CRITICAL LINKS OF WATER SUPPLY TO CRUCIAL WATER CONSUMERS UNDER AN EARTHQUAKE

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ABSTRACT :

Observations from past earthquakes, such as the 1906 San Francisco earthquake, the 1994 Northridge earthquake, and the 1995 Hyogoken-Nanbu (Kobe) earthquake, have clearly demonstrated that compromising water supply systems after an earthquake not only impairs fire fighting capacity, but also disrupts residential, commercial, and industrial activities, and threatens the economic well-being, security, and social fabric of the communities they serve. In the event of a major earthquake, crucial water consumers, such as acute care facilities, must remain operational to rein in the losses, and this calls for the need for seismic mitigation of water supply to these crucial water consumers. A key step in the seismic mitigation is to identify critical links of the water supply that significantly affect these crucial water consumers. This paper presents a method for identifying critical links of water supply to crucial water consumers under an earthquake. Two conditional probability quantities are proposed that describe the effects of damage to each individual pipe on the crucial water consumers under an earthquake. With the aid of Monte Carlo simulations, the concept of efficient frontier is employed to identify the critical links. As an illustration, the critical links for a crucial water consumer are identified in a hypothetical water supply system using the proposed method.

KEYWORDS: Earthquakes, Water supply systems, Critical links, Crucial water consumers, Upgrade benefit index, Damage consequence index

1. INTRODUCTION

The basic function of a water supply system is to deliver water from sources to customers. Water flows from sources to customers through a network of pipelines, pumps, valves, and other appurtenances, and it is also stored in tanks and reservoirs to accommodate fluctuations in demand due to varying rates of usage or fire protection. Pipelines, pumps, valves, storages, and the supporting infrastructures together comprise a water supply system. Observations from past earthquakes, such as the 1906 San Francisco earthquake (O'Rourke et al. 1992, O'Rourke et al. 2006), the 1994 Northridge earthquake (Lund and Cooper 1995), and the 1995 Hyogoken-Nanbu (Kobe) earthquake (Eidinger 1998), have clearly demonstrated that, in the event of an earthquake, water supply systems may sustain various kinds of damage, such as pipeline ruptures or leakages, and result in reduction of water delivery capability. Compromising a water supply system after an earthquake not only impairs fire fighting capacity, but also disrupts residential, commercial, and industrial activities, and threatens the economic well-being, security, and social fabric of the communities they serve.

In an event of a major earthquake, some water consumers, such as acute care facilities and/or hospitals, play vital roles in emergency response and must remain operational to rein in the losses. These water consumers are referred herein as crucial water consumers. A survey of the residents in high seismic risk communities (Nigg 1998) showed that that water pipeline systems and major hospitals are two of the most important infrastructure elements that must remain operational in the event of a major earthquake. Those surveyed also indicated that they are more willing to invest in the seismic mitigation of these infrastructure elements. A key step in the seismic mitigation of water supply to these crucial water consumers is to identify critical links that significantly affect their water supply under an earthquake.

This paper proposes a method to identify critical links of water supply to crucial water consumers under an earthquake. The paper starts with definitions of several probabilistic measures, followed by descriptions of a hypothetical water supply system and simulation procedure used in this work. Monte Carlo simulations and the concept of efficient frontier are then employed to identify critical links of water supply to crucial consumers. As an illustration, critical links of a water consumer are identified using the proposed method.

2. RELIABILITY MEASUREMENT AND CONDITIONAL PROBABILITY QUANTITIES

A consumer of a water supply system is represented as a Node i with water demand Q_i in a hydraulic network model. The water supply reliability for the consumer i can be measured by the probability, $P(Q_i)$, of Q_i satisfied. $P(Q_i)$ can be estimated for each consumer of a water supply system, and its spatial distribution reflects the spatial variation of water supply reliability among various consumers within the system.

Two probabilistic measures associated with the water demand at Node i, Damage Consequence Index (DCI_{ij}) and Upgrade Benefit Index (UBI_{ij}), are defined to measure the impact of a Pipe j on the reliability of water supply to a consumer i and to identify critical links that significantly affect the $P(Q_i)$ (Wang and Au 2008). The DCI_{ij} for Pipe j is defined to reflect the consequence from damaging the pipe. It is expressed as:

$$DCI_{ij} = \frac{P(Q_i) - P(Q_i | L_j)}{1 - P(Q_i)} \tag{2.1}$$

in which $P(Q_i|L_j)$ is the conditional probability of Q_i satisfied given that Pipe j is damaged. DCI_{ij} is the percent reduction of $P(Q_i)$ given that Pipe j is damaged, and its relative value is a measure of Pipe j's impact on the reliability of water supply to consumer i.

The UBI_{ij} for Pipe j is expressed as:

$$UBI_{ij} = \frac{P_{upgrade_j}(Q_i) - P(Q_i)}{1 - P(Q_i)} \quad (2.2)$$

in which $P_{upgrade_j}(Q_i)$ is the conditional probability of Q_i satisfied in a system where Pipe j is "upgraded". The term "upgrade" herein means that the probability of pipe damage given an earthquake occurs is negligible compared to its value before upgrade. In Monte Carlo simulations (see later), this is enforced by setting the damage occurrence probability to be practically zero. UBI_{ij} is the percent increase of $P(Q_i)$ given that Pipe j is upgraded, and it ranges from 0 to 1. The relative value of UBI_{ij} is a measure of the Pipe j's impact on the reliability of water supply to consumer i. The extreme value of $UBI_{ij} = 0$ indicate that the upgrade of Pipe j has no impact on the reliability of water supply to consumer i, as opposed to $UBI_{ij} = 1$ which implies that upgrade of the Pipe j guarantees the water supply to consumer i.

Because UBI_{ij} describes the benefits to consumer i that result from upgrade of Pipe j, it corresponds directly to the context of seismic mitigation. UBI is used as the primary index in this work, and critical links in seismic mitigation are those with relatively large UBI values. The meaning of DCI, on the other hand, is complementary to UBI but less direct since it is related to the consequence of damage. Nevertheless, it is shown later that in the context of the problem herein the two indices are related. Identification of critical links using DCI and UBI are illustrated in this work using a hypothetical water supply system, which is described in the next section.

3. HYPOTHETICAL WATER SUPPLY SYSTEM

Figure 1 shows a hydraulic network model of the hypothetical water supply system, which is the same example system used in Users Manual of the hydraulic analysis software EPANET (Rossman 2000). The system contains 92 junctions and 117 pipes representing about 66 km of pipelines in a service area of about 10 km^2, 59 consumer demand nodes with a total demand of 40,634 liter/min (10,736 gallon/min), three storage tanks, two reservoirs representing a river and a lake, and two pumps that extract water from the river and lake. Water flow starts from the river in the north of the system or the lake in the north-west of the system, and it follows a general trend of from north to south and west to east. The main water source of the system is the river, which provides about 80% of the water.

The largest consumer demand is 17,076 liter/min at Node 203. The 117 pipes in the system have diameters varying from 200 mm (8 inch) to 760 mm (30 inch). As shown in Figure 1, most of the pipes with diameters of 610 mm (24 inch) or above are used to deliver water from the river, the main water source, to Node 203, the largest demand node in the system. In this study, the pipes with diameters of 610 mm (24 inch) or above are assumed to be steel pipes, as opposed to cast iron pipes that are assumed for the remaining pipes with relatively small diameters.

4. MONTE CARLO SIMULATIONS WITH GIRAFFE

Seismic performance of the hypothetical water supply system is evaluated using Monte Carlo simulations in conjunction with a special hydraulic analysis computer program, Graphical Iterative Response Analysis of Flow Following Earthquakes, or GIRAFFE (Shi et al. 2006, and Shi 2006). GIRAFFE incorporates a special algorithm for the treatment of negative node pressures in a heavily damaged water supply system to provide a more realistic assessment of the seismic performance (Markov et al. 1994). The algorithm has been used to simulate the flow and pressure distributions of the San Francisco Auxiliary Water Supply System after the 1989 Loma Prieta earthquake (Markov et al. 1994) and those of the Los Angeles Water Supply System after the 1994 Northridge earthquake (Shi et al. 2006, and Wang 2006). Similar algorithm was also described by Tanaka (1996) and Hwang et al. (1998), and was applied to the Memphis water supply system (Hwang et al. 1998).

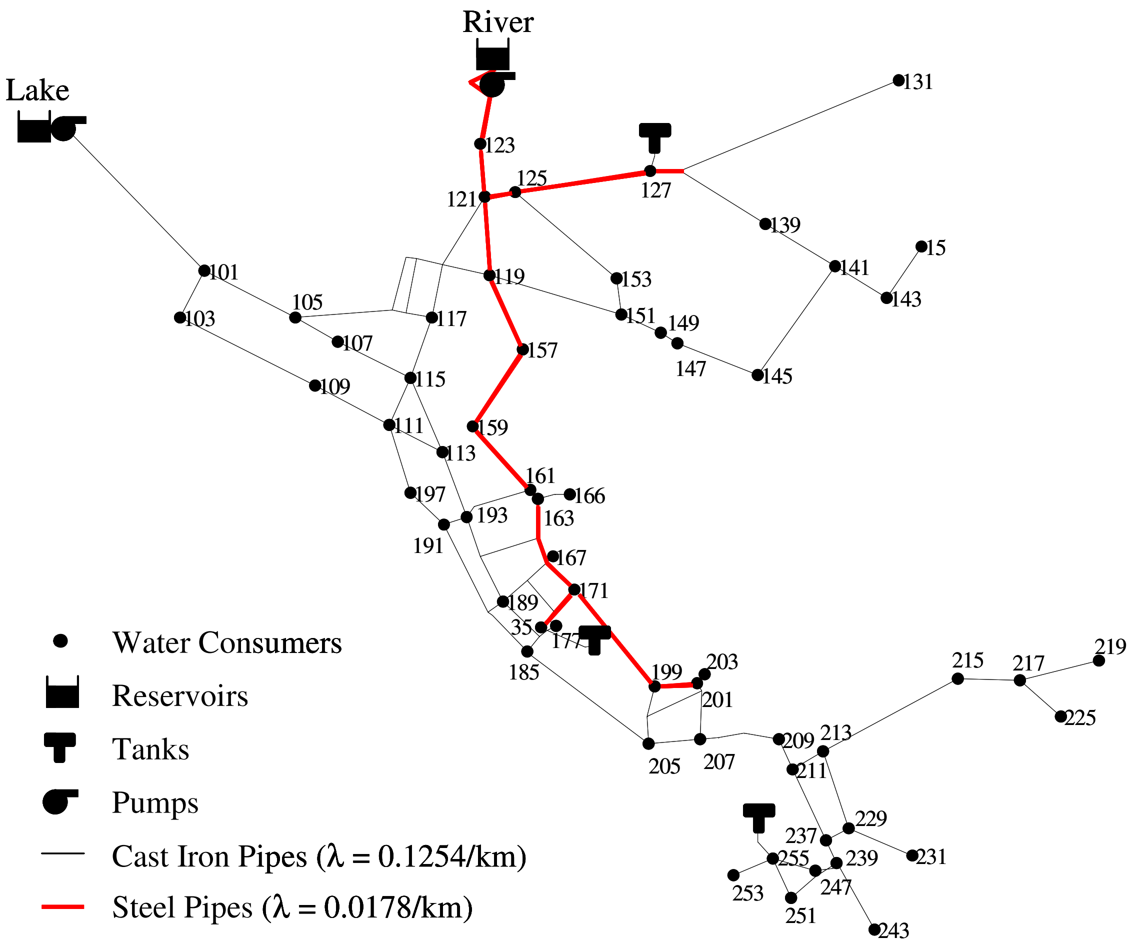

Figure 1. Schematic View of a Hypothetical Water Supply System

The occurrence of damage in each pipe was simulated using a Poisson process with a damage rate, λ. The value of λ for steel pipes (with diameters 610 mm or above) and cast iron pipes (with diameters smaller than 610 mm) are assumed to be 0.0178 and 0.1254 damage per kilometer of pipe length, respectively. These values correspond to a peak ground velocity (PGV) of 50 cm/sec in accordance with the λ versus PGV regressions developed from observations of the 1994 Northridge earthquake (Jeon and O'Rourke 2005, Jeon 2002). This work focuses on seismic response of the pipeline system, and the three storage tanks, two reservoirs, and two pumps in the hypothetical system are assumed intact in the simulations. Observations from past earthquakes show that the seismic effects on other components, such as pump stations, storage tanks, and reservoirs, are of secondary significance when compared with those of the pipeline network (Lund and Cooper 1995).

5. CRITICAL LINKS OF WATER SUPPLY TO CRUCIAL WATER CONSUMERS

A key step in the seismic mitigation of water supply to crucial water consumers is to identify critical links that significantly affect their water supply under an earthquake. A Pipe j is considered as a critical link of water supply to Node i, when the upgrade of Pipe j has relatively significant impact to the reliability of water supply to Node i (i.e., the UBI_{ij} is relatively large). This section proposes a method to identify critical links with the aid of efficient frontier. As an illustration, critical links of water supply to Node 203 are identified using the proposed method.

5.1. Upgrade Analysis Using Conditional Samples

For a given water consumer i (e.g., Node 203), a Pipe j has a UBI_{ij} that can be estimated from a separate set of

Monte Carlo samples in which the damage occurrence probability of the upgraded Pipe j is set to 0, i.e., $P_{upgrade}(L_j) = 0$. As a complicated water supply system might contain a large number of pipes, identification of critical links in such system involves a large number of separate Monte Carlo runs for estimating UBI of each pipe. Consider, for example, the hypothetical water supply system used in this work, which contains 117 pipes. Then, totally 117 separate Monte Carlo runs are needed to estimate 117 UBI for the respective 117 pipes. As critical links are those with relatively large UBI, they are identified by comparing these 117 UBI.

In the context of the problem herein, repeated Monte Carlo runs for different upgrade configurations can be avoided by noting that Monte Carlo samples under the upgraded scenarios can be obtained from the conditional samples of a single Monte Carlo run for the nominal scenario, i.e., without upgrade provision. In the single Monte Carlo run for the nominal scenario, a subset of the samples in which the given Pipe j is observed intact can be treated as an equivalent set of Monte Carlo samples that the given Pipe j is upgraded. Consider, for example, a nominal scenario Monte Carlo run with 10,000 samples. If Pipe 321 is found intact in 9,933 out of the 10,000 samples. These 9,933 samples can be treated as an equivalent set of Monte Carlo samples in which Pipe 321 is upgraded such that no damage occurs in it. UBI for Pipe 321 then can be estimated from these 9,933 samples using the following equation:

$$UBI_{ij} = \frac{\frac{n_2}{m_2} - \frac{n_1}{m_1}}{1 - \frac{n_1}{m_1}} \tag{5.1}$$

in which m_1 is the number of all Monte Carlo samples under the nominal scenario, n_1 is the number of Monte Carlo samples in m_1 that Q_i is satisfied; m_2 is the number of Monte Carlo samples that no damage occurs in Pipe j, and n_2 is the number of Monte Carlo samples in m_2 that Q_i is satisfied.

5.2. Efficient Frontier

Upgrade decisions often need to address cost-benefit concerns. Naturally, the larger the amount of resources allocated for upgrade, the larger the increase in system reliability and UBI. A diagram of benefit versus cost provides a convenient means for making upgrade decisions under limited resources. Here, we consider plotting UBI versus the number of upgraded links in the system. Note that for a given number of links to upgrade, the resulting benefit, in term of UBI, depends strongly on which link is to be upgraded. For a given number of links to upgrade, the upgrade configuration (characterized by a set of links to be upgraded) that results in the highest UBI corresponds to the critical links. This leads to the concept of "efficient frontier".

Figure 2 shows the UBI efficient frontier for Node 203 with the number of upgraded links increasing from one to ten. The UBI efficient frontier increases nonlinearly from 0.28 with upgrade of one link to 0.93 with upgrade of ten links. Figure 3 shows spatial distribution of the ten critical links (i.e., Pipes 229, 177, 321, 187, 175, 329, 231, 183, 179, and 191) that are selected from the UBI efficient frontier. The ten critical links are located along the trunk lines that deliver water from main water source (i.e., the river) to the Nodes 203.

The group of critical links is shown to occur in a recursive fashion. Consider, for example, the group of ten critical links determined from group UBI efficient frontier includes the group of nine critical links from the group UBI efficient frontier and one additional link. The order of adding critical links is shown in Figures 2 and 3 (i.e., Pipes 229, 177, 321, 187, 175, 329, 231, 183, 179, and 191), and it is found that the order does not necessarily follow the decreasing order of the UBI for each individual pipe (i.e., Pipes 229, 177, 321, 187, 175, 183, 231, 329, 201, and 179). For example, the sixth largest UBI occur in Pipes 183. However, the efficient frontier in Figure 2 shows that the sixth pipe added to the critical link group is Pipe 329. The UBI values for pipe groups that contain pipes with the largest individual UBI value are shown in Figure 2, and they are slightly less than the UBI efficient frontier, particularly when the number of pipes is six, seven, nine, or ten. A group of links that have the largest UBI individually do not necessarily have the largest group UBI, or form part of the efficient frontier.

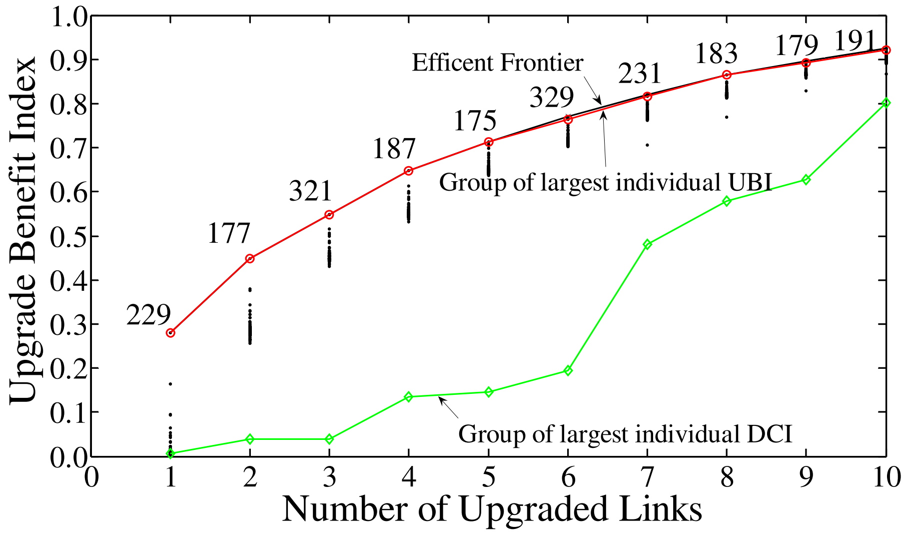

Figure 2. Efficient Frontier for Node 203

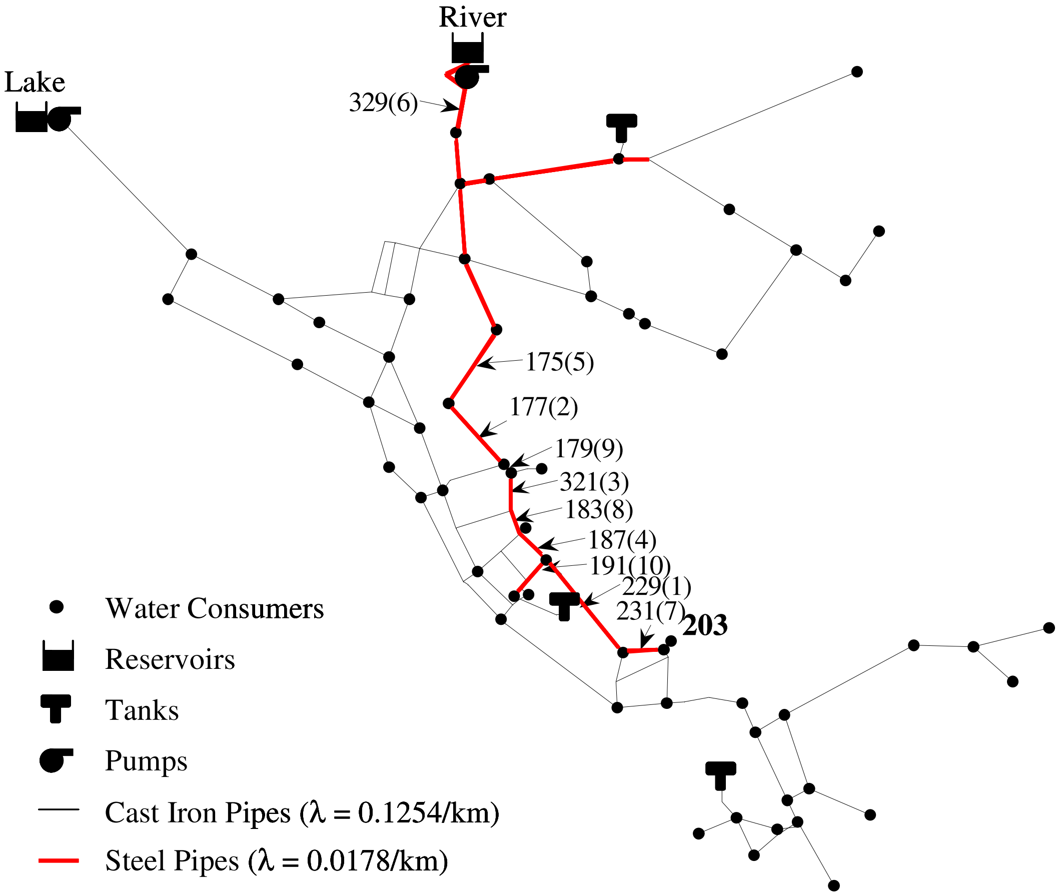

Figure 3. Spatial Distribution of Critical Links from UBI Efficient Frontier for Node 203 (Number in the parenthesis after the pipe ID indicates the order of adding the critical links to the critical link group)

6. DCI AND UBI RELATIONSHIP

As mentioned before, DCI and UBI are based on two different considerations, i.e., reduction of $P(Q_i)$ due to pipe damage and increase of $P(Q_i)$ as a result of pipe upgrade, respectively. Nevertheless, they are related through an identity that can be derived from the total probability theorem:

$$P(Q_i) = P(Q_i|L_j)P(L_j) + P(Q_i|\overline{L_j})P(\overline{L_j}) \tag{6.1}$$

in which $P(L_j)$ and $P(\overline{L_j})$ are probability of Pipe j damaged and intact, respectively. Dividing both side by $P(Q_i)$:

$$1 = \frac{P(Q_i|L_j)}{P(Q_i)}P(L_j) + \frac{P(Q_i|\overline{L_j})}{P(Q_i)}P(\overline{L_j}) \tag{6.2}$$

Replacing the unity on the left hand side by $P(L_j) + P(\overline{L_j})$ and rearranging gives:

$$\frac{P(Q_i|\overline{L_j}) - P(Q_i)}{1 - P(Q_i)} = \frac{P(Q_i) - P(Q_i|L_j)}{1 - P(Q_i)} \frac{P(L_j)}{P(\overline{L_j})} \tag{6.3}$$

That is,

$$UBI_{ij} = DCI_{ij} \frac{P(L_j)}{P(\overline{L_j})} \tag{6.4}$$

Equation 6.4 shows that UBI_{ij} is a product of DCI_{ij} and the odds of Pipe j damage, i.e., $P(L_j)/P(\overline{L_j})$. A numerical example to validate Equation 6.4 is given by Wang and Au (2008). For a given Node i, the DCI_{ij} reflects the effect of system characteristics, such as system connectivity, redundancy, and damage probabilities of pipes other than the given Pipe j, while the odds signifies the influence of the damage probability of this given Pipe j. The equation suggests that, as far as upgrading benefit to Node i is concerned, both the consequence of damage (DCI) and the likelihood of damage (the odds) should be factored in. For example, for two pipes with equal damage consequence (DCI), the one with a higher odds of damage should be upgraded first. On the other hand, among the pipes that have the same odds of damage, the one with a high damage consequence has a higher upgrade priority. These deductions from Equation 6.4 are quite intuitive. Note that the odds is a nonlinear function of $P(L_j)$, and it increases indefinitely when $P(L_j)$ approaches to 1. Therefore, when the odds is close to 1, UBI_{ij} tends to be large and less sensitive to DCI_{ij}; the corresponding Pipe j is likely to be a critical link.

7. CONCLUSIONS

This paper describes a process to identify critical links of water supply to crucial water consumers under an earthquake. Reliability of water supply to a consumer i with water demand Q_i can be measured by the probability, $P(Q_i)$, of Q_i satisfied. Two conditional probability quantities of $P(Q_i)$, Damage Consequence Index (DCI_{ij}) and Upgrade Benefit Index (UBI_{ij}), are proposed to measure the impact of Pipe j on the reliability of water supply to a consumer i and to identify critical links that significantly affect water supply to the consumer i.

UBI is shown to be the primary index in identification of critical links for crucial water consumers, and critical links are pipes with relatively large UBI values. Although DCI and UBI are based on two different considerations, they are interrelated such that, for a water consumer i, UBI_{ij} is a product of DCI_{ij} and the odds of Pipe j damage. For the given water consumer i, DCI_{ij} reflects the effect of system characteristics, such as system connectivity, redundancy, and damage probabilities of pipes other than the given Pipe j, while the odds of Pipe j damage signifies the influence of the damage probability [$P(L_j)$] of the given Pipe j.

The concept of efficient frontier has been employed to identify group of critical links of the system under an earthquake. Although the order of adding critical link to the group of critical links does not necessarily follow the decreasing order of the UBI for each individual pipe, the group of critical links is shown to occur in a recursive fashion. It is also found that, a group of links that have the largest UBI individually do not necessarily have the largest group UBI, or be the group of critical links.

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