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Seismic Resilience Enhancement of Urban Water Distribution System Using Restoration Priority of Pipeline Damages

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Received: 7 November 2019; Accepted: 23 January 2020; Published: 26 January 2020

Abstract: The malfunction of the water distribution system (WDS) following severe earthquakes have significant impacts on the post-earthquake rescue. Moreover, the restoration priority of earthquake-induced pipeline damages plays an important role in improving the post-earthquake serviceability of WDS and the "seismic resilience". Thus, to enhance the seismic resilience of WDS, this study develops a dynamic cost-benefit method and introduces three existing methods to determine the restoration priority of pipeline damages based on a quantitative resilience evaluation framework. In this resilience evaluation framework, the restoration priority is firstly determined. Then the time-varying performance of post-earthquake WDS is modeled as a discrete event dynamic system. In this model, the system state changes after the reparation of pipeline damage, and the system performance is simulated by a hydraulic model to be consistent with the system state. In this study, this method is also tested and compared with other existing methods, and the results show that the system resilience corresponding to the restoration priority obtained by this method is close to that obtained by the global optimization method with a relative difference of less than 3%, whereas the calculation complexity is about 0.4% of the optimization model. It is concluded that this proposed method is valid.

Keywords: water distribution system; seismic resilience; post-earthquake restoration; repair priority

1. Introduction

The water distribution system (WDS) is an important lifeline infrastructure system to facilitate continuous service to its customers widely distributed over urban areas. When an earthquake disaster occurs, 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 the seismic performance of WDS for disaster prevention and mitigation.

Many models have been developed to evaluate the structural damage of pipelines and system performance affected by those damages. For example, Takada and Tanabe [1], O'Rourke and Liu [2], Shi [3] utilized a mechanical model to analyze the structural response of pipelines to transient ground seismic wave propagation or permanent movements of the ground. Isoyama et al. [4], Jeon and O'Rourke [5] also used statistic formulas to estimate the average repair rate of pipelines according to earthquake damage records. Moreover, American Lifeline Alliance (ALA) [6] developed seismic fragility formulations for structural components of WDS, such as pipelines, tanks, and other water supply facilities. Based on the seismic fragility analysis of structural components, system-level response evaluation of WDS is conducted in various ways. For example, Li and He [7], Adachi and Ellingwood [8], and Lim and Song [9] evaluated the seismic serviceability of WDS via measuring the network connectivity reliability. Hwang et al. [10], Shi and O'Rourke [11], Yoo et al. [12], and Laucelli and Giustolisi [13] also utilized the hydraulic model for flow and pressure analysis to better understand of post-earthquake serviceability of WDS. Those above-mentioned models are of great importance for advance preparations to minimize the degree of system performance losses immediately after an earthquake. However, it was known these models are still limited in assisting in dealing with the system performance losses.

In recent years, resilient community and seismic resilience have become the forefront of earthquake disaster prevention and mitigation. The seismic resilience includes the effects of losses, mitigation, and rapid recovery [14]. Various studies have been carried out on resilience evaluation of WDS, and focus has been on quick recovery of performance losses after earthquakes. Davis [15] divided the normal water service into five categories: (1) water delivery, (2) quality, (3) quantity, (4) fire protection, and (5) functionality. Although the characteristics and interactions of the five categories during the post-earthquake restoration were explained, no quantitative metric was introduced. Cimellaro et al. [16] proposed a quantitative index to measure seismic resilience according to the performance curve of WDS by using time controlling after earthquakes. Diao et al. [17] proposed a global resilience analysis (GRA) approach for WDS in different failure modes including pipe burst, excess demand, and substance intrusion. This approach was believed as an efficient tool for resilience analysis of WDS. The GRA approach also assumed that all the failures are repaired simultaneously in a relatively short time—within 24 h. However, the reality is that the failures in the WDS are neither be repaired in 48 h, nor simultaneously. In the report by Shi et al. [18], 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 [19]. Another example includes the 22 February 2011, Christchurch earthquake. It took 30 days to restore the water service of Christchurch city to 95% of its pre-earthquake level [20]. In Kammouh et al.'s research [21], 32 earthquakes with magnitude range from M6.0~M9.5 were investigated. A large number of pipelines can be damaged in the WDS after a severe earthquake. In these earthquakes, the WDS restoration periods of time are varying differently. The longest restoration duration lasted 73 days, and the median restoration duration lasted eight days. 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 well-evaluated repair priority may help improve the service of the WDS after earthquakes and eventually result in enhancing the seismic resilience of WDS.

Choi et al. [22] established a simulation model for post-earthquake restoration by producing the probabilistic seismic event and quantifying the system restoration rate over time by hydraulic stimulation with EPANET2. Although this simulation model intends to propose a superb restoration plan, the restoration priority is determined by attributes of damage pipes and only the break pipes are considered in the restoration. 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. 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 [22,23], (ii) prioritizing the repairs by heuristic multi-criteria method [24,25], and (iii) prioritizing the repairs by an optimization method [26,27]. According to the results of the competition, the optimization method is more capable of providing a solution with the highest resilience index. 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.

Therefore, this study firstly defines a quantitative 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 three existing methods (the single-criterion method, the multi-criteria method, and the global optimization method) are investigated. Moreover, a discrete-event-simulation-based model is developed to simulate the restoration process of the WDS under the restoration priority determined by the mentioned methods. In this study, all four methods were tested in a water distribution system (WDS) in a case study.

2. Materials and Methods

2.1. Definition of the Seismic Resilience of WDS

The concepts of resilience are routinely used in research in different disciplines. In engineering disciplines, Bruneau et al. [14] 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 accept 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." To quantify the resilience, a resilience index is built upon the post-earthquake performance of the WDS during a period from t_0 to t_{end} (see Figure 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 ($t_2<t<t_{\text{end}}$). These three stages can respectively reflect the resistant, absorptive and restorative abilities of the WDS under that earthquake. Resilience is then quantified according to the targeted performance curve $F(t)$ and the expected performance curve:

$$RI = \frac{1}{t_{\text{end}} - t_0} \int_{t_0}^{t_{\text{end}}} F(t)dt \quad (1)$$

where $F(t)$ is an index to measure the performance of the water distribution system at time t.

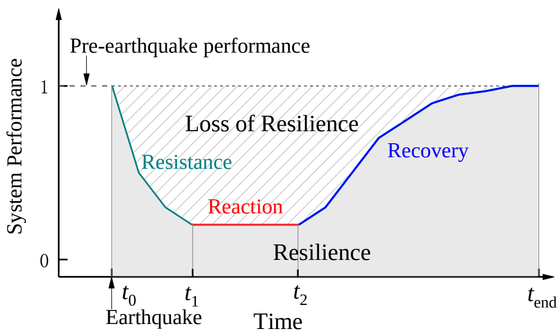

Figure 1. Performance curve of a water distribution system (WDS) following an earthquake.

According to the hydraulic simulation results of the WDS, the post-earthquake performance of the WDS, $F(t)$, is evaluated by the ratio of the actual supply to the required demand of the entire system.

$$F(t) = \frac{\sum_{i=1}^{N} Q_{avl,i}(t)}{\sum_{i=1}^{N} Q_{req,i}(t)} \quad (2)$$

where $Q_{avl,i}(t)$ is the available supply of node I at time t, Q_0 is the required demand of node I at time t, N is the number of nodes in the WDS.

2.2. General Framework for Seismic Resilience Evaluation

Figure 2 shows the framework for seismic resilience evaluation. A brief explanation of each step is provided below. To evaluate the seismic resilience of WDS, the performance of WDS is assessed through hydraulic simulation. The water distribution system components in the simulation include the pipelines, reservoirs, pumps, and other facilities. The current simulation only includes the seismic damages to pipelines.

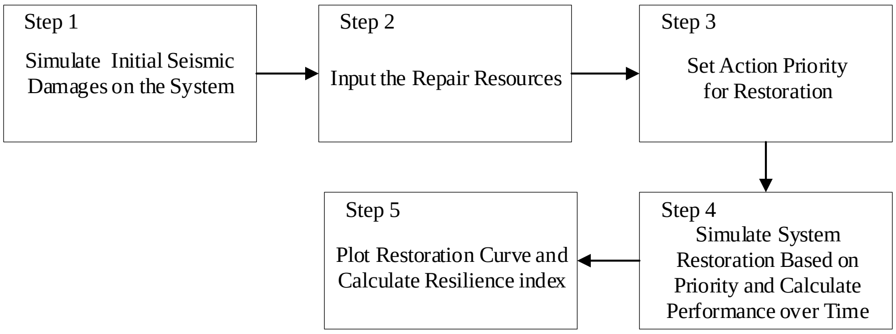

Figure 2. Flow chart of the framework for seismic resilience evaluation.

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. Consider and input the available restoration resources, including the repair crew, equipment, and material. In this study, only the repair crews with sufficient support are considered, while the equipment and material requirement variation 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 detail in Section 2.3.

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 modifications of EPANET [28]. 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 2.4.

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 Equation (1).

2.3. Determine the Restoration Priority of Pipeline Damages

In this section, three existing prioritization methods are firstly investigated. Following the investigation, a new prioritization method is presented. The new method takes account of the WDS performance benefits and the status of the WDS during the restoration (Section 2.4.1 for explanation).

2.3.1. Introduction to Existing Methods

(1) The single-criterion method

This method consists of three steps: (1) Select a proper criterion to evaluate the importance of pipelines in the WDS, (2) Determine a measurable indicator for the chosen criterion, and calculate the indicators for pipelines, (3) Sort the priority for damaged pipelines according to the indicators, to determine the priority for restoration actions. This method follows assumptions that (a) the prioritization method should be 'as easy as possible' [23], and (b) the restoration actions can be prioritized even without hydraulic simulation. The key step of the method is to choose the criterion. Existing commonly used criteria include the pipe diameter [23], the water flow through the pipeline, the distance to water source [22], and other pipe attributes related to the restoration action. For example, "Pipes carrying higher water flow get higher repair priority" [22] is used as a single-criterion to determine the restoration priority for break pipes. The hydraulic importance (*HI*) of a pipeline is an index to quantize the decrease of the pressure of the WDS by excluding pipe [29]. The calculation of the *HI* can also assess the impacts of a pipe failure through closing the pipe, shown in Equation (3), which is suitable to determine the restoration priority for the damaged pipelines.

$$HI_j = \frac{1}{n}\sum_{i=1}^{n}(h_i^0 - h_i^j) \tag{3}$$

where HI_j is the hydraulic importance of pipeline j, ${h_i}^0$ is the pressure head at node i in normal working conditions, ${h_i}^j$ is the pressure head at node i in the conditions of closing pipeline j, n is the number of the nodes in the WDS.

(2) The multi-criteria method

This method consists of three steps: (1) Select two or more criteria to prioritize the restoration actions. (2) Classify the selected criteria as the primary criterion, secondary criterion and so on. (3) Prioritize the restoration actions by the primary criterion, as described in the single-criterion method. If any actions get the same priority by using the primary criterion, the second criterion is to be used to prioritize them. This method has been used in Luna et al. [30] studies. In detail, they give a higher priority to the breaks than the leaks (the prime criteria) and a next priority to the pipelines with a higher diameter (the secondary criteria). In the restoration process of the WDS after the 1994 Northridge earthquake, The LADWP (Los Angeles Department of Water and Power) [31] repaired the failures in the WDS through a three-criteria. Criterion 1 (the primary criterion) prioritizes the failure in the trunk pipeline than the distribution pipelines. Criterion 2 (the secondary criterion) prioritizes the break than the leak. Criterion 3 (the tertiary criterion) prioritizes the straight-line distance of the failure to the nearest water source, with the closest pipelines getting the highest priority.

(3) The global optimization method

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

$$\text{Search for } \vec{S} = (I_p, R_q); I_p \in E_{phase1}, R_q \in E_{phase2} \tag{4}$$

$$\text{Maximizes}: \ RI = F(\vec{S}) \tag{5}$$

where $Ephase_1$ is the set of actions in the isolation phase (see Section 2.4.1 for explanation), Ip is the action p, $Ephase_2$ is the set of actions in the reparation phase, R_q is the action q, $\vec{S}$ is the restoration sequence (priority) of all actions, *RI*, calculated by Equation (1), is the objective function. The optimization model can be solved by using the evolution algorithms, such as a genetic algorithm [26,32,33], which requires tens of thousands of times of hydraulic simulations resulting in a couple of days for calculation [27].

2.3.2. The Dynamic Cost-benefit Method

This study developed this dynamic cost-benefit method, in which assigning a repair crew to a restoration action is regarded as an "investment". The duration time 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 the action is determined by a dynamic indicator (*DI*), the ratio of the benefit to the cost, shown in Equation (6).

$$DI_m(S) = \frac{\Delta F_m(S)}{T_m} \tag{6}$$

where T_m is the duration time 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 Equation (2). $DI_m(S)$ 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 the restoration is performed (see Figure 3). Therefore, the list of restoration actions changes and its restoration priority keeps changing as well. That is why the indicator of Equation (6) is named as a dynamic indicator. The procedures of the method are described as follow:

1. Calculate $F(S)$ by Equation (2), and the performance of the WDS is in the current status S.
2. Obtain the actions set and the time taken by 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 Figure 3).
3. Calculate the performance of the WDS in the status S while the action m is completed, F (S+m). Evaluate the performance growth of the WDS, $\Delta F_m(S) = F(S+m)-F(S)$.
4. Evaluate the $DI_m(S)$ for each action m according to Equation (6).
5. Give higher priority to the action with higher $DI_m(S)$, and update the current status once the action has been performed.
6. Repeat 1~5 until all the restoration actions are performed.
7. Each restoration action gets a dynamic importance indicator.

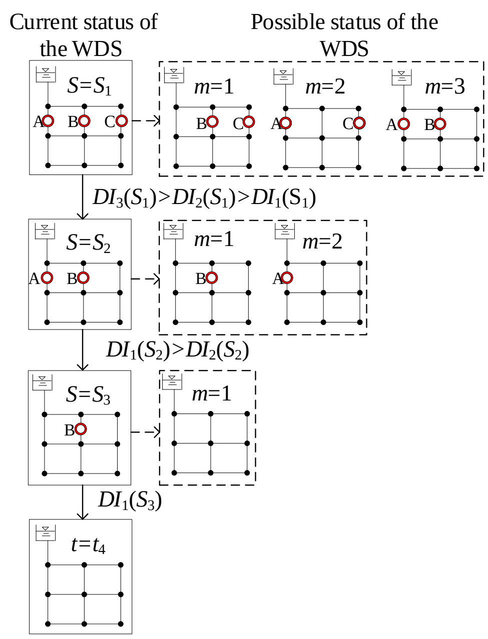

Figure 3. Illustration of the cost-benefit method schematic.

2.4. Post-Earthquake Restoration Simulation

2.4.1. Assumptions and Simplifications

To capture the characteristics of the real-time restoration process of the water distribution system after an earthquake, a simulation model of the restoration process is established based on the records of the post-earthquake restoration of WDS. Table 1 summarizes the assumptions and simplifications applied in the proposed model. The main features of this model include: (i) the damage types of pipelines are divided into breaks and leaks by using the descriptions developed by Shi et al. [18], (ii) different damage types require different kinds of restoration actions. For instance, a broken pipe requires two successive actions -isolation and replacement - to be recovered, while a leaking pipe only needs one action - reparation. (iii) the duration time of restoration actions can vary to repair different damages of the pipelines.

Table 1. Model assumptions.

No	Assumptions	Tabucchi & Davidson [31]	Luna et al. [30]	Ouyang & Wang. [34]	Zhang et al. [26]	Choi et al. [22]
1	Restoration work is independent of each other, and there is no mutual support between repair crews;	○	○	○	○	○
2	Regardless of the movement time of repair crews between different locations;	×	○	○	○	×
3	The damage locations of pipelines are determined before the restoration;	×	○	○	×	○
4	The repair priority of damages is determined before the restoration and keep unchanged during the restoration process;	×	○	○	×	○
5	Only the damages of pipeline are included, the pump stations and the tanks are intact;	○	○	×	○	○
6	The physical status of WDS changes when restoration action performed;	○	○	○	○	○
7	Each crew can only carry out a single restoration action at a time;	○	○	○	○	○
8	When a repair crew completes a task, a new repair task is assigned immediately, without rest.	×	○	○	○	○

Notes: ○ include, × not include.

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.

Although lots of pipelines and facilities damaged after an earthquake, the water supply should never stop if it is still able to provide water to the public. It is necessary to keep water supplying for supporting vital public services, such as hospitals. In the 2016 Tainan earthquake, patients with earthquake-related injuries constituted 62.8% of all traumatic patients in the 24-h aftermath [35]. There is much more water demand for hospital post-earthquake than pre-earthquake. Failure of a large number of pipes does not necessarily result in catastrophic impacts [17]. the study of Diao et al. [17] shows that some networks can still deliver 86% of total demand with 70% of pipes failed if critical pipes remain undamaged. Therefore, the water distribution network is assumed to be continuing to supply water during the restoration period.

2.4.2. The Simulation Model of the Restoration Process

The restoration simulation model, based on the discrete-event simulation model, 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.

There are four key elements in the restoration simulation model: entity, resource, variables, and event. The entities are the components in the real water distribution network such as pipelines, reservoirs, pumps and other facilities. The resource refers to the repair crew and repair material. The resource is a special type of element that can move and provide service to entities. The variables describe the states of the entity and resource. For pipelines, four types of variables/status (undamaged/open, leaking, broken, and closed) are considered. The event refers to a set of actions including isolation, reparation, and replacement. The event should be performed by the resources.

When an event (restoration action) has been performed, the variables (status) of the entities (pipelines) and resources (repair crews) related to the event will also 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 event/action is determined by Equation (7) [36]:

$$T = \begin{cases} 0.25 \cdot n_{valve} & , \quad isolation \\ 0.156 \cdot d^{0.179} & , \quad replacement \\ 0.223 \cdot d^{0.577} & , \quad reparation \end{cases} \tag{7}$$

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

The restoration priority of events (actions) should be set before scheduling the restoration process. The restoration events shall be sequenced according to the restoration priority. As shown in Figure 4, the event is assigned to each available repair crew in sequence. The strategy to determine the restoration priority for each event is shown in Section 2.3.

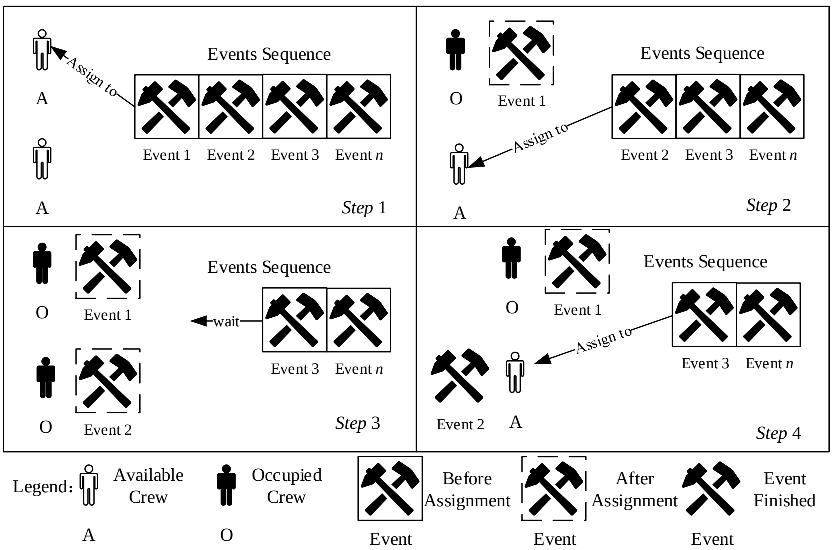

Figure 4. The procedure of the events assigned to the crews.

Once the restoration priority for each event is set, a restoration schedule can be developed based upon the restoration priority and time taken by each event. Taking the damage scenario of WDS in Figure 5 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 events (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 2. Each crew will follow the given schedule to isolate, repair and replace damaged pipes. The restoration process of the WDS is presented in Figure 5. In 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. Figure 5 and Table 2 show that the schedule of the restoration process is determined by (a) the assumptions discussed in Section 2.4.1, (b) the rules of the discrete-event simulation model and (c) the restoration priority for each event.

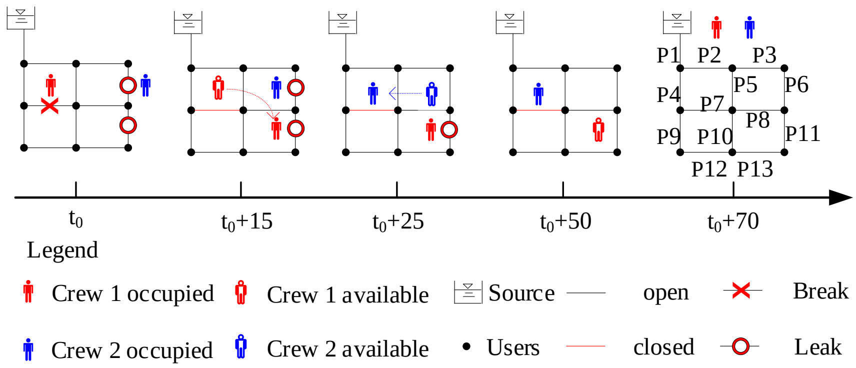

Figure 5. An example of the post-earthquake restoration process of WDS.

Table 2. The schedule of the restoration.

Time	Events Occurred	Events Finished	The Pipe Status
t_0	The isolation of P7.The reparation of P6	—	—
$t_0 + 15$	The reparation of P11	The isolation of P7.	P7: break→closed
$t_0 + 25$	The replacement of P7	The reparation of P6	P6: leak→open
$t_0 + 50$	——	The reparation of P11	P11: leak→open
$t_0 + 70$	——	The replacement of P7	P7: closed→open

The break pipe can be isolated by close the valves nearby. As shown in Figure 6, according to the positions of valves, the pipelines are divided into four categories. In the restoration simulation, to close a valve, a pipe containing it must be closed. A break pipe can be isolated by close itself if it is type 3. Two or more pipes need to be closed for the pipeline category 0, 1, or 2. Figure 7 illustrates the WDS segments formed by valves isolations. If the pipe P6 in segment 3needs to be isolated, then P3, P8, and P11 need to be closed.

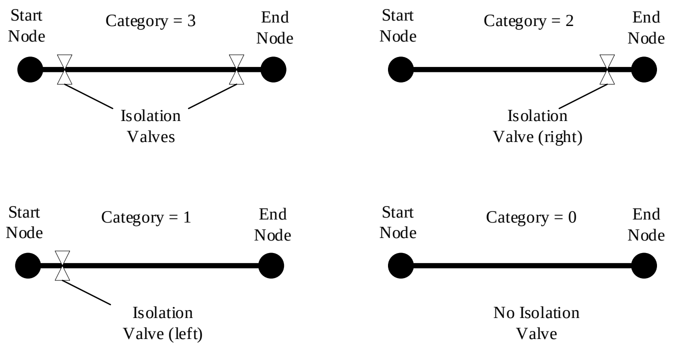

Figure 6. Pipeline categories according to the valve's position.

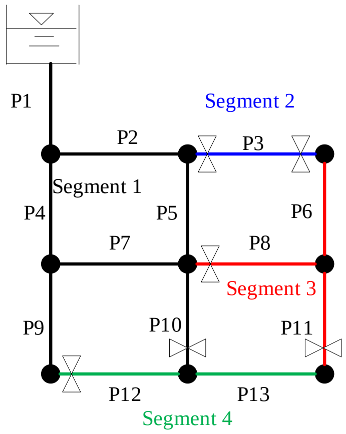

Figure 7. Illustration of segments formed by valves.

2.4.3. Performance Assessment of the WDS

To assess each performance of the WDS during the restoration process, an extended period of 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. Figure 8 shows the models for the broken and leaking of the pipelines in the hydraulic model [11,37]. As presented, the leak (Figure 8a) is modeled by adding a dummy node with no demand, a fictitious pipe and an empty reservoir in the middle of the pipe (Figure 8b). 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 fictitious 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 [11]. The break (Figure 8c) is modeled by adding a dummy node, a fictitious pipe and a reservoir at both ends of the broken pipe (Figure 8d). The settings in break model are the same as 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.

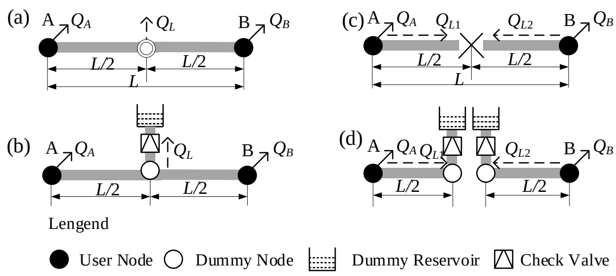

Figure 8. The hydraulic model of leak and break. (**a**) Illustration of the pipe leak, (**b**) Hydraulic model for pipe leak, (**c**) Illustration of the pipe break, (**d**) Hydraulic model for pipe break.

In the hydraulic simulation, the Pressure Driven Analysis (PDA) approach is applied [38], as shown in Equation (8). If the water pressure at node *i* satisfies the required pressure ($H_i \geq H_{req}$), the required demand is fully distributed. 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}).

$$Q_{avl,i} = \begin{cases} 0 & , \quad H_i < H_{min} \\ Q_{req,i} \cdot \sqrt{\frac{H_i - H_{min}}{H_{req} - H_{min}}} & , \quad H_{min} < H_i < H_{req} \\ Q_{req,i} & , \quad H_{req} < H_i \end{cases} \tag{8}$$

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. Application and Results

3.1. Example Network and Damage Scenarios

The restoration priority methods described above and the restoration simulation model are applied to the WDS of Modena (see Figure 9). Modena is a medium city in the Emilia-Romagna region of northern Italy. The area of Modena is 183.2 square kilometers. The WDS of Modena city is used as a benchmark by Bragalli et al. [39] for the optimization design of WDS, the hydraulic model of this WDS is open access at the website of the Centre for Water Systems in Exeter University. The Emilia-Romagna region is prone to earthquakes, seismic events frequently occurred in this region since the 1800s [40]. In May-June 2012, consecutive earthquake sequence affected this region. The major event is the ML 5.9. earthquake on 20 May 2012, and produced serious damages. Modena is one of the cities hit by these seismic events [41]. As shown in Figure 9, the network is comprised of four reservoirs with fixed pressure heads, 268 user nodes and 317 pipes. The nodes' elevations are distributed in a range from 30.39 m to 41.38 m, and the pipe diameters are ranging from 100 mm–400 mm. The normal water demand of the entire network is 406.94 L/s and the total length of the pipe is 71,810 m.

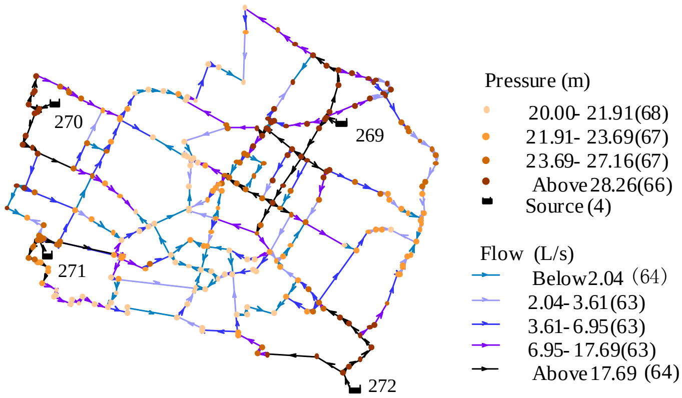

Figure 9. The water distribution network of Modena.

To compare the differences between the results of the three existing restoration prioritization methods and the proposed dynamic cost-benefit method, nine earthquake damage scenarios are randomly generated. The number of damaged pipelines in each scenario is presented in Table 3. 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 the 2008 Ms8.0 Wenchuan earthquake [42]. 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 Figure 10). Table S1 in Supplementary Material shows the detail information for each scenario.

Table 3. The damage information summary of nine scenarios.

Damage Scenarios No.	Number of Breaks	Number of Leaks	Number of Damages
1	4	28	32
2	10	22	32
3	16	16	32
4	8	64	72
5	22	50	72
6	36	36	72
7	14	123	137
8	42	95	137
9	69	68	137

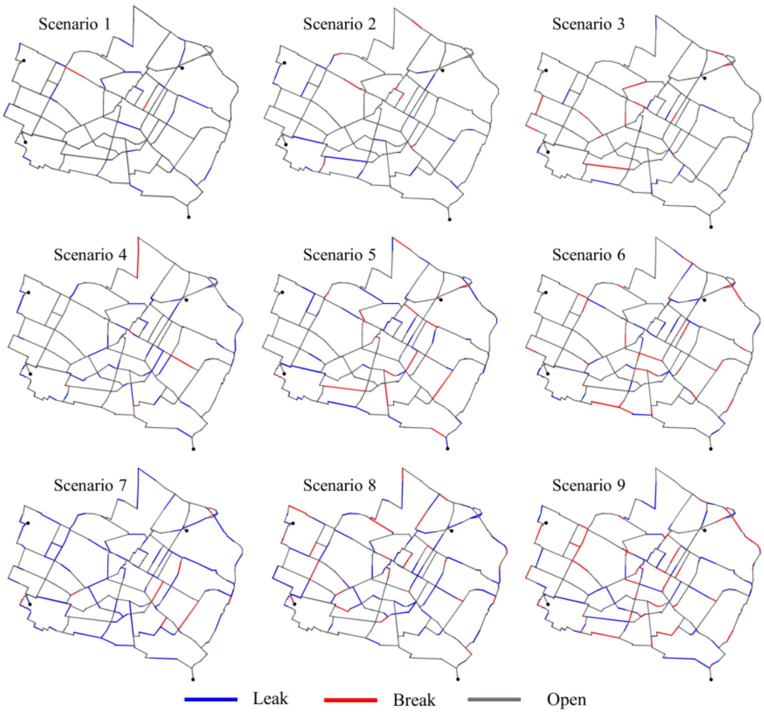

Figure 10. Damage scenarios.

3.2. Parameters of the Restoration Simulation

In the post-earthquake restoration simulation, the number of available repair crews was 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 Figure 1 is the time that all damages have been attended and recovered. In the restoration simulation, an extended period hydraulic simulation was executed with a time step of 1 h or the time interval between two sequential restoration actions. In each time step, the pressure-driven analysis (PDA) is utilized in the hydraulic simulation, and the required pressure head H_{req} is set as 20 m, while the minimum pressure head H_{min} is 0 m. The settings of the four methods for restoration priority are shown in Table 4. It should be noted that the priority rules used by MCM are almost the same as those used by LADWP in the 1994 Northridge earthquake.

In Section 3.3, the assumption is accepted that shut-off valves exist at both ends of each pipe, which means all pipes are category 3 (Figure 6) in the WDS. In Section 3.4, the effects of pipelines categories considering the position of valves are discussed.

Table 4. Parameters of the methods for restoration priority determination.

Abb.	Method	Description
SCM	the single-criterion method	Sorting the events by the hydraulic importance (*HI*)
MCM	the multi-criteria method	Primary criterion: damage type, break prior to the leak Secondary criterion: the straight-line distance to water resources
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 events by the *DI*

3.3. Results of Applications (Valves at Both Ends of Pipelines)

3.3.1. Comparison of Resilience Index (RI)

After the restoration simulation for each damage scenario of the WDS, the post-earthquake performance, F(t), from t_0 to tend was obtained, and the seismic resilience index was calculated by Equation (1). Table 5 presents the RI of each damage scenario by using each method. In Table 5, the restoration priorities determined by the global optimization method (GOM) and the dynamic cost-benefit method (DCBM) have higher *RI* values than the restoration priorities determined by the single-criterion method (SCM) and the multi-criteria method (MCM). This finding suggests that, in terms of resilience, the GOM and DCBM provide better restoration schedules for the post-earthquake restoration of the example WDS than the SCM and MCM in most scenarios. Among all the methods, the best restoration priority is 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%}. For scenario 1, the *RI*s of the DCBM and the GOM are the same as each other resulted from that the restoration priority is almost the same (the restoration priority is in Table S2 in Supplementary Material). It was also found the *RI* values of the multi-criteria method (MCM) are the smallest in almost every scenario (except for scenario 1). The smallest *RI* values suggest that the indicator "straight-line distance to water resources" may be an ineffective index compared with the hydraulic importance (used in single-criterion method) for assessing the restoration priority of damaged pipelines.

Table 5. *RI* values for the four methods.

Scenario No.	SCM	MCM	GOM	DCBM
1	0.9011	0.9028	**0.9335**	**0.9335**
2	0.9280	0.9071	**0.9422**	0.9411
3	0.8992	0.8841	**0.9171**	0.9146
4	0.8096	0.7846	**0.8383**	0.8354
5	0.7866	0.7542	0.8194	**0.8200**
6	0.8475	0.8098	**0.8808**	0.8752
7	0.7162	0.6990	0.7717	**0.7853**
8	0.7231	0.6886	**0.7586**	0.7415
9	0.7356	0.7006	0.7421	**0.7446**

Note: Bold text denotes the highest value for each scenario.

Due to the lack of earthquake damage records and recovery information, the methods were tested on the basis of simulated earthquake events. To the best of our knowledge, only Tabucchi and Davidson [31] validated the water distribution network restoration simulation based on the real restoration records in the earthquake. The hydraulic model of the damaged network in this study and in the research of Tabucchi and Davidson [31] are both built based on the same model developed by Shi and O'Rourke [11]. As mentioned before, the restoration rules used in MCM (multi-criteria method) are almost the same as the restoration rules used by the Los Angeles Department of Water and Power following the 1994 Northridge earthquake. As shown in Table 5 the *RI* values of DCBM (cost-effective method) are about 3.40%–12.35% higher than the *RI* values of MCM.

3.3.2. Overview of Performance Curves

Table S3 in Supplementary Material shows the restoration events and performance at each time step. Figure 11 presents the performance curves obtained from studying the nine scenarios by each method based on Table S3. 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 events, determined by the number of broken pipes (listed in Table 3), is too small to make a difference. Moreover, the isolation priorities between different methods are almost the same (in Table S2). Performance enhancements are observed for all methods in the isolation phase. 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 Scenarios 2, 3, and 6, the sharp climbing in the 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. The climb 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.

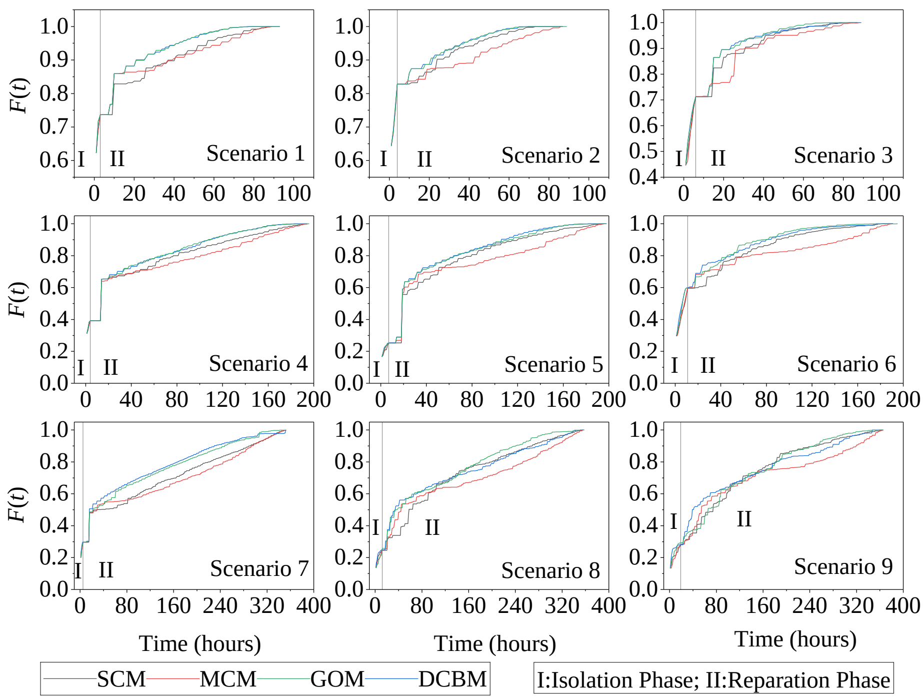

Figure 11. The functionality recovery curve for nine scenarios.

The enhancements of both the performance in the isolation phase and the reparation phase imply that there are two kinds of important pipelines in the network. The first kind of pipelines greatly affects the performance of the water distribution network when it is broken. Therefore, this kind of pipeline should be isolated as soon as possible. The second kind of pipelines affects performance when it closed. They need to be replaced as early as possible to restore the post-earthquake performance of the WDS.

3.3.3. Performance Curves of GOM and DCBM in Scenario 7

Although the *RI*s obtained by both the GOM and DCBM are very close to each other, there are differences between their restoration processes. To compare the restoration processes determined by the restoration priorities obtained by GOM and DCBM, the post-earthquake performance curves of Scenario 7 obtained by the two methods are detailed in Figure 12. Figure 12a shows the turning Points A to F on the curves present the differences between the curves of GOM and DCBM. The isolation phase of the curves is from Point A to Point B, and the reparation phase is from Point B to Point F. The two curves are close to each other on the whole, and the average relative difference of performance ($F(t)$) between the two curves is only 2.00%. This finding shows that *RI*s are close between the two methods. The two curves are almost overlapped between Points A and D, and the curve of the GOM is lower than the DCBM from Point D to Point E. Then the performance of the GOM becomes higher from Point E to Point F than the DCBM. A sharp increase can be seen at Point C in Figure 12b. The restoration events performed between Points B and point D are presented in Table 6 (detail information can be found in Table S3). It shows that the restoration event "replaced pipe 292" is the main cause for the sharp increase. Figure 13 also shows the topology and flow parameters of the example WDS near the Pipe 292. The Pipe 292 carries 77.7% of the water supplied by the reservoir 269. This finding indicates that Pipe 292 is a trunk pipeline that should be replaced as soon as possible. Therefore, both methods can identify the key pipeline and assign a high restoration priority to this pipeline. As shown in Figure 12c, the performance curve of the GOM becomes higher than the DCBM from Point E. It is because Pipe 40 has been replaced earlier in the GOM than in the DCBM.

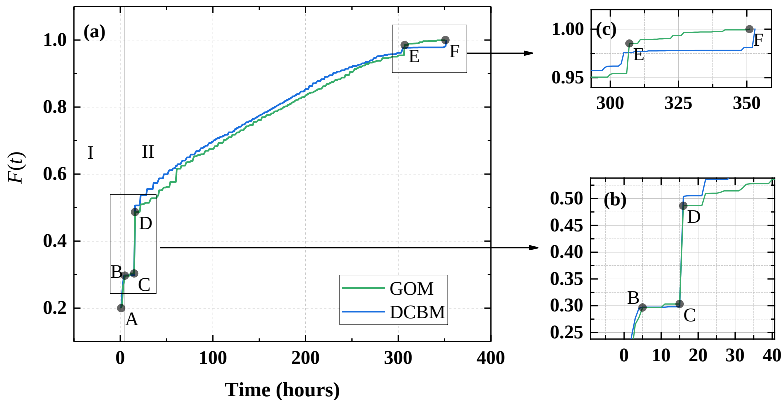

Figure 12. The performance curves in Scenario 7. (**a**) Overview of the performance curves, (**b**) Performance curves between point B and point D, (**c**) Performance curves between point E and point F.

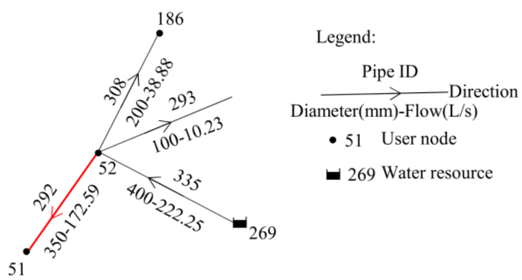

Figure 13. The partial network around resource 269.

Table 6. Part of the reparation events of the global optimization method (GOM) and the dynamic cost-benefit method (DCBM) for Scenario 7.

Time (hour)	GOM		DCBM		Remark
	Event Finished	F(t)	Event Finished	F(t)	
4	All break pips are isolated	0.2966	All break pips were isolated	0.2976	B
10	Repaired pipe 103	0.3033	No action	0.2976	
11	No action	0.3033	Replaced pipe 313	0.2983	C
15	Replaced pipe 292	0.4865	Replaced pipe 292	0.5060	D
21	Replaced pipe 59; Repaired pipe 107	0.5095	Replaced pipe 59; Repaired pipe 158	0.5367	
…	…	…	…	…	…
306	Replaced pipe 40; Repaired pipe 47	0.9852	No action	0.9759	E
…	…	…	…	…	…

3.3.4. Performance Curves of SCM, MCM, and DCBM in Scenario 6

The post-earthquake performance curves of Scenario 6 are selected to illustrate the differences in the restoration process determined by the SCM, the MCM, and the DCBM. Figure 14 shows the performance curves of Scenario 6 by using the three methods. The isolation phase is between Point A and Point B, and the reparation phase is between Point B and Point F.

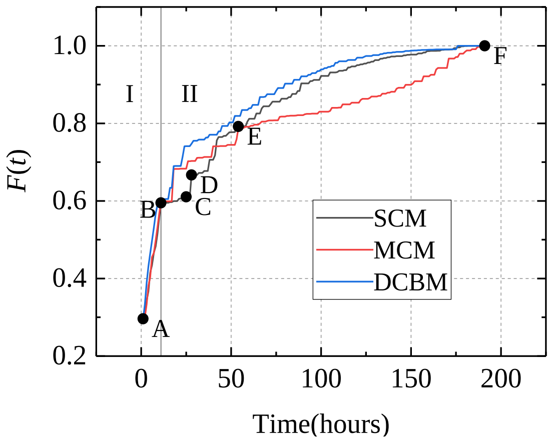

Figure 14. The functionality curves for the single-criterion method (SCM), the multi-criteria method (MCM), and DCBM in Scenario 6.

Compared to the DCBM, the performance curve of the SCM climbs slowly between B and C. Table 7 presents the restoration events performed between B and D according to the SCM (detail information can be found in Table S3). Table 7 also shows the replacement of Pipe 135 causes a dramatic climbing in the performance curve of the SCM, after the reparations of Pipe 291, 66, and 68. This is because SCM cannot determine or show the types of pipeline damages. It was found the replacement of isolated pipelines, according to their break types, triggers higher performance growth of the WDS than reparation of a leaking pipeline.

Table 7. Part of the restoration events of the SCM for Scenario 6.

Time (hour)	Event Finished	F(t)	Remark
10	All break pipes are isolated	0.5949	B
17	Repaired pipe 66	0.5997	—
20	Repaired pipe 291	0.6057	—
24	Repaired pipe 68	0.6104	C
27	Replaced pipe 135	0.6668	D

From Point E to Point F, the restoration priority is dominated by the secondary criterion of the MCM, "straight-line distance to the nearest resource". The performance curve of the MCM goes flat compared to the other two methods, implying that the criterion may not be an effective criterion to prioritize the restoration events. Some leaks at branch pipelines may be near the water sources, but their reparations bring less performance growth of the water distribution network than the leaks far from the sources in the trunk pipeline. Under this condition, these kinds of near-source leaks may not need to be repaired early due to the resource limitation.

3.3.5. Computation Complexity of the Four Methods

This section is to compare the computation complexities of the four prioritization methods described in Section 2.3 and Table 4. The computer used is with Intel Core i5-8500 3.00 GHz and 8 GB RAM. The problems are modeled in MATLAB 2019a.

In the restoration simulation, the hydraulic model with damage scenario is generated first. Hydraulic simulation is then performed by EPANETpdd.dll [28]. During the hydraulic simulation, the statuses of damaged pipelines change with the restoration actions. The time spent on the hydraulic simulation and update statuses of pipelines of the hydraulic model of the WDS takes the main part of the whole procedure of each method. The number of single period hydraulic simulations (SPHS) of WDS is regarded as an indicator to measure the computation complexity of each method. Table 8 presents the number of SPHSs and time required for each method in the nine damage scenarios. The GOM takes the largest time and number of SPHSs, which correspond to the largest computational burden. In the different damage scenarios of the WDS, the number of SPSH of DCBM is about 0.10%–0.34% of the GOM, and the MCM has the least computational time and number of SPSH due to no SPHS is required in its procedure. Table 4 indicates the great advantage of the DCBM over GOM in terms of computation complexity.

Table 8. The number of hydraulic simulations and time required for each method.

Scenario No.	SCM		MCM		GOM		DCBM	
	Number	Time(s)	Number	Time(s)	Number	Time(s)	Number	Time(s)
1	317	2.25	0	0.15	590626	3975.40	631	8.31
2	317	2.31	0	0.15	655128	4496.94	671	9.14
3	317	2.32	0	0.15	671438	7989.63	751	10.60
4	317	2.29	0	0.19	2445231	16900.74	2858	43.49
5	317	2.32	0	0.19	2660022	23482.23	3677	49.75
6	317	2.32	0	0.20	2269009	145421.06	3585	55.80
7	317	2.31	0	0.23	5144953	52331.85	9912	179.72
8	317	2.34	0	0.26	4562696	355996.76	10712	200.64
9	317	2.41	0	0.29	4265958	363976.64	12234	243.88

The GOM requires the largest time and number of SPHSs 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 of hydraulic simulation (EPHS). 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 events 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 SPHS are still needed.

3.4. Results of Application (Considering Positions of Valves)

To consider the effects of the positions of valves illustrated in Figure 6. In this subsection, the position of valves in the WDS of Modena is randomly generated. The proportions of each pipeline category are set the same to the benchmark WDS of BPDRR in CCWI/WDSA 2018 [36]. The pipeline categories considering the valves' positions of Modena are shown in Figure 15. The seismic damage Scenarios 1, 2, and 3 of the WDS are applied.

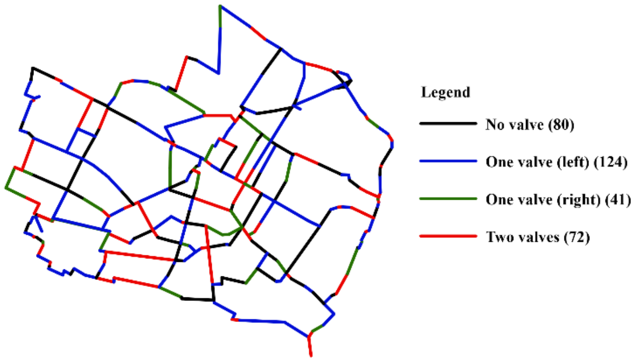

Figure 15. Illustration of pipe types distribution.

Table 9 shows the *RI* values for each method and Figure 16 shows the restoration curves. The *RI* values and restoration curves indicate that the GOM and DCBM provide better restoration schedules than the SCM and MCM when considering the positions of valves, which is consistent with the result in Section 3.3. In addition, the *RI* values considering valves' positions are less than these values without considering valves' positions. The *RI* values for DCBM considering valves' position are 1.02%, 0.27%, and 1.21% less than these values without considering the valve's position in Scenarios 1, 2, and 3, respectively. Therefore, the DCBM is effective no matter considering valves' positions or not.

Table 9. *RI* values considering the positions of valves.

Scenario No.	SCM	MCM	GOM	DCBM
1	0.8587	0.8939	**0.9268**	0.9240
2	0.8893	0.9020	**0.9410**	0.9385
3	0.8651	0.8679	**0.9083**	0.9035

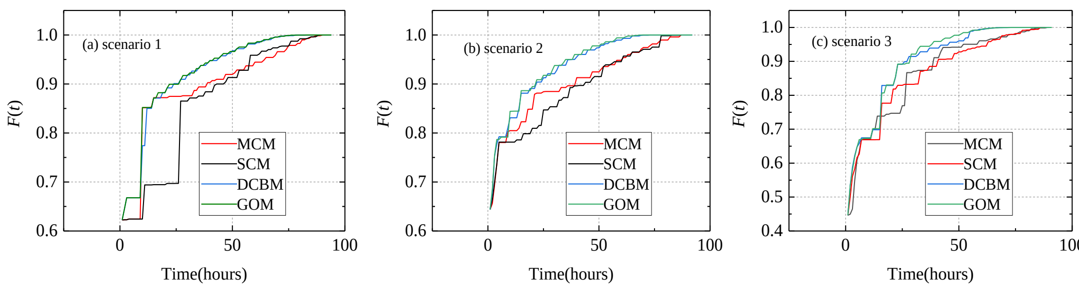

Figure 16. Restoration curves considering the positions of valves. (**a**) Scenario 1, (**b**) Scenario 2, (**c**) Scenario 3.

4. 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 increase 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, the application results of the proposed method were compared with the other three existing prioritization methods (a. the single-criterion method based on hydraulic importance, b. the multi-criteria method based on the type of damage and the distance to sources, and c. the global optimization method targeting for maximum resilience). The results show that: (i) the global optimization method achieves higher resilience index than the other three methods in most scenarios, and the resilience indexes obtained by the proposed dynamic cost-benefit method are very close to resilience indexes obtained by the global optimization method, with less than 3% relative differences, (ii) it was found 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, (iii) it was found the global optimization method and the dynamic cost-benefit method can identify the priorities of the pipeline repairs/replaces. It was also found these methods could significantly affect the performance of the WDS during restoration process, (iv) neither the hydraulic importance of pipeline used in the single-criterion method nor the straight-line distance to sources used in the multi-criteria method are an effective criterion to prioritize the restoration actions, (v) the global optimization method takes the largest computation complexity among the four methods. On the contrary, the computation complexity of the proposed dynamic cost-benefit method takes only about 0.1%~0.34% of the global optimization method.

This proposed model has some limitations. For example, in the simulation model for the post-earthquake restoration of WDS, the assumptions and simplifications make important impacts on the validity of the proposed model, although this study was developed based on previous research and existing references. Some factors, such as the travel time of repair crews should be considered in the model in the future. In addition, due to the uncertainty in seismic damage determination and the post-earthquake restoration process, stochastic analysis by Monte Carlo simulation should be taken into consideration to evaluate the seismic resilience of the WDS in the future. Nevertheless, many researchers shall find this method useful as a reference for the disaster resilience evaluation of infrastructure systems.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/3/914/s1, Table S1: DamageScenarios.xlsx, Table S2: RestorationPriority.xlsx, Table S3: RestorationRecord.xlsx.

Author Contributions: Conceptualization, Z.H., D.M., and B.H.; methodology, B.H.; validation, B.H.; formal analysis, Z.H.; writing—original draft preparation, Z.H.; writing—review and editing, D.M., B.H., W.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant numbers 51978023 and 51678017.

Acknowledgments: We would like to warmly thank reviewers for their remarkable comments.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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