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SEISMIC RESILIENCE-BASED OPTIMIZATION RECOVERY MODEL OF WATER DISTRIBUTION NETWORKS

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Abstract

Water distribution networks (WDNs) are important components of urban critical infrastructures. In previous strong earthquakes, WDNs suffer from serious damages and need long time to recover. Therefore, improving the seismic resilience derives more and more concerns by the public and decision-makers. In this paper, the seismic resilience-based pipe optimal recovery model is proposed. Considering the function characteristic of WDNs, the satisfaction degree index (SDI) is introduced to measure the performance of WDNs. Flow analysis method is employed to calculate the hydraulic information. Then, a demand-based seismic resilience index is defined as the area under the SDI curve. In order to provide a scientific guidance of post-earthquake pipe recovery activities, the time-dependent demands of consumers and the multiple recovery resource supply are considered. For the consumer demand model, we simulate the critical and general nodes by piecewise functions, respectively. The critical nodes include earthquake shelters and hospitals, and the general nodes include residential and industrial nodes. For the recovery resource model, the recovery materials and staff are modeled separately to reflect the real supply situations. The construction matrix is generated to clearly reflect the supply plan of recovery resource. On the basis, the genetic algorithm is used to obtain the optimal pipe recovery scheme. Taking the WDN in Mianzhu, China, as an example, above framework is illustrated and the SDI recovery curve is obtained. Results show that the SDI curve can be divided into several stages based on the given demand and recovery resource supply conditions. More importantly, the initial recovery resource storage and the subsequence supply condition obviously influence the recovery process and the resulting resilience level of WDNs.

Keywords: resilience, optimization, water distribution network, genetic algorithm, pipe, consumer demand, recovery resource

1. Introduction

Water distribution networks (WDNs), as important components of urban critical infrastructures, play key roles in providing water service for various daily and industry activities and maintaining health of human lives [1]. Unfortunately, the WDNs are not seismic resilient due to the distributed and complicated characteristics. In previous earthquakes, such as the San Fernando earthquake (M_L=6.6, 1971), the Kobe earthquake (M_L=7.2, 1995), and the Wenchuan earthquake (M_L=8.0, 2008), the WDNs suffered from serious damages and took long time to recover [2], which leads to high economic loss and heavy social pressures. Therefore, improving the seismic resilience of the WDNs is of significance for the modern cities.

Resilience of critical infrastructures has drawn much attention in the past twenty years and many contributions have achieved [3-5]. However, compared to other infrastructures such as power systems and transportation systems, the resilience research of WDNs derives less attentions [6]. In existing studies related to seismic resilience of WDNs, researchers focus more on components such as pumps and tanks while less on the pipeline recovery strategy, especially the recovery sequence. Note that pipes are the most important components of the WDNs as well as the most vulnerable ones after earthquake, so, its recovery strategy is the key to improve the seismic resilience of the WDN as a whole.

This paper proposes a seismic resilience-based pipe recovery model of WDNs. In order to provide a reasonable solution, the time-dependent demands of consumers and multistage supply of recovery resource are considered in this model. The remaining parts of this paper are organized as follows. Section 2 introduces the seismic resilience evaluation model of WDNs. Section 3 introduces the pipe recovery model, including the consumer demand model, recovery resource supply model, and the optimal pipe recovery model. Then, a case is illustrated in Section 4. Conclusions are given in Section 5.

2. Seismic resilience evaluation of WDNs

Fig. 1 shows the performance level (PL) of WDNs before, during, and after an earthquake. Before t_0, the WDN operates normally with the PL equal to 1. The earthquake occurs at t_0, and PL rapidly decreases to a low level due to the damages of the WDN. t_0~t_0 is the preparation or transition stage. In this stage, various emergency strategies are implemented to guarantee the basic water demands. Recovery activities begin at t_1, then the PL gradually recovers and reaches to the normal level at t_2.

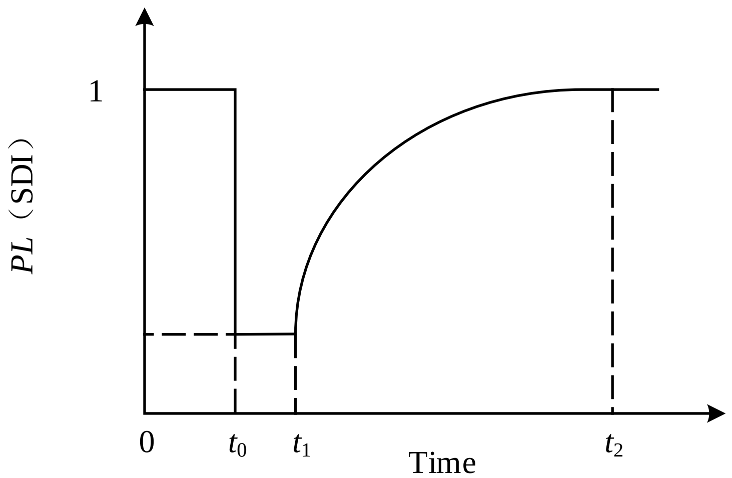


Fig. 1 Performance level curve of WDNs

For WDNs, the basic function is to satisfy the water demands of consumers. To quantify the satisfaction degree of consumers, the satisfaction degree index (SDI) is defined as the PL of WDNs. It is written by

$$SDI(t)=\sum_{i=1}^{n}w_i(t)NSD_i(t) \tag{1}$$

where $w_i(t)$ is the weight coefficient of node i at time t; n is the node number; $NSD_i(t)$ is the satisfaction degree of node i. Generally, the consumers can always receive enough water if the obtained head exceeds the demand one. After the earthquake, many pipes are damaged, hence the demands may not be satisfied well. Therefore, *NSD* can be measured by the obtained head as follows

$$NSD_i(t)=\begin{cases}1 & h_i(t)\geq h_{i0}(t)\\ \dfrac{h_i(t)}{h_{i0}(t)} & h_i(t)<h_{i0}(t)\end{cases} \tag{2}$$

where $h_i(t)$ is the demand head of node i at time t, $h_i(t)$ is the nodal head of node i at time t, which can be quantified by seismic hydraulic flow analysis method [7].

In Fig. 1, it is obvious that shorter recovery time and higher real-time SDI contribute to a more resilient WDN. Therefore, the seismic resilience of WDNs is defined by

$$SRI=\frac{\int_{t_0}^{t_c}SDI(t)\,dt}{t_2-t_1} \tag{3}$$

where *SRI* is the seismic resilience index, which equals to the area between the *SDI* curve and the time axis shown in Fig. 1.

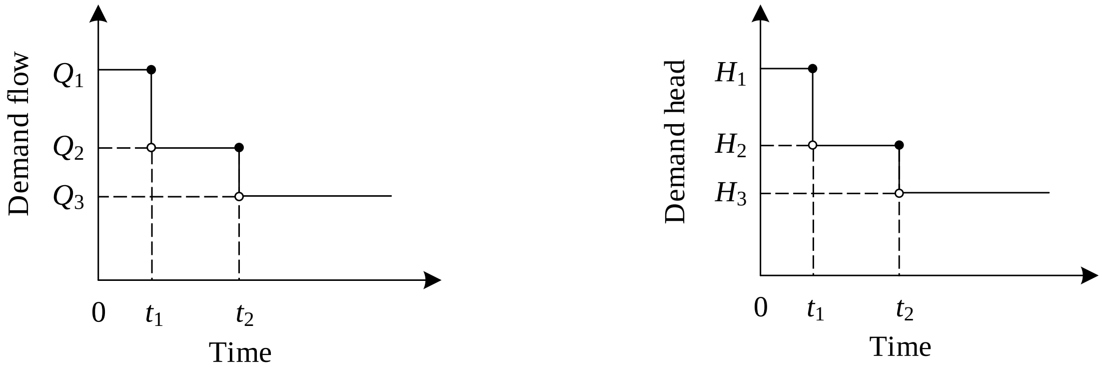
3. Pipe recovery model

After an earthquake, most pipes suffer from damages to different degrees. Therefore, the total recovery time of WDNs can be so long that the demands of consumers may change in recovery process. In addition, the recovery resources may be supplied in multiple times, which also influences the pipe recovery activities. Therefore, these factors should be considered in the pipe recovery model.

3.1 Consumer demand model

In post-earthquake recovery process, both the WDNs and other systems are repaired gradually, including buildings, power systems, etc. Thus, the consumer demands of different nodes can change over time. Herein, the demands of critical and general nodes are modeled respectively.

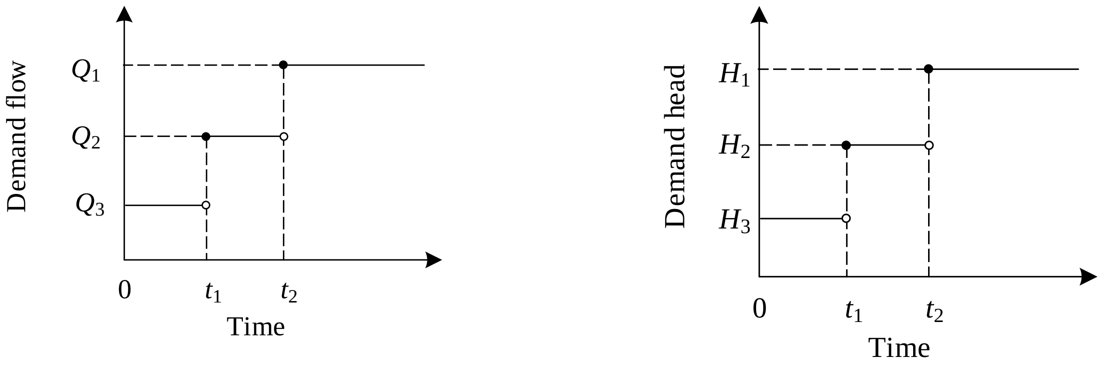
For critical nodes, earthquake shelters and hospitals are considered. (1) Earthquake shelters. The water demands of earthquake shelters are high in the initial recovery stage because many buildings and utilities are damaged and the original places are not fitted to live. Thus, a large majority of people will congregate in the shelters. With the progress of recovery activities, the functions of buildings and utilities are recovered gradually, so people return to their original places continuously, leading to the decreasing demands of earthquake shelters. For simplifications, the time-dependent demands of earthquake shelters, including the demand flow and demand head, are reflected by piecewise functions as shown in Fig. 2. The specific values in different time points should be determined based on the engineering experience, maximal capacity, and design code considering the real data are difficult to access. (2) Hospitals. the change of demand flow of hospitals has similar characteristics to earthquake shelters. In the initial recovery stage, the demand flow is high because many wounded people need to be treated in hospitals. As more people are cured and leaved, the total demand flow become lower than before. Different from the earthquake shelters, the demand head of hospitals need to keep the pre-earthquake level during the whole recovery process. On the basis, the demand flow of hospitals can also be modeled by the same piecewise functions with Fig. 2 (a), and the demand head is seen as a constant value the same with the pre-earthquake level.



(a) Demand flow (b) Demand head

Fig. 2 Time-dependent demands of earthquake shelters

For general nodes, the demand tendencies are opposite to earthquake shelters. Herein, the residential and industrial users are modeled separately. (1) Residential users. As people move to shelters from home, the demands of residential users reduce obviously in the initial recovery stage. Then, the demands increase gradually because people begin to return their home after the buildings and utilities are recovered. Similarly, the piecewise functions are used to characterize the time-dependent demands of the residential users as shown in Fig 3. (2) Industrial users. The demand tendencies of industrial users are similar to those of residential users. However, the demand flow and head of industrial users in the initial recovery stage can be zero because the industrial activities are stopped. Therefore, for the demand model in Fig. 3, Q_3 and H_3 need to take 0 for the industrial users.



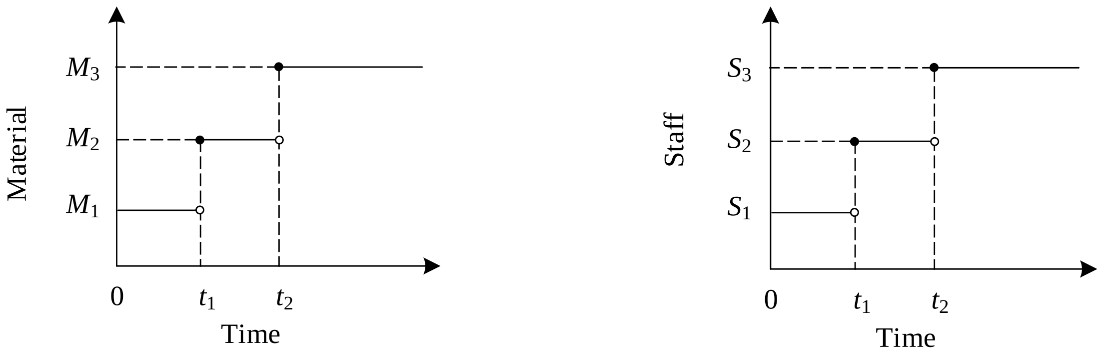
(a) Demand flow (b) Demand head

Fig. 3 ime-dependent demands of residential users

3.2 Recovery resource supply model

Recovery resource includes recovery material and staff. In previous studies, they are modeled by a unified virtual unit without considering the difference. For example, Ouyang et al. [8] assumed that one unit of recovery resource, referring to one work team with sufficient material and staff, is required for one damaged component in the resilience analysis of power systems. However, material and staff may be supplied in different paces after earthquake, which influences the recovery of pipes. For example, even though the staff are sufficient, the recovery activities must be stopped if the materials are exhausted, and vice versa. On the basis, this paper models the material and staff by piecewise functions separately as shown in Fig. 4. Herein, recovery staff is the unit of workers responsible for all related jobs in recovery, such as inspection, recovery, and operation.

Note that the recovery materials can be insufficient, thus not all pipes are recovered in the end. In addition, the recovery staff can be more than two, thus parallel repairs of different pipes can be done in recovery process. The two situations are considered in this model.



(a) Material (b) Staff

Fig. 4 Recovery resource supply plans

3.3 Optimal pipe recovery model

Pipe recovery sequence is the key to improve seismic resilience of WDNs. Mathematically, it is a combination optimization problem and can be solved by various methods. Herein, the genetic algorithm (GA) is chosen to search the optimal pipe recovery strategy.

Generally, GA includes the following steps. (1) Initial populations generation. Considering one pipe is restored only once, an initial solution is represented by a gene and each one stores a pipe number to be restored. For example, the gene 123456 means the current pipe recovery sequence is 1→2→3→4→5→6. Generally, the initial population can be generated by random method or heuristic algorithm. (2) Population evaluation. Since a gene represents a specific pipe recovery sequence, the *SRI* calculated by Eq. (3) is used to evaluate the current gene. (3) Selection operator. Roulette wheel strategy is adopted herein. The gene with larger *SRI* has more chance to transfer to next generation. (4) Crossover operator. Two selected genes are taken to produce two offspring in a crossover rate. In order to avoid the repeated pipe number in the same offspring gene after crossover operation, the repeated but uncrossed parts in one offspring gene are exchanged with the corresponding parts of the other one. (5) Mutation operator. Two elements of one offspring gene are randomly selected and exchanged in a mutation rate. (6) Terminating criterion. When the population reaches to a stead state or the maximal iteration number, the algorithm stops.

In step (2), when the recovery materials are sufficient and the number of recovery staff is one, all pipes can be repaired one by one, thus, the sequence restored in the gene can be used as the recovery sequence in practice. It should be noted that some pipes cannot be repaired when the recovery materials are insufficient, or can be repaired parallelly when the number of recovery staff is more than one. Therefore, the recovery resource supply condition should be considered in pipe recovery model. Based on the current gene representing the pipe recovery sequence, the corresponding recovery scheme used in practice is given by two steps. First, determine the pipes to be repaired (or cannot be repaired) according to the recovery materials supply condition. Second, determine the pipe state (before recovery, under recovery, recovery finished) according to the recovery staff supply condition. The number of under-recovery states equals to the number of recovery staff. Herein, the construction matrix is generated to display the specific pipe recovery scheme. For example, for the gene of 12345, the initial recovery materials are sufficient. One recovery staff is available in the first two days after earthquake, and two staff exists afterwards (i.e., another one staff is available in the third day). Thus, the construction matrix is shown in Table 1. It is shown that all pipes can be recovered in five days. After the third day, two staff can work parallelly until all recovery activities are finished. Although the sequence in gene is 54321, pipe 3 and 4 can be repaired in the third day. In addition, the recovery time for each pipe can be known by this table. For example, pipe 1-3 need one day to recover while pipe 4 and 5 needs two days.

Table 1 Construction matrix

Pipe No.	Sequence in gene	Time/day						
		1	2	3	4	5	6	7
5	1	■						
4	2		■	■				
3	3			■				
2	4				■	■		
1	5				■	■		

*Note: Grey cells mean the pipes are under recovered.

4. Case study

In order to illustrate above model, the WDN in Mianzhu, China, is analyzed. The WDN layout is shown in Fig. 5. The earthquake intensity is VIII based on Chinese design code. Other information refer to [1].

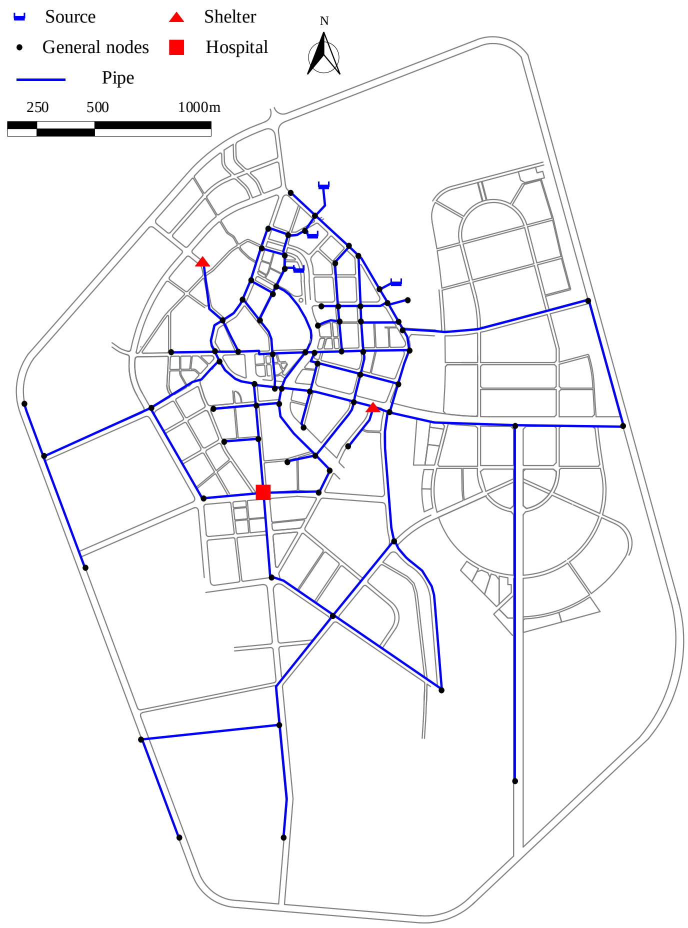
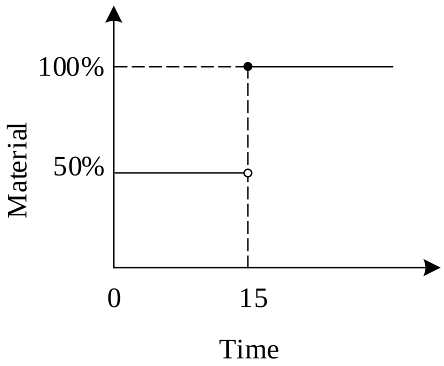
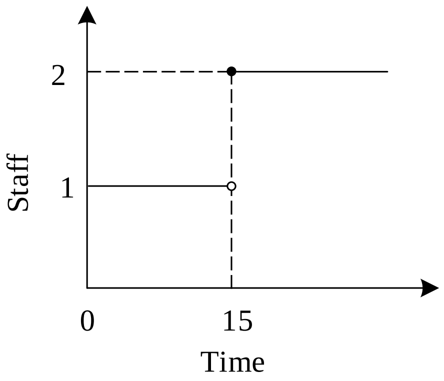


Fig. 5 WDN in Mianzhu

For the earthquake shelters, the timepoints in Fig. 2 are 3 and 30, respectively. The corresponding demand values are determined based on the Chinese design code (GB51143) [9]. For hospitals, the demand flow takes two times of the pre-earthquake level in the first month. After that, it reduces to 1.5 times of the pre-earthquake level. For the demand head, it takes 20 m during the whole recovery process. For residential consumers, the demand flow takes 0.8 times of the pre-earthquake level, and the demand head takes 3 m in the first three days and 5 m afterwards. For industrial consumers, the demand flow and head are zero in the first thirty days. After that, the demand flow takes 0.8 times of the pre-earthquake level, and the demand head takes 10 m. The recovery resource supply plans are shown in Fig. 6.



(a) Material



(b) Staff

Fig. 6 Recovery resource supply plans in case study

The GA runs 150 times and the *SDI* curve is given in Fig. 7. Obviously, the *SDI* curve can be divided into five stages. (1) Stage 1 (A→B, 0~3 days). In this stage, though the demands of critical consumers are high, the *SDI* still has a high level because the demands of general consumers are low. (2) Stage 2 (B→C→D, 3~15 days). In the fourth day, the *SDI* reduces obviously because the demands of general consumers increase to 10 m from 5 m. As more pipes are repaired, the *SDI* becomes higher gradually. (3) Stage 3 (D→E, 15~30 days). In this stage, the consumer demands keep unchanged. Considering another one staff is available in the 15th day, two staff can work together and the pipes can be repaired parallelly, which makes the *SDI* increases more rapidly than before. (4) Stage 4 (E→F→G, 30~50 days). The *SDI* decreases slightly because the demands of industrial users are added in this stage. Considering a large majority of pipes have been repaired, the *SDI* reduces unobviously. (5) Stage 5 (G→H, 50~140 days). *SDI* keeps 100% in this stage. Note that all pipes are repaired in the 76th day. Based on this figure, *SRI* is 0.955.

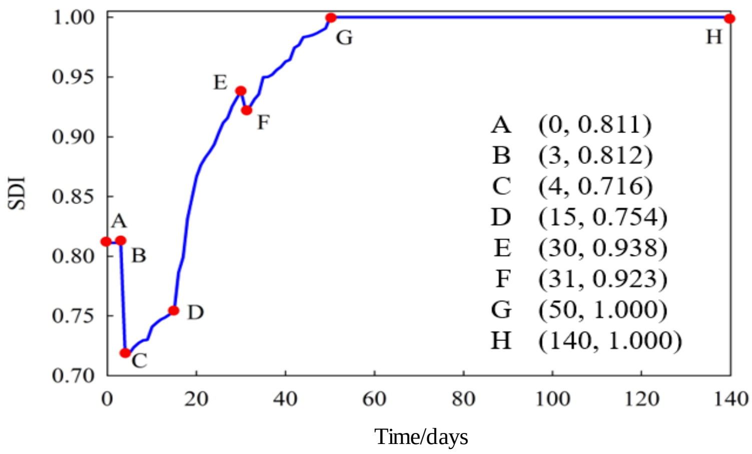


Fig. 7 SDI curve

To sum up, the initial recovery resource storage and subsequent supply plan has significant impacts on the *SDI* and *SRI* of the WDNs. Therefore, a scientific recovery resource supply plan should be further studied in the future.

5. Conclusions

This paper proposes a post-earthquake pipe optimization recovery model of the WDNs using GA. First, a demand-based index is built to measure the resilience level of WDNs. Then, the pipe recovery model is introduced in detail, including the time-dependent consumer demand model, recovery resource supply model, and the GA-based pipe optimal recovery model. In order to illustrate above framework, the WDN in Mianzhu, China is analyzed. Results show that the initial storage of recovery resource and the subsequent supply plan play key roles in the seismic resilience of the WDNs.

6. Copyrights

7. References

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