SERVICEABILITY OF WATER TRANSMISSION NETWORK SYSTEMS DURING POST-EARTHQUAKE PERIOD

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SUMMARY

Monte Carlo type simulation methods were developed to evaluate the reliability of a water supply system during post-earthquake period. The performance evaluation methods for a simulated sample of damaged networks proposed in this paper were intended to be used for the transmission network of a relatively large water supply system and is capable of considering the network topology, pipe qualities, the capacities of supply and distribution stations and the system operating strategies. The methods were applied to the seismic reliability evaluation of actual water supply systems, and the expected macroscopic serviceabilities during a hypothetical seismic disaster were examined.

INTRODUCTION

A large scale water supply system is usually made up of supply stations, distribution stations, transmission lines and distribution networks(see Fig.3). In such a system, water supply is always controlled by operaters in supply and/or distribution stations. Especially during the post-earthquake period, the control of distribution by operaters, following the isolation of damaged sections by the activation of shut-off valves, may strongly affect the performance of the system.

With the above feature of the large scale water supply system in mind, the system performance after an earthquake should be evaluated by considering not only the physical or hydraulic conditions but also the system operating strategy. Two methods (Possible Flow Method - I and Shortest Route Method) to be described in this paper are able to tell, for a simulated sample of damaged network, whether or not the demand at each demand node can be met by considering the physical and topological characteristics of the network including the total capacity of the system and system operating strategy (supply strategy). As examples, the seismic reliabilities of actual water supply networks were evaluated by using the Monte Carlo simulation technique.

MONTE CARLO SIMULATION

The general flow chart of the seismic reliability analysis of a water supply system to be discussed in this paper is shown in Fig.1. The procedure is basically a Monte Carlo simulation method. As shown in Boxes 1 through 4 in Fig.1, a damaged state of the network system is first simulated by considering pipeline damage probabilities for a specified earthquake event. Then, the system performance of the damaged network is evaluated by using the methods introduced in the latter sections (Box 5). If a sufficient number of these evaluations are performed for the specified earthquake event, the probability (serviceability probability) that a certain demand node is ser-

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viceable during the specified earthquake event is obtained. If the repairs of failure elements are included in the analysis, the recovery process of the network is probabilistically evaluated(Refs.1 and 2).

POSSIBLE FLOW METHOD - I (PFM - I)

PFM-I is capable of evaluating the macroscopic system performance of a large scale trunk network during post-earthquake period in which the energy potential at each node can be specified(Refs.1 and 2). According to the theory of flow in liquid filled pipes, the volume of water that can be conveyed between every pair of the adjacent nodes is evaluated by considering the energy heads at nodes and the quality of the pipe. This volume of water is called the "branch flow"; q_{mn}. Also, the capacities of supply stations and the demands at demand nodes have to be given(see Fig.2).

The route that conveys the maximum volume of water among all the routes from supply node k to demand node i is defined as the maximum possible flow route, and the volume conveyed by this route is the maximum possible flow f_{ki};

$$f_{ki} = \max_{\substack{\text{all routes} \\ \text{from } k \text{ to } i}} \left(\min_{\substack{\text{all branches} \\ \text{in a route from } k \text{ to } i}} q_{mn} \right) \tag{1}$$

$$k = 1, M, \quad i = 1, N, \quad (m,n) : \text{branche in a route from } k \text{ to } i$$

where q_{mn}, M and N are the branch flow, the number of supply nodes and demand nodes, respectively. The calculation of Eq.(1) and the search for the maximum possible flow route is carried out by an algorithm similar to that of the "Shortest Route Algorithm" in Network Theory(Refs.1 and 2).

For a damaged state simulated on the basis of the damage probability assigned to each node and pipeline, the "maximum possible flow" f_{ki} and its route from supply node k to demand node i are determined by considering the branch flow defined above. Then, the nodes are ordered in accordance with the preassigned strategy to be described later and water is supplied according to this priority order. The water required at demand node i is conveyed through the maximum possible flow route. In every stage of supply, the maximum possible flows must be reduced after each higher priority node is supplied. When all the maximum possible flows from one supply node becomes zero, namely the capacity of that particular supply node is reached, the above procedure is repeated for another supply node. When all the supply nodes have been examined, the evaluation process terminates and whether a demand node is satisfied with its demand or not is examined.

As discussed in Introduction, the supply strategy plays an important role in the performance evaluation of the water transmission networks. The supply strategy here means to give the priority order to demand nodes when supply is continued or resumed after an earthquake. Therefore, some rational and practical strategies must be assumed that are capable of giving a priority order to the demand nodes. This process corresponds to the system operation by control of valves and pumps in a real system. Two cases of supply strategies are examined in this paper. A supply strategy is determined by considering that nodes are first selected in the decreasing order of f_{ki}'s since the nodes with larger maximum possible flows naturally possess more favorable conditions with respect to the hydraulic sense. The two strategies adopted in this paper aree:

Case 1	When there are more than one nodes with the same maximum possible flow f_{ki}'s, the node with a larger demand has the higher priority to be served.
Case 2	Conversely, the node with a smaller demand has the higher priority to be served.

If the nodes with larger demands are given priority (Case 1), the areas with water will be concentrated. On the contrary, if the nodes with smaller demands are given priority (Case 2), the areas with water will be more scattered within the whole service area. Some of the other conceivable strategies may be found in Refs. 1 and 2.

SHORTEST ROUTE METHOD (SRM)

The "Shortest Route Method (SRM)" is applicable to a network in which the branch flows cannot be calculated for all branches because of the network characteristics(Ref.1). Accordingly, SRM is suited for system performance evaluation of small to intermediate networks, whose performances are strongly influenced by supply strategy during the post-earthquake period , or of a large-sized network when its serviceability is examined by including lower level networks. As in the case of PFM-I, demand nodes should be ordered by a certain rule. SRM differs from PFM-I in that the former uses a certain more approximate hydraulic resistance from a supply node to a demand node to order the demand nodes than the latter. The flow capacities of pipe is not considered in SRM. Consequently, the constraint considered in SRM is simply : Total Supply $\geq$ Total Demand.

The flow resistance R_{ij} between adjacent nodes i and j is defined as the energy loss when water flows in the pipe from i to j. By using the Hazen-Williams formula, R_{ij} may be expressed as follows(Ref.1):

$$R_{ij} = 10.666 \cdot C_{ij} \cdot D_{ij} \cdot L_{ij} \tag{2}$$

where C_{ij}, D_{ij} and L_{ij} are coefficient of velocity, pipe diameter in meter and pipe length in meter, respectively. Based on the flow resistances given to each branch, the minimum (total) flow resistances from a supply station to demand nodes can be obtained. This minimum flow resistance can be easily calculated by using the "Shortest Route Algorithm" in Network Theory. In the system performance evaluation introduced in this paper, the demand nodes are ordered in the increasing order of the minimum flow resistance, and they are supplied according to this order until the total supply capacity is reached. Note that,in the study reported here, the fundamental strategy adopted in SRM is similar to that adopted in PFM-I , namely the node having more favorable condition with respect to hydraulic sense is given higher priority to be supplied. However, different supply criteria may be used in SRM by modifying the minimum flow resistances according to the strategy adopted. Also, it should be noted that the flow capacities in some branches may be exceeded in the process of the evaluation by SRM.

ILLUSTRATIVE EXAMPLES

Computer programs have been developed according to the flow chart shown in Fig.1. PFM-I and SRM were incorporated into Box 5 in the flow chart. The trunk networks of Tokyo and Kawasaki were analyzed by using these computer programs.

DAMAGE PROBABILITY OF PIPELINE: Before the simulation, pipeline damage probability must be assigned. Damage to nodes themselves is not considered in the following analyses. The procedure to assign damage probabilities to buried pipelines adopted in this paper uses the basic falure ratio R_f(number of failures per km) for a given earthquake intensity, which is to be modified(multiplied) by three factors each representing the effect of ground (C_g), pipe material (C_p) and buried depth (C_d), that is to say, $R_{fm} = C_g \cdot C_p \cdot C_d \cdot R_f$. Assuming that the number of failures is Poisson-distributed along the length of the pipeline with mean occurrence rate R_{fm}, the probability of failure P_f of the pipeline between k and l becomes as follows;

$$P_f = 1 - \exp\left(- \sum_{e=1}^{n} R_{fm} \cdot L_e \right) \tag{3}$$

where n and L_e are the number of pipe sections between nodes k and l and the length of pipe section with different damage probabilities. As the basic failure ratio R_f for a given intensity, number of failures per km of cast-iron water pipe with buried depth of 1 ~ 3 m was used (Ref.1). The factors C_g and C_p were determined by using the damage ratios of water pipes obtained from past earthquakes including the Kanto (1923) and the 1978 Miyagi-ken-oki earthquake. To determine the buried depth factor C_d, the amplification of seismic motion within a single-layered surface ground was approximately considered. The values of these factors used in the following simulations can be found in Refs.1 and 2.

WATER SUPPLY SYSTEM OF TOKYO: Water supply system of Tokyo is extremely complex with 1,545 km of transmission pipelines and distribution mains with their diameters varying from 400 to 2700 mm. Only the trunk network was analyzed in this paper (see Fig.3), which is able to describe more than 80 % of the total flows involved in the actual system.

The model network for the evaluation by PFM-I is indicated in Fig.2. The branch flows were calculated by considering the pipe qualities and the energy heads at nodes. Although thare is only one pipeline between a pair of adjacent nodes, water may be conveyed in two directions and the branch flows may be different due to the characteristics of the adjacent nodes. The capacities of supply stations, which are indicated in the model network as the branch flows from the supply stations, and the demands were given by referring to the values in the normal operation period.

Five hundred simulated states of damage of the network were generated for R_f = 0.16 which is the average failure ratio of water pipes in Tokyo caused by the Kanto earthquake. The results are shown in Fig.3. Two cases of supply strategies described earlier (Cases 1 and 2) are compared in the figure. As can be seen from Fig. 3, the supply strategy may strongly affect the resulting serviceability probability S_i which is defined as S_i = (Number of Times Demand Satisfied at Node i)/ (Number of Simulations). The larger the demand of a node is, the reduction in S_i's from Case 1 to Case 2. For example, at Okura distribution station (node 19) which has the second largest demand in the network, the serviceability probability decreased from 0.65 for Case 1 to 0.19 for Case 2. However, in this complex system, it is impossible to compare the superiority (or inferiority) of a supply strategy simply by the values of S_i observed above.

WATER SUPPLY SYSTEM OF KAWASAKI(Ref.3): Kawasaki city, the 10th largest city in Japan with a population of about a million, is adjacent to Tokyo on its north-east boundary. The trunk network of the Kawasaki water supply system is shown in Fig.4. The network consists of 4 supply stations, 4 distribution stations and 45 demand nodes. The number of customers in the system is more than three hundred thousand, which corresponds to about one-tenth of the Tokyo system analyzed previously. As can be seen from Fig.4, the branch flows are impossible to calculate for this network. Consequently, SRM was used to evaluate the system performance. Although it is not shown in Fig.4, the feasible directions of the branch (both or one directional flow) was taken into account for each branch.

A very high basic failure ratio of R_f=0.56 was assumed as a hypothetical seismic disaster in order to clearly see the regional difference in serviceability characteristics. The result of five hundred simulations is shown in Fig.5. The serviceability probabilities in the south-east portion are generally lower than those in the north-west portion because of the ground condition and the relatively large demand in this area. Several nodes in the south- west portion shows low serviceability probabilities. This is mainly because of the fact that the small sized pipes are used in this portion. It is noted that the small sized pipe has a large flow resistance(see Eq.(2)).

CONCLUSIONS

Although the results of the study in this paper are believed to be utilized for the practical seismic design decision and the establishment of predisaster plans, more efforts are clearly needed for improving the system performance evaluation methods and for making various assumptions more realistic. For example, damage to nodes themselves and effects of power outages should be considered, especially for a system like the one in Tokyo.

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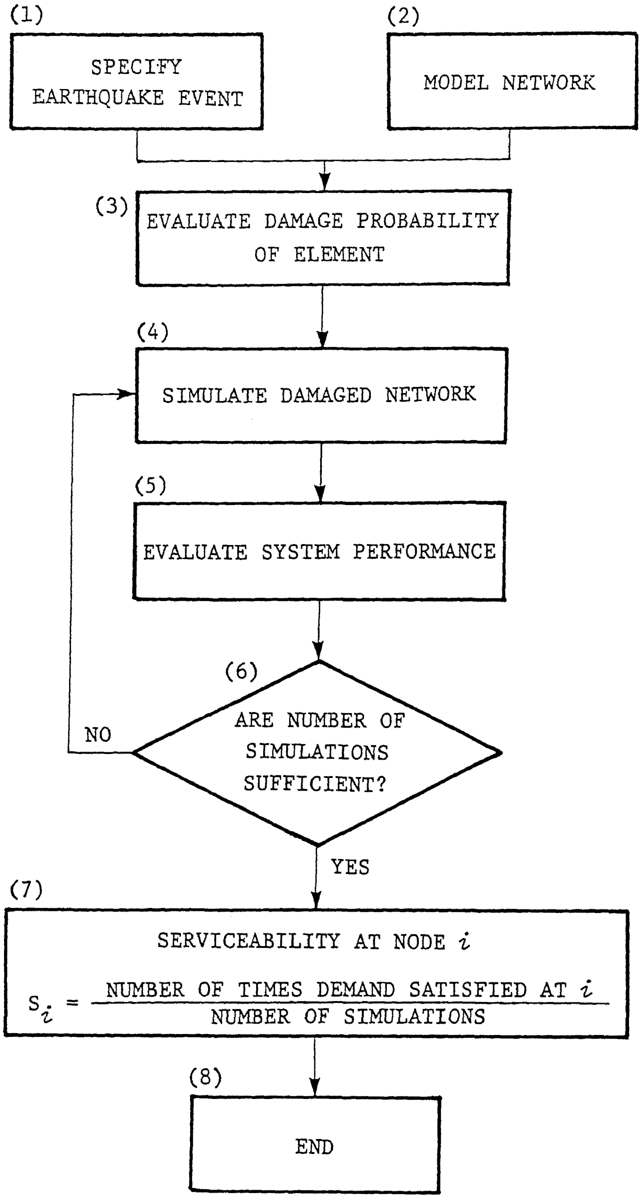

Fig. 1 GENERAL FLOW CHART OF SYSTEM RELIABILITY EVALUATION BY MONTE CARLO SIMULATION

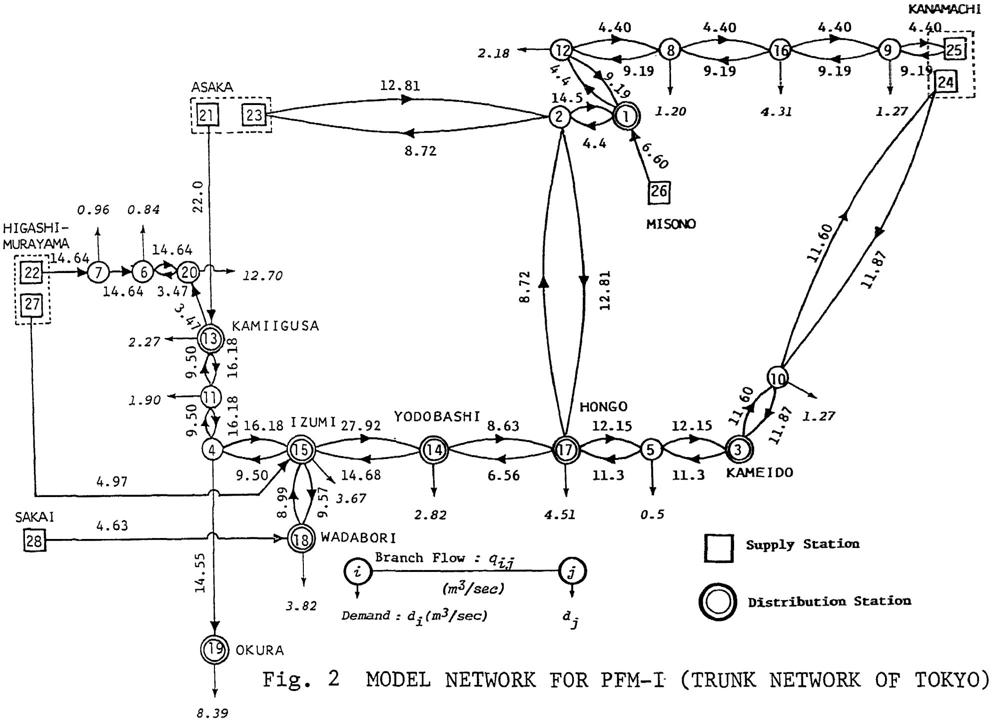

Fig. 2 MODEL NETWORK FOR PFM-I (TRUNK NETWORK OF TOKYO)

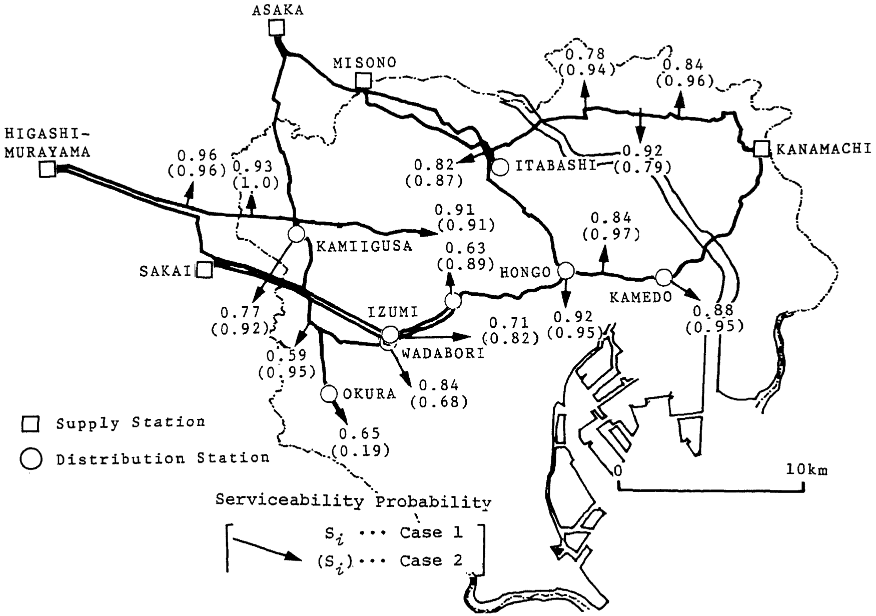

Fig. 3 SERVICEABILITY PROBABILITY OF TOKYO NETWORK BY PFM-I
—— CASE 1 AND CASE 2(THOSE WITHIN PARENTHESIS)
(R_f = 0.16, 500 SIMULATIONS)

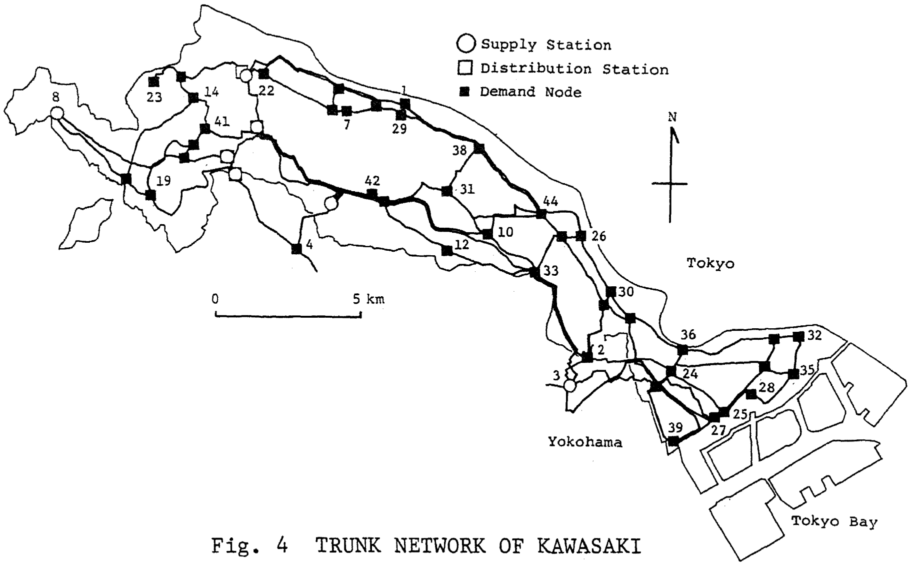

Fig. 4 TRUNK NETWORK OF KAWASAKI

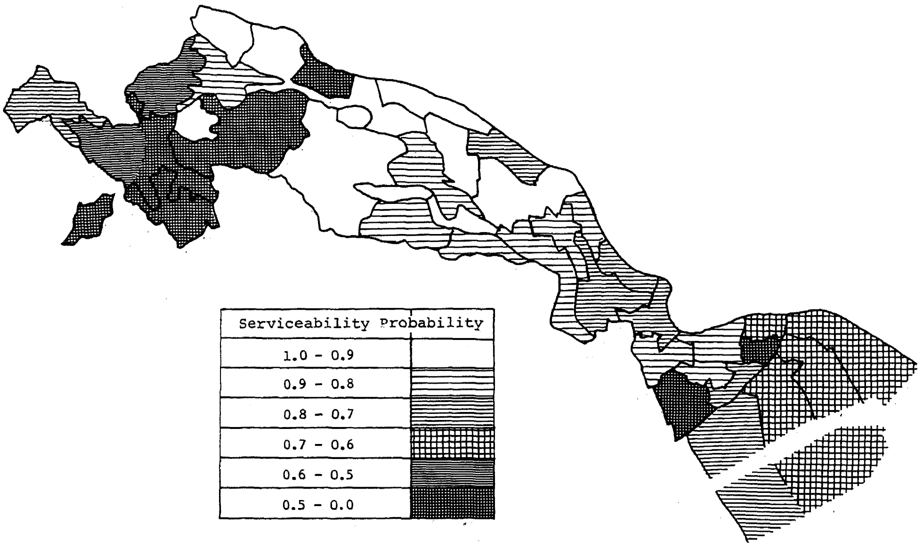

Fig. 5 SERVICEABILITY PROBABILITY OF KAWASAKI NETWORK BY SRM (R_f = 0.56, 500 SIMULATIONS)