Evaluation of Fire Protection Capacity in Disasters Based on Disaster Resilience Curve

N. Hirayama, T. Yamada, M. Wada, S. Itoh, and C. A. Davis

ABSTRACT

After the 2011 Tohoku disaster, water supply utilities in Japan have encouraged to address issues of disaster prevention and resilience in water system. The purpose of this study is to develop an evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity. In this study, an evaluation model based on disaster resilience curve, which could describe disaster mitigation and resilience in water service, was developed. The distribution network analysis including emergence of the fire extinguishing quantity of water was carried out, the number of node available as fire hydrant was calculated in accordance with the requirements of hydraulic pressure at nodes. The fire protection capacity of the water distribution system in the emergency restoration period for the actual distribution network of the Kobe City was evaluated with the numerical evaluation model. Then, an evaluation procedure on the fire protection capacity of water supply distribution system based on disaster resilience curve was proposed. As a result, it was pointed out that more disaster resilient water system would require not only disaster preparedness but also business continuity management system

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INTRODUCTION

After the 2011 Tohoku disaster, water utilities in Japan have been promoting to address issues of disaster prevention and resilience in water system. In Japan, business continuity planning and management is required for public works, and government of Japan has encouraged municipal government to establish business continuity planning. The Business Continuity Guidelines 3rd ed. – Strategies and tactics to overcome any incident – was published by Cabinet office, Government of Japan [1]. Ministry of Economy, Trade and Industry published Guidelines for Business Continuity Plans [2].

Ministry of Health, Labour and Welfare, the Government of Japan published the Guidelines for disaster prevention of earthquake disasters in water supply sectors, and it was pointed out that it is significant to establish the PDCA cycle based on the disaster management cycles [3]. The Handbook for emergency response and operation in water sector was published by Japan Water Works Association [4]. In this guidelines and this handbook, it is indicated that Business Continuity Management (BCM) in water sectors is required for emergency response to the unexpected incidents. Business Continuity Planning for Water Utilities: Guidance Document was published by Water Research Foundation [5]. This technical report indicates that water utilities need a Business Continuity Plan (BCP) and a Business Continuity Plan's and goal is maintaining solid operations – financially, managerially, and functionally, after any incident.

Recently, many researchers and water professionals conduct research projects on establishment of BCM in water sector. However, the evaluation method of business continuity in water service after the disasters has been hardly examined. Actually, BCM would involve the implementation of PCAD cycle of Business Continuity Planning (BCP) and it is required to evaluate the business continuity of water service during the restoration period. Thus, the purpose of this study is to develop an evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity with the disaster resilience curves.

METHOD

In this paper, the objective of this study is to evaluate earthquake resilience of water distribution system from the viewpoint of fire protection function. EPANET2 [6] was used for numerical analyses in this study.

Business Continuity and Disaster Resilience Curve

BCM is defined as a compilation of processes that identifies and evaluates potential risks to an organization and develops the organization's resilience by ensuring critical objectives are met the resources necessary to achieve those objectives are available [7]. Water Research Foundation indicated that BCP is an integral part of the emergency management system, which typically includes a suite of plans for a lager utility or one comprehensive plan for a smaller utility [5]. It was pointed out that it is important that business continuity planning be integrated into a utility's culture and, as such, consistent with the utility's mission. In addition, the execution of BCP in water sector is proposed as the following:

1. Define the scope
2. Establish written policy by the water utility Executives
3. Define the incident
4. Provide basic assumptions

5. Integrate with other plans

Figure 1 shows the concept of BCP and disaster resilience curve [1]. Thus far, many water utilities try to carry out the disaster prevention & preparedness, and the risk and crisis management based on the concept of BCP as a critical infrastructure which citizens' lives and the economy rely on. In addition, some activities of water utilities for the establishment of BCP were reported [8]. In the previous recovery & reconstruction planning and BCP in water utilities, water supply ratio or available quantity of water have been used as an evaluation indicator of the restoration curves. Sakaki, *et al.* [9] developed the earthquake disaster risk evaluation modeling of not only water supply ratio and emergency restoration period but also opportunity loss of water, which is defined as the difference between the amount of water available in emergency and normal time. Davis and O'Rourke [10] and Davis [11] introduced and characterized five water service categories that are important for quantifying the total post-earthquake restoration of a water system. These categories are water delivery, quality, quantity, fire protection, and functionality services. In addition, Davis [12] presented a case study on applying these service restorations to the Los Angeles Water System following the 1994 Northridge earthquake. Hirayama and Davis [13] developed the quantitative evaluation model for evaluation of performance of disaster prevention in water sector. With the implementation of BCP and BCM in water sector, it is more indispensable to evaluate on business continuity of water service. Thus, in this study, it is develop the evaluation procedure of water service in the aftermath of earthquake using disaster resilience curves of fire protection.

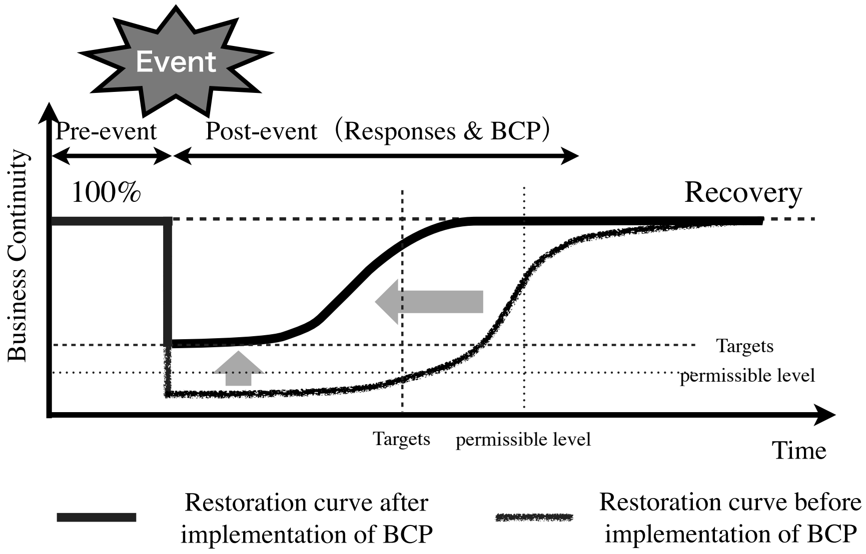


Figure 1. Concept of BCP and disaster resilience curve [1]

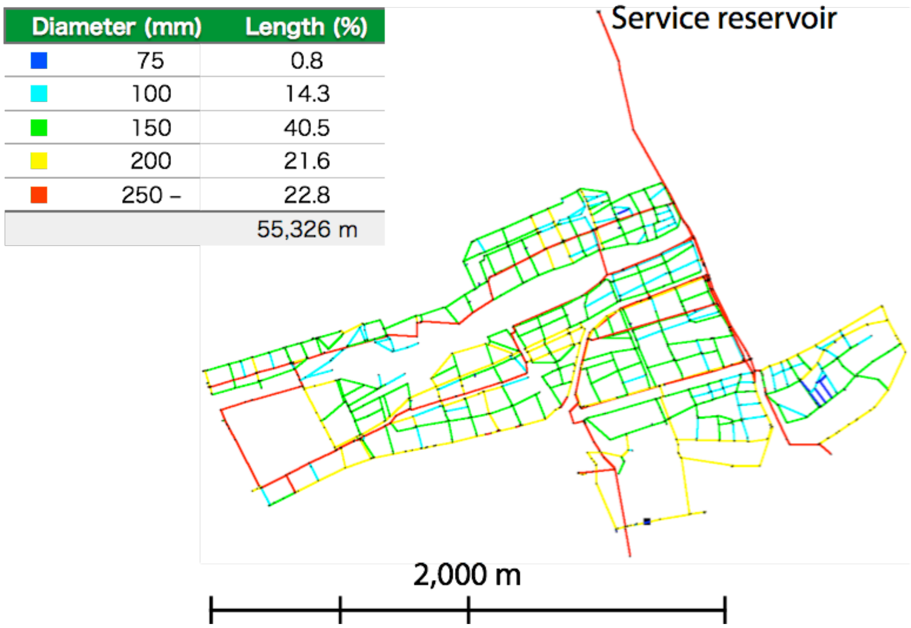
Performance indices

Earthquake resilience could be evaluated as opportunity loss of water, water supply ratio, and fire protection capacity in restoration period after earthquake. In calculating of water supply ratio, the conditions of water supply after earthquake are no damage pipe in the route from water reservoir to water demand point and more 10 m water head at the water demand point [14]. Opportunity loss of water is defined as the difference between the amount of water available in emergency and normal times, water which would be available if the disaster does not occur [9].

In general, design for fire hydrants in Japan is according to Japanese standards for water sources necessary for fire defense [15]. In this paper, fire protection is defined as capability of fire fighting at every node in conditions of additionally 3.0 m^3/min water demand for firefighting and positive water pressure at the next nodes, which connect the fire hydrant [16]. In this pipe network analysis, Hazen-Williams Coefficient was used as 110 and time factor in pipe network hydrologic accounting was 1.82 in normal times as observed in evaluation areas and 1.00 in emergency.

Evaluated Areas and Their Characteristics

The evaluation area in this study is Nada Low-layer water distribution area in Kobe City, as shown in **Figure 2**. These water distribution systems are gravity flow system and based on 2013 Kobe Pipeline mapping system (P-DES).



Diameter (mm)		Length (%)
🟦	75	0.8
🟦	100	14.3
🟩	150	40.5
🟨	200	21.6
🟥	250 –	22.8
		55,326 m

Figure 2. Nada Low-layer water distribution area in Kobe City

Distribution Network Analysis in a Seismic Condition

In this study, when we make a distribution analysis after earthquake, the hazard of earthquake was the same scale of the 1995 Kobe earthquake. The cross-tabulation table related to diameter and peak ground velocity (PGV) is shown in **Table 1**.

Table 1. Pipe length ratio related to diameter and PGV in Nada

Distribution area	Pipe length (m)	Diameter	Peak ground velocity (PGV)				Subtotal (%)
			60 cm/s	100 cm/s	140 cm/s	180 cm/s	
Nada	54,327	– 75 mm	0.6	0.0	0.2	0.0	0.9
		100 mm	4.0	3.4	4.9	2.1	14.5
		150 mm	9.3	7.3	18.9	5.7	41.2
		200 mm, 250 mm	9.0	4.3	7.2	1.5	22.0
		300 mm –	4.3	4.6	9.9	2.7	21.4
		Subtotal (%)	27.9	21.5	39.2	11.5	100.0

The node with negative pressure is considered as no-flow node through which no water can pass or a partial flow node through which water can pass with reduced flow rates compared with those predicted by conventional hydraulic network analysis [17]. In a case that some node has negative pressure in pipe network hydrologic analysis results, pipe network analyses will be conducted after removal of these nodes with negative pressure.

Water supply ratio

Cornell University [17] developed a pipe network analysis tool, which describes a seismic condition in EPANET software. In this study, the ratio of water supply during restoration period after earthquake was evaluated with GIRAFFE.

The calculation process of water supply ratio has five steps. First, damage probability of each pipe is estimated according to the pipe damage estimation procedure and the fragility curves of pipe caused by quake [18]. Pipe material, pipe joint type, diameter, geographical features, and Peak Ground Velocity (PGV) are required for this estimation formula. Then, number of damage position is calculated based on Poisson distribution of damage probability of pipe. Third, condition of damage to pipe is determined with Monte Carlo method. The damage condition has two categories. One category of pipe damage is a detachment of pipe joint, which causes completely pipe break and disconnection of pipes. The other is a pipe leakage. In this paper, pipe leakage type has five levels, defined in GIRAFEE algorithm. Pipe leakage level is determined with Monte Carlo method. Then, pipe mapping data set including damaged pipe caused by quake is laid for pipe network analysis.

Pipe network hydrologic analysis is conducted to the pipe mapping data set with assumed damage on EPANET2. In a case that the calculated pressure of either node is negative, the node with negative pressure is excluded from the pipe mapping date set. After checking the connectivity of the pipe network, pipe network analysis is carried out again. When none of nodes has negative pressure in the calculation result, pipe network hydrologic accounting result is confirmed.

At the last step, the emergency recovery process is examined with the recovery process numerical simulation model. Emergency recovery rate depend upon pipe diameter. The recovery rate for a pipe break on more than or equal to 250 mm dia. pipeline was 0.63 location per day, and that for less than 250 mm dia. pipeline was 2.0 location per day, according to observations in 1995 Kobe earthquake [9]. In this paper, the recovery operation would first be conducted upstream and large pipeline of the water distribution network.

Opportunity loss of water

In the context of this paper, 'Opportunity Loss' of water is defined as the amount of emergency water not provided to citizens for some reason while there was a demand on citizens' side [9]. Thus, an integration value of the quantity of water not provided to citizens during the emergency restoration period was calculated.

Fire protection capacity

In this section, evaluation procedure for fire protection capacity during emergency restoration period after earthquake is described. The leakage caused by pipe breaks depends on condition, location, water pressure of pipe break, and so on. The leakage from damaged pipe is estimated by eqn. (1) as the following

$$Q = C \times P^{\alpha} \qquad \text{eqn. (1)}$$

The leakage volume is designated by *Q*. *C* represents Hazen-Williams Coefficient. The pressure of damaged conduit is designated by *P* and a represents pipe damage mode coefficient. In this paper, we set that the coefficient *C* is 2.0×103 and the coefficient *α* is 1.15.

It was pointed out that the leakage from service connections is a reason to decrease water pressure after earthquake disasters [18]. Uno, *et al.* [19] estimated the number of damage service connection as 1861 sites in Nada Low-layer distribution area. Thus, we take the leakage from service line into account in this evaluation process. The leakage from damaged service line is estimated by the same equation (1). The coefficient *C* for service connection leakage was 3.0×104 and the coefficient *α* is the same 1.15. In addition, the calculated leakage from service connection was added to water demand in each node.

The ratio of node with fire protection capability was examined with hydraulic accounting on EPANET2. In the emergency restoration period, the repair number of service connection was constant 50 sites per day.

COMPUTATIONAL RESULTS

Evaluation Results of Fire Protection in Normal Condition

The fire protection function of Nada Low-layer Distribution Network in normal was evaluated by the available ratio of fire hydrant. **Figure 3** shows the map of water pressure of Nada distribution network in normal condition.

Figure 3. Map of water pressure in Nada network in normal condition

Nada distribution network is gravity flow. This figure indicates that the pressure head of most nodes in the upper stream, which is near to distributing reservoir, becomes the value from 30 m to 35m. The pressure head in the downstream are more than 40 m. The calculated map of nodes with fire protection function in Nada network is shown in **Figure 4**. As a result, the ratio of availability for fire protection was evaluated at 0.99. These nodes, which do not have fire protection function, are connected to 100mm dia. distribution branch and are located in the place of higher altitudes in this distribution area.

Figure 4. Map of nodes with fire protection function in Nada distribution network

Evaluation Results of Fire Protection after Earthquake Disaster

The calculated map of water pressure after earthquake disaster is shown in **Figure 5**, and **Figure 6** illustrates the map of nodes with fire protection function or without in Nada distribution after the event.

Figure 5. Map of water pressure in Nada distribution network after the earthquake disaster

Figure 6. Map of nodes with fire protection function in Nada distribution network after the event

Because of leakage with 62 damage to distributing main and 1861 damage to service pipe, the pressure head of approximately 300 nodes became the negative pressure. Then, it was pointed out that it is hard to be said that sufficient water and the water pressure can be secured in Nada Low-layer distribution area after the earthquake disaster. In addition, the number of node with fire protection function would decrease and the ratio of available node for fire protection was evaluated at 0.75. It may be said that fire protection function of Nada distribution area decreases to approximately three-fourths in the normal. It was pointed out that it is indispensable not only to promote the earthquake resistance of pipeline for mitigation of weakening fire protection function but also to improve the local firefighting capability by the securing of water utilization for fire fighting.

The disaster resilience curves of fire protection capacity, disaster resilience curve of water supply ratio and opportunity loss of water of the present network were calculated. The evaluation result of fire protection capability with disaster resilience curve is shown in **Figure 7**.

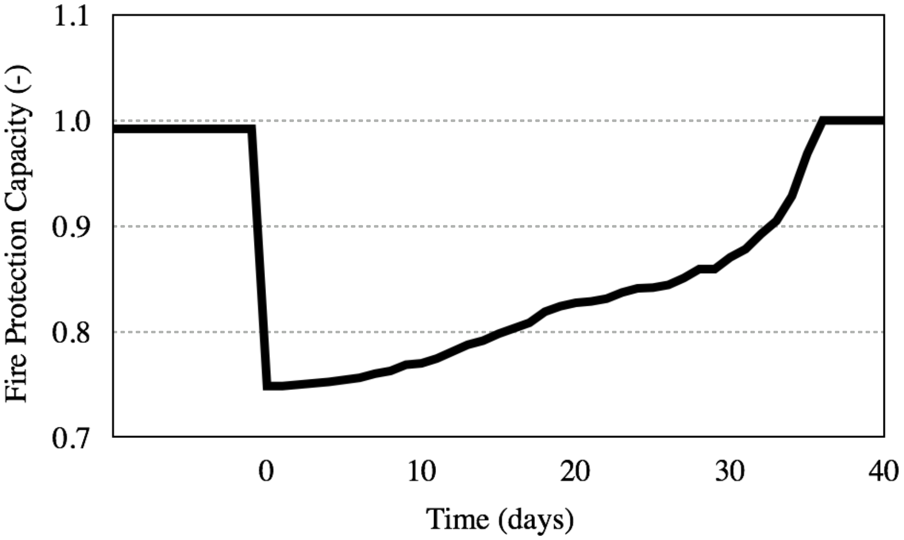


Figure 7. Disaster resilience curve of fire protection capability in Nada distribution network

In the disaster resilience curve of fire protection capability as Figure 7, recovery rate increased after 28th days. In this paper, the priority of the emergency recovery operation does not be considered. This is a reason why a recovery effect of the pressure head in the water distribution network by the pipeline reconditioning on the disaster preliminary period is small. Thus, it was indicated that disaster countermeasure of the water distribution system would require to mitigate the reduction of fire protection function in the initial response period, and to examine a water distribution network restoration strategy to improve the capacity to recover quickly from disasters. Consequently, it was pointed out that it is essential to establish business continuity management system in water utility for the water utility services to customers such as quantity, quality, water accessibility, water delivery, and fire protection function of water in addition to earthquake-resistant technologies.

CONCLUTIONS

In this study, an evaluation model based on disaster resilience curve, which could describe disaster mitigation and resilience in water service, was developed. The distribution network analysis including emergence of the fire extinguishing quantity of water was carried out, the number of node available as fire hydrant was calculated in accordance with the requirements of hydraulic pressure at nodes. The fire protection capacity of the water distribution system in the emergency restoration period for the actual distribution network of the Kobe City was evaluated with the numerical evaluation model. The findings of this study are as follows.

1. An evaluation method on the fire protection capacity of water distribution system from the viewpoint of business continuity with the disaster resilience curves was developed.
2. The fire protection function of Nada Low-layer Distribution Network in restoration period after earthquake disaster was evaluated. As a result, the number of node with fire protection function would decrease and the ratio of available node for fire protection was evaluated at 0.75. It was pointed out that it is indispensable not only to promote the earthquake resistance of pipeline for mitigation of weakening fire protection function but also to improve the local firefighting capability by the securing of water utilization for fire fighting.
3. From the calculated disaster resilience curve of fire protection capability, it was indicated that disaster countermeasure of the water distribution system would require to mitigate the reduction of fire protection function in the initial response period, and to examine a water distribution network restoration strategy to improve the capacity to recover quickly from disasters.
4. Consequently, it was pointed out that it is essential for disaster resilient water system to establish business continuity management system in water utility for the water utility services to customers such as quantity, quality, water accessibility, water delivery, and fire protection function of water in addition to earthquake-resistant technologies.

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