Hydraulic State Estimation of Post-Earthquake Water Distribution Systems

Ying Xu[1] , Yuebin Wu[2] and Dagang Lv[3]

1 Doctor, Municipal & Environmental Engineering Faculty, Harbin Institute of Technology; Harbin 150090; Tel: 0451-86282123; Email: joexying@126.com
2 Professor, State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology; Harbin 150090; Tel: 0451-86282123; Email: ybwu@hit.edu.cn
3 Professor, Civil Engineering Faculty, Harbin Institute of Technology; Harbin 150090; Tel: 0451-86282095; Email: ludagang@hit.edu.cn

ABSTRACT

The damage of a post-earthquake water distribution system depends on seismic intensity. If the earthquake causes the water distribution system to leak, even though the system can continue to provide water supply for customers, the supply pressure tends to decline and the service level of the system becomes worse. Hydraulic state estimation helps utilities to assess the performance of post-earthquake water distribution systems and to make better decisions restore the water distribution systems. Based on the analysis of seismic intensity; the quantitative leakage area model is introduced to describe the failure intensity of pipes. And then, this paper combines the leakage area model and the hydraulic analysis model to establish the post-earthquake hydraulic analysis model of the water distribution systems. The leakage magnitude and the node pressure are modeled by the leakage area. The post-earthquake hydraulic model is solved using Matlab. Finally, the proposed model is demonstrated on an example water distribution system. The supply pressures at nodes with the failure of pipes are obtained resulting from the earthquake. This study builds a foundation for performance assessment and restoration of post-earthquake water distribution systems.

KEYWORDS

Post-earthquake Water Distribution Systems; Hydraulic State Estimation; Hydraulic Analysis Model; Leakage Area

INTRODUCTION

The water distribution systems provide purified water for industry, daily living, and fire demand and so on. It is the foundation of economic development and living improvement. The delivery ability of water distribution system is especially important for disaster relief and reduction after the earthquake and other natural disasters. Due to the operations of power, communication and medical service systems depend on the water distribution system, the seismic performance of water distribution systems contributes greatly to the seismic capacity of a city.

The hydraulic state of post-earthquake water distribution systems is different from the normal systems. The seismic performance of water distribution systems means to the capacity of water distribution systems which could meet the special water demand such as water quantity and pressure after the earthquake. It is difficult to locate, then isolate and repair the slightly and moderately destroyed connections and nodes because of the large quantity the wide distribution and the covered destroyed positions of underground water pipelines. Consequently, the post-earthquake water distribution systems will be in service with leakages. Hydraulic state estimations could help utilities to assess the performance of post-earthquake water distribution systems and to make better decisions to the restoration.

HYDRAULIC ANALYSIS MODEL OF POST-EARTHQUAKE WATER DISTRIBUTION SYSTEM

Performance analysis of water distribution system. The performance of water distribution system depends on five parameters: flow rate *q*, head loss *h*, diameter *D*, length of pipe *L* and condition of pipe wall *C*. If the pipe is damaged in earthquake, the *D*, *L* and *C* won't change, but *q* and *h* will be different from the normal delivery water state. In this thesis the performance of post-earthquake water distribution system is based on the hydraulic analysis of node pressure *H*.

Establish of hydraulic analysis model. The existing analysis models of the post-earthquake water distribution system are comprised of three models. The first one is that deleting the damaged pipeline from the water system and analyzing the else water system (Markov, 1994); the second one is that locating the fictitious node in the middle of the damaged pipeline and analyzing the new water system (Hwang & Lin, 1997). The last model is that taking the leakage as the frictional head loss (Kameda & Goto, 1984). Although the three models have reasonable aspects, they all ignore the different level of leakage status in earthquake, so simply adopting any model will be at a loss.

Based on the analysis and summery of the domestic and abroad analysis models the following improved model is introduced. If the pipelines is damaged by the earthquake, according to different damaged level (the damaged level is fuzzy defined by the random probability), the hydraulic analysis model has the following patterns:

(1) When the pipelines are damaged heavily or destroyed, the pipelines will loss the

water delivery function, then the pipelines should be deleted from the water system and supposing the valves at the ends of pipelines are closed;

(2) When the pipelines are damaged slightly, because of leakage the pipelines are still delivering the water that is the flow rate of the pipelines is decreased. Then according to the general hydraulic analysis simply method of water distribution system the amount of leakage will distributed to the two nodes at the ends of pipeline;

(3) When the pipelines are damaged moderately, because of the huge amount of leakage the big head loss will be brought, the hydraulic performance of the pipe would change suddenly. Then a new node should be supposed in the middle of the pipe and the original pipe is divided into two pipes connected by the new node.

Process of hydraulic analysis in post-earthquake water distribution system. According to the principle of mass conservation during operation the flow rate flows into any node equal to the flow rate flows out of the node, which is shown as following:

$$\mathbf{A}q + Q + Q_L = 0 \tag{1}$$

In which,

q——vector of flow rate in pipes;
Q——vector of flow rate in nodes;
Q_L——flow rate of the leak point.
$\mathbf{A}[a_{ij}]$——joined matrix,

$$a_{ij} = \begin{cases} 0, \text{ when the pipe } j \text{ is connected to node } i; \\ 1, \text{ when the node } i \text{ is the beginning point of pipe } j; \\ -1, \text{ when the node } i \text{ is the ending point of pipe } j. \end{cases}$$

The flow rate of the pipe i to j is shown as Hazen-Williams Formula:

$$q = 0.278 \cdot C \cdot D^{2.63} \cdot (H_j - H_i)^{0.54} / L^{0.54} \tag{2}$$

In which,

q——flow rate of pipe, m^3/s;
D——diameter of pipe, m;
H_i——pressure of node, m;
L——length of pipe, m;
C——Hazen-Williams Coefficient related to pipe material and state.
Change the equation (2) as the following pattern:

$$q = s \cdot h^{n-1} \cdot h = r \cdot h \tag{3}$$

In which, $s = 0.278 \cdot C \cdot D^{2.63} / L^{n}$; $h = H_j - H_i$; n=0.54; $r = \dfrac{0.278 \cdot C \cdot D^{2.63}}{L^{0.54} \cdot (H_j - H_i)^{0.46}}$.

Because of $h = \mathbf{A}^{\mathbf{T}} \cdot H$, $\mathbf{A}^{\mathbf{T}}$ is the transport matrix of the joined matrix **A**, substitute the equation (3) into the equation (1):

$$\mathbf{ARA}^{\mathbf{T}} + Q + Q_L = 0 \tag{4}$$

In which, **R**= $\begin{bmatrix} r_1 & & 0 \\ & \cdots & \\ 0 & & r_m \end{bmatrix}$.

The equation (4) is the basic equation of the hydraulic analysis in the post-earthquake water distribution system. So the process of the hydraulic analysis is shown as following:

(1) Form the joined matrix according to the beginning points and ending points of all the pipelines;
(2) Calculate the damaged probability of pipelines in earthquake, according to the results the damaged level and the leakage model are determined;
(3) Determine the related joined matrix based on the different models, if the fictitious node would be set, the joined matrix containing the fictitious node should be formed;
(4) Suppose the initial pressure of all the nodes is $H_0(\mathrm{m})$;
(5) Calculate the flow rate of all the pipelines and nodes and form the matrix **R** and the vector of flow rate in nodes;
(6) Solve the system of equations and calculate the pressure of the new node; according to the pressure of the new node calculate the flow rate of pipelines and nodes once more, then form the matrix **R** and the vector of flow rate in nodes again; when after calculate the difference of the flow rate in pipes and nodes, if the difference satisfies the precision the calculation finishes, otherwise the calculation would be on until satisfying the precision.

The key to this hydraulic analysis model is the definition of leakage analysis model in the damaged pipelines, the detail calculating model of the leakage will be introduced in the following sections.

LEAKAGE ANALYSIS MODEL

Determination of leakage model. The typical leakage models are the spot type leakage model and the consistent type leakage model. The spot type model is usually utilized in the anti-earthquake analysis of the water distribution system. Suppose that the leakage happens in the middle of pipelines and the leakage area could be determined by the stress analysis of structure or the damaged probability, at this time the amount of leakage is related to the pressure of leakage point. The position of leakage and the leakage area can't be determined in the consistent type model; however, the total leakage level of water distribution system could be deduced through the difference of flow rate between the water factory and the water users. The whole amount of leakage is not divided equally into every pipes or nodes and the leakage is related to the local pressure of water networks, also is limited to the whole leakage level.

The above two models have advantages respectively. The spot type model is a theoretical model with predictive ability and is widely utilized in the analysis of the post-earthquake water distribution system and the anti-earthquake reliability. The consistent type model actually reflects the working status of the water distribution system, but the consistent type model is not utilized in prediction of performance for the post-earthquake water distribution system due to the lack of the relation between the leakage level and the earthquake characteristic.

In 1986 China Urban Water Supply Association took the leakage of the water distribution system as an important problem in project to research, at the same time referencing the results of Japan Water Works Association gave the spot type model which called Chinese spot type leakage model (Kameda, 2000). In the model the damaged level of pipelines is reflected by the leakage area which is shown as following:

$$Q_L = 0.421 A_L \cdot \sqrt{H_L} \tag{5}$$

In which,

Q_L ——amount of leakage, m^3/s;

A_L ——leakage area, m^2;

H_L ——pressure of leak point, m.

Formula of leakage area. The leakage area A_L of pipelines could be the quantization parameter in the damaged condition. The earliest researcher of the damaged state and the leakage area of pipelines by the earthquake is Ballantyne from U.S (Ballantyne and Berg, 1990). In 1990, based on the statistics of the actual earthquakes Ballantyne suggested that: when the pipelines were basically under good condition, A_L=0; when the pipelines were under moderate damaged condition, A_L=0.3A, in which the cross-section area of pipe is A; when the pipelines were under seriously damaged condition, $A_L=A$. Suppose the probability of the slightly damaged condition is P_1, the probability of the moderately damaged condition is P_2 and the probability of the heavily damaged condition is P_3, then the leakage area of pipelines is shown as following:

$$A_L=(0.38\cdot P_2+P_3)\cdot A \quad (6)$$

The above formula is closely related to the damaged probability of pipelines, usually, according to the damaged intensity of the earthquake the pipelines are divided into five damaged levels: basically good, slightly damaged, moderately damaged, heavily damaged and destroyed. In order to make the damaged probability and the destruction rate P_t (positions/km) in earthquakes correspondingly, supposed the destruction rate of pipelines satisfies Poisson distribution, the damaged probability of pipelines would be calculated:

$$P = -\ln(1-P_t)/L \quad (7)$$

In which, P is the damaged probability of pipelines; L is the length of pipelines, m; P_t is the destruction rate of pipelines, positions/km.

In order to comprehensive estimate the damaged level of pipelines, according to the analysis of the earthquakes, the damaged probability of pipelines is shown in the following Table 1 (Gao & Wang, 1998).

Table 1. Classification of the Damaged Level and The Damaged Probability

Damaged level	Damaged probability
basically good	$P_1 \geq 0.7$
slightly damaged	$0.5 \leq P_1 < 0.7$
moderately damaged	$P_1 < 0.5 \cap P_3 < 0.25$
heavily damaged	$0.25 < P_3 \leq 0.5$
destroyed	$0.5 < P_3$

CASE STUDY

A circularity water distribution system is shown as Figure 1. There are 101 pipelines, 61 nodes and a source node. The pressure of source is constant of 40m. The length and diameter of all the pipelines and the flow rate of nodes are known. The Hazen-Williams Coefficient is 130 and the precision is 0.001L/s. The computer language of Matlab is used to simulate the hydraulic state of the water distribution system.

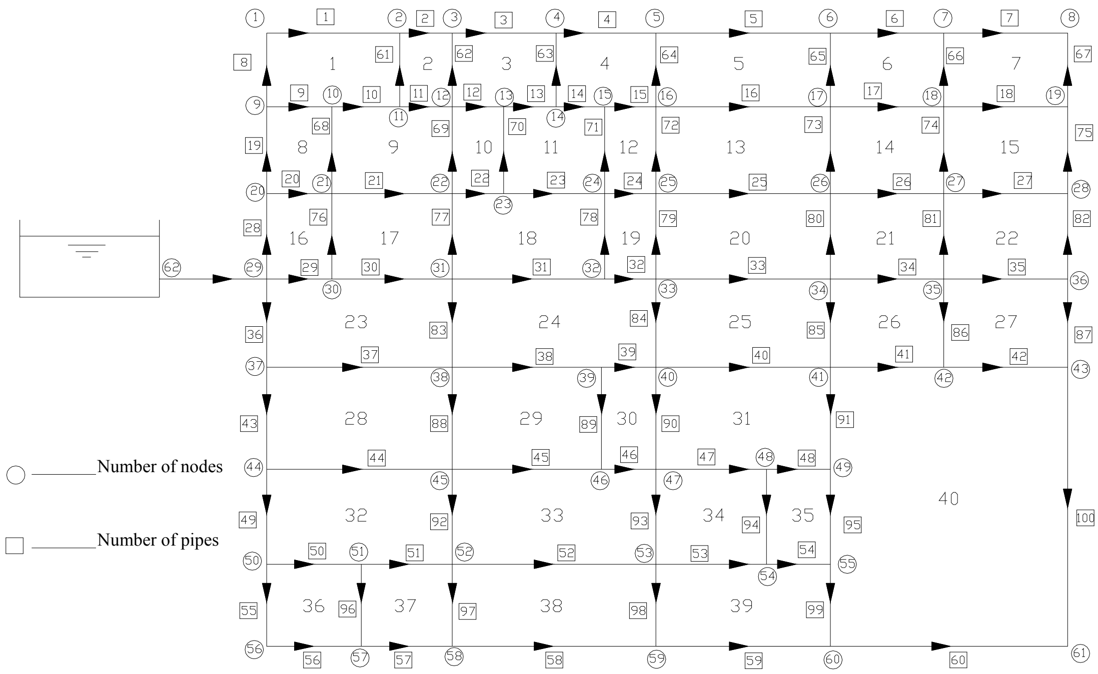

Figure 1. The networks of a water distribution system

Due to the damaged probability of every pipes is same, the damaged level of Case1 is slightly damaged, so the second hydraulic analysis model is utilized; In Case2 the ten pipes of water system are under the condition of moderately damaged, so the third hydraulic analysis model is used and ten fictitious nodes are set on the damaged pipes.

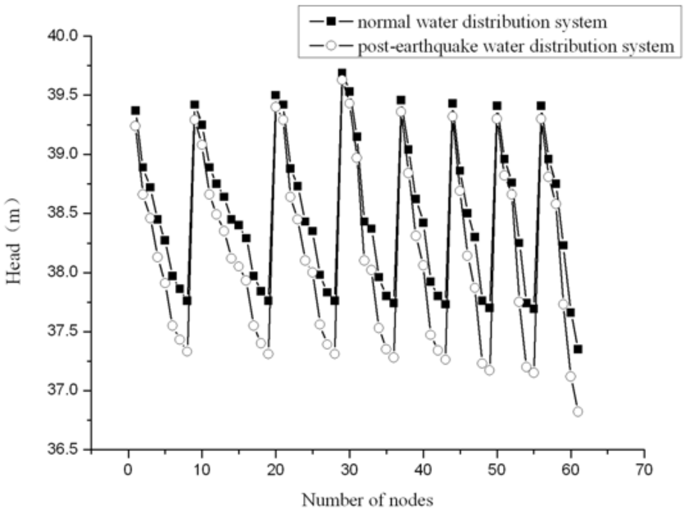

Figure 2. Results of Case1

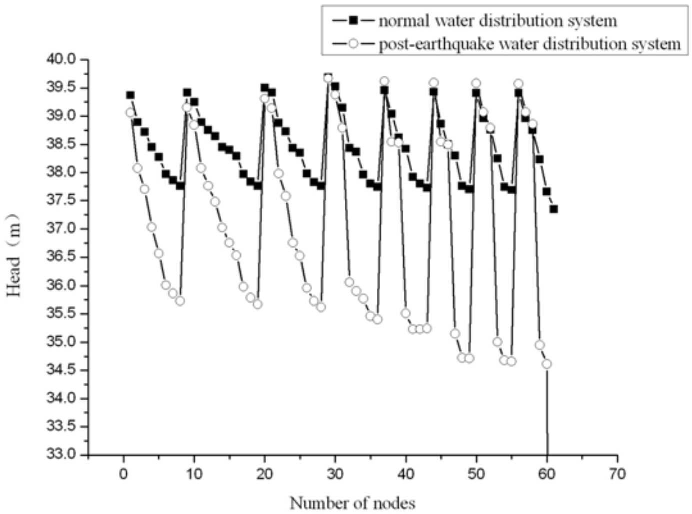

Figure 3. Results of Case2

The result of Case1 is shown in Figure 2. It clearly indicates that the head of every node in the post-earthquake water distribution system is lower than that of the normal water system. The result of Case2 is shown in Figure 3. The head of nodes in the post-earthquake water distribution system decrease sharply and the head of the farthest node (No.61) is almost zero which illuminates that this node can't meet the water delivery need.

CONCLUSION

Based on the analysis of the leakage model, the hydraulic analysis model of the post-earthquake water distribution system is improved. According to the different damaged level and probability, the formula of leakage area is determined which is added in the hydraulic analysis of the post-earthquake water distribution system. The three improved models of the post-earthquake hydraulic analysis are put forward on the basis of the different damaged level. The results of a case study show that this kind of improved models could be utilized, and also the model considers the effect of the different damaged level on the water delivery state. So the improved models could estimate the hydraulic state of the post-earthquake water distribution system particularly and accurately.

REFERENCES

Ballantyne D.B., Berg E., Kennrdy J., Reneau R., Wu D.(1990). Earthquake loss estimation modeling of the Seattle water system. *Report of U. S. Geological Survey*.

Gao, X.W., Wang, J.(1998). Method of earthquake damage prediction for water supply system. *J. Building Science*. 1998(14), 3:12-18.

Hwang H.M. & Lin H.(1997). *GIS-Based evaluation seismic Performance of water delivery systems*. Center for Earthquake Research and Information, The University of Memphis, 1997.

Kameda H., Goto H., Kasuga T. (1984). System reliability and serviceability of water supply pipelines under seismic environment.*Proceedings of the 8th World Conference on Earthquake Engineering*,1984,7:491-498.

Kameda H. (2000). Engineering management of lifeline systems under earthquake risk. *Proceedings of the 12th World Conference on Earthquake Engineering*. Auckland, 2000

Markov (1994). *An evaluation of seismic service ability of water supply networks with application to San Francisco auxiliary water supply system*. National Center for Earthquake Engineering Research, State University of New York at Buffalo, Buffalo, NY, 1994.