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Post-earthquake restoration of pipeline damages to enhance seismic resilience of water distribution system

B. Hou(1), Z. Han(2), W. Wang(3), D. Ma(4)

(1) *Assistant Prof., College of Architecture and Civil Engineering, Beijing University of Technology, benweihou@bjut.edu.cn*
(2) *PhD student, College of Architecture and Civil Engineering, Beijing University of Technology, hanzhao@emails.bjut.edu.cn*
(3) *Associate Prof., College of Architecture and Urban Planning, Beijing University of Technology, ieeww@bjut.edu.cn*
(4) *Prof., College of Architecture and Urban Planning, Beijing University of Technology, mdh@bjut.edu.cn*

Abstract

For the water distribution system (WDS) damaged by severe earthquake, the earthquake-damaged pipelines cannot be repaired in a short time due to the limitation of post-earthquake restoration resources. In couple of weeks after the earthquake, the system may still be operating at a low-pressure level with leakages. Therefore, the restoration priority of damaged pipelines is a key factor to effectively improve the post-earthquake performance of the WDS, which eventually impacts the seismic resilience of WDS. This paper proposed a novel sorting method (namely, dynamic cost-benefit method) to determine the restoration sequence of pipeline damages, which accounts for the time-varying of physical states of WDS. Firstly, a time-varying analysis model for post-earthquake functionality of WDS is established to evaluate the seismic resilience of WDS. Then, the dynamic cost-benefit method which takes account of the time-varying characteristics of the WDS, is proposed to determine the restoration priority of damaged pipeline. At every time-step of the post-earthquake restoration process, the proposed method calculates the repair efficiency of every damaged pipeline and selects the pipeline that holds the highest repair efficiency for reparation. In case study, the restoration sequences obtained by the proposed method and the global optimization method were implemented to evaluate the seismic resilience of a WDS. The application results show that the seismic resilience of WDS with the restoration sequence obtained by the proposed method is similar to that by the optimization method, whereas the computation complexity of the proposed method is less than 1% of the optimization method. Therefore, the dynamic cost-benefit method is capable to get nearly optimal restoration prioritization with less computation burden.

Keywords: Water distribution system; Seismic Resilience; Post-earthquake restoration; Restoration priority

1. Introduction

Water distribution system (WDS) is an important lifeline infrastructure system to facilitate continuous service to its customers widely distributed over urban areas. Following an earthquake, the structural damages of pipelines and other facilities may result in prolonged disruption of water services, and further increased socio-economics losses. Therefore, it is crucial to evaluate and enhance the seismic performance of WDS for disaster prevention and mitigation. In recent years, seismic resilient community has become the forefront of earthquake disaster prevention and mitigation [1]. Various studies have been carried out on resilience evaluation of WDS, and focus on quick recovery of performance losses after earthquakes.

Cimellaro et al. [2] proposed a quantitative index to measure seismic resilience of WDS according to the its post-earthquake performance curve by using time controlling after earthquakes. Diao et al. [3] proposed a global resilience analysis (GRA) approach for WDS in different failure modes including pipe burst, excess demand, and substance intrusion. The GRA approach assumed that all the failures are repaired simultaneously in a relatively short time (within 24 hours). However, the reality is that the earthquake-induced damages in the WDS are neither be repaired in 48 hours, nor simultaneously. In the research by Shi et al. [4], the 1994 Northridge earthquake caused extensive damages in the Los Angeles water distribution system, including 98 damages in trunk lines and 1013 damages in distribution pipelines. It was found that the post-earthquake WDS recovery has lasted 8 days. In addition, the reparation of all the damages took almost 6 months [5]. Due to the limitation of available repair crews and resources, it is essential to determine the repair priority of damages, owing to the reason that a smart repair priority may help improve the service of the WDS after earthquakes, and eventually result in enhancing the seismic resilience of WDS.

In the 16th International Computing & Control for Water Industry Conference (2018), a special competition session, “Battle of Post-Disaster Response and Restoration” (BPDRR), is set to deal with the restoration of a WDS after earthquakes, and make the best use of the available restoration resources [6]. The solutions to prioritize the repair of damages presented by competitors can be divided into three types: (i) prioritizing the repairs by single-criterion like the diameter of damaged pipelines [7,8], (ii) prioritizing the repairs by heuristic multi-criteria method [9,10], and (iii) prioritizing the repairs by an optimization method [11,12]. According to the results of the competition, the optimization method is more capable of providing a solution with the highest resilience. However, it is noted the computation time taken by the optimization is much longer than the other two methods. Therefore, it becomes necessary to develop a new method to get better results of reparation priority within a faster computation time.

This study firstly defines a quantitatively index to evaluate the seismic resilience of WDS. Then, a framework to quantitatively evaluate the seismic resilience of WDS is built. Next, to determine the restoration priority of pipeline damages, a new dynamic cost-benefit method is developed, and the global optimization method is also investigated. In case study, the two methods were tested in a real WDS to make comparisons.

2. Seismic resilience evaluation of WDS

The concepts of resilience are widely adopted in field of many disciplines. In earthquake engineering disciplines, Bruneau et al. [1] define the community seismic resilience as “the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes”. Based upon this, we adopt the definition of the seismic resilience of WDSs as “the joint ability to resist any possible seismic hazards, repair the initial damage, and recover to normal operation.”

2.1 Measurement of resilience

To quantify the seismic resilience of WDS, a resilience index is built upon the post-earthquake performance of the WDS during a period from t_0 to t_{end} (see Fig. 1), where t_0 is the time of occurrence of an earthquake, t_{end} is the end time of restoration. The post-earthquake period covers a disaster resistance stage ($t_0<t<t_1$), a

reaction stage ($t_1<t<t_2$) and a recovery stage ($t_2<t<t_{end}$). These three stages can respectively reflect the resistant, absorptive and restorative abilities of the WDS under that earthquake.

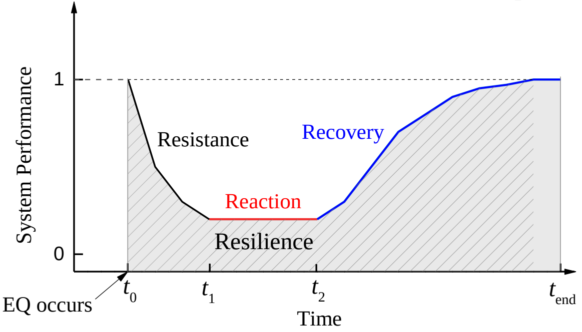

Fig. 1 - Performance curve of a WDS following an earthquake

The resilience index is then quantified according to the performance curve:

$$RI = \frac{1}{t_{end}-t_0}\int_{t_0}^{t_{end}} F(t)dt = \frac{1}{t_{end}-t_0}\int_{t_0}^{t_{end}} \frac{\sum_{i=1}^{n} Q_{avl,i}(t)}{\sum_{i=1}^{n} Q_{req,i}} dt \tag{1}$$

where $F(t)$ is the system performance of the water distribution system at time t. $Q_{avl,i}(t)$ is the available water supply of user node i at time t, and is evaluated by the hydraulic simulation of the WDS. $Q_{req,i}$ is the required demand of user node i before the earthquake, n is the number of user nodes in the WDS.

2.2 Framework to evaluate seismic resilience

Figure 2 shows the framework for the seismic resilience evaluation. A brief explanation of each step is provided below. The post-performance $F(t)$ is assessed through hydraulic simulation of WDS at each time. The water distribution system components in the simulation include the pipelines, reservoirs, pumps, and other facilities.

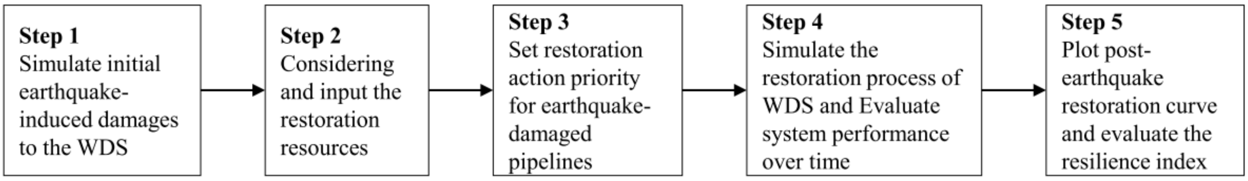

Fig. 2 - Framework for seismic resilience evaluation of WDS

Step 1. Simulate the initial seismic damage of the system immediately after the earthquake. The damages of pipelines are determined by earthquake intensity and fragility curves of pipelines. The hydraulic model of WDS with damages is established. The damages of other facilities, such as pump stations and valves, are not considered in this study.

Step 2. Input the available restoration resources, including the number repair crews, equipments, and materials. In this study, only the repair crews with sufficient support are considered, while the equipment and material requirement variations of different damages are not considered.

Step 3. Set the restoration priority for all discovered damages. A lot of pipelines are damaged after a severe earthquake and there are not enough repair crews available to attend to all the repairs of the damages immediately. Therefore, it is necessary to set a restoration priority for these damages. The methods of determining the restoration priority are described in details in section 3.

Step 4. The system restoration simulation starts according to the pre-determined restoration priority determined in Step 3. The restoration process of the WDS is conducted by repairing the damaged pipelines one after another. Once a damaged pipeline has been fixed, the hydraulic model of the WDS is synchronously updated. The performance of the WDS is monitored through the hydraulic simulation executed by an extension of EPANET [13]. The restoration process continues until the system recovers to its pre-earthquake status. The restoration simulation model of the restoration process is developed in section 2.3.

Step 5. Once the restoration process is completed, each performance of the WDS can be obtained from the simulation results. The simulation results are corresponding to the restoration priority applied in Step 3. Based on it, the performance curve can be plotted and the seismic resilience index can be calculated by Eq. (1).

2.3 Post-earthquake restoration simulation

To capture the characteristics of the real-time restoration process of water distribution system after an earthquake, a simulation model of restoration process is established based on the status of post-earthquake restoration of WDS. The assumptions and simplifications applied in the proposed model is similar to that by Zhang et al. [11] and Luna et al. [14]. The main features of this model include: (i) Only the damages of pipeline are included, the pump stations and the tanks are intact; the damage locations of pipelines are determined before the restoration; the damage types of pipelines are divided into breaks and leaks by using the descriptions developed by Shi et al. [4] (ii) Different damage types requires different kinds of restoration actions. For an instance, a broken pipe requires two successive actions -isolation and replacement - to be recovered, while a leaking pipe only needs one action - reparation. The time duration of different restoration actions varys depending on the charateristics of damaged-pipelines. (iii) Restoration work is independent of each other, and there is no mutual support between repair crews. Each crew can only carry out a one restoration action at a time, and the transportation time of repair crews between different locations is not included. (iv) The restoration process is divided into two phases: isolation phase and reparation phase. In the isolation phase, only isolation actions are prioritized and performed. Following the isolation phase, the actions of replacement and reparation are then prioritized and performed in the reparation phase. (v) The physical status of WDS changes after a restoration action is performed.

The restoration simulation model, based on the discrete-event simulation model [14], is applied to describe the relationship between the restoration actions and the status of WDS. The restoration model simulates the time-varying process of the restoration by tracking changes in the system status generated by the restoration actions. When an restoration action has been finished, the status of the pipelines and repair crews related to the action will change accordingly. In the model, the status of the pipes changes from broken to closed when they are isolated, and change from closed to undamaged/open when they are replaced. For a broken pipe, it should be isolated before being replaced. In addition, a leaking pipe only requires a reparation, and the pipe status changes from leaking to undamaged once its reparation is finished. The duration time T of each kind of restoration action is determined by Eq. (2) [6]:

$$T = \begin{cases} 0.25 \cdot n_{valve} \ , \quad isolation \\ 0.156 \cdot d^{0.179} \ , replacement \\ 0.223 \cdot d^{0.577} \ , \ reparation \end{cases} \tag{2}$$

where n_{valve} is the number of valves need to be closed, d is the diameter of the damaged pipe, *isolation*, *replacement*, and *reparation* are the types of restoration actions related to the damaged pipes.

The priority of restoration actions should be set before scheduling the restoration process. The restoration actions shall be sequenced according to the restoration priority. The strategy to determine the restoration priority for each action is shown in section 3.

Once the restoration priority for each action is set, a restoration schedule can be developed based upon the restoration priority and time taken by each action. Taking the damage scenario of WDS in Fig. 3 at time t_0 as an example, there are three damages and two repair crews. The pipes P6 and P11 have one leak each, and the P7 has one break. Thus, four restoration actions (isolation of P7, replacement of P7, reparation of P6, reparation of P11) are required. If the restoration priorities are isolation of P7 first, reparation of P6 second, reparation of P11 third, and replacement of P7 last, the restoration schedule is developed in Table 1. Each crew will follow the given schedule to isolate, repair and replace damaged pipes. The restoration process of the WDS is presented in Fig. 3. At the beginning, Crews 1 and 2 are dispatched respectively to isolate P7 and repair P6. Once the Crew 1 finishes the isolation task, it moves to repair P11. At the same time, Crew 2 starts to replace P7 when P6 has been repaired. Fig. 3 and Table 1 show that the schedule of the restoration process is determined by a) the assumptions listed aforementioned, b) the rules of discrete-event simulation model and c) the restoration priority for each action.

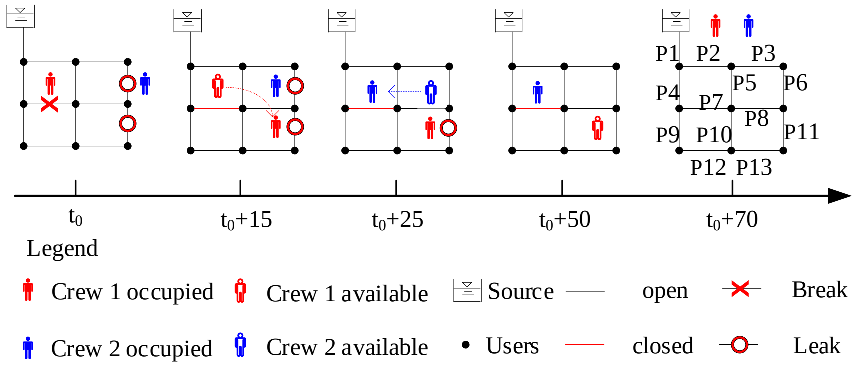

Fig. 3 – Illustration of the post-earthquake restoration process of WDS.

Table 1 - Schedule to restoration actions

Time	**Occurred Action**	**Finished Action**	**Pipeline status**
t_0	Isolation of P7. Reparation of P6	-	-
t_0+15	Reparation of P11	Isolation of P7.	P7: break→closed
t_0+25	Replacement of P7	Reparation of P6	P6: leak→open
t_0+50	-	Reparation of P11	P11: leak→open
t_0+70	-	Replacement of P7	P7: closed→open

2.4 System performance analysis during the restoration process

To assess the performance of the WDS at each time step during the restoration process, an extended period hydraulic simulation of the WDS is executed. The simulation has a total duration from t_0 to t_{end} with a time step of 1 hour. For each step, the status of the pipes will also be updated once they are isolated, repaired or replaced. Fig. 4 shows the models for broken and leaking of the pipelines in the hydraulic model [15,16]. As presented, the leak (Fig. 4(a)) is modeled by adding a dummy node with no demand, a fictitious pipe and an empty reservoir at the middle of the pipe (Fig. 4(b)). The elevation of the dummy node and reservoir are both equal to the average of the elevations of the end node of the pipe. A check valve is built into the fictious pipe, allowing water to flow only from the leaking pipe to the reservoir but not the reverse. The roughness and minor loss coefficients of the fictitious pipe are taken as infinite and 1, respectively. The diameter of the fictitious pipe is determined by the leak orifice area which determined by the leak type [15]. The break (Fig. 4(c)) is modeled by adding a dummy node, a fictitious pipe and a reservoir at both ends of the broken pipe (Fig. 4(d)). The settings in break model are same to the leak model except for that the diameter of the fictitious pipe in the break model is determined by the sectional area of the break pipe instead of the leak orifice area.

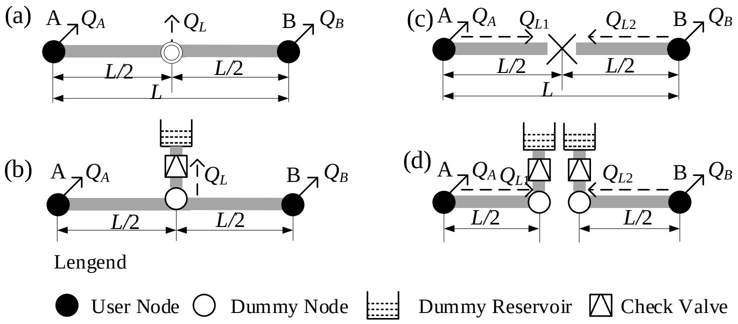

Fig. 4 - The hydraulic models of pipe leak and break. (a) Illustration of the pipe leak; (b) Hydraulic model for pipe leak; (c) Illustration of the pipe break; (d) Hydraulic model for pipe break.

In the hydraulic simulation, the Pressure Driven Analysis (PDA) approach is applied [7,17,18], as shown in Eq. (3). If the water pressure at node *i* satisfies the required pressure ($H_i \geq H_{req}$), the required demand is fully supplied. If the water pressure at node *i* is less than the required pressure, but larger than the minimum pressure ($H_{min}<H_i<H_{req}$), the required demand is partially supplied is depending on the nodal pressure. Finally, no water can be supplied for node *i* if its pressure is below the minimum pressure (H_{min}).

$$Q_{avl,i} = \begin{cases} 0 & , \quad H_i \leq H_{min} \\ Q_{req,i} \cdot \sqrt{\dfrac{H_i - H_{min}}{H_{req} - H_{min}}} & , \quad H_{min} < H_i < H_{req} \\ Q_{req,i} & , \quad H_{req} \leq H_i \end{cases} \tag{3}$$

where $Q_{avl,i}$ is the available water supply at node *i*, $Q_{req,i}$ is the required water demand at node *i*, H_i is the actual head at node *i*, H_{min} is minimal pressure head to supply water on the node, H_{req} is the pressure head required to fulfill the demand.

3. Restoration priority of pipeline damages

3.1 The global optimization method

To prioritize the restoration actions, the discrete nonlinear combinatory optimization model is established in this method [11,12]. The optimization model is generalized as:

$$\text{Search for } \vec{S} = (I_p, R_q); I_p \in E_{isolation}, R_q \in E_{reparation} \quad \text{to } \textit{maximize} \quad RI = F(\vec{S})$$

where $E_{isolation}$ is the set of actions in the isolation phase (see assumption (iv) in section 2.3 for explanation); $E_{reparation}$ is the set of actions in the reparation phase; *Ip* and R_q are restoration actions; $\vec{S}$ is the restoration sequence (priority) of all actions; *RI*, evaluated by Eq. (1), is the objective function. The optimization model can be solved by using the evolution algorithms, such as genetic algorithm [11,12], which requires tens of thousands of times of hydraulic simulations resulting in couples of days for calculation [11].

3.2 The dynamic cost-benefit method

This study proposed the dynamic cost-benefit method to determine the priority of restoration actions, in which assigning of a repair crew to a restoration action is regarded as an “investment”. The time duration taken by the restoration action is regarded as the “cost” of the “investment”. The performance growth of the WDS generated by the action is treated as the “benefit” of the “investment”. The priority of actions is determined by a dynamic indicator (*DI*), the ratio of the benefit to the cost, shown in Eq. (4).

$$DI_m(S) = \frac{\Delta F_m(S)}{T_m} \tag{4}$$

where T_m is the time duration taken by the restoration action *m*, *S* stands for the current status of the WDS, $\Delta F_m(S)$ is the performance growth of the WDS generated by the action *m* in the WDS status *S*, which can be calculated by Eq. (1). $DI_m(S)$ is the dynamic importance indicator of the action *m* while the WDS is in status *S*.

Since the benefit of each restoration action depends on the current status of the WDS, it changes when the status of the WDS changes after a restoration action is performed (see Fig. 5). Therefore, the list of restoration actions changes, and its restoration priority keeps changing as well. That is why the indicator of Eq. (4) is named as a dynamic indicator. The procedures of the method are described as follow:

Step 1: Calculate the performance of the WDS in the current status $F(S)$ by Eq. (1).

Step 2: Obtain the actions set and the time duration of each action in the current status *S*. For instance, the actions set is {1, 2, 3} in the status S_1, while {1, 2} in the status S_2 (see Fig. 5).

Step 3: Calculate the performance of the WDS in the status *S* while the action *m* is finished, $F(S+m)$. Evaluate the performance growth of the WDS, $\Delta F_m(S) = F(S+m)-F(S)$.

Step 4: Evaluate the $DI_m(S)$ for each action *m* according to Eq. (4).

Step 5: Give higher priority to the action with higher $DI_m(S)$, and update the current status once the action has been finished.

Repeat steps 1~5 until all the restoration actions are performed. Then each restoration action gets a dynamic importance indicator.

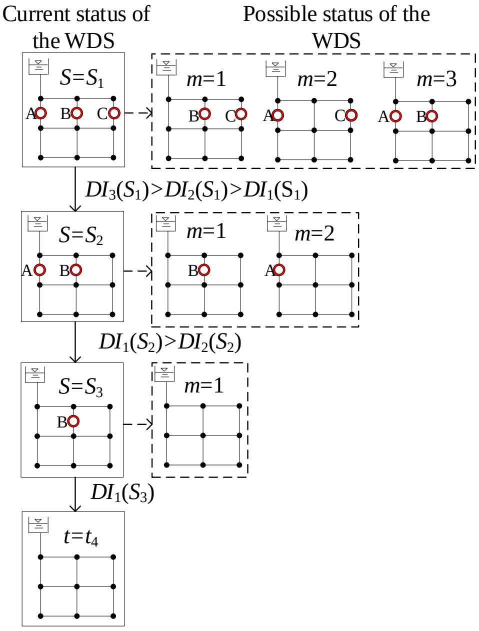

Fig. 5 - Illustration of the dynamic cost-benefit method

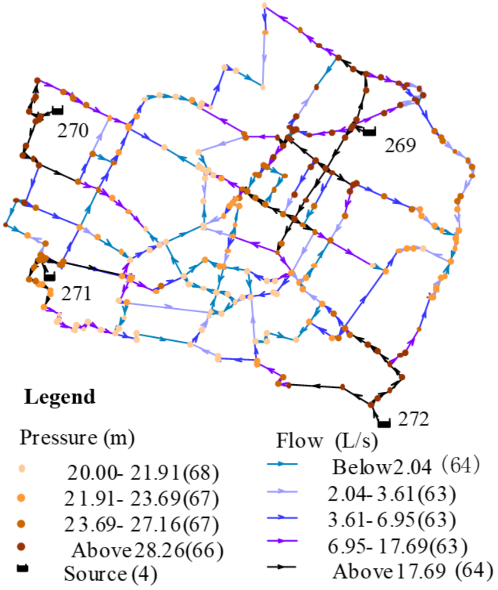

Fig. 6 - The water distribution system of Modena

4. Case study

The restoration priority methods described above and the restoration simulation model are applied to the WDS of Modena (see Fig. 6). This is a benchmark network in the field of optimal design of water distribution system [19]. The network is comprised of four reservoirs with fixed pressure heads, 268 user nodes and 317 pipes. The nodes' elevations range from 30.39m to 41.38m, and pipe diameters range from 100mm to 400 mm. The water demand of the entire network under normal operation is 406.94 L/s and the total length of the pipeline is 71.8 km.

4.1 Parameter setting

To compare the differences between the results of the global optimizaiton methods and the proposed dynamic cost-benefit method, nine earthquake damage scenarios are randomly generated. The number of damaged pipelines is determined according to the seismic repair rates of water supply pipelines and the length of pipelines in the WDS. The repair rates are acquired from the field investigation of 2008 Ms8.0 Wenchuan earthquake [20]. In particular, the repair rates of cast iron pipelines under the Chinese seismic intensity {VII, VIII, IX} are {0.44, 0.94, 1.90}. These repair rates are applied to the scenarios {1~3,4~6,7~9} respectively. For each repair rate, three ratios of pipe break to pipe leak {1:9, 3:7, 5:5} are adopted to simulate different damage levels induced by the variety of geotechnical conditions and the strength degradation of pipelines. The locations of the damaged pipelines are randomly chosen for the nine scenarios (see Fig. 7).

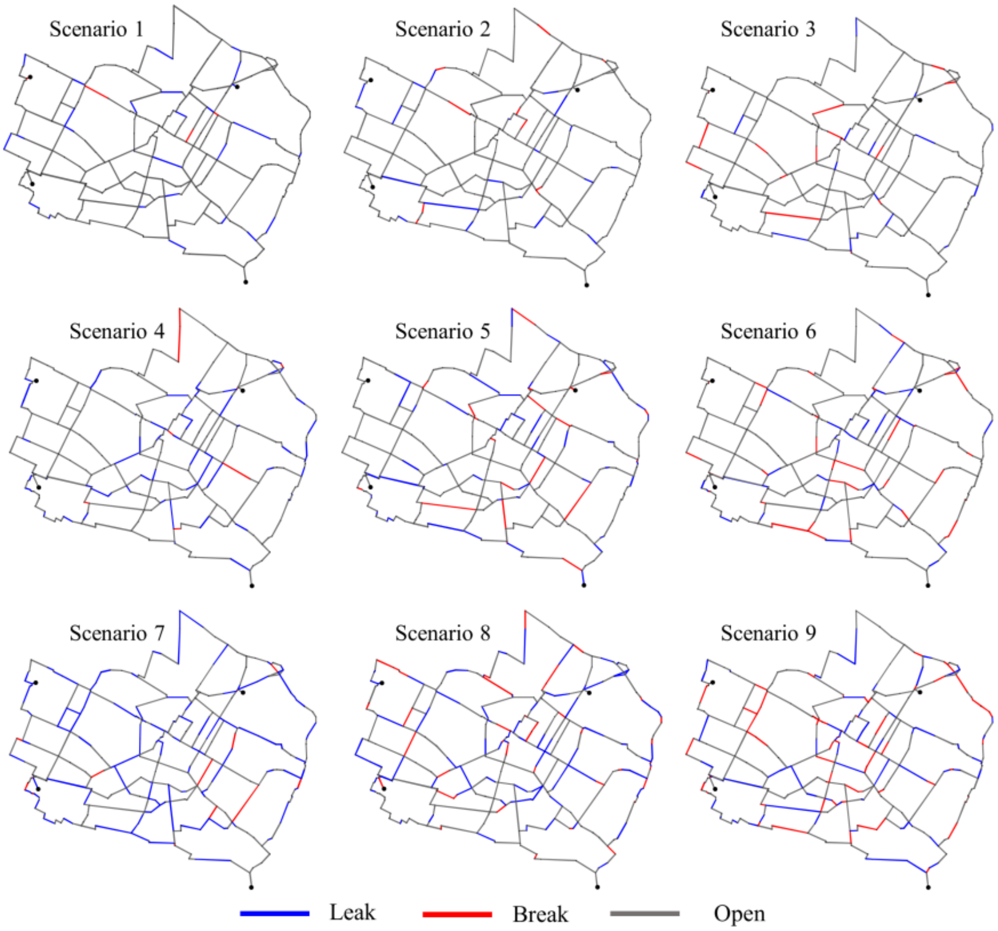

Fig. 7 - Seismic damage scenarios to the WDS

In the post-earthquake restoration simulation, the number of available repair crews is set as two. The post-earthquake restoration would terminate whilst all the damaged pipelines have been recovered to normality. The t_{end} of the post-earthquake restoration in Fig. 1 is the time that all damages have been recovered. In the restoration process simulation, an extended period hydraulic simulation was executed with a time step of 1 hour or the time interval between two sequential restoration actions. In each time step, the pressure driven analysis is utilized in the hydraulic simulation, and the required pressure head H_{req} is set as 20m, while the minimum pressure head H_{min} is 0 m. The settings of the methods for restoration priority are shown in Table 2.

Table 2 – Model parameters for restoration priority determination

Abbreviation	**Method**	**Description**
GOM	the global optimization method	Solved by Genetic Algorithm, the population size is 300， the evolutionary generation is 100, the crossover probability is 0.9, the mutation probability is 0.1
DCBM	the dynamic cost-benefit method	Sorting the actions by the *DI*

4.2 Application results

After the restoration simulation for each damage scenario of the WDS, the post-earthquake performance, $F(t)$, from t_0 to t_{end} was obtained, and the seismic resilience index was calculated by Eq. (1). Table 3 presents the *RI* of each damage scenario by using each method. In Table 3, among all the scenarios, the best restoration priority is mainy provided by the GOM. Meanwhile, the *RI* of the DCBM is close to the GOM. The relative differences between the *RI*s of the DCBM and the GOM for scenarios {1~9} are {-1.76%~2.25%}. And for scenario 1, the *RI*s of the DCBM and the GOM are same to each other resulted from that the restoration priority are almost the same.

Table 3 - RI values for different scenarios

Scenario No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
GOM	0.9335	0.9422	0.9171	0.8383	0.8194	0.8808	0.7717	0.7586	0.7421
DCBM	0.9335	0.9411	0.9146	0.8354	0.8200	0.8752	0.7853	0.7415	0.7446

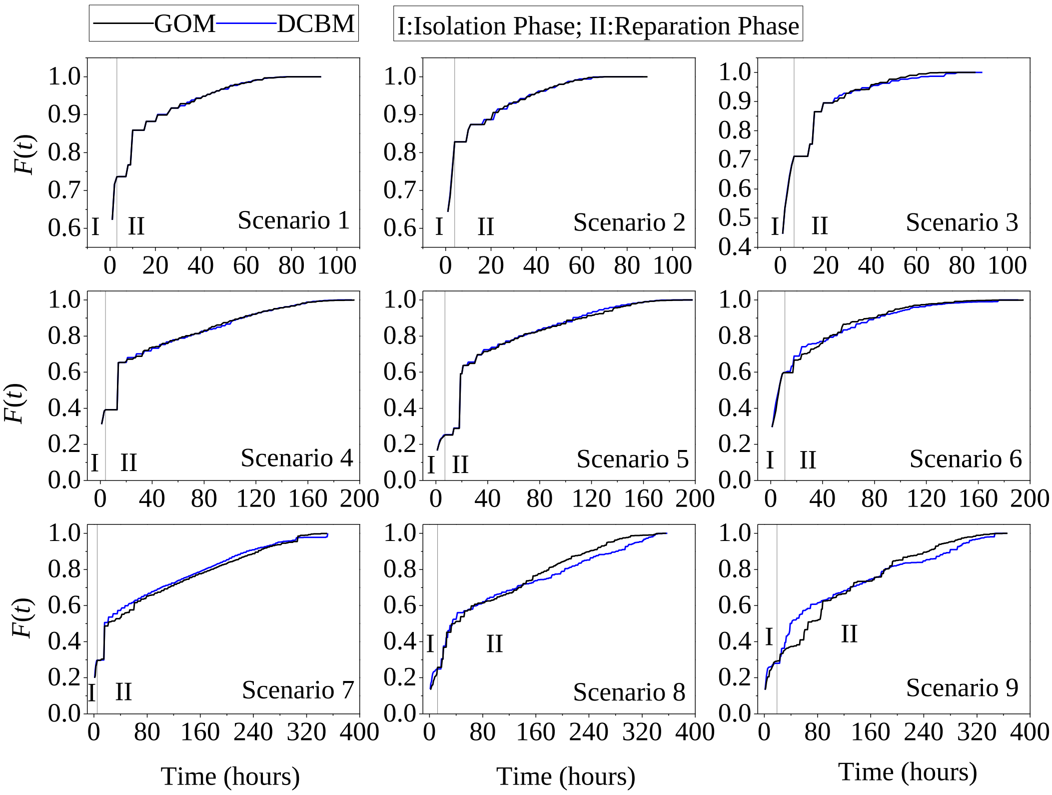

Fig. 8 - The performance recovery curve of WDS in nine scenarios.

Figure 8 presents the performance curves obtained from studying the nine scenarios by each method . It was found the curves in general increase as the restoration progresses. In the isolation phase, the performance curves are almost overlapped with each other in Scenarios 1, 2, 4, and 7, which suggests that the restoration priorities of different methods in the isolation phase have little difference. These overlaps result from that the number of isolation actions, determined by the number of broken pipes, is too small to make a difference. Moreover, the isolation priorities between the two methods are almost the same. It was found that isolating the broken pipes can enhance the post-earthquake performance of the WDS. That is, isolating the broken pipes would not only reduce the water losses, but also save the energy in the WDS. The saved water and energy can be used to satisfy users' demands and increase the performance curve. In the Scenarios 2, 3, and 6, the sharp climbing in performance curve means the isolation of broken pipes is an effective way when a trunk pipeline is damaged. In the reparation phase, the performance curves climb greatly at the beginning of Scenarios 1, 3, 4, 5, and 7, which is caused by the replacement of the isolated pipelines. It indicates that the water supply is greatly affected when some trunk pipelines are isolated. Once these pipelines are reopened, the performance will enhance dramatically.

The computation time cost by the hydraulic simulation of the WDS takes the main part of the whole procedure of each method. The number of one-time hydraulic simulations is regarded as an indicator to measure the computation complexity of each method. Table 4 presents the number of SPHSs of each method in the nine damage scenarios. The GOM takes the largest number of one-time hydraulic simulations, which correspond to the largest computational burden. In the different damage scenarios of the WDS, the computational complexity of DCBM is about 0.10%~0.34% of the GOM. The GOM takes the largest number of hydraulic simulations because the genetic algorithm is used to solve the optimization problem in its procedure. In the evolution process of the genetic algorithm, the performance of WDS corresponds to every possible restoration schedule (individual) at each generation. It needs to be evaluated through the restoration simulation, causing an extended period (time) hydraulic simulation. There are two main factors affecting the number of hydraulic simulations, being a) the population and generation setting in the genetic algorithm, and b) the length of the extended period hydraulic simulation. The former is affected by specific technologies utilized in the generic algorithm. The latter is affected by the number of restoration actions related to the number of pipeline leaks and breaks. Although the *RI* values of individuals are stored to avoid repeated calculation, tens of thousands of one-time hydraulic simulations are still needed.

Table 4 - The number of hydraulic simulations for each method.

Scenario No.	1	2	3	4	5	6	7	8	9
GOM	649285	664143	650162	2539382	2450004	2269009	6133849	4307759	3569562
DCBM	631	671	751	2858	3677	3585	9912	10712	12234

5. Conclusions

Lots of pipelines are damaged during a severe earthquake and it can affect the water distribution systems (WDS). Owing to the limited post-earthquake available resources, it is necessary to prioritize the restoration actions of the damages. This study thus proposed a dynamic cost-benefit method to determine the restoration sequence of the WDS damaged by earthquakes to enhance the post-earthquake performance of WDS, with a further goal to increasing the seismic resilience of the WDS. In this study, the post-earthquake restoration process of the WDS was simulated according to the restoration priority by a discrete event dynamic system-based model. It was found the post-earthquake status and hydraulic performance of the WDS changed according to the process of restoration actions. The seismic resilience was also evaluated based on the post-earthquake performance curve of the WDS in this study.

The dynamic cost-benefit method for restoration prioritization is proposed to get better post-earthquake performance curves of the WDS with less computation burden. In the case study, application results of the proposed method were compared with the global optimization method. The results show that: (i) the performance curves obtained by the global optimization method and the dynamic cost-benefit method are close to each other. This indicates that the resilience indexes of these two methods are similar to each other; (ii) the global optimization method takes plenty of computation burden, whereas the computation complexity of the proposed dynamic cost-benefit method takes only about 0.1%~0.34% of the global optimization method.

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