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Comparative Study of Hydraulic Simulation Techniques for Water Supply Networks under Earthquake Hazard

Do Guen Yoo [1], Joo Ha Lee [1] and Bo Yeon Lee [2,*]

[1] Department of Civil Engineering, The University of Suwon, Gyeonggi-do 18323, Korea; dgyoo411@suwon.ac.kr (D.G.Y.); leejooha@suwon.ac.kr (J.H.L.)
[2] Department of Architecture, The University of Suwon, Gyeonggi-do 18323, Korea
* Correspondence: bylee@suwon.ac.kr; Tel.: +82-31-229-8170

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Abstract: Water supply facilities such as waterworks systems are facilities that supply residential and industrial water essential for humans to live and it is essential for these facilities to be prepared for earthquake hazards. In the present study, new hydraulic analysis procedures that can complement problems in existing model were proposed for performance quantification under seismic hazards. Detailed procedures for estimating the serviceability of water supply networks using pressure dependent demand (PDD) and pressure dependent leakage (PDL) techniques were proposed. The developed methodologies can simulate many pipe leakage and breakage situations more realistically. The methodologies were applied to representative pipe networks to investigate the models and new performance quantification indicators were additionally presented. The developed models are judged to be usable as a basic tool finding for guidelines because they can simultaneously quantify the amount of leakage calculated from the viewpoint of suppliers as well as the water availability of consumers when an earthquake hazard has occurred.

Keywords: water supply networks; performance indicator; earthquake hazard; hydraulic analysis; demand driven analysis; pressure driven analysis

1. Introduction

Water supply networks (WSNs) are one of the social infrastructures, have functions to transport, distribute and supply clean water and are very complex connected systems combining water supply pipes, pumps and valves. The role of WSNs is to provide the users with water with appropriate quality at the required water pressure to demand points while maintaining the flow rate required by the users. Social infrastructures (large buildings, schools, public facilities, roads and waterworks), which are large in scale and spatially widely distributed, are quite vulnerable to earthquake hazards and damage to social infrastructures directly or indirectly affects human life. Therefore, WSNs system are also large and spatially widely distributed, most of them are buried underground where not all situations can be identified. Therefore, they are quite vulnerable to earthquake hazards that can cause large damage even when occurred only once on a large scale.

As for studies on earthquake hazard quantification reflecting the hydraulic characteristics of water supply facilities, initial studies applied to simplified water supply systems were conducted by Whitman and Hein [1] and Hall and Newmark [2]. Thereafter, Wang [3], Shi [4], Shi et al. [5], Wang and O'Rourke [6] and Bonneau [7], Bonneau et al. [8], Yoo [9] and Hou and Du [10] conducted earthquake damage quantification studies linked with hydraulic analyses on pipe networks. Yoo [9] developed REVAS.NET (Reliability EVAluation model of earthquake hazard for water supply NETwork), which is software for estimating hydraulic reliability based on structural breakage due to seismic hazards for all water supply facilities. In addition Yoo et al. [11] actually applied the developed model to domestic WSNs to evaluate the seismic reliability and proposed a pipe diameter optimal design model based on the results (Yoo et al. [12]). However, studies related to the proposed earthquake hazard performance quantification used non-commercial software, EPANET2 (Rossman [13]), a representative model of demand driven analysis (DDA). DDA carries out hydraulic analysis under the premise that all the quantities of water supplied in the pipe network are considered as known values. Therefore, DDA cannot directly simulate water losses (leakage, breakage) due to abnormal situations such as earthquake hazards, pipe breakage accidents and the decline of consumers' water availability due to resultant water pressure drops.

To complement such a problem, the Quasi pressure driven analysis (Quasi-PDA) method, which suppresses negative pressure generation through repetitive DDA analyses, has been applied to models already developed. In general, when abnormal results such as negative pressure have occurred, the Quasi-PDA method induces normal results to be derived through methods such as the utilization of an emitter and a virtual reservoir. The GIRAFFE model [14] (Graphical Iterative Response Analysis for Flow Following Earthquakes) is a model for evaluation of WSNs' reliability against earthquake hazards developed based on studies conducted by Wang [3], Shi [4], Shi et al. [5], Wang and O'Rourke [6] and Bonneau [7] and Bonneau et al. [8]. It visually implements reliability evaluation results through interworking with geographic information system functions. However, when simulating pipe failure phenomena with the EPANET2, the quantity of water leaked was reflected through the addition of a virtual reservoir but the demand of nodes decreasing due to pipe failure was not considered. In addition, when solving the problem of negative pressure occurring in EPANET2 of abnormal states such as earthquakes, this model removes the node where negative pressure occurs and all the pipes connected to this node when modeling thereby deriving results that underestimate the reliability of the pipe network. In the REVAS.NET model, the demand of the node decreases following the pipe failure is considered and when negative pressure is generated by hydraulic analysis, the basic demand of the relevant node is set to 0 and the hydraulic analysis is repeatedly conducted. The most important problem in these methods is that pressure deficit conditions cannot be simulated in EPANET2 in a "mathematically accurate way." This methodology can adopt repetitive EPANET2 simulations to simulate pipe breakage but the results cannot assure that demand driven engines are accurate for many outflow situations such as leakage and breakage. Eventually, using EPANET2 (or Quasi-PDA) together with the DDA approach to simulate the pressure deficit conditions of network may be questionable as has been widely suggested by many research papers (Ang and Jowitt [15]; Giustolisi et al. [16]).

Pressure driven analysis (PDA) for WSNs has been actively studied by many researchers recently (Baek et al. [17–19]; Giustolisi et al. [20]; Wu et al. [21]; Lee et al. [22]). Since the supply (generally the sum of the usage and the leakage) is changed by the residual head, PDA is a method to conduct analysis assuming the supply as an unknown quantity. PDA is divided into pressure dependent demand (PDD) analysis, pressure dependent leakage (PDL) analysis and pressure dependent demand & leakage (PDDL) analysis. PDD analysis is determined by the head-outflow relationship (HOR), which is set based on the minimum head and the sufficient head and simultaneously calculates the head and the suppliable flow rate which are in a non-linear relationship. PDL analysis is determined by the relational expression indicating that leakage quantities change according to the pressure head in the pipe and simultaneously calculates the pressure head and leakage quantities in the pipe using an expression expressed with a combination of leakage coefficients. Representative relational expressions include the fixed and variable area discharge (FAVAD) expression proposed by May [23]. Recently, Klise et al. [24] developed a water network tool for resilience (WNTR), which is a new open source Python package that helps water supply plants investigate the water serviceability (WSA) and recovery time for each earthquake scale, location and hydraulic strategy. Although the WNTR proposes PDDL analysis, it uses the emitter coefficient presented in EPANET2 during PDL analysis and does not propose any detailed procedure for the application of PDA.

In the present study, a detailed procedure was proposed for estimating the reliability of WSNs using a PDA that derives more appropriate hydraulic analysis results under earthquakes. In addition, reliability quantification indicator related to the new leakage quantity were presented through the PDA results and the differences from the existing reliability index (system serviceability) were analyzed. Finally, the proposed methodologies were applied to representative WSNs and compared with the results of REVAS.NET applied with a modified DDA model.

2. Methodology

2.1. Pressure Dependent Demand & Leakage (PDDL) Simulation

Yoo et al. [25] presented simulation situations according to the water usage relationship for hydraulic analysis as shown in Table 1 and suggested that in the case of abnormal situations such as earthquake hazards or areas where the leakage is large, since the supply and the usage are not the same, PDA that can consider changes in the supply and leakage quantities according to water pressure should be conducted.

Table 1. Pipe network analysis simulation situations based on water usage relationships (Yoo et al. [25]).

Simulation Situation	Water Usage Relationship	Example
Normal situation	Supply = total usage(demand)	New planning and design of mid-long term WSNs
	Supply = usage + leakage quantity	Analysis of the current pipe network considering general leakage quantity
Abnormal situation	Supply = usage + leakage quantity	Analysis of the pipe network in situations where the effect of leakage quantity is dominant
	Supply < usage	When the supply is insufficient due to drought, changes in demand, etc.
	Supply < usage + leakage quantity	When pipe breakage has occurred due to various causes

PDA can be divided into PDD analysis, PDL analysis and PDDL analysis depending on whether the water pressure-dependent factors are considered as suppliable demand, leakage quantity or both factors (Figure 1). The description of each analysis method is as follows.

- (DDA) A technique for calculating the pressure head of a point using continuity equations and cyclic equations under the assumption that demands by demand point are known values and can be supplied always(usage, leakage quantity and so forth, are entered as demands)
- (PDA) A technique to conduct numerical analyses considering the suppliable quantity for each demand node and the leakage quantity of the pipe as pressure dependent factors and as variables that must be determined through pipe network analysis
- (PDD) The available quantity for each node is determined by the head-outflow relationship (HOR) set based on the minimum head and the sufficient head and the head and the suppliable flow rate that are in a non-linear relationship are simultaneously calculated.
- (PDL) This is determined by the relational expression indicating that leakage quantities change according to the pressure head in the pipe (representative relational expression—FAVAD) and simultaneously calculates the pressure head and leakage quantities in the pipe using an expression expressed with a combination of leakage coefficients by pipe and the leakage index.
- (PDDL) A method of analysis considering both PDD and PDL analyses

In particular, as shown in Table 2, in cases where hydraulic analysis, in which the breakage of many pipes and water distribution reservoirs are presumed such as the case of earthquakes where large scaled damage is considered, is carried out, pressure dependent demand & leakage (PDDL) analysis should be conducted so that more realistic hydraulic analysis results can be derived.

Table 2. Appropriate analysis techniques according to the purposes of pipe network analysis.

Purpose of Pipe Network Analysis	Description	Results of Demand DrivenAnalysis	Appropriate Method	Related Research
Emergency linkage between water supply areas	When a problem has occurred in the block, figure out the quantity of water that can supplied in an emergency and the areas whether the water can be supplied following the opening of emergency linkage pipelines	The sufficient head is satisfied	DDA	Secure local waterworks supply stability
		Poor outflow (the sufficient head has not been reached)	PDD	
		Not suppliable (negative pressure occurred)	PDD	
Hydraulic review following pipe doubling	Figure out the suppliable areas in cases where water is supplied through doubled pipes as problems occurred in large caliber pipes	The sufficient head is satisfied	DDA	Secure wide regional waterworks supply stability
		Poor outflow (the sufficient head has not been reached)	PDD	
		Not suppliable (negative pressure occurred)	PDD	
Supply shortage simulation	Hydraulic review in cases where the block inflow rate (supply) is smaller than the usage	Not suppliable areas/poor outflow areas appeared	PDDs	Local project in which restrictive water rationing is usual
Simulation of changes in leakage quantities between before and pipe network maintenance	Hydraulic analysis before and after pipe network maintenance considering leakage quantities, usage, etc.	Analysis of areas where water flow rates are high	DDA	Pipe network maintenance master plan
		Cases where the ratio of the leakage quantity to the usage is high because the water flow rate is high	PDL	
Analysis of pipe network breakage due to accidents or disasters	Analysis of pipe breakage due to accidents or cases where many pipes or facilities such as water distribution reservoirs have been broken	When the effect of single pipe breakage is small	DDA	Establish emergency response plans
		When the effect of single pipe breakage is large	PDDL	
		When the effect of breakage of many pipes or water distribution reservoirs due to large scaled earthquakes is large	PDDL	

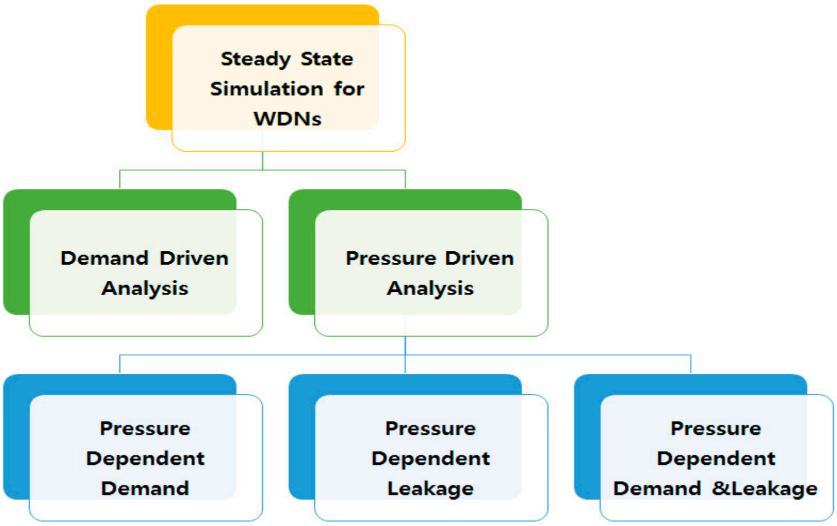

Figure 1. Steady flow pipe network analysis technique classification system reflecting the newest technology.

2.2. REVAS.NET

Yoo et al. [11,12] presented a seismic reliability evaluation tool for water supply systems called REVAS.NET (Reliability EVAluation model of earthquake hazard for water supply network). It quantifies the water supply serviceability through a series of processes of earthquake occurrence and attenuation, the determination of component (pipe, tank and pump) failure conditions and failure modeling based on hydraulic simulations. The running procedure and model construction of REVAS.NET are as shown in Figure 2. The detailed procedures can be found in Yoo et al. [11,12]. In this paper, only those parts that are related to the differences between the proposed methods are presented.

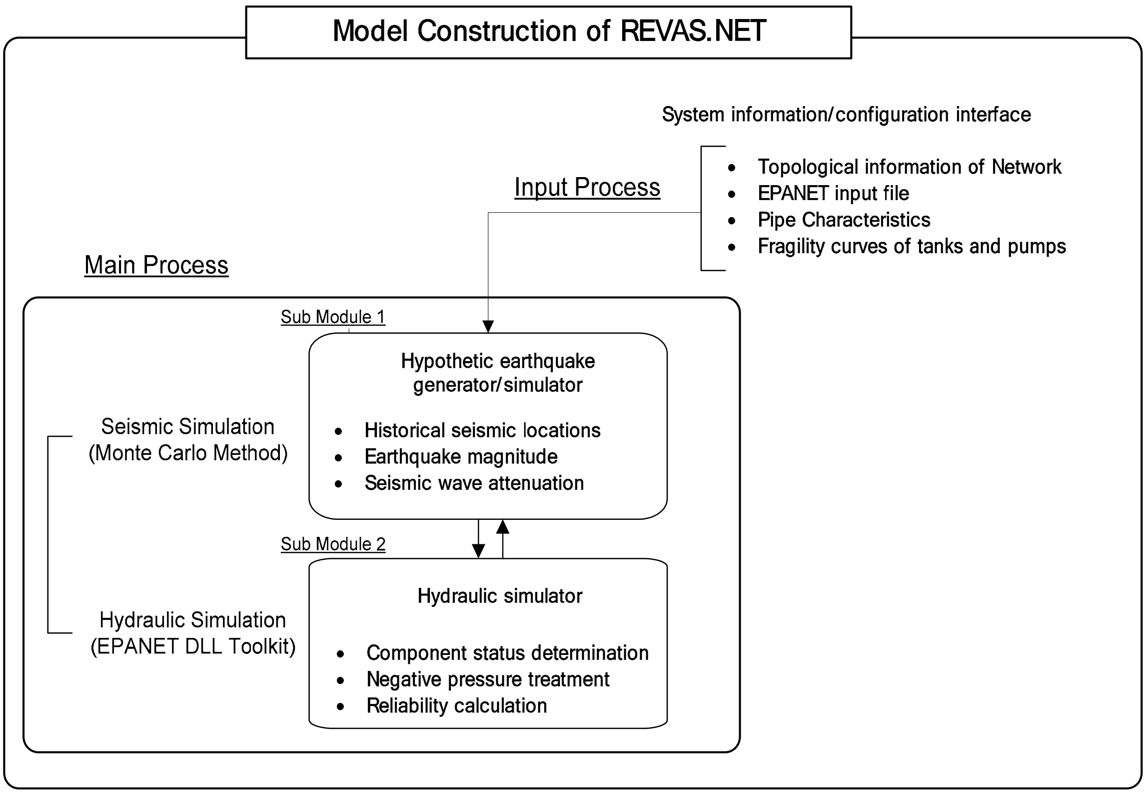

Figure 2. REVAS.NET running procedure and model construction (Yoo et al. [26]).

In the earthquake hazard estimation model, when the conditions of individual components (water distribution reservoir, pumping station and pipe) due to earthquakes have been determined, the conditions should be appropriately applied to the hydraulic analysis program to derive the results. In REVAS.NET, once the destruction of the reservoir and pumping station has been determined, the destruction of the water distribution reservoir on EPANET2 (Demand Driven Analysis Model) used in hydraulic analysis is implemented by closing all pipes directly connected to the water distribution reservoir and the destruction of the pumping station is implemented by stopping the operation state of the relevant pump. In the case of pipes, since pipe conditions are divided into leakage and breakage, the leakage quantity according to the leakage area of the pipe was calculated and the outcome was reflected with the emitter function of EPANET2. This method is generally called Quasi-PDA and the emitter coefficient is entered to simulate the leakage phenomenon indirectly. The equation presented by Puchovsky [26] to calculate the emitter coefficient is as shown by Equation (1) and it indicates the relationship between the breakage or leakage hole cross-sectional area and the flow coefficient. In REVAS.NET, when pipe leakage has occurred, 10% of the pipe cross-sectional area was applied in a lump as the leakage-hole area.

$$C_D = \left(\frac{2g}{r_w}\right)^{0.5} A \tag{1}$$

Here, C_D is an emitter coefficient, g is a gravitational acceleration, A denotes leakage hole cross-sectional area and r_w is specific weight of water

In general, when DDA is conducted, unrealistic results may be generated such as the occurrence of negative pressure (Gupta and Bhave [27], Tanyimboh and Tabesh [28], Mays [29]). Therefore, when negative pressure has appeared as a result of EPANET2, the negative pressure should be taken care of through repetitive operation. In REVAS.NET, when negative pressure had occurred, the negative pressure was taken care of by setting the basic demand of the node where the negative pressure had occurred to 0 and repeatedly conducting hydraulic analysis until the negative pressure did not occur.

2.3. Proposed Method

Table 3 shows a comparison between the analysis of REVAS.NET and that of the proposed model when earthquake damage was presumed on the pipe. In REVAS.NET, when leakage has occurred in the pipe, the emitter coefficient is entered into the bottom node of the leakage pipe. However, in the proposed model, two coefficients (leakage coefficient/breakage coefficient) of the FAVAD equation are directly entered and the leakage quantity of the pipe is directly estimated. When a breakage has occurred in a pipe, techniques such as leakage are used but the pipe state is changed to “closed” to block the flow of water.

Table 3. Comparison between the proposed model and REVAS.NET.

Status of Pipe	REVAS.NET	Proposed Model
Leakage	The emitter coefficient is entered into the bottom node of the pipe where the leakage has occurred (single coefficient)	The C1 and C2 values of the FAVAD equation are entered into the pipe where the leakage has occurred (leakage coefficient/breakage coefficient)
Breakage	(1) During the simulation of hydraulic analysis, the pipe state is set to “closed” to block flows (2) The emitter coefficient is entered into the top node of the broken pipe	(1) During the simulation of hydraulic analysis, the pipe state is set to “closed” to block flows (2) The FAVAD coefficient is entered into the broken pipe
Hydraulic Simulation Technique	Quasi-PDA	Full-PDA

In the case of the HOR relationship of PDD analysis, the form of power function presented by Wagner et al. [30] was applied to the pipe network applied in the present study, the minimum water pressure at which water can be supplied was set to 0 and the sufficient water pressure at which consumers can be satisfied was set to 28 m (40 psi) (Anytown Network) to simulate the hydraulic analysis.

In the case of PDL, the leakage quantity is determined by the relational expression indicating that the leakage quantity is changed according to the pressure head in the pipe and the pressure head and leakage quantity in the pipe are calculated simultaneously using the expression expressed by the combination of the leakage coefficients by pipe material and the leakage index to apply the fixed and variable area discharge (FAVAD) equation. The concept and expression of FAVAD used in the present study were first proposed by May [23] and they are as shown in Equation (2).

$$L = (0.6\sqrt{2g}(C1(P)^{0.5} + C2\left(P\right)^{1.5}\right) \quad (2)$$

Here, $C1$ means breakage leakage coefficient (m^2/unit length), $C2$ means background leakage coefficient (m^2/unit length × head variation) and P is average pressure head

When Equation (2) is utilized, the daily leakage quantity can be calculated by using the leakage quantity per hour calculated through the measurement of the minimum flow at night and the average water pressure in the pipe network. As for the multiplier value of the FAVAD concept, Lambert [31] presented that the multiplier value appeared in a range of 0.5–2.5 depending on the pipe material, leakage position and breakage type and that in particular, the value was generally shown to be 1.5 in the case of the leakage of pipes made of plastic, which is dominantly background leakage that cannot be easily detected, occurring in connection areas and junctions while being shown to be close to 0.5 in the case of those leakages that show the same characteristics of breakage and pipes made of a metal. Therefore, in the case of general pipe network systems in which background leakage and breakage leakage are mixed, the FAVAD equations in the form of Equation (1) are generally applied and coefficient values such as $C1$ and $C2$ should be set in hydraulic analysis. Lambert et al. [32] measured the minimum flow rate at night in an actual pipe network to select $C1$ and $C2$ in Equation (2), presented that the $C1$ and $C2$ values applicable in the relevant pipe network were 0.517 and 0.0481, respectively and proposed the final Equation (3). The AZP (Area Zone Pressure) in Equation (3) means the average water pressure in the water supply area.

Since the coefficient proposed by Lambert et al. [32] is a value for calculating the leakage quantity of the entire pipe network system, while the leakage quantities of individual pipes are separately calculated in the present study, $C1$ and $C2$ values were set appropriately considering the water pressure distribution and the number of pipes in the target pipe network. Since the purpose of the present study is to derive reliability evaluation results through PDA and compare the relevant results with the results of the model of REVAS.NET, in this study, the $C1$, $C2$ values of normal, leakage and breakage states were appropriately assumed for analysis. In this paper, $C1$ and $C2$ values of normal, leakage and breakage states are properly assumed. When actually applied later, since FAVAD coefficients have uncertainty, in cases where reference $C1$, $C2$ values can be set through the measurement of the minimum flow rate at night, the relevant values should be used. Therefore, in this model, the value of $C1$ was set to 0.0001 and the value of $C2$ was set to 0.000005. In the case of breakage, the values of 0.001 and 0.0001 were entered respectively to analyze the results.

$$L = 0.517 \times AZP^{0.5} + 0.0481 \times AZP^{1.5} \quad (3)$$

Here, AZP means Area Zone Pressure.

2.4. Reliability Quantification Factors

2.4.1. System Serviceability (S_s)

System Serviceability (S_s) is an indicator intended to quantify the results of earthquake simulations through hydraulic analysis when earthquake simulations are implemented. Among reliability calculation studies of water distribution network, Gupta and Bhave [33] were the first to suggest pressure dependent analysis in reliability evaluation through volume reliability factor. This is used in REVAS.NET (Reliability EVAluation model of Earthquake hazard for water supply NETwork), which is software for calculation of hydraulic reliability following structural breakage due to earthquake hazards developed by Yoo [9]. In the present study, System Serviceability (S_s), which is known to be appropriate as a reliability factor (Cullinane et al. [34], Tabucchi et al [35] and Lansey [36]) was used. The reliability factor calculation method is as shown in Equation (3).

$$\text{System Serviceability }(S_s) = \frac{\sum Q_{avl,i}}{\sum Q_{inl,i}} \tag{4}$$

Here, $Q_{avl,i}$ is available nodal demand at node i and $Q_{inl,i}$ is required nodal demand at node i.

System Serviceability (S_s) is a factor for evaluating the serviceability of the system following earthquake hazards. It is the ratio of the required demand to the available supply. When this value is 1, it can be concluded that the service of system is continued properly. Yoo [9] defined this value as a factor that is defined and used as availability or serviceability indicating the serviceability of WSNs.

2.4.2. Leakage Ratio Index ($\mathrm{L_{ri}}$)

This model assumed that water can be supplied even when the quantity that must be actually supplied is not satisfied because the usage and leakage quantity have increased or decreased. That is, this model assumed that water can be supplied even when the quantity that must be actually supplied is larger than the quantity of water in the actual water purification plant. Therefore, this model includes not only S_s but also the indicator of leakage quantities (L_{ri}) according to water pressure reliability factors when evaluating the system serviceability. $\mathrm{L_{ri}}$ is a factor for evaluating the serviceability of the system. It is expressed as the ratio of the total required demand of the system to the leakage quantity of the entire pipe. The calculation method of this reliability factor is given in Equation (4). An L_{ri} value of 1 means that the leakage quantity and the required demand are the same and this indicates that the supply should be doubled.

$$\text{Leakage Ratio Index }(\mathrm{L_{ri}}) = \frac{\sum L_{i,}}{\sum Q_{inl,i}} \tag{5}$$

Here, L_i is leakage at pipe i and $Q_{inl,i}$ is required nodal demand at node i.

2.5. Model Configuration

The overall model flow chart of the proposed model is as shown in Figure 3. The demand, water pressure and the numbers of nodes and pipes are identified in the first step, the applicable pipe network information. In the process of assuming earthquake scenarios, many scenarios are assumed, pipes where leakage occurs are increased or reduced one by one and the state of pipes is changed into a state of breakage to evaluate the serviceability according to changes in the leakage quantity. As hydraulic analysis methods, PDD analysis and PDL analysis are used based on PDA. Finally, in the step for the hydraulic performance quantification, the serviceability of the system following earthquake hazards is quantified using disasters using the system serviceability (S_s) and leakage ratio index (L_{ri}) through the leakage quantity and the actual supply.

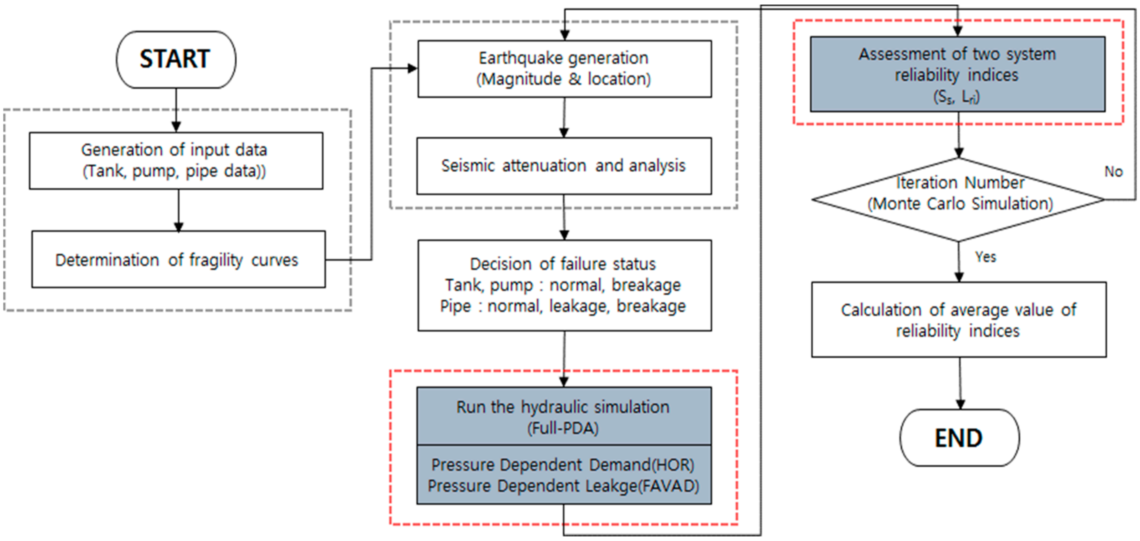

Figure 3. Proposed model running procedure.

3. Application and Results

3.1. Applied Pipe Network

The proposed method is applied to Anytown Network (Figure 4), a well-known benchmark network in the field of waterworks pipe networks (Yoo et al [25]). Anytown Network is a pipe network presented first by Walski et al. [37]. Jung et al. [38] modified this pipe network and used for pipe design to minimize the total cost and maximize system robustness. The pipe originally connected to two water distribution reservoirs was removed and a fixed head was formed so that water is supplied from a single reservoir. Through the foregoing, the head of a fixed water source is heightened from 3 m (10 ft) to 73.2 m (240 ft). The demand required by the entire system is 1113 LPS (liter per second), 17,640 GPM (gallon per minute) and the total length of the pipe is 81,382 m (267,000 ft). The demander's ground heights are distributed in a range from 6 to 37 m (20 to 120 ft) and the pipe diameters are composed of 152–762 mm (6~30 inch).

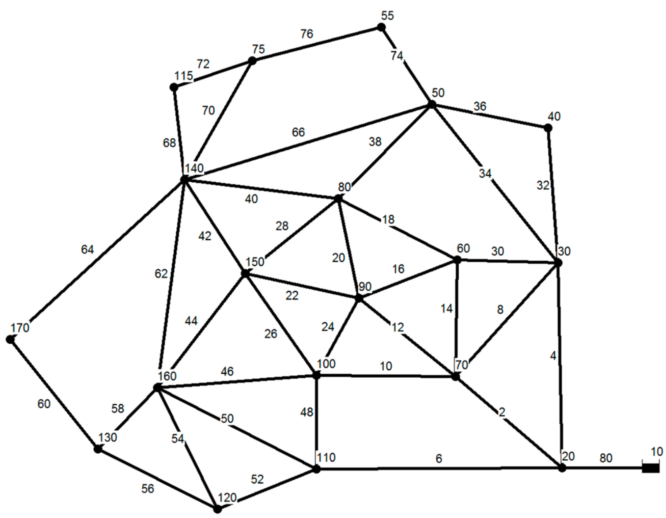

Figure 4. Shape of Anytown Network.

3.2. Earthquake Occurrence and Pipe Damage Scenario Setting

The present paper is focuses on comparing the differences between the results of the hydraulic analysis of REVAS.NET and that of the proposed model. Therefore, a total of 30 earthquake hazard assessment scenarios were constructed assuming a situation where a single earthquake of magnitude 4 (M4) has occurred. Yoo et al. [39] suggests that a minimum of 10 to 5000 Monte Carlo simulations should be performed in order to obtain a consistent system reliability factor that does not show large variance in REVAS.NET. The changes in the number of repetitions as such are affected by the size of the pipe network and the number of pipes. Since the number of pipes in this applied pipe network is relatively small, 30 earthquake scenarios were generated and used for analysis in the present study.

3.3. Application and Results

Of the 30 scenarios in total, 20 scenarios were shown to derive stable and converged results by the proposed model (PDA analysis) and the results of the 20 scenarios were compared quantitatively with REVAS.NET. Table 4 shows the number of pipes where leakage or breakage occurred according to the scenario in which an earthquake of magnitude 4 occurred. Leakages occur in a range of at least 11 to a maximum of 29 and breakages were shown to occur in a range of 1 to 5. In the case of leakages, the leakage quantity deviation may be large according to the leakage-hole size compared to pipe diameters. However, in the case of pipe breakage, it can be predicted that the influence of pipe breakage is relatively large because the flow is cut off and the entire flow rate is lost.

Table 4. Number of pipe according to pipe status (normal, leak, breakage).

Scenario	**Number of Pipe**		
	Normal	**Leak**	**Breakage**
S1	18	16	4
S3	16	19	3
S4	16	19	3
S7	18	17	3
S8	22	15	1
S10	10	27	1
S11	10	24	4
S12	16	19	3
S13	22	11	5
S14	17	18	3
S15	18	16	4
S17	9	28	1
S18	10	23	5
S22	6	29	3
S23	15	19	4
S24	22	14	2
S25	15	21	2
S26	14	21	3
S27	23	11	4
S28	19	18	1
Average	15.80	19.25	2.95

Table 5 presents the results of the proposed model by scenario and the results of REVAS.NET. The results of a total of 20 scenarios showed that the average value of serviceability Ss, which is a performance indicator of the system by the proposed model, was 0.871. This value means that if M4 earthquake occurs, water cannot be supplied for 12.9% of the total demand. The Ss index value by REVAS.NET which is directly comparable was shown to be 0.347, indicating that the serviceability of the proposed model is about 2.5 times higher than that of REVAS.NET. This result is identical to the tendency of the results of comparison between PDA and DDA models presented in Lee et al. [40]. Lee et al. [40] once found that the DDA technique underestimated the system serviceability than PDA for two abnormal scenarios (demand increase, pump failure). This result is attributable to the fact that in the case of the DDA technique, the water pressure of the node is underestimated under the assumption that the demand flow rate of each node is 100% satisfied and it can be seen that the proposed model can calculate the serviceability of more realistic systems.

Table 5. Comparison results between proposed model and REVAS.NET.

Scenario	Proposed Model						REVAS.NET
	Actual Water Supply (LPS)	Deficit (LPS)	Outflow (LPS)	Leakage (LPS)	S_s	L_{ri}	S_s
S1	806	306	1314	508	0.725	0.456	0.202
S3	1010	103	1369	360	0.907	0.323	0.354
S4	1048	65	1530	482	0.942	0.433	0.246
S7	**819**	**293**	**1246**	**427**	**0.736**	**0.384**	**0.199**
S8	724	389	1080	356	0.651	0.320	0.305
S10	1074	39	1343	269	0.965	0.242	0.459
S11	1028	84	1566	538	0.924	0.483	0.225
S12	1060	53	1424	364	0.953	0.327	0.576
S13	696	417	1095	399	0.625	0.359	0.348
S14	956	157	1365	409	0.859	0.367	0.149
S15	995	117	1395	400	0.894	0.359	0.383
S17	1070	43	1380	310	0.962	0.279	0.490
S18	954	158	1416	461	0.858	0.415	0.264
S22	1062	51	1703	641	0.954	0.576	0.261
S23	**937**	**176**	**1457**	**520**	**0.842**	**0.467**	**0.356**
S24	1073	40	1346	273	0.964	0.246	0.416
S25	1059	54	1441	382	0.951	0.343	0.457
S26	1042	71	1383	342	0.936	0.307	0.370
S27	881	232	1366	485	0.792	0.436	0.300
S28	1081	32	1277	197	0.971	0.177	0.582
Average	**969**	**144**	**1375**	**406**	**0.871**	**0.365**	**0.347**

* Total Demand (LPS): 1113.

Since Ss index derived as a result of the proposed model does not take into account the leakage quantity that can occur in the system, the judgment of the reliability of earthquake hazards through the consideration of factors is also necessary. An index additionally proposed in the present study is the Leakage ratio index (L_{ri}), which is defined as the ratio of the loss of pipes caused by the earthquake to the demand required by the system. This index can be thought to be the ratio of the flow rate lost in the pipe before being supplied to consumers due to earthquakes to the supply in normal situations. The average L_{ri} value calculated with the proposed model is 0.365, indicating that the flow rate corresponding to 36.5% of actual demand can be lost due to pipe leakage/breakage following earthquake hazards.

As suggested in the present study, to quantify the serviceability of the system due to actual earthquake hazards, the indexes of S_s and L_{ri} should be considered synthetically. Although the average S_s of the proposed model was quantified to be 0.871, this value was derived under the assumption that even the leakage/breakage calculated in the system can be sufficiently produced and supplied. That is, this factor value is valid only when there is the ability to produce 1375 LPS (column 'outflow' indexed in Table 5), which is the sum of the leakage quantity (406 LPS, column 'leakage' in Table 5) used as the value of the numerator when calculating the average L_{ri} value and the suppliable flow rate (969 LPS, column 'actual water supply' Table 5) entered into the numerator when calculating Ss and supply it to the system. For instance, let us assume that the facility capacity of the Anytown system supply source is 1258 LPS, which is 1.13 times the basic demand (1113 GPM) and compare the results of S7 and S23 scenarios shown in bold face in Table 5. In the case of scenario S23, Ss is high as 0.842 but the loss of the system is also relatively high. Therefore, to reproduce the serviceability of 0.842, a flow rate of 23,094 should be supplied. Since this result indicates that a flow rate exceeding the facility capacity of the supply source should be supplied, it can be predicted that the actual serviceability will be shown to be lower than this value. In contrast, in the case of scenario S7, although the value of Ss was shown to be 0.736, which is somewhat lower than that of S23, the flow rate that should be supplied considering the loss was 1246 LPS, which can be supplied within a range that does not exceed the capacity of the facility. Therefore, the index (L_{ri}) related to losses as such can be said to be not only meaningful as the index but also usable in additional evaluation of serviceability considering the actual facility capacity.

Figure 5 shows the results of the two indices proposed in the present study drawn as a diagram on a plane. In general, when the value of S_s increases, the value of L_{ri} is expected to decrease in inverse proportion. However, the inverse proportionality as such can occur when the final supply flow rate is fixed at a constant level and the result cannot be identified when all the indicators of all scenarios have been shown in a diagram because the final supply flow rates by scenario vary greatly between 1073 and 1703 LPS (17,000 and 27,000 GPM). Figure 5 shows the resultant values of two indicators of the scenario in which the supply (outflow) corresponds to 1325 to 1388 LPS (21,000 to 22,000 GPM) among the earthquake scenarios. It can be identified that as Ss increased, the tendency of decreases in L_{ri} appears clearly.

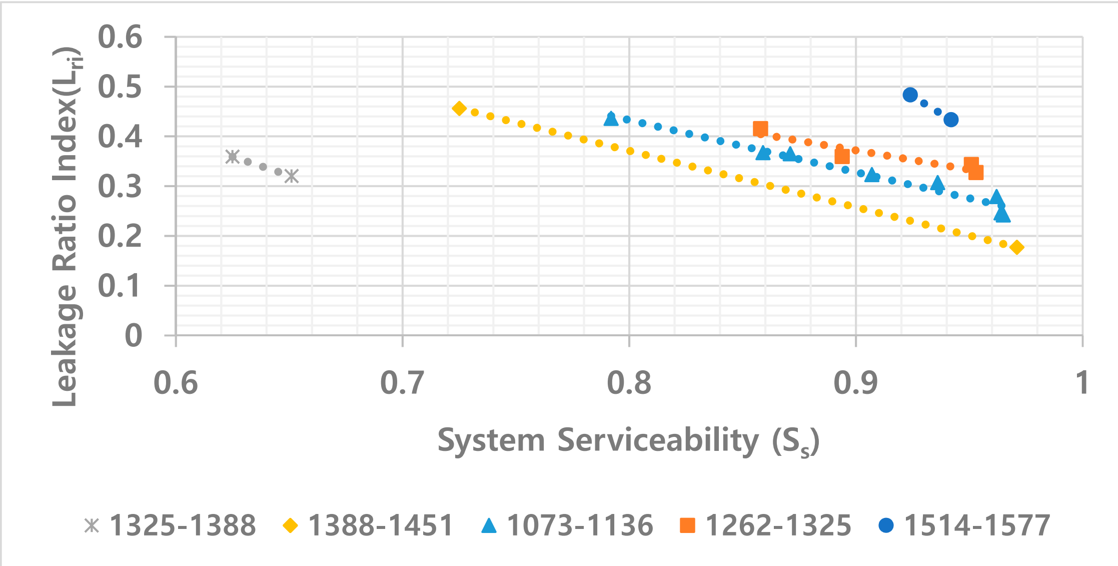

Figure 5. Relationships between S_s and L_{ri} by the section of the total supply flow rate.

As shown in Figures 6 and 7, the proposed model is able to quantitatively estimate the usage that can be supplied and the lost flow rates occurring in individual pipes that cannot be directly calculated in the existing REVAS.NET and can spatially analyze and present them.

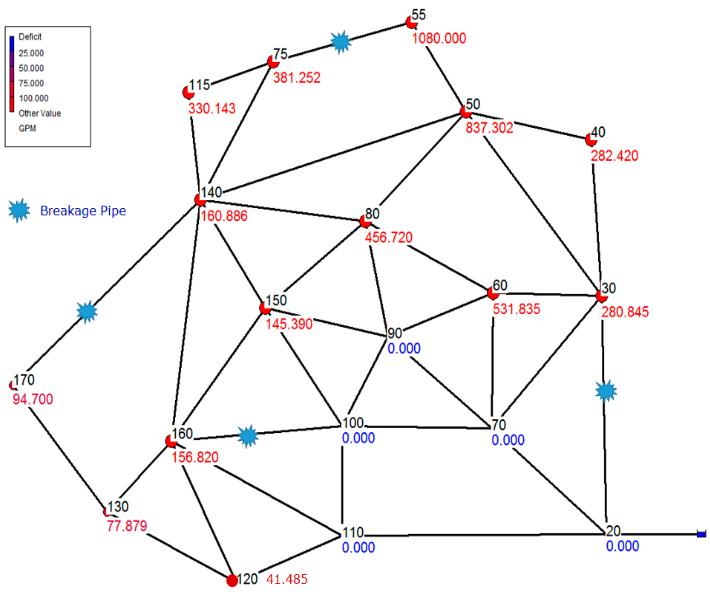

Figure 6. Results of estimation of the usage that can be supplied by node according to scenario S1.

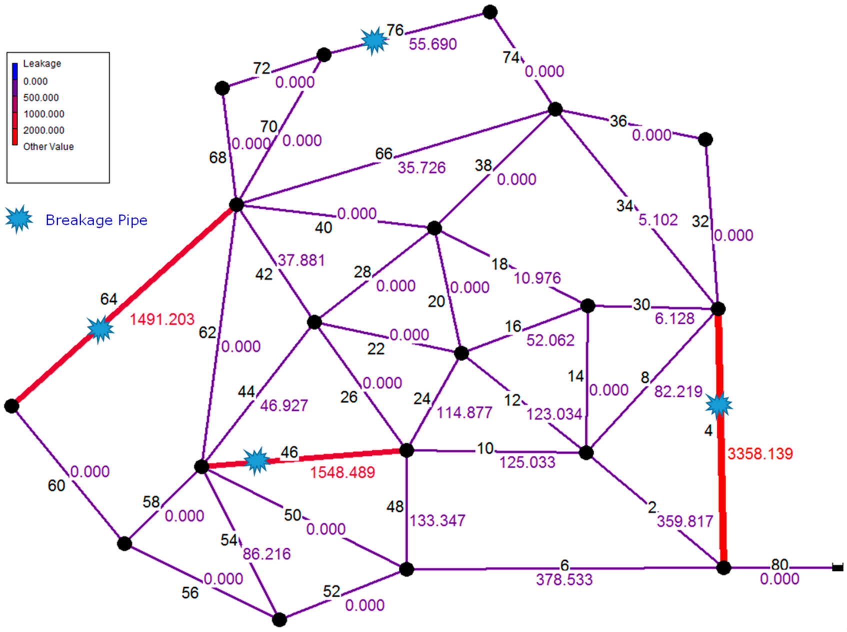

Figure 7. Results of estimation of lost flow rates (leakage, breakage) by pipe according to scenario S1.

Next, changes in the reliability of the system according to the number of pipes where leakage and breakage occurred were reviewed. Table 6 shows changes in the reliability indices of the proposed model and REVAS.NET according to the number of leaked pipes. On reviewing the results, it can be seen that no direct proportional or inverse proportional relationship between the reliability indices and the increase in the number of leaked pipes appeared. This is because leakage quantities can appear in diverse forms depending on the diameter of the pipe where leakage occurred and the area of the pipes where leakage occurred.

Table 6. The results of the proposed model and REVAS.NET according to the number of leaked pipes.

Number of Leaked Pipe	Proposed Model		REVAS.NET
	S_s	L_{ri}	S_s
11	0.708	0.397	0.324
14	0.964	0.246	0.416
15	0.651	0.320	0.305
16	0.085	0.049	0.090
17	0.736	0.384	0.199
18	0.915	0.272	0.365
19	0.934	0.361	0.392
21	0.944	0.325	0.414
23	0.858	0.415	0.264
24	0.924	0.483	0.225
27	0.965	0.242	0.459
28	0.962	0.279	0.490
29	0.954	0.576	0.261

Unlike the foregoing, Table 7 shows changes in the reliability index of the proposed model and REVAS.NET according to the number of break pipes and Figure 8 shows the results of the proposed model according to the number of pipe breakages. On reviewing the results, it can be seen that Ss decreases proportionally while L_{ri} increases proportionally as the number of break pipes increases indicating that unlike pipes where leakage has occurred, when a pipe has been broken, not only water losses increase but also water flow paths are blocked so that the reliability of the entire system is greatly affected. Therefore, in terms of recovery from damage, rather than leaked pipes, restoring break pipes first can lead to the improvement of system reliability within a short period of time.

Table 7. Results of the proposed model and REVAS.NET according to the number of break pipes.

Number of Break Pipe	Proposed Model		REVAS.NET
	S_s	L_{ri}	S_s
1	0.887	0.254	0.459
2	0.958	0.294	0.437
3	0.898	0.388	0.308
4	0.835	0.440	0.293
5	0.741	0.387	0.306

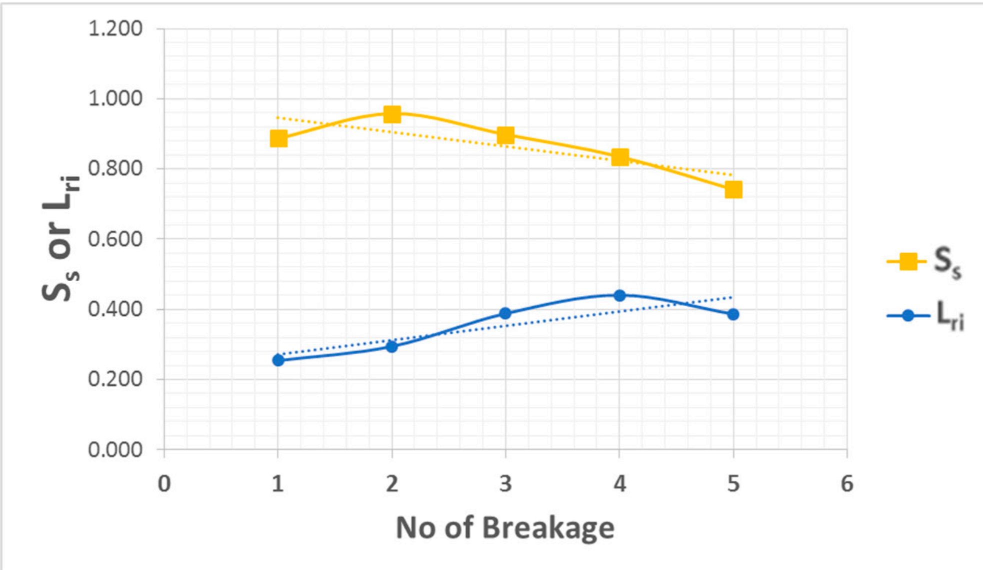

Figure 8. Comparison of the results of analysis of the indices of REVAS.NET according to the number of breakages.

Although the results as written above may be thought to be natural, the quantified results of the proposed model are very important from the viewpoint of decision makers who need to decide whether the water supply system should be continuously operated following the occurrence of earthquake damage. For instance, decision makers can determine the suspension or continuation of the overall operation of the system depending on the degree of damage to water supply facilities due to earthquakes and may continue operation only in some areas. In cases where the operation is suspended, alternative water should be supplied to consumers without fail using bottled water or water wagons. If water can be continuously supplied or supplied only to some areas despite the damage to the system due to the earthquake, the additional finances and manpower inputs for the supply of alternative water and secondary damage (continued outage) can be reduced. For the judgment on whether or not to continue operation, the quantification of damage presented in this model is essential and the quantity of water that must be additionally produced and supplied (which must cover the water loss due to earthquake) and the facility capacity necessary to satisfy the set serviceability can be quantitatively identified using the proposed indices. In addition, changes in the serviceability following the recovery of break pipes can be also figured out quantitatively.

4. Conclusions

The reliability of the system should be evaluated for the design, operation and maintenance of WSNs. The indicators applied to the evaluation and estimation of system reliability are calculated using the results of hydraulic analysis such as water pressure, suppliable flow rate and pipe flow rates at nodes. In particular, the evaluation of reliability in abnormal situations such as earthquakes is greatly affected by the results of hydraulic analysis because the system under unstable conditions should be analyzed. Therefore, for reasonable evaluation of the reliability, a hydraulic analysis technique approximating the behavior of the actual system should be applied. In the present study, for the quantification of earthquake hazard preparedness performance of water supply facilities, new hydraulic analysis methodologies and procedures that can complement problems in the existing model were proposed. Using PDD (Pressure Dependent Demand) and PDL (Pressure Dependent Leakage) techniques, detailed procedures for the estimation of the reliability of WSNs were proposed. The developed methodologies can simulate many pipe leakage and breakage situations more realistically. The methodologies were applied to representative virtual pipe networks to review the models and new performance quantification indicators were additionally presented for analysis.

Following the application, models developed earlier such as REVAS.NET showed a tendency to underestimate the reliability of the system and such results were actually identified to be unrealistic. In addition, the two indicators proposed in the present study (S_s and L_{ri}) were identified to be mutually complementary when the supply flow rates were similar and mainly usable as factors for evaluation of reliability from the viewpoints of users and suppliers, respectively. In particular, Ss, which is an existing system reliability evaluation factor, has a disadvantage of being unable to evaluate the water loss caused by earthquake hazards and can be utilized in judging whether suppliable from the viewpoint of users. L_{ri}, which is an index considering water loss, is a factor that indicates the degree of water loss due to earthquakes and can be used as a measure for determining whether to continue the operation of the system following the occurrence of earthquakes from the viewpoint of suppliers.

The present study was conducted focusing on comparing and analyzing the results of changes in the hydraulic analysis techniques. In future studies, the techniques should be applied to systems with more diverse characteristics (e.g., a system in which two or more water supply sources exist). In particular, in the case of earthquake hazard models, uncertainty always exists in earthquake occurrence and input factors. Therefore, measures for quantitative evaluation of the foregoing are positively necessary. In addition, uncertain parameters such as C1 and C2 in FAVAD equation is used. Therefore, these kinds of uncertainties should be considered and quantified.

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References

1. Whitman, R.V.; Hein, K.H. Damage Probability for a Water Distribution System. In Proceedings of the Current State of Knowledge of Lifeline Earthquake Engineering, New York, NY, USA, 30–31 August 1977; pp. 410–423.
2. Hall, W.; Newmark, N. Seismic Design Criteria for Pipelines and Facilities. *J. Tech. Councils ASCE* **1978**, *104*, 91–107.
3. Wang, Y. Seismic Performance Evaluation of Water Supply Systems. Ph.D. Thesis, Cornell University, Ithaca, NY, USA, January 2006.
4. Shi, P. Seismic Response Modeling of Water Supply Systems. Ph.D. Thesis, Cornell University, Ithaca, NY, USA, January 2006.
5. Shi, P.; O'Rourke, T.D.; Wang, Y. Simulation of earthquake water supply performance. In Proceedings of the 8th National Conference on Earthquake Engineering, Oakland, CA, USA, 18–22 April 1977; Paper No. 8NCEE-001295. EERI: Oakland, CA, USA.
6. Wang, Y.; O'Rourke, T.D. Characterizations of seismic risk in Los Angeles water supply system. In Proceedings of the 5th China-Japan-US Symposium on Lifeline Earthquake Engineering, Haikou, China, 26–28 November 2007.

7. Bonneau, A.L. Water Supply Performance during Earthquakes and Extreme Events. Ph.D. Thesis, Cornell University, Ithaca, NY, USA, 2008.
8. Bonneau, A.L.; O'Rourke, T.D. *Water Supply Performance during Earthquakes and Extreme Events*; Technical Report MCEER-09-0003; University of Buffalo, State University of New York: Buffalo, NY, USA, 2009.
9. Yoo, D.G. Seismic Reliability Assessment for Water Supply Networks. Ph.D. Dissertation, Korea University, Seoul, Korea, 2013.
10. Hou, B.W.; Du, X.L. Comparative Study on Hydraulic Simulation of Earthquake-Damaged Water Distribution System. In Proceedings of the International Efforts in Lifeline Earthquake Engineering, Chengdu China, 2014; pp. 113–120.
11. Yoo, D.G.; Jung, D.; Kang, D.; Kim, J.H.; Lansey, K. Seismic Hazard Assessment Model for Urban Water Supply Networks. *J. Water Resour. Plan. Manag. ASCE* **2016**, *142*. [CrossRef]
12. Yoo, D.G.; Kang, D.; Kim, J.H. Optimal Design of Water Supply Networks for Enhancing Seismic Reliability. *Reliab. Eng. Syst. Saf.* **2016**, *146*, 79–88. [CrossRef]
13. Rossman Lewis, A. *EPANET 2: Users Manual*; U.S. Environmental Protection Agency: Cincinnati, OH, USA, 2000.
14. GIRAFFE. *GIRAFFE User's Manual*; School of Civil and Environmental Engineering, Cornell University: Ithaca, NY, USA, 2008; Available online: https://www.cee.cornell.edu/cee (accessed on 14 February 2019).
15. Ang, W.K.; Jowitt, P.W. Solution for Water Distribution Systems under Pressure-Deficient Conditions. *J. Water Resour. Plan. Manag.* **2006**, *132*, 175–182. [CrossRef]
16. Giustolisi, O.; Savic, D.; Kapelan, Z. Pressure-Driven Demand and Leakage Simulation for Water Distribution Networks. *J. Hydraul. Eng.* **2008**, *134*, 626–635. [CrossRef]
17. Baek, C.W. Development of HSPDA model for analysis of water distribution systems under abnormal operating conditions. Ph.D. Dissertation, Korea University, Seoul, Korea, 2007.
18. Baek, C.W.; Jun, H.D.; Kim, J.H. Estimating the Reliability of Water Distribution Systems Using HSPDA Model and Distance Measure Method. *J. Korea Water Resour. Assoc.* **2010**, *43*, 769–780. [CrossRef]
19. Baek, C.W.; Jun, H.D.; Kim, J.H. Estimation of the Reliability of Water Distribution Systems using HSPDA Model and ADF Index. *J. Korea Water Resour. Assoc.* **2010**, *43*, 201–210. [CrossRef]
20. Giustolisi, O.; Kapelan, Z.; Savic, D.A. Extended Period Simulation Analysis Considering Valve Shutdowns. *J. Water Resour. Plan. Manag.* **2008**, *134*, 527–537. [CrossRef]
21. Wu, Z.Y.; Wang, R.H.; Walski, T.M.; Yang, S.Y.; Bowdler, D.; Baggett, C.C. Extended Global—gradient Algorithm for Pressure-dependent Water Distribution Analysis. *J. Water Resour. Plan. Manag.* **2009**, *135*, 13–22. [CrossRef]
22. Lee, H.M.; Yoo, D.G.; Kang, D.; Jun, H.; Kim, J.H. Uncertainty quantification of pressure-driven analysis for water distribution network modeling. *Water Sci. Technol. Water Suppl.* **2016**, *16*, 599–610. [CrossRef]
23. May, J. Leakage, pressure and control. In Proceedings of the BICS International Conference on Leakage Control, London, UK, March 1994.
24. Klise, K.A.; Bynum, M.; Moriarty, D.; Murray, R. A software framework for assessing the resilience of drinking water systems to disasters with an example earthquake case study. *Environ. Model. Softw.* **2017**, *95*, 420–431. [CrossRef] [PubMed]
25. Yoo, D.G.; Shin, E.H. Recent Trends and Proper Applications of Hydraulic Analysis Technique of Water Distribution Networks. *Mag. Korean Soc. Hazard Mitig.* **2018**, *18*, 45–51.
26. Puchovsky, M.T. *Automatic sprinkler systems handbooks*; National Fire Protection Association (NFPA): Quincy, MA, USA, 1999.
27. Gupta, R.; Bhave, P.R. Comparison of methods for predicting deficient-network performance. *J. Water Resour. Plan. Manag.* **1996**, *122*, 214–217. [CrossRef]
28. Tanyimboh, T.T.; Tabesh, M. Discussion comparison of methods for predicting deficient-network performance. *J. Water Resour. Plan. Manag.* **1997**, *123*, 369–370. [CrossRef]
29. Mays, L. *Water Supply Systems Security*; McGraw-Hill Education: New York, NY, USA, 2004.
30. Wagner, J.M.; Shamir, U.; Marks, D.H. Water distribution reliability: Simulation methods. *J. Water Resour. Plan. Manag.* **1988**, *114*, 276–294. [CrossRef]
31. Lambert, A. What do we know about pressure: Leakage relationships in distribution systems? In Proceedings of the IWA Conference in Systems Approach to Leakage Control and Water Distribution System Management, International Water Association, Brno, Czech Republic, 16–18 May 2001.

32. Lambert, A.; Fantozzi, M.; Shepherd, M. Pressure: Leak flow rates using FAVAD: An improved fast-track practitioner's approach. In Proceedings of the Computing and Control for the Water Industry (CCWI 2017), Sheffield, UK, 5–7 September 2017.
33. Gupta, R.; Bhave, P.R. Reliability analysis of water-distribution systems. *J. Environ. Eng.* **1994**, *120*, 447–461. [CrossRef]
34. Cullinane, M.; Lansey, K.; Mays, L. Optimization-availability-based design of water-distribution networks. *J. Hydraul. Eng.* **1991**, *118*, 420–441. [CrossRef]
35. Tabucchi, T.; Davidson, R.; Brink, S. Simulation of post-earthquake water supply system restoration. *Civil Eng. Environ. Syst.* **2010**, *27*, 263–279. [CrossRef]
36. Lansey, K. Sustainable, robust, resilient, water distribution systems. In Proceedings of the 14th Water Distribution Systems Analysis Conference, Adelaide, Australia, 24–27 September 2012; pp. 1–18.
37. Walski, T.; Brill, E.; Gessler, J., Jr.; Goulter, I.; Jeppson, R.; Lansey, K.; Lee, H.; Liebman, J.; Mays, L.; Morgan, D.; et al. Battle of the Network Models: Epilogue. *J. Water Resour. Plan. Manag.* **1987**, *113*, 191–203. [CrossRef]
38. Jung, D.; Kang, D.; Kim, J.H.; Lansey, K. Robustness-based design of water distribution systems. *J. Water Resour. Plan. Manag.* **2014**, *140*, 04014033. [CrossRef]
39. Yoo, D.G.; Jung, D.; Kang, D.; Kim, J.H. Seismic-reliability-based optimal layout of a water distribution network. *Water* **2016**, *8*, 50. [CrossRef]
40. Lee, H.M.; Yoo, D.G.; Kim, J.H.; Kang, D. Hydraulic simulation techniques for water distribution networks to treat pressure deficient conditions. *J. Water Resour. Plan. Manag.* **2015**, *142*, 06015003. [CrossRef]