Estimation of Earthquake-induced Water Supply Interruption Losses

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1. INTRODUCTION

Water distribution system may sustain various damages to its facilities and lead to a considerable water outage, resulting in huge economic losses and significant losses to human lives during the seismic event. It is concerned that Nankai Trough earthquake will occur in near future. Central to west area of Japan will suffer severe damage to their infrastructure. In this context, the water distribution system in Tanabe city is chosen as the case study. The research process is shown in Fig. 1.

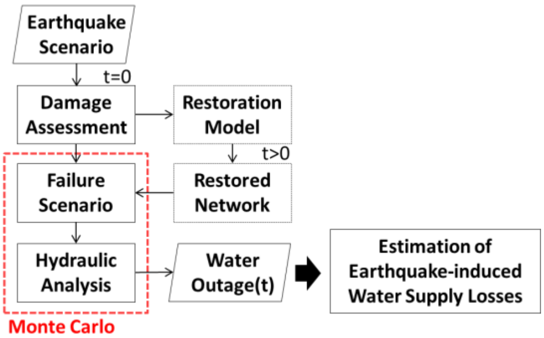

Fig. 1 Research Process

2. DAMAGE ASSESSMENT

(1)Seismic Model

The seismic model of Nankai Trough Megaquake developed by Cabinet office of Japan is used in this study. The seismic hazard map and liquefaction hazard map provide important indicators for damage assessment of water distribution system. In which PGV and liquefaction potential index are the important parameters that have influence on the behavior of water pipes, and the PGA is related with the failure probability of pumping stations.

(2)Malfunction of Pumping Stations

The malfunction of pumping stations following an earthquake could occur not only by its physical damage, but also the outage of connecting electrical power system. Hence, the probability of malfunction of a pumping station concerned with the effect of electrical power interruption can be expressed by Eq.1:

$$P_f = 1 - (1 - P_{physical})(1 - P_{power}) \qquad (1)$$

Physical damage (i.e. direct damage) to the pumping stations can be modeled as seismic fragility curves, which define the probability of exceeding or reaching conditional damage state as the function of ground motion intensity. In this study, the fragility curves developed in the HAZUS-MH are used for estimating the failure probability of pumping stations. A probabilistic assessment model for electrical power interruption proposed by Nojima et al.(2003) are adopted in this study.

(3)Damage Assessment of Buried Pipelines

In order to show the spatial correlation of pipelines, pipes are decomposed into several segments based on 250m-mesh with PGV assigned to each segments.

The repair ratio (repairs/km) of pipe segments is calculated based on the equation developed by JWRC. The failure probability of a water link can be computed by the Poisson process as:

$$P_f = 1 - \exp(-\textstyle\sum_{i=1}^{m} R_m(v_i) \times \Delta L_i) \qquad (2)$$

The calculation result under the Nankai Trough Megaquake model, the failure probability of pipelines and pumping stations is illustrated in Fig. 2.

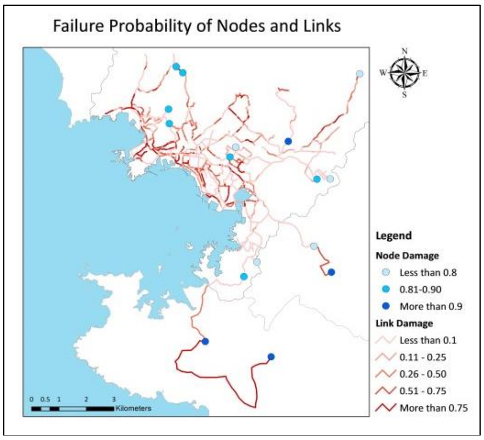

Fig. 2 Failure Probabilities for Water Nodes and Links

(4)Failure Scenario

In general, damages of buried pipes can be classified into two categories: leakage and breakage. One pipe can have multiple leakages and breakages due to earthquake. Pipe leakages and breakages are randomly distributed in the system according to the repair rate R_m, length L and failure probability of pipes P_f.

In this study, the Monte Carlo simulation is used to determine the failure scenario of water distribution system. The numbers of damages in pipe can be obtained by generating the inter-arrival distance L_n repeatedly until the cumulative length exceed the pipe length L.

$$L_n = -\frac{1}{R_m}\ln(R_1) \qquad (3)$$

where R_1 is the random uniform variable between 0 and 1. After generating the numbers of failures based on the calculation, the Monte Carlo simulation is also used to determine the damage state of each failure.

KEYWORD: Water distribution system, loss estimation, hydraulic analysis, Monte Carlo simulation

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In this study, totally 250 iterations are implemented in a Monte Carlo simulation for the upper 95% confident level prediction.

3. HYDRAULIC ANALYSIS

(1)Modeling Water Supply System in EPANET

A water system consists of pipes, junctions, pumps and reservoirs are modeled in EPANET. The flow analysis is performed based on the pump's design flow and constant pattern of daily water demand in each demand node.

In order to calculate the hydraulic system state, the water demand of the consumers is assigned to the relevant nodes as the driving parameter. Thus, Voronoi diagram is used to allocate demands to the nodes in this study.

(2)Negative Pressure Treatment

EPANET has an assumption is that the flow are continuous everywhere and all demand pattern must be satisfied. EPANET results in unrealistic negative pressure and overestimated outflow during the hydraulic analysis of damaged water distribution system.

In order to fix the unacceptable result of negative pressure, several steps are required to be taken: 1) Identify the demand nodes with negative pressure; 2) decrease the amount of customer demands with the highest negative pressure nodes until there is no negative pressure at demand nodes; and then 3) determine the remaining nodes with negative pressure in the system; 6) decrease the customer demands at all the demand nodes until minimum nodes with negative pressure are remain. Finally, the topology of damaged water distribution system with minimum negative pressure is built.

(3) Correction of Outflow at Demand Nodes

The hydraulic model for the damaged water distribution system is enhanced to correctly account for the actual outflow at the demand nodes where the pressure head falls below the minimum service level required to supply the full demand.

$$Q_i^{avl} = \begin{cases} Q_i^d & , \; for\ H \geq H_{sev} \\ Q_i^d \left(\frac{H_i - H_{min}}{H_{ser} - H_{min}}\right)^{0.5} & , \; for\ \ H_{min} \leq H < H_{sev} \\ 0 & , \; for\ H < H_{min} \end{cases} \tag{5}$$

(4)Hydraulic Result

The seismic performance of a water distribution system is reflected by the serviceability (SI).

The SI is the relative index that compares the serviceability for the utility network, in terms of available outflow at demands nodes for intact and damaged water distribution system.

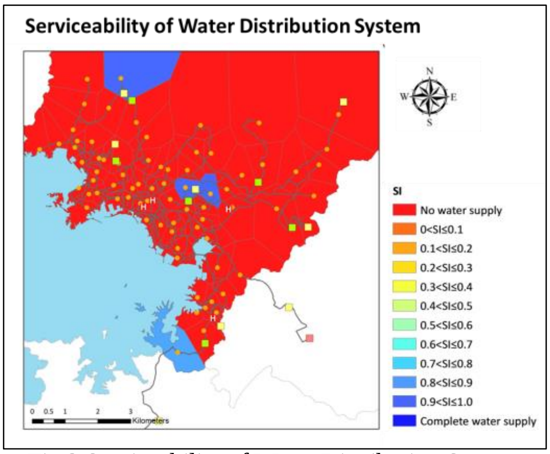

Fig.3 Serviceability of Water Distribution System

4. LOSS ESTIMATION

The earthquake-induced water supply losses can be determined using the concept of resilience.

$$L_R = \int_{t_0}^{t_1} [1 - SI(t)]\, dt \tag{6}$$

The number of repairs in any particular day can be specified according to deterministic restoration model. Hydraulic states for repaired water distribution system are solved using the proposed method. The restoration curve and loss of resilience for the water distribution system in Tanabe city is represented in Fig. 4.

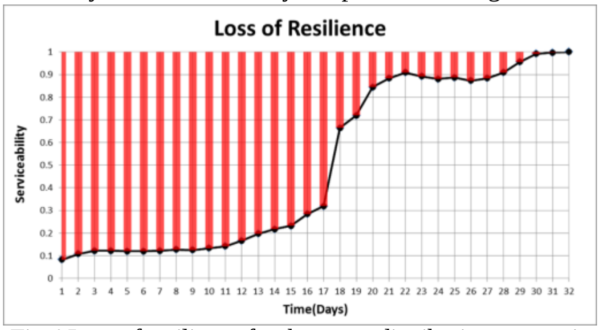

Fig.4 Loss of resilience for the water distribution system in Tanabe city

5. CONCLUTION

In order to better understand the seismic performance of water distribution system which is able to reflect the real post-earthquake conditions, such as amount of water outage, percentage of affected consumers and the malfunction impact on medical activities, hydraulic analysis method is chosen in this study. An improved method of hydraulic analysis for the water distribution system is proposed. The hydraulic computation was conducted by using the EPANET, and the misleading negative pressure generated by the demand-driven assumption was solved by considering flow-head relationship.

The proposed method provided a simple way to solve the negative pressure issue through the adjustment of the consumer demand. Since it is not necessary to reconstruct the modeled network during the simulation process, the proposed method was flexible for application to different states of water distribution system and capable of incorporating restoration process or the seismically improved network. The spatial pattern of restoration process and effect of earthquake countermeasure, therefore, are represented in this study as a basis of decision-making process.

The seismic performance of the water distribution system in Tanabe city under the Nankai Trough Megaquake scenario is measured in terms of serviceability, malfunction impact, and loss of resilience. The relatively vulnerable area was identified by the spatial pattern of serviceability. Malfunction impact indicates the number of affected customers or number of patients who may suffer the insufficient medical care due to water outage. Besides, the effect of earthquake countermeasure is defined as increase of the resilience. The optimal countermeasure can be determined based on these three seismic performance measures. Although the accuracy of the simulation results needs to be verified, this improved method provides a simple quantitative method for seismic performance assessment.

REFERENCE

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