs the program as necessary. In the second component which calculates water failure rates, regional distributions of both seismic intensity of each scenario earthquake and liquefaction potential are registered in advance. Therefore, an operator just selects scenario earthquake and inputs other data such as population and length of pipe replacement to calculate water failure rates. Results are automatically drawn on a map. As most of the procedures are automated, this system is accessible to many people.

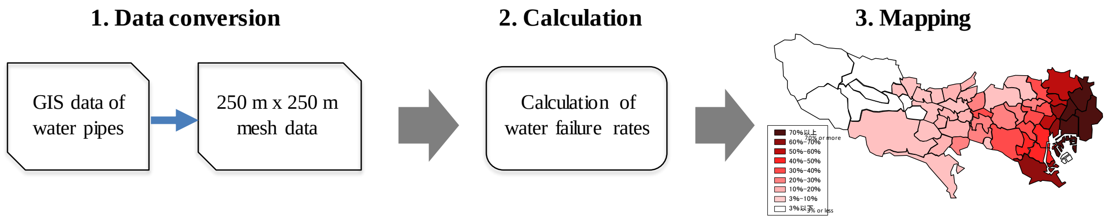

Figure 6 Structure of the simulation system

Figure 7 shows expected water failure rate of each administrative district in the event of the Northern Tokyo Bay Earthquake of M7.3. Water failure rates are generally higher in areas having stronger seismic intensity. However, compared with figure 3, 4 and 5, water failure rates are higher in eastern areas where liquefaction potential is high and also areas where rate of DCIP with seismic-resistant joint is low, even though seismic intensity are almost the same in these areas. In this way, this system uniquely accounts for several key factors which influence water failure rate such as seismic intensity, pipe material and liquefaction potential. This system enables water utilities to understand where water failure rates are highest, designate which districts have priority for replacing pipes and develop a strategic plan for effective replacement.

Figure 7 Expected water failure rate of each administrative district in the event of the Northern Tokyo Bay Earthquake of M7.3

To examine the effect of a pipe replacement project on reducing water failure rate in detail, changes of expected future water failure rate in three administrative districts are calculated based on two different patterns of pipe replacement project (table 4). Firstly, expected water failure rates of three districts in the event of the Northern Tokyo Bay Earthquake are calculated based on the current pipe conditions as of FY 2014. Though the values of district A and B are relatively low (around 15%), district C has a significantly high value (78.1%). This is because district C is located in the eastern part of Tokyo where both liquefaction potential and seismic intensity are high.

Then, expected water failure rates based on future pipe conditions as of FY 2022 are calculated taking length of pipes to be replaced into account. A forecast is conducted based on two different scenarios.

Table 4 Changes of future water failure rates of three districts based on different regional allocation of pipe replacement in the event of the Northern Tokyo Bay Earthquake

Fiscal year		Expected water failure rate (Length of pipes to be replaced)		
		District A	District B	District C
2014		15.3%	15.8%	78.1%
2022	Scenario 1	8.9% (270 km)	8.5% (230 km)	55.9% (200 km)
2022	Scenario 2	10.6% (195 km)	10.6% (155 km)	24.3% (350 km)

In the first scenario, total length of pipes to be replaced by FY 2022 in three districts is 700 km, and the length is allocated to three district almost equally; 270 km for A, 230 km for B and 200 km for C, respectively. In this case, expected water failure rates as of FY 2022 are around 9% in district A and B, but still high (55.9%) in district C. In the second scenario, half of the length is allocated to district C where water failure rate is high. In this case, water failure rates as of FY 2022 would be around 10% in district A and B, and 24% in district C. These results mean that by changing regional allocation of pipe replacement projects water failure rates of some districts could be improved significantly, though total length of pipe replacement is the same.

In this way, the simulation system is able to evaluate quantitatively the effect of a pipe replacement project on reducing water failure rate. By using this system, water utilities can optimize regional allocation of pipe replacement projects.

As this system uploads the latest pipe information, utilities can monitor improvement of water failure rates as a result of pipe replacement. Subsequently, utilities can evaluate the validity of replacement plans and discuss the need for modifying them. Also, showing the effectiveness of a replacement project quantitatively to residents and related entities will contribute to gaining their support for implementation.

This system is able to predict water failure rates in the event of future earthquakes under various conditions. An operator can randomly modify variables, such as population, and subsequently predict water failure rates in case of extreme changes. As for the total length of water pipes to be replaced, an operator can modify not only total length but also regional allocation, enabling utilities to understand how water failure rates would change accordingly.

Conclusions

This system is a useful tool which enables utilities to develop strategic plans for pipe replacement through quantitative prediction of water failure rate for each district, and to evaluate the progress and effectiveness of implementation. As the system operates on commercially available software (Microsoft Office), it is widely accessible to water utilities around the world.

References

Final Survey Report of Water Facility Damage Caused by the Great East Japan Earthquake (2013). The Ministry of Health, Labour and Welfare, Tokyo, Japan.

Kawakami, H. (1996). Relationship between configuration and connectivity of highway systems during earthquakes. *Proceedings of the 1st symposium on the disaster by near-field earthquake*, 169-172

Long-term Evaluation of Earthquake Activities along Sagami Trough (2004). The Ministry of Education, Culture, Sports, Science and Technology, Tokyo, Japan.

Report of damages on drinking water facility caused by the Mid Niigata Prefecture Earthquake (2005). Ministry of Health, Labour and Welfare, Tokyo, Japan.

Report of damages on drinking water pipes and related equipments caused by the Great East Japan Earthquake (2012). Japan Water Works Association, Tokyo, Japan.

Report of the Special Project for Earthquake Disaster Mitigation in the Tokyo Metropolitan Area - subproject I: Characterization of the plate structure and source faults in and around the Tokyo Metropolitan area (2012). Ministry of Education, Culture, Sports, Science and Technology/Earthquake Research Institute of the University of Tokyo, Tokyo, Japan.

Report on damage prediction caused by inland earthquakes in Tokyo (1997). Tokyo Metropolitan Government, Tokyo, Japan.

Survey and analysis of water pipe damage caused by the Great Hanshin Earthquake (1996). Japan Water Works Association, Tokyo, Japan.

Survey conducted by the Ministry of Land, Infrastructure, Transport and Tourism (2011). Tokyo, Japan. (http://www.mlit.go.jp/common/001040649.pdf)

Yasuda S., Ishida E. and Hosokawa N. (2009). Present and future hazard maps for soil liquefaction, *Journal of Japan Society of Civil Engineers*, 65(1), 188-194