SYSTEM RELIABILITY AND SERVICEABILITY OF WATER SUPPLY PIPELINES UNDER SEISMIC ENVIRONMENT

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SUMMARY

A comprehensive method is developed for assessment of seismic damage, system reliability and variation of serviceability during post-earthquake recoveries of water supply pipelines. Discussion is presented with emphasis on the physical basis for model idealization, choise of reliability measures that are useful for engineering judgment and practice, and verification of the system models in the light of damage from actual earthquakes. The damage data on the water supply system for Sendai City during the 1978 Miyagiken-oki Earthquake are used extensively for this purpose.

INTRODUCTION

Assessment of the system reliability and serviceability of water supply pipelines during and after strong earthquakes constitutes a major part of lifeline earthquake engineering. It involves (1) estimation of seismic hazards for the service area, (2) estimation of structural behavior of lifeline components, and (3) evaluation of functional reliability. Recent advances in this area have made it possible to evaluate not only connectivity of pipeline networks but also various levels of their serviceability in terms of flow rate, supplied water amount, etc. (Refs. 1--4).

Despite these remarkable developments, it should be pointed out that only inadequate discussion has been made as to verification of those proposed analytical models. It is particularly important to ensure (1) that basic physical processes implemeted in the models properly reflect the real world, (2) that suitable reliability measures are chosen so that they are useful for engineering judgment and decision, and (3) that results on system reliability generated from the models can explain quantitatively the functional damage of water supply systems caused by actual earthquakes. In this paper, the simulation models developed by the authors (Ref.1) are examined from these three points of view. Discussion is concentrated on comparison with structural and functional damage to the water supply system for Sendai City caused by the June 12, 1978 Miyagiken-oki Earthquake.

FUNCTIONAL REQUIREMENTS FOR WATER SUPPLY SYSTEMS DURING POST-EARTHQUAKE PERIODS

A post-earthquake period may be divided into four typical stages. Minimum functional requirements for the water supply system vary with each stage as described below.

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Stage I: Supply for fire-fighting immediately following the earthquake.
Stage II: Supply to critical locations like refuge zones*, hospitals, etc.
Stage III: Supply to support minimun daily lives during restoration periods.
Stage IV: Normal supply with all restoration works completed.

This study deals with the system reliability in Stages II--IV. It excludes Stage I, for functional reliability for urban lives is the main subject of this study.

For stage II, connectivity of the main distribution pipe network between the supply and demand nodes is dealt with. This treatment comes from two reasons. First, minimun requirement for water supply during Stage II can be relatively at a low level. A standard value of 3 lpcpd** is proposed in Japan. This is about one percent of normal supply. Secondly, critical demand nodes for Stage II are limited number of important locations. Modern pipelines for main water distribution networks are reasonably earthquake resistant: observe in Fig.1 that the main water distibution pipes for Sendai City, with diameters of at least 300 mm, underwent only five pipe breakages during the Miyagiken-oki Earthquake. Under these circumstances, it can be anticipated that the minimun water supply required during Stage II can be achieved if the supply and demand nodes are connected by at least one of the alternative paths in the main distribution networks.

During Stage III, citizens will return to their homes as far as possible. Repair works for the water supply system will start toward its goal, Stage IV. Therefore, the damaged system is required to supply at least minimum amount of water for daily lives, even before repair works are finished. Supply of 105 lpcpd has been suggested for a minimun requirement. Throughout the transitional period from Stage III to Stage IV, it is assumed that all repair works for main distribution pipes have been finished, and loss of system serviceability is dominated by leakage from damaged branch pipes with smaller diameters, say 50--200 mm, which form terminal distribution subnetworks. This would be justified from Fig.2, showing much larger number of branch pipe failures than the main pipe failures in Fig.1.

It should be noted that all of the four stages are not necessarily present in all damaging earthquakes. Miyagiken-oki Earthquake, for example, did not cause any serious fire, and consequently Stage I was missing. It caused damage relating to Stage II only in a limited part of Sendai City. In most of damaging earthquakes only Stage III--IV will be involved. As the earthquake hazard increases Stage II or even Stage I will come into the scope.

MODELS FOR ASSESSMENT OF SYSTEM PERFORMANCE AND RELIABILITY

With a view of the problem as stated above, simulation models have been developed for obtaining useful information on the behavior of water supply systems during and after strong earthquakes. Details of the models are

*In many Japanese big cities, refuge zones for emergency evacuation have been included in their urban disaster mitigation plans.

**lpcpd = litters per capita per day.

presented in Ref.1. The outlines are described below, along with some modification which were made after Ref.1.

Simulation of Pipe Failures and Network Connectivity (Stage II Analysis)

Pipe failure in the main distribution networks is simulated by combining the random pipe failure criteria developed through the pipe response analysis with the simulated random ground motion and liquefaction. For each sample simulation, the connectivity between the supply node and the critical demand nodes is checked. By repeating this procedure, one can determine the failure probability of any pipe sections as well as the connectivity reliability for any critical demand nodes. In the connectivity analysis, careful treatment must be made in identifying redundant paths. Redundancy of the networks is affected by allocation of sluice values particularly at junctions and intersections of the pipelines.

Analysis of Serviceability under Earthquake-Induced Leakage Conditions (Stage III/IV Analysis)

Fig.3 shows the flow network of the main distribution pipelines for Zone 6, Fig.2, of Sendai City water supply system. The numbered circles represent branch nodes. Each branch node distrubutes water supply to the corresponding subnetwork of branch distribution pipes.

Network flow analysis is the main part of the simulation model developed for Stage III/IV analysis. Each branch node is examined as to the flow rate it can supply to its dependent subnetwork: the flow rate P_i from branch node is actual consumption Q_i plus leakage L_i from damaged branch pipes still remaining unrepaired.

Estimation of the leakage factor is an essential part of model identification. It was assumed that the leakage factor attains its maximun value at the ground velocity of 30 cm/sec, minimun at 10 cm/sec, and varies linearly inbetween. This assumption may be supported by Fig.4 showing the pipe failure rate* r_f plotted against the ground motion velocity V (Ref.5). Observe that the value of r_f increases with V only for $V<30$ cm/sec, whereas for larger values of V, r_f is constant on the whole. It has been shown (Ref.5) that leakage rate per pipe breakage is fairly constant, say 300 litters per day, regardless of the number of pipe breakages. This together with Fig.4 will support the above assumption regarding the leakage rate.

Simulation of Ground Motion and Soil Liquefaction

A simulation model presented in Ref.6 is used in this study to generate spatially correlated earthquake motion. It has been slightly changed from that proposed in Ref.1 after modification of the strong motion dataset for attenuation equation. Microzonation of ground motion velocity in Fig.1 has been performed on this modified model.

It is assumed that soil liquefaction will necessarily cause major pipe

*The value of r_f has been determined as the number of major pipe failures, Fig.2, per kilometer of pipe length measured along buried pipes with diameters no less than 75 mm.

failures. The Probability of liquefaction is represented by

$$P(L|P_L=x) = \begin{cases} 1-(x-15)^2/225; & 0 \leq x < 15 \\ 1 & ; \quad x \geq 15 \end{cases} \tag{1}$$

where P_L= liquefaction potential proposed by Tatsuoka (Ref.7).

MEASURES OF FUNCTIONAL RELIABILITY

The system performance of water supply systems under seismic environment can be evaluated in various ways by using the analytical models described above. In the following, some key parameters that are useful for this purpose are discussed.

Network Connectivity (Stage II)

As stated above, connectivity reliability is the main parameter to represent the functional reliability for Stage II. However, this parameter is not discussed further in this paper, since the Miyagiken-oki Earthquake did not cause such extensive damage to involve Stage II throughout Sendai City. Estimated connectivity reliabily for Kyoto City based on ficticious earthquake has been presented in Ref.1.

Local Serviceability (Stage III/IV)

Local serviceability is represented in terms of the water flow rate supplied from a branch node to its dependent subnetwork. Two parameters are used for this purpose; i.e., for the branch node i,

(1) expected supply-demand ratio: r_{qi}

$$r_{qi} = \frac{1}{n_s} \sum_{k=1}^{n_s} Q_i^{(k)} / P_{di} \tag{2}$$

(2) probability of demand satisfied: r_{ni}

$$r_{ni} = (\text{number of simulation in which } Q_i=P_{di})/n_s \tag{3}$$

in which n_s=number of repeated simulations, P_{di} and Q_i demand and actual consumption from the branch node i, respectively, in term of flow rate, and $Q_i^{(k)}$ = value of Q_i in the k-th simulation.

The expected supply-demand ratio r_{qi} is the ratio of the expected actual consumption to demand, which may be useful as a quantitative measure of satisfaction on the side of consumers. The probability r_{ni} may be useful for a measure to be used by the supplier. There is a relation $r_{ni} < r_{qi}$. Fig.5 shows the values of r_{qi} and r_{ni} for the branch nodes 7,17 and 41 in Fig.3.

Global Serviceability (Stage III/IV)

The gloval system serviceability may be evaluated by using

(3) required total supply per day: W_t

$$W_t = \frac{1}{n_s} \sum_{k=1}^{n_s} \sum_{i=1}^{n_b} P_i^{(k)} \cdot T = \frac{1}{n_s} \sum_{k=1}^{n_s} \sum_{i=1}^{n_b} \{Q_i^{(k)} + L_i^{(k)}\} \cdot T \qquad (4)$$

in which n_b = number of branch nodes, P_i = total flow rate from the node i which is the sum of actual consumption Q_i and leakage L_i: (k) stands for the k-th simulation, and T=length of a day.

If the value of W_t exceeds the capacity of supply plants, the system is unable to meet the demand until repair works reduce leagake to a certain level. Such conditions are observed in Fig.6 which compares W_t for damaged and undamaged states. Fig.7 shows how the serviceability is improved, namely W_t decreases, as repair works proceed.

FURTHER COMPARISON WITH ACTUAL DAMAGE

Besides parameters representing the functional reliability, some quantities related to the system performance have been evaluated in this study so that they will facilitate verification of the analytical models developed herein. Some of them are presented below. Again, they are compared with damage to the water supply system for Sendai City caused by the 1978 Miyagiken-oki Earthquake.

Pipe Breakages along Main Distribution Pipelines

In Fig. 1, major part of the main water distribution network is shown, of which the sections with the failure probability larger than 0.35 are identified by heavy lines. It may be observed that locations of actual failures agree fairly well with those sections with high failure probabilities.

Leakage from Damaged Pipes

The actual water amount lost through leakage from damaged pipes have been estimated (Ref.8) from the difference between the actual supplies on the days before and after the eartquake. In Fig.8, the leakage obtained from the simulation model is compared with that estimated from actual data. For zones with relatively small service areas (Zones 2--5), the simulated leakage is systematically larger than actual leakage: this will require further refinement of the model. However, the agreement is satisfactory as to the leakage in large zones (Zones 1 and 6), and also for the whole Sendai City.

CONCLUDING REMARKS

Simulation models have been developed for assessment of functional reliability of water supply pipeline networks at various stages of the post-earthquake period. Discussion has been made with emphasis on comparison with actual data from the Sendai City water supply system damaged by the 1978 Miyagiken-oki Earthquake. The results of analysis generally demonstrate the appropriateness of the models developed herein.

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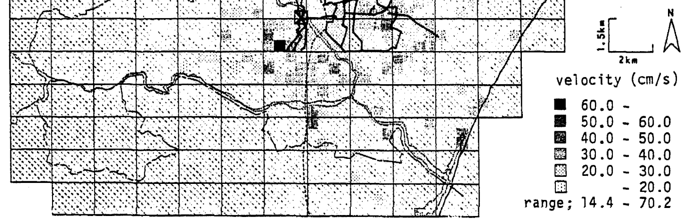

Fig.1 Ground Motion Microzonation and Failure of Main Water Distribution Pipes (1978 Miyagiken-oki Earthquake; Sendai City)

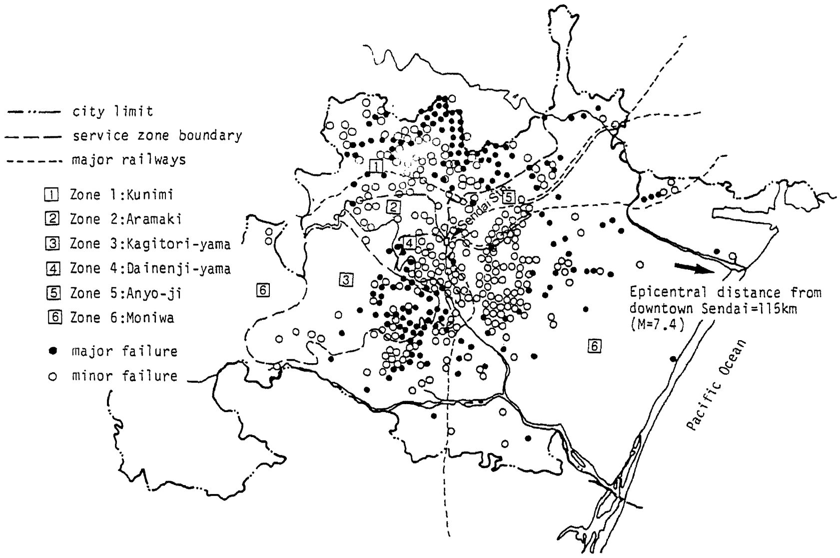

Fig.2 Failure of Branch Water Distribution Pipes (1978 Miyagiken-oki Earthquake; Sendai City)

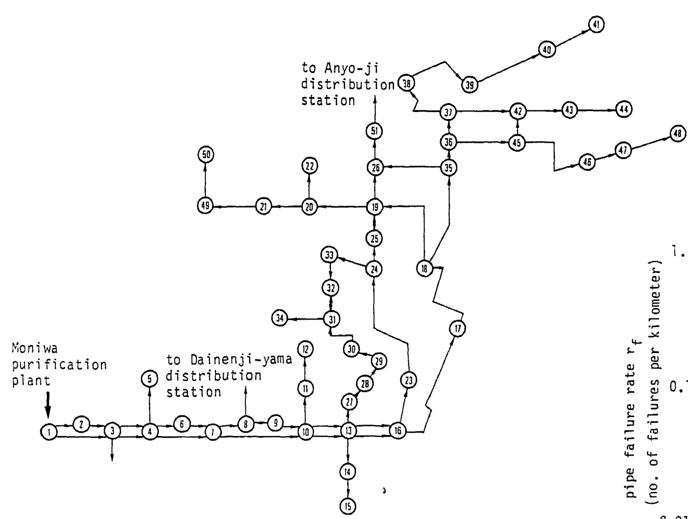

Fig.3 Network Model for Stage III/IV Analysis of Zone 6 Water Supply System

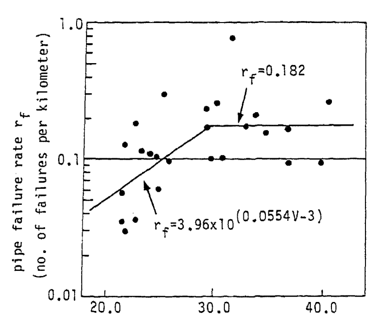

Fig.4 Branch Pipe Failure Rate

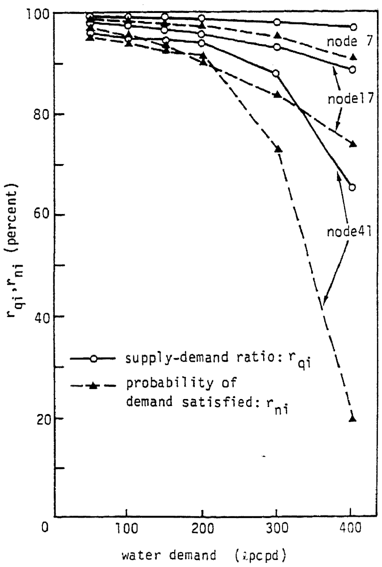

Fig.5 Estimated Local Serviceability

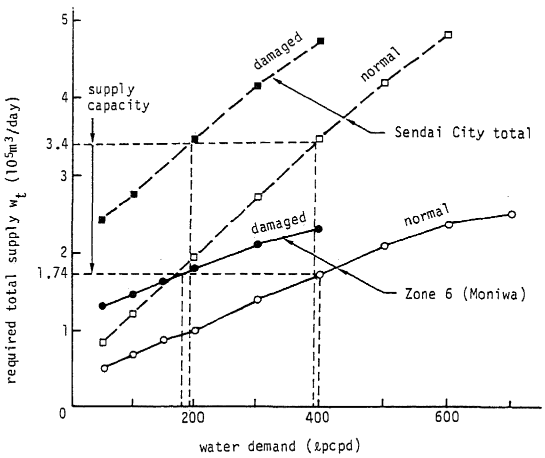

Fig.6 Estimated Global Serviceability

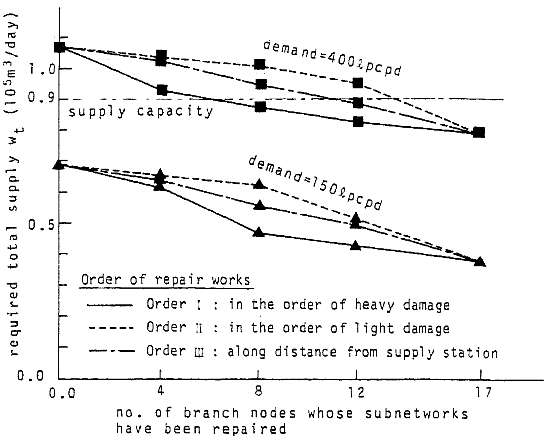

Fig.7 Variation of Global Serviceability during Restoration Process (Zone 1)

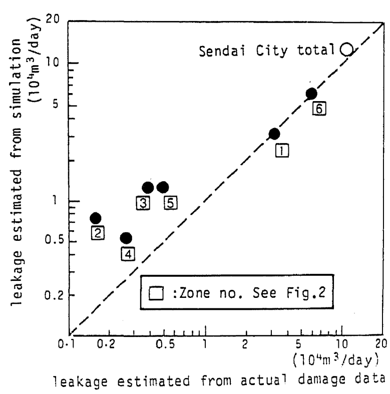

Fig.8 Estimated Leakages from Simulation and Actual Data