SEISMIC PERFORMANCE CONTROL ANALYSIS ON WATER NETWORK SYSTEM

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ABSTRACT :
When an earthquake occurred, the water supply network can not keep generally service performance and there is some leakage phenomenon. In order to evaluate the seismic performance of the water supply network, it is necessary to conduct the service performance analysis of the water supply network based pipe leakage model. The analysis method is presented and discussed deeply in this paper, and a hydraulic leakage model is also built. Through the connectivity analysis and the continuity equation solution, the node flows and node water heads can be gotten, and finally the service performance of the water supply network can be evaluated too. In addition, An example of the water supply network is illustrated and discussed deeply. All of above methods may be applied to analyze seismic performance on practical water supply network.

KEYWORDS: water supply network, leakage model, seismic failure, seismic performance analysis

1. INTRODUCTION

Water supply network is an important part of the lifeline systems. When the strong earthquake occurred in recent years, there were many structure damages and function failures in the water supply network, which had brought many difficulties to people's life, and had brought huge economic losses. Thus, it is significant to analyze and estimate rightly the service capability of the water supply network before and after the earthquake. In addition, it is also an important problem part to study the pipe network design and enhance seismic resistance of the pipe network.

Seismic performance of the water supply network refers to the ability that the water supply network can satisfy special water requirements of the city (flow rate and water pressure) after the earthquake [1, 2]. The buried pipelines are numerous, geographically distributed, and the locations of the damages are often covert, except the pipes that were destroyed or leaking heavily can be discovered rapidly, and then isolation measures were adopted promptly, the majority with the slight or moderate damage was very difficult to discover and repair after the earthquake. Therefore, the water supply network often worked with leakage after the earthquake [3]. It is important that seismic performance control analysis on water supply network should be made. In this paper, the method of hydraulic analysis is improved and the leakage model is given. Further, the seismic performance control analysis on water supply network is discussed deeply.

2. THE DAMAGE STATE SIMULATION OF THE PIPE NETWORK

In order to estimate the work state and the service capability of the pipe network, the first step is to simulate the damage state of the pipe network accurately. In this paper the damage state simulation of the pipe network based on the earthquake disaster prediction was showed and the degree of damage to the pipeline was distinguished into three grades [4, 5]. Which the damage grades of pipe with socket joint are:
Basically good or slight damage: the pipes have slight deformation, but no damage, no leakage, and no repairing, and could work in good condition.
Moderate damage: the pipe joints become loose, and there are leakages, but the pipe could still work.

Heavy damage: the pipe joints are damaged, or the pipe can't supply water and it must be replaced.

The evaluation criterion of pipe damage grades are written following:

$s<[u_a]$ Basically good or slight damage (without leakage)

$[u_a] \le s \le 2[u_f]$ Moderate damage (with leakage)

$s > 2[u_f]$ Heavy damage (failure)

In which, s is the displacement of the joint; $[u_a]$ is the ultimate cracking displacement of the pipe; $[u_f]$ is the ultimate leaking displacement of the pipe.

When the connectivity analysis of a pipe network, the assumption is made that deleting the disconnected nodes which have no flow in it and no output flow, so there is no flow in the pipeline connected with the disconnected node. And the pipelines with moderate damage are in leaking. Because the randomicity of the earthquake motion, the diversity of the site condition, and the complicacy of the buried pipe, it is very difficult to locate the leakage positions [6]. Therefore, the Chinese-point-leakage-model (short for the C model) is used in this paper. In this model, if the leakage occurs, the leakage position is the pipeline's center point, and a virtual node is used to simulate the leakage that must be added on the center point.

The leakage flow Q_L at a virtual node may be estimated by the following formula [7]

$$Q_L = \begin{cases} 0.421 A_L \cdot \sqrt{H_L} & H_L > G_L \\ 0 & H_L \le G_L \end{cases} \tag{2.1}$$

$$A_L = \pi D_L (s - u_a) \qquad s \le 2[u_f] \tag{2.2}$$

Where A_L is the leakage area (m^2); H_L is the water head at the virtual node (m); G_L is elevation at the virtual node (m); D_L is the diameter of the leakage pipe (m); s is the deformation at the joint (m); u_a is the ultimate cracking displacement of the pipe (m); u_f is the ultimate leaking displacement of the pipe(m).

3. HYDRAULIC ANALYSIS OF THE LEAKAGE NETWORK

When an earthquake occurred, the main work of hydraulic analysis is to determine the flow rates of the demand nodes, as well as to find the failure nodes and flow lack nodes, and then to calculate the failure area and the economic loss (including the direct loss and indirect loss), finally, to evaluate the damage degree and serviceability of the water distribution system, which influence of a single pipeline can be seen by the hydraulic analysis of the damaged water supply network [1]. That the break of a single pipeline can cause a large area has no water supply, so the redundancy of the network should be taken into consideration. Generally, the larger the pipeline's redundancy is, the safer the network will be, which is as a consequence has been provided for safe design of the pipe network.

3.1. Mass Conservation Equation

After an earthquake, the leaking water supply system should still satisfy the mass balance equation of the node flow rate. A network including the actual nodes and the virtual nodes is formed, through the damage simulation of the post-earthquake network. For the actual node i, the mass conservation equation can be written following:

$$Q_i + \sum_{j=1}^{mo} q_{ij} = 0 \qquad (i = 1, 2, \cdots N) \tag{3.1}$$

$$Q_i = \begin{cases} Q_{nor} & H_i \geq G_i + H_{\min} \\ Q_{nor}\left(\dfrac{H_i - G_i}{H_{\min}}\right)^{0.5} & G_i < H_i < G_i + H_{\min} \\ 0 & H_i \leq G_i \end{cases} \tag{3.2}$$

For the virtual node i, the mass conservation equation can also be written:

$$Q_{Li} + \sum_{j=1}^{mo} q_{ij} = 0 \qquad (i = 1, 2, \cdots NL) \tag{3.3}$$

Where q_{ij} is the flow in link ij (m^3/s), Q_i is the flow at the actual node i (m^3/s), Q_{nor} is the design flow at the actual node i (m^3/s), Q_{Li} is the leakage flow at virtual node i (m^3/s), H_i is the water head at node i (m), G_i is the elevation at node i (m), $H_{\min}$ is the minimum water pressure at node i (m), *mo* is the number of links, *N* is the number of actual nodes, and *NL* is the number of virtual nodes.

3.2. Energy Conversation Equation

The pipe network should also satisfy the conversation of energy, which is that each node can only have a value of water head [8]. For each link, the flow and the water head loss in it should satisfy the following equation:

$$q_{ij} = s_{ij}(H_i - H_j)^{\alpha} \tag{3.4}$$

Where, s_{ij} and α are coefficients relating to the material and the diameter of the pipe. In this paper, Hazen_Williams expression is adopted [8, 9]

$$s_{ij} = 0.2785 C_{HWij} D_{ij}^{2.63} L_{ij}^{-0.54} \tag{3.5}$$

$$\alpha = 0.54 \tag{3.6}$$

In which, C_{HWij} is the Hazen_Williams friction factor for pipe ij, D_{ij} is the diameter of pipe ij (m), and L_{ij} is the length of pipe ij (m).

3.3. Control Analysis of the Node Pressure and the Node Flow

Both the flow of the pipe and the water head of the node are unknown. At the water source, the pressure is fixed but the flow is variable. For a water distribution system, the continuity equation (3.1) is linear, but the head loss equation (3.4) is nonlinear. Because it is difficult to solve a nonlinear equation for a large network, therefore, for the simplifying purpose, the linearization theory is employed in this paper.

The flow direction is consistent with the head loss direction. Taking $C_{ij} = s_{ij}\left|H_i - H_j\right|^{\alpha-1}$, then the equation (3.4) can be written as:

$$q_{ij} = C_{ij}(H_i - H_j) \tag{3.7}$$

and taking $R_i = Q_{nor}\dfrac{|H_i - G_i|^{-0.5}}{H_{\min}}$ then equation (3.2) can be written as:

$$Q_i = \begin{cases} Q_{nor} & H_i \geq G_i + H_{\min} \\ R_i(H_i - G_i) & G_i < H_i < G_i + H_{\min} \\ 0 & H_i \leq G_i \end{cases} \tag{3.8}$$

In the same way, taking $R_{Li} = 0.421 A_L |H|_L^{-0.5}$, then equation (2.1) can be written as:

$$Q_{Li} = \begin{cases} R_{Li} H_{Li} & H_{Li} > G_{Li} \\ 0 & H_{Li} \leq G_{Li} \end{cases} \tag{3.9}$$

Substituting equation (3.7), (3.8) and (3.9) into (3.1) and (3.3), from which a set of linear equation can be deduced. Linear theory is an iterative technique, starting with the initial value for H_i, the linear equation is solved for H_i. Through repeated iterations the value of H_i converge to the correct value.

4. EXAMPLE

A water supply system [9] is presented in Fig.1, in which it is a city sits in the hilly region, and a river is taken as the water source of the water supply system. The network system includes 33 nodes and 49 pipe links, and water intake is about 1 kilometer away from the upper reaches of the river, and purification structure sits near the water intake. In order to improve the reliability of the water distribution system and lighten the burden of pumping station, a high position reservoir was built at upland near the city. In the normal state, at the highest demand time the total flow rate of the water supply network is 770.5L/s, including 617.6L/s from the pumping station and 152.9L/s from the high position reservoir. The pressures of the pumping station and the high position reservoir are respectively 167.71m and 153.75m. and the minimum free head of all demand nodes is 24m. In addition, spigot and socket cast iron pipes are used in the network, material of the joints is asbestos cement. The ultimate cracking displacement and the ultimate leaking displacement of the joint are respectively 0.2 mm and 2 mm. The 36.8 km pipelines have been laid in the city, including 36.1km pipelines of which the diameter is greater than 200 mm. The outlet conduits' diameters are respectively 600 mm and 450 mm at the pumping station and the high position reservoir. And the diameters of the rest of pipelines are between 500 mm and 150 mm. Fig.2 shows the damage level of the network under earthquake intensity Ⅶ, and fig.3 shows the damage level of the network under earthquake intensity Ⅷ.

All nodes' pressure and link's flow can be calculated through hydraulic analysis of the network in normal state. The result is that pipe damages are mainly distributed over the smaller pipes at the Ⅲ soil site (the diameter of the pipes less than 200 mm) and Ⅱsoil site (e.g. The pipes of No.17 , No.18 , No.7 and No.28, all diameters of which are 150 mm). Comparing between the nodes' free water heads under intensity Ⅶ and those in normal state, results are shown in fig. 2, the range of water head loss distribution is presented in tab.1. It is shown that all nodes' pressures have some decrease ranging between 0 m and 7 m. The most heavily decrease node is at node 15, which value of the decrease is 7.98m, the cause of which is that all the pipes connected with node 15 are in the state of moderate damage. At the same time, it can be seen from fig.2 and tab.1 that nodes near the water source have smaller decreases, because leakages are occurred in those pipes far from the water source, which have a slight influence on the upriver nodes. The node 10 has the lowest free head of 22.32m (the water head loss is 2.66 m, correspondingly), which is 1.68 m lower than the designed minimum free head of the node. There are three nodes of which the free water heads are lower than the designed minimum free head of the node, which is shown in tab.2. Leakage flow of the pipe network is 0.0424 m^3/s, and the leakage level of the network is 5.25％. In the same way, comparing between the nodes' free water heads under intensity Ⅷ and those in normal state, the results are shown in fig.3. The range of water head loss distribution is presented in tab.1. It can be seen from the tab.1 that the nodes of which water head decreases distribute between 7 m and 10 m are nearly 15% of the nodes, and there are 6 nodes, which the water head decrease exceeds 10 m. The largest decrease is occurred at node 15, the value of the decrease is 13.21 m. The node 8 has the lowest free head of 20.77 m (the water head loss is 8.32 m, correspondingly), which is 3.23 m lower than the designed minimum free head of the node. Under intensity Ⅷ, there are 8 nodes which have lower free water heads than the designed minimum free head of the nodes. At those nodes, the flows also decrease, as tab.2 shows. Leakage flow of the pipe network is 0.165m^3/s, and the leakage level of the network is 17.90％.

Table 4.1 Node earthquake water pressures distribution

Water head drop (m)		0-5	5-7	7-10	10-15
I =7 Node		1,2,3,4,9,10,11,19,20,21,22,23,24,25,29,30,31	5,6,7,8,12,13,14,16,17,18,26,27,28	15	
Node subtotal		17	13	1	0
I=8	Node (before control)	1,10,22	2,3,9,21,23,24,31	4,5,6,7,8,11,17,19,20,25,26,27,28,29,30	12,13,14,15,16,18
	Node subtotal	3	7	15	6
	Node (after control)	1,2,9,10,22,31	3,4,5,6,7,8,11,12,17,19,20,21,23,24,25,26,28,29,30	13,14,15,16,18	
	Node subtotal	6	19	5	0
Annotate: 32, 33 are the water source nodes, and out of statistic; I refers to Intensity.					

Table 4.2 Decreases of the node earthquake flows

I	node	8			9			10			
7	ΔQ (L/s)	0.6			0.1			0.9			
8	node	6	7	8	9	10	11	13	15	29	30
	ΔQ (L/s) (before control)	0.4	1.0	2.4	1.1	1.9	1.5	0.8	0.1	0.1	0.7
	ΔQ (L/s) (after control)	0	0	0.9	0.2	1.1	0.3	0	0	0	0.1
ΔQ refers to decrement of node flow; I refers to Intensity.											

If the pipe network is control analyzed, the damage state of pipes can be lightened. In this example, the pipes 2-31 and 21-23 are repaired by control analysis, and the results are represented in fig.4, tab.1 and tab.2. Thus, the free water heads have increased to varying degrees at all demand nodes, the maximum value of increase is 5.12 m occurring at node 15, and the minimum value is 0.72 m occurring at node 1. It can be seen from the table 4.1 that a majority of nodes' water head decrease values are reduced to less than 7 m. At the same time, it is shown in table 4.2 that the number of nodes of which the flow decreases in damage state is reduced from 10 to 5, and the node flows increased after control analysis. Therefore, it can be seen that the serviceability of the water supply network is improved greatly after control analysis.

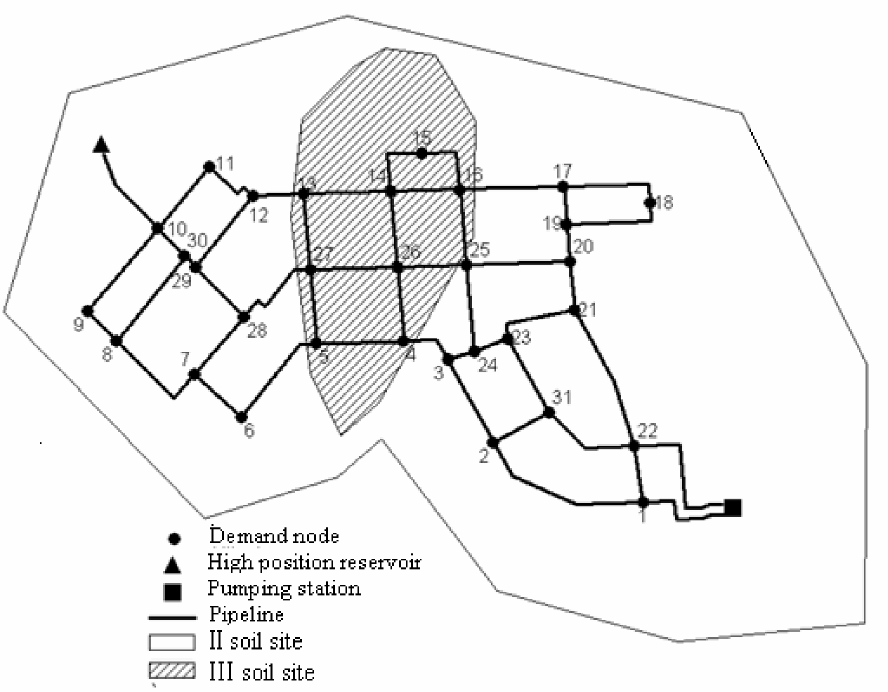

Fig.1 The plan view of the ground condition and pipe network

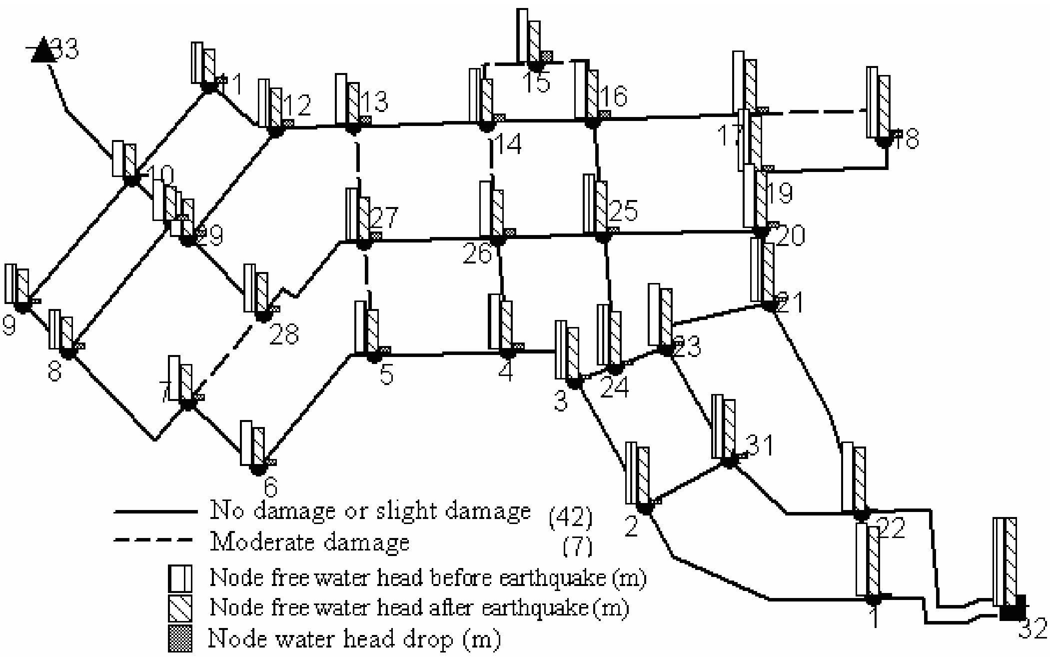

Fig.2 Damage state of the pipe network and Node water pressure changes
before and after the earthquake at the earthquake intensity of 7

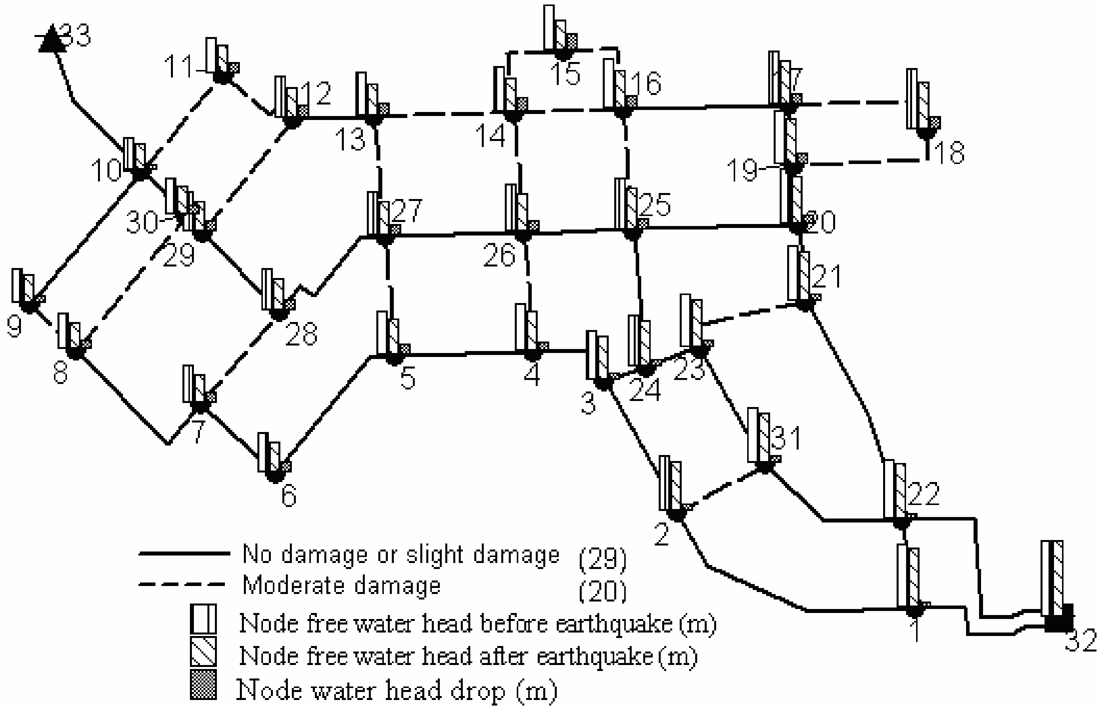

Fig.3 Damage state of the pipe network and Node water head changes before and after the earthquake under the earthquake intensity of 8

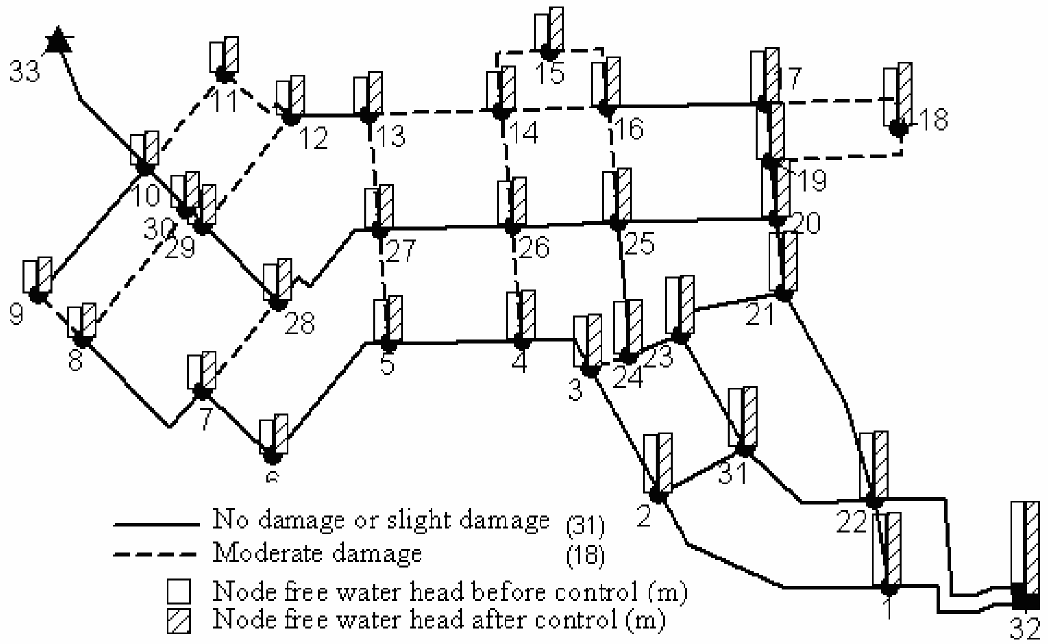

Fig.4 Damage state of the pipe network and Node free head changes before and after the control under the earthquake intensity of 8

4. CONCLUSIONS

In this paper, the earthquake function analysis approach of the water supply network is improved, and a new control analysis method is presented. The damage state of the pipe network is simulated based on the deformations of the pipeline joints. In order to analyze and calculate the network conveniently, the damage state of pipe is redefined and the heavy damaged pipes are deleted, then the connectivity of the pipe network is analyzed and the no-water-nodes are judged. And the hydraulic analysis of the network after earthquake is done too. All of these will play a significant meaning and role in earthquake performance, earthquake reconstruction, earthquake retrofit and the service efficiency of the water supply network.

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