Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

11-3-1

SEISMIC SERVICEABILITY ON WATER SUPPLY SYSTEMS

Mahmoud KHATER[1], Mircea GRIGORIU[1], and Thomas O'ROURKE[1]

[1]School of Civil and Environmental Engineering, Cornell University,
Ithaca, New York U.S.A.

SUMMARY

A simulation method is developed for estimating the serviceability of water supply systems subject to earthquakes. The method involves (i) generation of damage states for water supply systems consistent with site seismicity; (ii) repeated hydraulic analyses of these systems in various damage states; and (iii) development of post-earthquake serviceability measures. It is based on a graphical interactive computer program developed recently at Cornell based on a general algorithm for hydraulic analysis. The proposed method is applied to the evaluation of the seismic serviceability of the Auxiliary Water Supply System (AWSS) in San Francisco.

INTRODUCTION

Loss of life, damage of buildings and lifelines, and fires are some of the effects of ground shaking during earthquakes. Fires following earthquakes constitute a significant risk to many cities in the U.S. because they can spread rapidly when available water supply for fire fighting is inadequate. For example, 28,000 buildings (approximately $5.8 billion at today's prices) burned in San Francisco during the first three days following the earthquake of April 18, 1906 due to a loss of virtually all water supply (Ref. 1).

This paper develops a methodology for evaluating the seismic serviceability of water supply systems. Serviceability is related to the average flow available at key hydrants of water supply systems damaged by ground shaking. Simulation is used to generate damage state consistent with site seismic intensity. The selection of hydrants can be based on potential fire scenarios. The proposed method is applied to the serviceability analysis of the AWSS in San Francisco.

METHOD Of ANALYSIS

Water supply systems are complex networks consisting of pipelines, junctions, valves, hydrants, tanks, pump stations, and other components. Their serviceability depends on the reliability of all these components and is affected by both seismic waves and permanent ground displacements. This study evaluates the serviceability of water supply systems when damage is limited to pipeline breaks caused by seismic waves. The methodology is general and can be extended to account for failure of any system component due to both seismic waves and permanent ground displacement.

Damage State Simulation Analytical and empirical methods can be used to characterize the seismic performance of the components of a water supply system. The analytical methods involve representations of seismic excitations, mechanical models of components, stress analyses, and failure criteria. The prediction of component performance can account for the uncertainty in earthquake, soil conditions, and present state of components (Ref. 2).

The empirical methods are based on observations on component performance in previous earthquakes. Figure 1 from Ref. 3 shows an approximate relationship between the mean rate of repairs for cast iron pipelines $\lambda(I)$ and Modified Mercalli Intensity I. It is based on repair statistics of cast iron pipelines damaged by seismic waves in six major earthquakes in California.

Consider a cast iron pipeline of length ℓ subject to an earthquake of intensity I. It can be assumed conservatively that the mean break rate is $\lambda(I)$ in Fig. 1. The probability of at least one break in the pipeline during an earthquake of intensity I is

$$P_F(\ell, I) = 1 - \exp(- \lambda(I)\ \ell) \tag{1}$$

if breaks occur according to a homogeneous Poisson process of intensity $\lambda(I)$. According to this model, pipelines can be either fully functional (0% damage) or disconnected (100% damage). The model can be refined by considering additional damage states. However, the likelihood and the capacity of pipelines in these states is difficult to estimate from available observations.

Hydraulic Analysis Consider a pipeline system and a pipe ij of this system connecting nodes i and j. The flow Q_{ij} in the pipe satisfies the (energy) equation

$$H_i - H_j = c_{ij}\ |Q_{ij}|^{n-1}\ Q_{ij} \tag{2}$$

in which c_{ij} = a coefficient of resistance, n = a parameter controlling head loss, $H_i = p_i/\gamma + h_i$ denotes the hydraulic head at node i and depends on specific weight of water γ, pressure p_i, and elevation h_i at this node. Flows Q_{ij} in pipelines merging at a node i must also satisfy the (continuity) condition

$$\sum_i Q_{ij} = D_i \tag{3}$$

in which D_i is a specified flow at node i. Equations 2 and 3 can be solved simultaneously to determine flows Q_{ij} and pressures p_i for all pipes and nodes of a water supply system. The Newton Raphson method can be used for solution.

The analysis is based on the assumption that air is admitted into pipelines when nodal pressures are below the atmospheric pressure, i.e., $p_i < 0$. This assumption is consistent with existing pipeline systems and can be implemented by the use of vacuum breaking valves.

Consider a node i with $p_i < 0$ and the pipelines ij. Flows Q_{ij} in these pipelines are zero (no-flow) if $H_i > H_j$ for all j. However, $Q_{ij} \neq 0$ when this condition is not satisfied at all nodes j. In this case, flows are analogous to flows in an open channel (partial-flow) for pipelines ij with $H_j < H_i$. The solution of Eqs. 2 and 3 involves several phases. First, nodes with negative pressures are identified and divided in two sets: no-flow nodes and partial-flow nodes. The no-flow nodes and corresponding pipes are eliminated sequentially, starting with the node of highest negative pressure. Flows and pressures are recalculated after each elimination. Then, partial-flow nodes are considered. Let i be a partial-flow node and ij a pipe with $H_j < H_i$. The partial flow in this pipe can be obtained from the flow in an equivalent pipe with the same diameter and length but a higher coefficient of resistance. This coefficient is so chosen that $p_i = 0$.

Pressures p_i can change sign and partial-flow nodes can become no-flow nodes or visa versa during the sequential elimination of no-flow nodes. Thus, pressure sign and node type are checked frequently. The algorithm also detects parts of a network that may be disconnected and eliminates them from the network.

Current methods for hydraulic analysis of water supply systems can be divided in two categories: (i) methods based on the condition that head loss is zero on any closed loop of pipes and Eq. 3. Flows Q_{ij} are the only unknown quantities in these equations. Pressures can be obtained from Eq. 2 (Ref. 4), and (ii) methods based on Eq. 3 in which flows Q_{ij} are obtained from Eq. 2. Thus, hydraulic heads are the only unknowns (Ref. 5). The use of these methods poses difficulties in modeling breaks and/or hydrants because one cannot specify pressures (Ref. 4) or flows (Ref. 5). In addition, these methods can predict large negative pressures at nodes. Such pressures cannot occur in actual systems due to leaks and existence of vacuum breaking valves.

Serviceability Analysis The method for estimating seismic serviceability of water supply systems involves: (i) generation of system damage states based on simulated pipeline breaks according to, e.g., the Poisson model in Eq. 1; (ii) determination of available flows with pressures exceeding a limit value $\bar{p}$ at specified hydrants; (iii) development of serviceability measures for water supply systems based on a graphical interactive computer program developed at Cornell. A flow chart of the computer program and some of its control menus are shown in Figs. 2 and 3, respectively.

Consider a fire scenario consisting of n fires demanding flows $\{q_i^*\}$, $i = 1, 2, \ldots, n$. Let $\{q_i\}$, $i = 1, \ldots, n$ be the available flows at the hydrants closest to these fires for a simulated damage state of the system. As previously indicated, pressures p_i at these hydrants must exceed $\bar{p}$. Since usually $n > 1$, the solution $\{q_i\}$ of the hydraulic analysis is not unique. Objective functions can be used to determine flows that are optimal in some sense. For example, it may be required that the flows minimize the function

$$e = \sum_{i=1}^{n} |q_i - q_i^*| \, u(p_i - \bar{p}), \tag{4}$$

where $u(x) = 1$ and zero for $p_i \geq \bar{p}$ and $p_i < \bar{p}$ respectively, or the functions

$$e_i = |q_i - q_i^*| \, u(p_i - \bar{p}) \qquad (i = 1, 2, \ldots, n) \tag{5}$$

The total available flow

$$q = \sum_{i=1}^{n} q_i \, u(p_i - \bar{p}\,) \tag{6}$$

is a random variable depending on the particular damage state considered in the hydraulic analysis. It is also a function of earthquake intensity and the objective function. The total available flow can be used to develop post-earthquake serviceability measures for water supply systems. These measures can be defined, e.g., by

$$S_1 = \frac{q}{\sum_{i=1}^{n} q_i^*} = \frac{q}{q^*} \qquad \text{or} \qquad S_2 = \frac{q}{q_0} \tag{7}$$

in which q^* is the total demand and q_0 is the total available flow of the undamaged system.

Values of S_1 and S_2 corresponding to simulated damage states and specified seismic intensities I can be regressed against I to develop global serviceability measures for water supply systems, referred to as "fragility" curves. Such curves can be developed for modifications of the original system obtained, e.g., by replacing some of its components with stronger components. Results can be used in sensitivity studies to identify the most critical components of a system.

CASE STUDY

The AWSS is the only high pressure water system of its type in the U.S. It is composed of approximately 190 km of buried pipe with internal diameters ranging from 250-500 mm. Nearly 160 km of the system is cast iron, to which about 30 km of ductile iron pipe have been added during the past several decades. The system is separated into an upper and a lower zone. Each zone operates nominally at a pressure of about 1 MPa, and the two zones can be interconnected to double the pressure in the lower zone.

During emergency operation the system has three principal sources of water. The primary source is a series of three reservoirs: the Twin Peaks Reservoir, the Ashbury Tank, and the Jones Street Tank, which hold 40,000 m^3, 2800 m^3,and 1900 m^3, respectively. Two pump stations constitute the second principal source of water. They can pump salt water from San Francisco Bay into the pipeline network. Each station has four diesel pumps, each of which can pump 9.5 m^3/min at 2 MPa. Five fireboat manifolds represent the third major source of water. They are located along the waterfront. The city's fireboat can be connected to any one of the manifolds to inject an additional 36 m^3/min at 1 MPa into the lower zone.

The proposed method has been applied to evaluate the seismic performance of the AWSS with the upper and the lower zones connected. The evaluation considers hydrants corresponding to a fire scenario proposed in Ref. 6. It is based on the objective function in Eq. 5 and the serviceability measure S_2 in Eq. 7. Two cases are examined: (i) the Twin Peaks Reservoir and the Jones Street Tank are operating and (ii) Pump Station No. 2 whose flow of 65 m^3/min at 1.0 MP is equally divided between the upper and the lower zones of the system and a fireboat pump with flow of 38 m^3/min at 1.0 MP (Fig. 3) are operating in addition to the Twin Peak Reservoir and the Jones Street Tank.

Figures 4 and 5 show "fragility" curves for AWSS obtained by the method proposed in this study (new method) and a method similar to the one in Ref. 4 (old method). Results show that (i) contributions of the pump station and the fireboat to available flow are significant and (ii) the old method underestimates the available flow. This method overestimates flow losses because negative pressures generally occur around breaks so that they create an unrealistically high outflow through the breaks.

CONCLUSIONS

A method has been developed for evaluating the seismic serviceability of a water supply system. The method involves hydraulic analyses of the system in simulated damage states consistent with site seismicity and statistical analyses of flows available in these states. It provides various measures of seismic serviceability and their variation with site seismic intensity and is based on a graphical interactive program developed at Cornell.

The method has been applied to the seismic serviceability analysis of the Auxiliary Water Supply System in San Francisco. Comparative studies have also been undertaken between the proposed method and current techniques. Results show that current techniques tend to underestimate available flow in damaged water supply systems.

REFERENCES

1. Scawthorn, C., "Fire Following Earthquake. Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco," Report for the All-Industry Research Advisory Council, Dames and Moore (1987).
2. Grigoriu, M., Khater, M., and O'Rourke, T., "Stochastic Beams on Elastic Foundation," Structural Safety Studies, ed., Yao, J. T.-P., Corotis, R., Brown, C. B., and Moses, F., ASCE, pp. 96-106 (1985).
3. O'Rourke, T. D., Grigoriu, M. D., and Khater, M. M., "Risk Assessment for Pipelines Subjected to Earthquake Movements," presented at US-Taiwan-Japan Seminar/Workshop on Lifeline Earthquake Engineering Taipei, Taiwan, pp. 25-27 (1985).
4. Wood, D. J., "The Analysis of Steady Flow in Pipe Networks," Proceeding of the First International Conference on Mathematical Modeling, Vol. 3, Department of Engineering Mechanics, University of Missouri-Rolla, pp. 1269-1280 (1977).
5. Jeppson, R. W., "Analysis of Flow in Pipe Networks," Ann Arbor Science, Ann Arbor, MI (1976).
6. Scawthorn, C., "Fire Following Earthquakes," paper presented at the First International Symposium on Fire Safety Science, Washington, D.C. (1985).

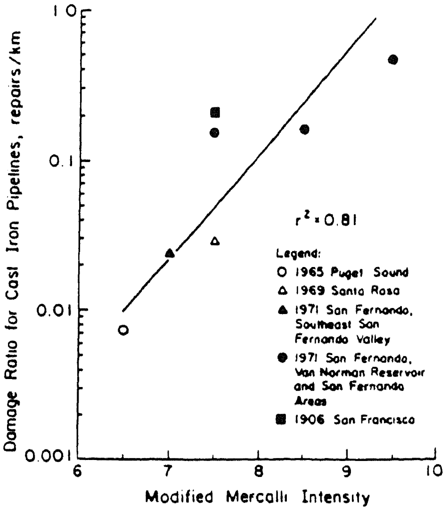


Figure 1. Mean Damage Ratio for Cast Iron Pipelines as a Function of Modified Mercalli Intensity (from Ref. 3).

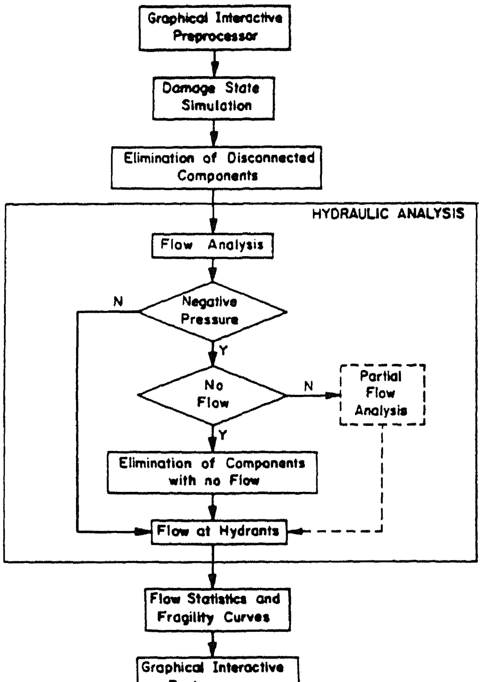


Figure 2. Computer Program for Serviceability Analysis.

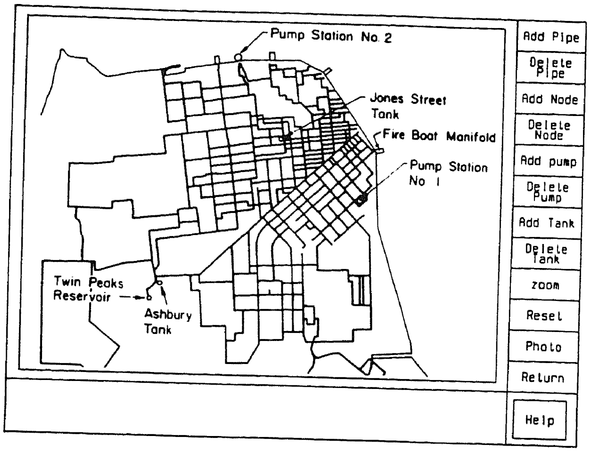
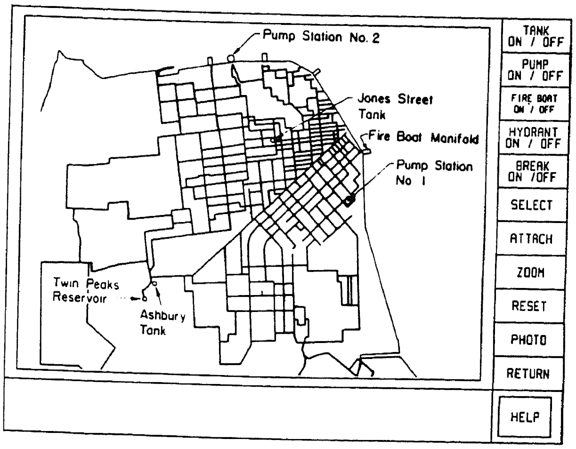


Figure 3(a). Menus of Interactive Program for Serviceability Analysis.

Figure 3(b). Menus of Interactive Program for Serviceability Analysis.



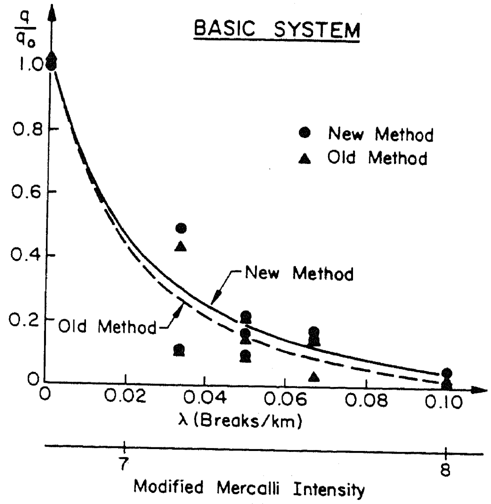


Figure 4. Serviceability Measures for Basic System.

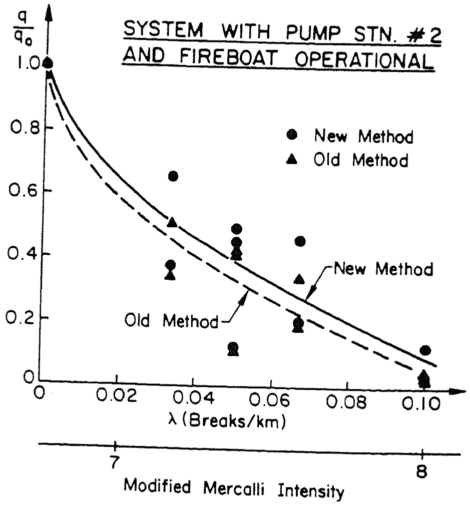


Figure 5. Serviceability Measures for System with Pump Station No. 2 and Fireboat Operational.