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A comprehensive framework for seismic risk assessment of urban water transmission networks

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ABSTRACT

Earthquakes are natural disasters which human beings cannot control, causing significant damage to the economy and society as a whole. In particular, earthquakes affect not only buildings but also lifeline structures such as water distribution, electric power, transportation, and telecommunication networks. The interruption of these networks is critical because it can directly damage the facilities and, at the same time, cause long-term loss of the overall system for society. In recent years, there has been increasing interest in the uncertainties of ground motion, deterioration of pipelines, and interdependency of lifelines. Therefore, it is essential to predict the damage through possible earthquake scenarios and accounting for factors affecting lifeline structures. This study proposes a comprehensive framework to quantify the impact of earthquakes on the connectivity of urban water transmissions. The framework proposes the following steps to predict damage from earthquakes: (1) estimate the ground motion considering the spatial correlation, (2) propose a modified failure probability of buried pipelines considering deterioration, and (3) evaluate the seismic fragility curves of network components and the interdependency among water treatment plants, pumping plants, and substations. For numerical simulations, an actual water network system in South Korea was constructed using graph theory, and the magnitudes and locations of the epicenters were determined based on historical earthquake data. Finally, the reliability performance indicators (e.g., connectivity loss and serviceability ratio) were measured when earthquakes of various magnitudes occurred in the urban area. This framework will enable the prediction of damage from earthquakes and enhance decision making to minimize the extent of damage.

1. Introduction

Significant natural disasters such as earthquakes, landslides, droughts, floods, and hurricanes have occurred in recent times, causing social disruption and economic losses [1,2]. In particular, natural disasters may have a significant influence on complex lifeline systems because social infrastructures in urban areas are highly concentrated. In addition, as the bulk of lifeline facilities are installed underground, it is difficult to recognize and repair the damage, which can lead to a long-term supply stagnation. Recent disasters have highlighted the need to predict damage to lifeline facilities and establish disaster recovery strategies for repairs.

The Pan-American Health Organization (PAHO) [3] analyzed the extent of damage to water distribution networks from natural disasters. Although the damage to the water facilities varied depending on the frequency and intensity of the occurrences, it was reported that earthquakes have significant influence on water network systems. Earthquakes cause the overall destruction of significant areas of system which results in loss of both life and property, and even more serious secondary damage, including fires following the earthquake, and gas leakages [4]. The probability of a strong earthquake is remote, but once it occurs, the functionality of water network systems could deteriorate. Therefore, it is essential for the earthquake engineering community to conduct a risk assessment of water transmission networks.

The Northridge earthquake in California (1994) and the Kobe earthquake in Japan (1995) caused significant damage to water distribution networks [5]. The Northridge earthquake resulted in 74 instances of damage to main water pipes with diameters greater 600 mm, and 1013 to main water pipes with diameters smaller than 600 mm [6]. In the case of the Kobe earthquake, 23 instances of damage occurred in main water pipes, resulting in disruption of drinking water supplies to approximately 15 million people. In 2016 earthquakes in New Zealand

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resulted in a number of problems in critical lifeline structures, that led to both direct and indirect economic losses as residential, commercial, and industrial activities were interrupted. This was a result of the interdependency of lifeline facilities (e.g., water distribution, electric power, transportation, and telecommunication) having an indirect effect on other lifelines (indirect loss) as well as damage to the lifeline itself (direct loss). Therefore, if earthquake damage is not repaired timeously, it could cause not only great discomfort in the lives of local residents, but also significant economic losses.

Various studies have been conducted to predict seismic hazard assessment of infrastructure based on topology-based connectivity. For example, Nuti et al. [7,8] proposed a methodology for seismic safety analysis of electric power, water distribution, and road networks, and they also conducted a seismic evaluation of electric power network at urban level [9]. Esposito et al. [10] worked on the seismic risk assessment of gas distribution networks including the fragility curves of system components, such as metering/pressure reduction stations. Rokneddin et al. [11] presented a finite-state Markov Chain Monte Carlo (MCMC) simulation to evaluate the reliability of ageing highway bridge networks, and proposed a bridge retrofit priority and ranking strategy based on transportation network topology. Ching and Hsu [12] analyzed seismic reliability of actual lifeline networks using Origin-Destination connectivity (O-D connectivity) reliability. With regard to water distribution networks, Yoo et al. [5] proposed a model to conduct the seismic hazard assessment of J-city and I-city in South Korea considering water network facilities such as water storage tanks and water pumping plants. Fragiadakis and Christodoulou [13], and Fragiadakis et al. [14] conducted a seismic reliability assessment of the Limassol water supply network in Cyprus by introducing the modified repair rates equation to account for the degradation of distribution pipelines. Moreover, Christodoulou et al. [15] proposed a methodology for assessment of Water Distribution Network (WDN) system based on network topology and component analysis. Osorio et al. [16] evaluated the seismic response of critical interdependent networks between water distribution and electric power networks, and proposed a recovery strategy to mitigate damage. In addition, Poljanšek et al. [17] presented a model to consider the interdependence of gas and electric power networks and conducted research on power losses in Europe according to the coupling strength. Regarding the non-simulation-based algorithm, Lee et al. [18] evaluated the post-hazard flow capacity of a road network considering the deterioration of bridges in Sioux Falls, USA, by means of a non-sampling-based matrix-based system reliability (MSR) method [19,20]. Song and Ok [21] proposed a multi-scale system reliability method to evaluate gas distribution networks in Shelby County, Tennessee, USA, using the MSR method as well. In addition, Lim and Song [22] proposed a selective recursive decomposition algorithm to evaluate risk assessment of water networks subjected to spatially correlated ground motions.

Previous studies have suggested an effective way to predict and assess damage from earthquakes. However, even if such analytical methods were developed, only limited studies have combined all the analytical methods. For example, Fragiadakis and Christodoulou [13] studied seismic reliability assessment considering the fragility of water treatment plants, water storage tanks, and pumping plants, but excluded water transmission network systems. Yoo et al. [5] excluded the interdependency of lifeline facilities and the spatially correlated ground motion prediction equation (GMPE) in their study. In other studies numerical simulations considering deterioration of pipelines were not conducted. To overcome the limitations of previous studies, this study proposes a comprehensive framework that incorporates the spatially correlated ground motion, deterioration of pipelines, and interdependency of water and electric power networks, as well as the fragility of water treatment plants, water storage tanks, and pumping plants. An actual water transmission network in A-city, South Korea, was used as the target region for applying the comprehensive framework, as A-city is subjected to frequent earthquakes.

The organization of this paper is as follows. Section 2 introduces the theoretical background of the comprehensive framework including network analysis, prediction of ground motion, damage to deteriorated pipelines, fragility curves of other facilities, and interdependency between water and electric power networks. In Section 3, we propose a comprehensive framework for seismic risk assessment of urban water networks. Section 4 describes an actual water transmission network in A-city in South Korea, and presents the results of the seismic risk analysis in accordance with earthquake magnitude, elapsed time, and interdependency. Finally, Section 5 concludes this study and recommends future study directions to add to and improve on this study.

2. Theoretical background

2.1. Network analysis

2.1.1. Graph theory

Graph theory is a powerful mathematical tool for easy control of complex network data. The graph theory comprises nodes (junctions) and edges (links), denoted by V and E, respectively, and can be expressed as $G = (E, A)$. The graphs are divided into directed and undirected graphs according to whether the direction between the initial node ($v1$) and end node ($v2$) is unidirectional or bidirectional, and a mixed graph exists when two graphs coexist together. The connectivity of the graph represents the topological structure of the network, and the entire network is represented by an $N \times N$ adjacency matrix A, where N is the total number of nodes in the network. The component of the adjacency matrix A is $A_{ij} = 1$ if the connection between nodes i and j is possible, otherwise 0. Using graph theory, it is possible to identify the shortest path and connectivity between sources and the sink node. In addition, it can be effectively used in a large network because it can easily reflect the destruction of links resulting from external disturbances such as earthquakes. Fig. 1 shows an example of a simple network and adjacency matrix.

2.1.2. Performance indicator

Once the failure probabilities of all water network facilities are known, the performance of the entire network can be evaluated. Various approaches for evaluating network performance can be utilized, depending on requirements of the user (i.e., connectivity and flow reliability). A proper indicator must be determined to enable accurate performance measurement, as it depends on network size, type, and topology of the graph. Therefore, it is important to define a failure status of the network by setting parameters that have a significant effect on the network. As a simple example, success and failure can be categorized depending on whether or not the water from the source node can reach the sink node. In addition, it is also possible to evaluate the importance of each storage tank (sink) considering the number of inhabitants supplied from the water treatment plant (source). Once the quantified network assessment methods are determined, the performance indicators can be evaluated accurately.

In this study, two performance indicators, connectivity loss (CL) and serviceability ratio (SR), were used to evaluate the network performance from source to sink. Both indices are vulnerability analysis based on connectivity. Typically, two quantified indicators can be classified into minor, moderate, and major damage states according to

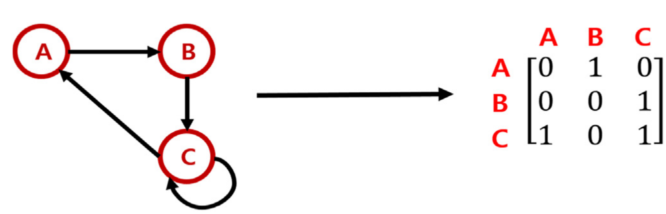

Fig. 1. Example of simple network and adjacency matrix.