13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Post-earthquake restoration of water distribution network: A resilience framework

Wei. Liu
Professor, State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China; Dept. of Civil Engineering, Tongji University, Shanghai, China

Zhaoyang. Song
PhD Student, Dept. of Civil Engineering, Tongji University, Shanghai, China

ABSTRACT: A demand-based seismic resilience analysis framework is proposed in this paper. Four pipe recovery strategies, including random, experienced, static importance-based and dynamic importance-based strategies, are introduced and simulated using two cases to compare their effects on improving resilience level. Based on simulation analysis, the importance-based strategies perform more efficiently in improving resilience than traditional practice prioritizing pipes nearby the water factory. In addition, although the dynamic-based strategy, the best one among the four, is not globally optimal, which is verified by exhaustion and genetic algorithms, it is still a near-optimal solution due to the limited error and high computation efficiency.
KEYWORDS: water distribution networks, seismic resilience, recovery, pipe importance, optimal strategy

Water distribution networks (WDNs) play critical roles in providing domestic and industrial water for the modern city, which are hence referred as one kind of important lifeline engineering system (Li 2005). However, previous earthquake investigations show that the seismic capacity of WDNs are very weak and difficult to restore. For example, more than 47,000 kilometers water pipes were damaged after the Wenchuan Earthquake, the factory water head in Mianzhu city, a city close to the epicenter, dropped substantially from 0.38Mpa to 0.1Mpa and only reached 0.19Mpa after 15 days (Liu et al. 2018). Based on the statistics of NIST, the average recovery period of WDNs after earthquake is as long as 4-8 weeks, which is far beyond people's expectations of 1-3 days (Cauffman 2016). Therefore, scientific recovery plans are necessary to make the WDNs return the normal function level efficiently after earthquake.

In recent decades, resilience has drawn much attention by scholars in lifeline field. Compared to traditional efforts aiming at improving the resistance ability of components or systems, resilience study put more emphasis on the post-disaster restoration (Bruneau et al. 2003; Cimellaro et al. 2010). For WDNs, the resilience researches include three aspects, namely, energy theory (Creaco et al. 2014; Todini 2000), graph theory (Herrera et al. 2016; Yazdani et al. 2011), and recovery-based theory (Cimellaro et al. 2016; Zhuang et al. 2013). However, the suggested restoration schemes are design-based and difficult to operate after earthquake, such as pipe material and topology optimization, pump update, and tank increase. In addition, pipe restoration is not studied in detail in these articles. In fact, pipes are main components of WDNs as well as the badly damaged ones after earthquake, hence, their restoration are worthy of further studied.

This paper is organized as follows: Section 1 introduces the demand-based seismic resilience framework of WDNs. Then, Section 2 proposes different pipe restoration strategies based on pipe importance theory. Section 3 illustrates the above frameworks and compare the effectiveness of various recovery strategies by two cases. In this section, the optimal recovery strategy is studied by different algorithms and compared with the strategy suggested in this paper. Section 4 gives the conclusions at last.

1. DEMAND-BASED RESILIENCE ANALYSIS FRAMEWORKS

Generally, the performance variation of WDNs before, during, and after an earthquake can be illustrated by the well-known performance curve, in which the vertical and horizontal axes represent system performance level (SPL) and time, respectively. Once an earthquake occurs at time t_0, the SPL can drop to a low level *I* quickly, which may equal to 0 when the water factory is closed to prevent the serious leak condition from worsening. Usually, this low SPL may last for several days ($t_0 < t < t_1$) before recovery activities are adopted. In this period, various resources are mobilized and the recovery schemes are developed by decision-makers. In addition, some emergency devices such as waterwheels are used to maintain the basic water demand of consumers. Then, recovery actions start at time t_1 and the SPL gradually reaches a new state finally, which may equal to or differ from the original one. Due to different recovery strategies, the SPL may increase along with different paths over time.

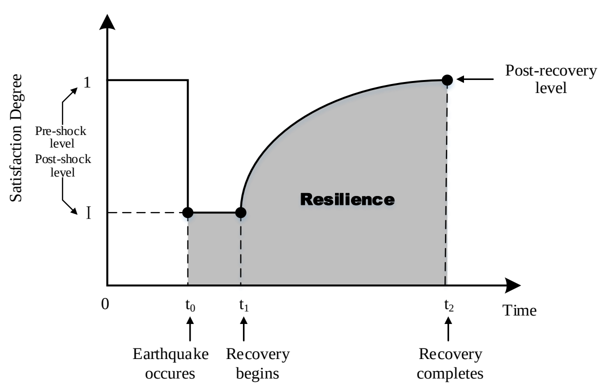

Figure 1: System performance curve

Considering the service of WDNs is well provided if consumers' demands are satisfied, a satisfaction degree index (SDI) is herein proposed to represent the SPL. Obviously, shorter recovery time and higher real-time SDI level mean better recovery capacity and hence more resilient WDNs. Therefore, system seismic resilience index, *SRI*, can be illustrated by the shadow area between the SPL and time axis and measured as follows:

$$SRI = \frac{\int_{t_0}^{t_c} SDI(t)\,dt}{\int_{t_0}^{t_c} TSDI(t)\,dt} \tag{1}$$

where *TSDI* is the SDI in the daily operational state and takes the constant 1 in this paper because its fluctuation is neglectable compared to that during earthquake; t_c is the control time, which usually takes the maximum recovery time. Herein, *SDI* is characterized by the water head as follows:

$$SDI = \frac{1}{n}\sum_{i=1}^{n}\begin{cases} 1 & h_i(t) \ge h_{i0} \\ \dfrac{h_i(t)}{h_{i0}} & h_i(t) < h_{i0} \end{cases} \tag{2}$$

where n is the number of nodes, h_{i0} is the demand head of node i, $h_i(t)$ is the nodal head of node i at time t, which can be quantified by seismic hydraulic flow analysis (referring to (Liu et al. 2016; Liu et al. 2014)).

2. PIPE RESTORATION STRATEGIES

Pipes are main parts of WDNs and also badly damaged after earthquake. In practice, the recovery sequence of these damaged pipes is usually decided by the distance from water factory expect for the ones close to critical facilities such as hospitals. However, previous studies show that the pipe recovery sequence in a network of such kind may influence the system recovery efficiency considerably (Baroud et al. 2014). In order to investigate these effects, the pipe importance theory is introduced in this section. For pipe j, its static importance index, $I_{s,j}$, is defined as the average growth heads of all nodes after its restoration as follows:

$$I_{s,j} = \frac{\sum_{i=1}^{n}\left(h_i^j - h_i^0\right)}{n} \tag{3}$$

where h_i^j is the head of node i after the restoration of pipe j, h_i^0 is the head of node i before recovery actions are taken. Then, the pipes can be repaired based on their I_s accordingly. However, after the pipe with the maximal I_s is restored, the importance indices of the unrestored pipes may change because the WDN essentially becomes a new one. Thus, the dynamic pipe importance index, $I_{d,j}$, can be defined as:

$$I_{d,j} = \frac{\sum_{i=1}^{n}\left(h_{d,i}^{j} - h_{d,i}^{0}\right)}{n} \tag{4}$$

where $h_{d,i}^{j}$ is the head of node i after the restoration of pipe j in the new WDN and $h_{d,i}^{0}$ is the initial head of node i in the new WDN. Then, the pipe recovery priority varies as time.

Two recovery strategies are introduced based on equations (3) and (4), namely, the static importance-based recovery strategy (S3) and the dynamic importance-based recovery strategy (S4). As benchmarks, two strategies are also studied, namely, the random and experienced recovery strategies (S1 and S2). For the experienced one, pipes close to water factory are repaired firstly. The resilience-based simulation flow of post-earthquake pipe restoration can be seen in Fig. 2.

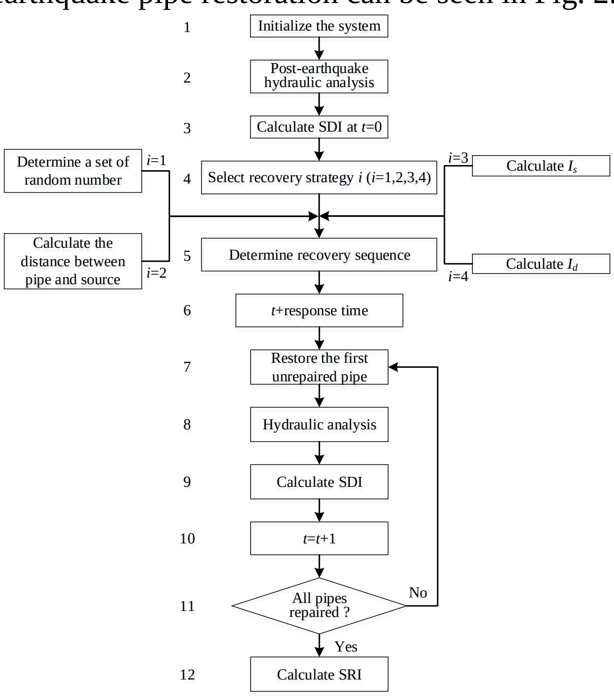

Figure 2: Simulation of different pipe restoration strategies

Herein, any damaged pipe is assumed to be repaired in one day with one unit of resource, which means one work team with enough repair equipment and crew. In addition, the recovery actions are assumed to be implemented instantaneously once the earthquake occurs, i.e., t_1=t_0, because the time used for decision-making and preparation (t_1−t_0) is usually shorter than the total control time (t_C−t_0) (Fig .1).

3. CASE STUDY

3.1. A small WDN

A small WDN with 6 nodes and 7 pipes (Fig. 3), in which node 6 is the water factory and nodes 1-5 are consumers, is modeled to compare the effectiveness of above four strategies. Herein, all pipe materials are made of grey cast iron, the earthquake intensity is VIII, and the demand head is 10 m.

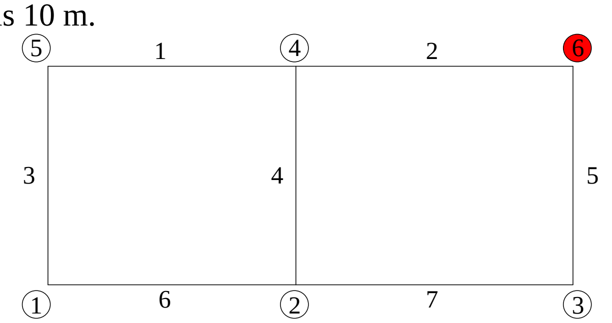

Figure 3: A small WDN

Pipe recovery sequences under the four strategies are: S1: 4→ 6 → 1→ 3 → 7 → 5 → 2; S2: 2 → 5 → 4 → 7 → 1 → 6 → 3; S3: 5 → 2 → 7 → 4 → 1 → 3 → 6; S4: 5 → 2 → 7 → 4 → 3 → 1 → 6. The pipe recovery sequence of S4 is almost the same with that of S3 except for the fifth and sixth pipes. The difference between static and dynamic importance values of pipes is shown in Section 3.3 because it is not obvious in this case.

Fig. 4 shows the SDI recovery paths of the four strategies. Obviously, S1 shows lower SDI compared to the other three. S3 and S4 show better effectiveness than S1 and S2 because the pipes with high I_s are restored firstly. In addition, S4 is the best of the four strategies due to its consideration of the impact of restored pipes on other unrestored ones, but its SDI increase is not obvious compared to S3. The *SRI*s of the four strategies are 0.3193, 0.6142, 0.6203, and 0.6205, respectively, which also prove above explanations.

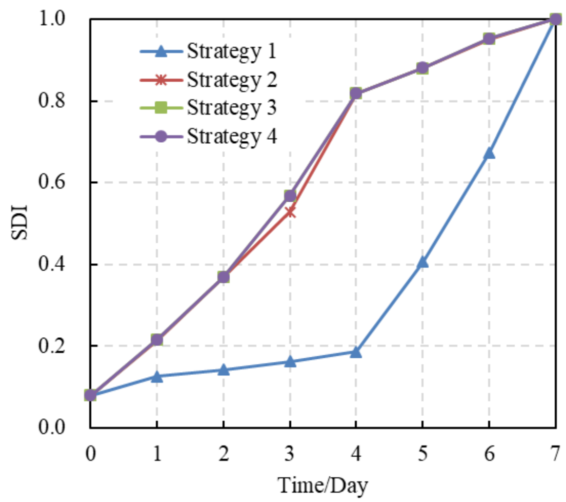

Figure 4: SDI recovery curves of different strategies in the small WDN

3.2. Discussions of the optimal recovery strategy

Based on above analysis, the recovery effectiveness of dynamic importance-based strategy (S4) is the best, which is also verified by our other cases (see Section 3.3). However, whether it is the globally optimal solution should be studied. Herein, taking above small WDN as an example, two ways are used to solve the problem, i.e., the exhaustion method (EM) and the genetic algorithm (GA).

With respect to the EM, any solution refers to one pipe recovery sequence and hence the scale of solution space for this WDN is 7! (=5040). After calculating the *SRI*s of all solutions, the best recovery strategy can be obtained, i.e., 2→7→4→5→3→1→6, with the *SRI* of 0.6214. Notably, the best recovery strategy is different from S4 and its *SRI* improves by 1.45%, which proves that S4 is not the globally optimal solution.

With respect to the GA, the determination of optimal recovery strategy can be mathematically abstracted as a typical combinatorial optimization problem. Generally, six key steps are modeled to solve this problem as follows (Li et al. 2008; Ouyang and Wang 2015):

1. Initial populations generation. Considering one pipe is restored only once, an initial solution is represented by a gene with 7 bits and each one stores a pipe number to be restored. In order to improve the search scope, the initial populations in this case include 100 randomly generated genes.
2. Population evaluation. Since a gene represents a specific pipe recovery sequence, its fitness degree can be quantified by *SRI* value.
3. Selection operator. Roulette wheel strategy is adopted herein. The gene with bigger *SRI* has more chance to transfer to next generation.
4. Crossover operator. Two selected genes are taken to produce two offspring in a crossover rate of 0.8. In order to avoid the repeated pipe number in the same offspring gene after crossover operation, the repeated but uncrossed parts in one offspring gene are exchanged with the corresponding parts of the other one.
5. Mutation operator. Two elements of one offspring gene are randomly selected and exchanged in a mutation rate of 0.1.
6. Terminating criterion. The maximum iteration number is set to 500 to avoid premature stop of the algorithm.

After 21 iterations, the optimal solution is obtained and remain unchanged in the following iterations, which is the same with that given by the EM. Therefore, the dynamic importance-based strategy is proved to be not the optimal solution through the results of the EM and the GA.

From the perspective of computation cost, the EM and the GA needs 2000s and 819s, respectively, to obtain the optimal solution whereas S4 only needs 3s. In addition, the relative error between S4 and the optimal solution is only 0.0009. Therefore, although the dynamic importance-based pipe recovery strategy is not the global optimal solution based on the results of the EM and the GA, it is still a near-optimal solution considering the neglectable error and low computation cost.

3.3. A medium WDN

A medium WDN with 19 nodes and 27 edges, in which node 19 is the water factor node and the others are consumer nodes (Fig. 5) is studied. The pipe materials, joints, Hazen-Williams coefficients, earthquake intensity, source and consumer head are the same with the small WDN in Section 3.1.

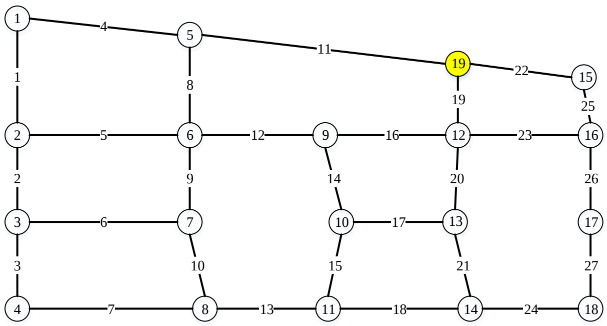

Figure 5: A medium WDN

Fig. 6 show the static importance values of 27 pipes in the medium WDN. In general, pipe location, or their distance from the source, has an important influence on I_s. For example, pipes close to the source such as pipes 11, 19 and 23 have higher I_s than pipes that are far from the source such as pipes 3, 6 and 10. But this pattern is not always true, for example, pipe 7 is much farther from the source than pipe 19 but has a higher I_s than the latter. In fact, the leak area (and consequently the leakage flow) of pipe 7 (0.049) is higher than that of pipe 19 (0.017). Therefore, the damage state influences I_s as well.

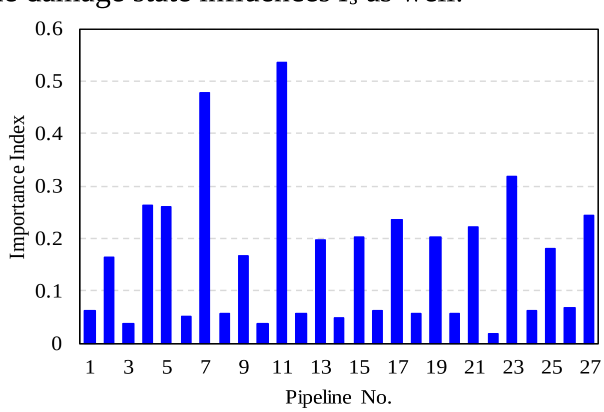

Figure 6: Static importance values of pipes in the medium WDN

Fig. 7 shows the variation of both dynamic importance value and priority rank of pipe 9 during recovery. In this figure, pipe I_d before recovery is 0.168 and changes during recovery until it becomes the most important pipe to be restored at step 8. Herein, its initial I_d (at step 0) ranks 13th among all pipes, i.e., it is the 13th pipe to be restored if static importance theory is adopted. Then, at step 1, it ranks 11th on the basis of its I_d, i.e., its rank advances one. Similarly, its rank at the following steps also advances until it becomes the most important pipe to be restored at step 8.

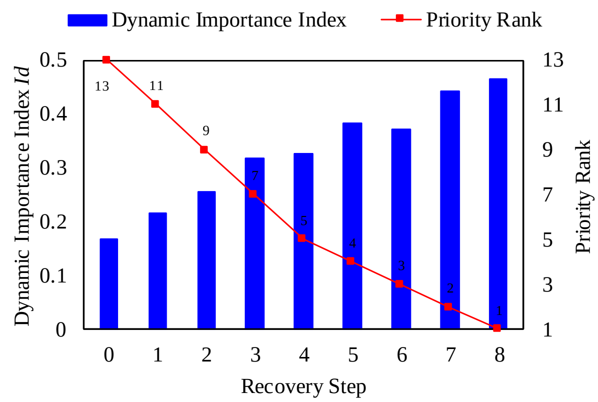

Figure 7: Dynamic importance values of pipes in the medium WDN

Similarly, four strategies are formulated as follows:

(1) S1: 16→21→13→26→18→8→6→27→2→19→10→5→25→14→20→17→11→15→1→7→24→22→4→3→12→9→23

(2) S2: 19→22→11→16→23→25→20→12→14→17→26→27→21→24→18→15→8→9→4→1→5→2→13→10→6→3→7

(3) S3:11→7→23→4→5→27→17→21→15→19→13→25→9→2→26→16→1→24→8→18→12→20→6→14→3→10→22

(4) S4:11→7→4→5→23→13→17→2→9→21→15→27→19→25→6→1→3→8→10→12→14→16→18→20→22→24→26

Fig. 8 shows the SDI recovery curve under the four strategies and more valuable details exist than the small WDN. As benchmarks, the recovery effectiveness of S1 and S2 is not obvious and S2 has a slightly higher *SRI* compared to S1. S3 enhances the resilience considerably, it needs 16 days to reach the maximum SDI level, which shortens 10 and 13 days compared to S1 and S2. Its *SRI* is as high as 0.851, which is higher by 22.8% and 20.7% than S1 and S2, respectively. In addition, S4 is still the best among the four strategies. Its *SRI* is 0.858, which is 23.8%, 21.7%, and 0.8% larger than those of S1, S2, and S3, respectively.

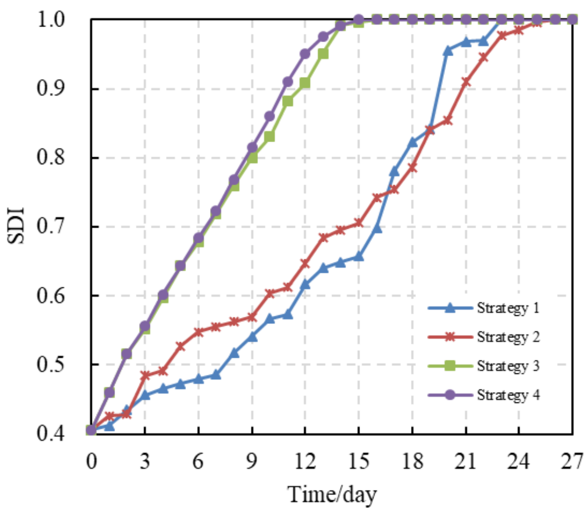

Figure 8: SDI recovery curves of different strategies in the medium WDN

Considering the huge scale of solution space (27!) if the EM is adopted, GA is used to search the optimal solution. In order to obtain the optimal solution, the stop criterion is set to 1000 iteration steps. Four independent simulations are conducted and four final solutions are obtained, in which three solutions are the same with S4 and one is different. For the different one, its *SRI* is lower than S4. Based on the calculation results, although S4 cannot be proved to be the best one, it is also accepted considering limited error and obvious recovery effectiveness.

4. CONCLUSIONS

A demand-based seismic resilience analysis framework of WDNs is proposed based on the hydraulic flow analysis. Then, four pipe recovery strategies, including random, experienced, static importance-based and dynamic importance-based strategies, are proposed and simulated using two cases to compare their effects on improving the resilience. After analysis, the recovery effectiveness of importance-based strategies is more obvious than the traditional practice prioritizing the pipes close to water factory. In these strategies, the dynamic importance-based strategy is the best because it shortens recovery time and ensures high consumers' satisfaction level during recovery. In addition, although this strategy is not the globally optimal one, which is demonstrated by the EM and the GA, it is still accepted due to the limited error and high computation efficiency.

5. REFERENCES

Baroud, H., Barker, K., Ramirez-Marquez, J. E., and MRoccoS, C. (2014). "Importance measures for inland waterway network resilience." *Transportation Research Part E: Logistics and Transportation Review*, 62, 55-67.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, J. C., and O'Rourke, T. D. (2003). "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra*, 19(4), 733-752.

Cauffman, S. A. (2016). *Community Resilience Planning Guide for Buildings and Infrastructure Systems*, Nation Institute of Standards and Technology, Washington, D.C.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). "Framework for analytical quantification of disaster resilience." *Eng. Struct.*, 32(11), 3639-3649.

Cimellaro, G. P., Tinebra, A., Renschler, C., and Fragiadakis, M. (2016). "New Resilience Index for Urban Water Distribution Networks." *J. Struct. Eng.*, 142(8), C4015014. 1-13.

Creaco, E., Franchini, M., and Todini, E. (2014). "The combined use of resilience and loop diameter uniformity as a good indirect measure of network reliability." *Urban Water Journal*, 13(2), 167-181.

Herrera, M., Abraham, E., and Stoianov, I. (2016). "A graph-theoretic framework for assessing the resilience of sectorised water distribution networks." *Water Resour. Manage.*, 30(5), 1685-1699.

Li, J. (2005). *Lifeline earthquake engineering-basic methods and applications*, Science Press, Beijing.

Li, J., Liu, W., and Bao, Y. F. (2008). "Genetic algorithm for seismic topology optimization of lifeline network systems." *Earthquake Eng. Struct. Dyn.*, 37(11), 1295-1312.

Liu, W., Song, Z. Y., and Miao, H. Q. (2018). "Modified Factor for Segmented Pipes in Chinese Pipe Seismic Design Code Based on Probability Density Evolution Method." *KSCE Journal of Civil Engineering*, 22(3), 951-961.

Liu, W., Xu, L., and Li, J. (2016). "Seismic design of water distribution networks using auto-generation techniques." *Structure and Infrastructure Engineering*, 13(7), 831-843.

Liu, W., Zhao, Y. G., and Li, J. (2014). "Seismic functional reliability analysis of water distribution networks." *Structure and Infrastructure Engineering*, 11(3), 363-375.

Ouyang, M., and Wang, Z. H. (2015). "Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis." *Reliab. Eng. Syst. Saf.*, 141, 74-82.

Todini, E. (2000). "Looped water distribution networks design using a resilience index based heuristic approach." *Urban Water Journal*, 2(3), 115-122.

Yazdani, A., Otoo, R. A., and Jeffrey, P. (2011). "Resilience enhancing expansion strategies for water distribution systems: A network theory approach." *Environ. Model. Software*, 26(12), 1574-1582.

Zhuang, B. Y., Lansey, K., and Kang, D. (2013). "Resilience/Availability Analysis of Municipal Water Distribution System Incorporating Adaptive Pump Operation." *Journal of Hydraulic Engineering-Asce*, 139(5), 527-537.