

# GIS –BASED SEISMIC DAMAGE LOCALIZATION FOR WATER SUPPLY SYSTEMS

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## SUMMARY

Urban water delivery network systems, particularly the underground components, can be damaged due to earthquakes, severely cold weather, heavy traffic loads on the ground surface, and other causes. In all these situations, the damage cannot be detected and located easily, especially immediately after the event. In recent years, real-time or near real-time damage assessment and diagnosis of buried pipelines has attracted much attention from researchers focusing on early detection of the damage severity and location. However, due to the complex nature of the physics that affect the pipe damage, particularly under seismic waves, such detection still remains difficult to achieve. As a possible solution, this study explores a method to rapidly detect and locate the damage in a water delivery system (1) by monitoring water pressure on-line at densely populated locations throughout the water system and (2) by comparing the spatial distribution of water pressure thus monitored with the patterns of the pressure computed and visualized under prescribed damage location and severity. It is envisioned that emerging sensors will make this not only technically possible, but also cost-effective in the very near future. In fact, this localization technology will serve as a next generation of the current SCADA (System Control and Data Acquisition) systems that the utility industry uses for operational purposes. The method will employ correlation analysis and other pattern recognition techniques that will be capable of identifying the location and severity of pipe damage. This will, in turn, make the post-event response (such as emergency repair, firefighting and supply of potable water) rapid enough to minimize societal and property losses. This research is also useful in enhancing the level of national security as described and recommended in "Making the Nation More Secure" (2003). This publication identifies future development of SCADA as one of the most critical agenda items for enhanced national security.

Damage patterns will be generated on the basis of a forward hydraulic analysis of water networks under simulated earthquakes with different Magnitudes and epicentral locations. A large catalogue of such patterns will be generated for this purpose. Regional water utilities will participate in this research as end users. The localization technology described above can also be applied to other lifeline systems such as power and transportation networks with appropriate modifications. The essence is the packaging of a

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dense sensor network with rapid and robust transmission capability, with the software for damage pattern recognition uniquely developed for each lifeline.

#### **INTRODUCTION**

Urban water delivery systems can be damaged by earthquakes, severely cold weather, excessive traffic loads on the ground surface and other causes. In practice, under seismic loads, multiple pipelines in the water network are damaged simultaneously, while other causes tend to result in a single location of pipe damage. In either case, the location and severity of damage cannot easily be identified, especially immediately after the event.

In recent years, real-time damage assessment and diagnosis of buried pipelines has attracted much attention from researchers focusing on establishing the relationship between damage ratio (breaks per unit length of pipe) and ground motion, taking the soil condition into consideration (Nishio [1], Takada [2], Yamazaki [3]). Eguchi [4] put forward a method in which nominal damage estimated through some earthquake parameters is updated gradually based on the collection of post-earthquake observation information. Shinozuka [5] developed a methodology to detect the damage location and severity with the aid of neural network methods, and applied the method to a water network that consisted of 31 nodes and 50 pipes. However, real water networks consist of a much larger number of nodes and links in a more complex topology. To address these difficulties, the methodology consists of three significant phases., In the first phase, the water pressure distribution patterns are computed for the damaged network by means of forward analysis, with the aid of hydraulic analysis code. The results are visualized using Geographic Information Systems (GIS) mapping. In the second phase, the correlation values between the water pressure distribution patterns are computed. A damage index is defined and evaluated for all the pipes on the basis of these correlation values. Finally, the inverse analysis is carried out to identify the possible damage locations and severity. In this paper, the Memphis Light, Gas and Water's (MLGW) water supply system is taken as a test bed and the correlation analysis method is applied for detection of damage locations and severity. The results show that this method provides a quick, effective, and practical tool for this purpose.

This study explores the inverse analysis method used to identify the location and extent of damage in the hope that emerging SCADA technology will be able to provide pressure and flow data on-line and in realtime for actual water delivery systems. Many SCADA systems have recently been installed in water delivery networks worldwide to transmit, by means of wireless communication, water pressure/flow-rate data collected at remote sensor units to a control center for the purpose of surveillance and control of system function. Taking advantage of existing SCADA systems to determine the location and extent of damage makes much more sense than using just the earthquake ground motion information, since the water pressure and flow-rate data are more sensitive to damage to the water delivery network. The proposed method, however, presents a significant technical challenge due primarily to the limited number of SCADA sensor units placed in large, spatially distributed and functionally complex water delivery networks. In this respect, the use of inverse analysis based on the correlation analysis technique as demonstrated in the present paper appears to be a promising approach to solving the technical difficulties.

# DATABASE DEVELOPMENT

To establish a relationship between water pressure variation at monitoring stations in a water delivery system, and damage location and severity, a substantial database for water pressure distribution patterns is required. To demonstrate the proposed inverse analysis method in this paper, the database has been generated by simulation of a hydraulic network representing MLGW's water system, with more than 900 nodes and 1,300 pipes. In this paper, we will consider damage conditions caused by the scenario earthquakes, where the damage is modeled as an orifice through which water leaks. The damage severity

is defined in accordance with the area of the orifice; major damage is represented by a pipe rupture equivalent to the pipe cross-sectional area, and minor damage is represented by a rupture equivalent to one hundredth (1/100) of the cross-sectional area. Other degrees of damage severity can be described by varying the equivalent rupture area. For simplicity, the pipe break is assumed to be located at the middle of a link between two directly connected nodes in the water delivery network.

The computer program developed by Tanaka [6] has been modified for the water delivery network used in this paper, and is used to perform the hydraulic analyses and generate the required pressure distribution pattern database. The simulation results are divided into two databases. The first is called "knowledge database" labeled as  $\Omega(k)$ , which consists of the water pressure distribution patterns corresponding to known damage distributions. This is obtained by the forward hydraulic analysis. The second is referred to as the "test database" labeled as  $\Omega(t)$ , which consists of the water pressure distribution patterns developed only on the basis of monitored pressure at each node with no knowledge of damage conditions.

# GIS-BASED VISUALIZATION OF MLGW'S WATER SYSTEM

**MLGW's water system.** Memphis Light, Gas and Water (MLGW) is the largest tri-service municipal utility in the nation. It supplies more than 400,000 customers in the Memphis and Shelby County area with electricity, natural gas and water. MLGW owns and operates one of the largest artesian water systems in the world. On a peak day, MLGW delivers approximately 200 million gallons of water to more than 248,000 customers. It consists of a large centrally-located low-pressure system, and several high-pressure systems on the outskirts of the city. The total system is comprised of approximately 1300 links and 960 nodes. The total length of the buried pipes is about 1370 km, with diameters ranging from 16 cm to 122 cm. The system has eight pumping stations in the low-pressure system, and one small pumping station in the high-pressure systems. In addition to these pumping stations, six booster pumps are used in the high-pressure systems, and there are nine booster pumps on the pipes through which the low- and high-pressure systems are connected. Since only one small pumping station exists in the high-pressure systems of the water supply is provided by the booster pumps and elevated tanks, depending on the demand conditions in the high-pressure system. Two other booster pumps are working in the low-pressure system to support an overloaded pumping station(http://www.mlgw.com/). Figure 1 shows a GIS map of MLGW's water supply network.

## Visualization of water pressure distribution pattern:

In order to determine the water pressure at each node, the hydraulic forward analysis is performed for MLGW's water system, with the results plotted in GIS format. Figures 2 through 4 show three distribution patterns under different damage conditions: pipe #526 suffers from damage corresponding to the orifice area equal to 100% (Figure 2) and 50% (Figure 3) of the pipe cross-sectional area, and pipe #100 suffers from damage corresponding to the orifice area equal to 100% of the pipe cross-sectional area (Figure 4).

The water pressure distribution contours determined from the water pressures calculated at all nodes provide some very useful information; (1) if two damaged pipes are located very far apart, then the water pressure distribution patterns are very different with correspondingly low correlation, and (2) if one pipe is examined under different levels of damage, then the water pressure distribution patterns are very similar with high correlation. This observation leads to the inverse analysis of the water system by means of the correlation analysis to determine the damage location in the corresponding water delivery network.



Figure 1. MLGW's Water System



Figure 2. Water Pressure Distribution Patterns (Pipe #526; Damaged Area/Area = Ad/A = 100%)



Figure 3. Water Pressure Distribution Patterns (Pipe #526; Ad/A=50%)



Figure 4. Water Pressure Distribution Patterns (Pipe #100; Ad/A=100%)

#### METHODOLOGY

The correlation coefficient is a measure of the degree of linear relationship between two variables, X and Y. When comparing the fitness of two models or patterns, the correlation is a good measure to estimate the fitness of the two models or patterns (in this case, the water pressure distribution patterns). In the present study, the correlation analysis will be used to detect (a) similarities of the water pressure distribution patterns, and (b) damaged pipes and damage severity.

The correlation coefficients are computed as follows:

 $R(T,P)=R(t_1, t_1, \dots, t_n, p_1, p_1, \dots, p_n)$ (1)

Where n= the number of monitoring stations in the MLGW's water system.

R(T,P) = correlation coefficient between T and P.

T=[ $t_1, t_1, \ldots, t_n$ ]= water pressure vector observed at monitoring stations in MLGW's water system. T  $\in \Omega(t)$ .

 $P=[p_1, p_1, \dots, p_n]$  = water pressure vector at the monitoring stations in MLGW's water system under the condition that MLGW's water network was damaged and the damage conditions are known

(either one pipe or multiple pipes damaged).  $P \in \Omega(k)$ .

Therefore, for the water pressure distribution patterns  $\Omega(t)$  and  $\Omega(k)$ , a correlation matrix is generated below:

$r_{11}$	$r_{12}$	•	$r_{1j}$	•	$r_{1n-1}$	$r_{1n}$
$r_{21}$	$r_{22}$	٠	$r_{2j}$	٠	$r_{2n-1}$	$r_{2n}$
٠	٠	•	•	•	•	•
•	•	•	٠	•	•	•
$r_{i1}$	$r_{i2}$	٠	$r_{ij}$	٠	$r_{in-1}$	r <sub>in</sub>
٠	٠	•	٠	٠	•	•
•	•	•	٠	•	•	•
$r_{m1}$	$r_{m2}$	•	$r_{mj}$	•	$r_{mn-1}$	r <sub>mn</sub>

where  $r_{i,j}$  is computed from Equation(1), m and n are the number of water pressure patterns in  $\Omega(t)$  and  $\Omega(k)$ , respectively. In the matrix, the columns correspond to water pressure distribution patterns from the "knowledge database" ( $\Omega(k)$ ), while the rows correspond to the water pressure distribution patterns from the "test database" ( $\Omega(t)$ ). The resulting matrix has (m•n) elements, which represent the correlation values between the water pressure distribution patterns from the "knowledge database" and "test database". For example,  $r_{i,j}$  represents the correlation coefficient between the observed pressure data from the i<sup>th</sup> distribution pattern in the "test database". Each correlation value in the matrix, for example  $r_{ij}$ , indicates the closeness between the i<sup>th</sup> observed water pressure distribution pattern from the "test database" and the "test database" and the "test database" and the "test database" the closeness between the i<sup>th</sup> observed water pressure distribution pattern from the "test database" and the "test database" and the "test database" and the "test database" the closeness between the i<sup>th</sup> observed water pressure distribution pattern from the "test database" and the "test database".

To determine which damage pattern best approximates the i<sup>th</sup> water pressure distribution pattern, we choose the maximum correlation value from i<sup>th</sup> row. For instance i=2, and if we find that  $r_{2,10}$  is the largest correlation value among  $r_{2,j}$ , then we can say that the water system may suffer the 10<sup>th</sup> damage pattern.

#### APPLICATIONS

For this paper, the MLGW's water system has been taken as a test bed. The procedures described above were applied to this water delivery systemfor two study cases: (1) Only one pipe suffers damage and (2) multiple pipes suffer different damage.

## Only one pipe damaged

Figure 5 indicates the observed water pressure distribution pattern. By applying formula (1) to the observed water pressure distribution patterns from the "test database" and the water pressure distribution patterns from the "knowledge database", the correlation matrix can be computed. Table 1 lists selected correlation values for one water pressure distribution from the "test database". The table identifies the pipe numbers and corresponding correlation values for pipes with correlation values greater than or equal to 0.88.



Figure 5. Observed Water Pressure Distribution for the Study Case of One Damaged Pipe

	Tuble II beleeted contention			values for the study cuse of one				5••• 1 -p •			
Pipe		292		525	526	527	528	529	530		1321
R		0.96		0.89	1.0	0.88	0.98	0.86	0.92		0.09
DMG		Maj.		Maj.	Maj.	Maj.	Maj.	Maj.	Maj.		

Table 1	Selected	Correlation	Values fo	r the Study	Case of	One Dama	oed Pine
1 a 0 10 1.	JUICULUU	Conciation	v alues to	n uic stuuv		Une Dama	2001100

From the table, we can see the largest correlation value is 1.0, which indicates that the observed water pressure distribution pattern is directly related to pipe 526 suffering major damage, as expected. These results can also be visualizes as shown in Figure 6



Figure 6 Visualization of Detection Results of Possible Damaged Pipes

In this case study, the correlation analysis can be used to identify the damaged pipe on the basis of observed water pressure patterns. This result indicates that the correlation analysis can be an efficient tool to detect the damage pipe based on current observations of water pressure patterns and a knowledge database of pressure patterns under damaged conditions.

## Multiple pipes damaged

For this study case, the damage patterns due to the seismic action are generated on the basis of a forward hydraulic analysis of MLGW's water network under two simulated earthquakes of different magnitudes, but with epicenters at the same location (Figures 7 and 8). A large catalogue of such patterns will be generated, as mentioned above. Figure 7 and Figure 8 represent two different damage situations and their results. The two simulated earthquakes in the New Madrid Seismic Zone have Magnitudes of 6.5 and 7.0, with epicenters at Marked Tree, Arkansas. A third earthquake, of Magnitude 7.5, was also analyzed. To generate the "knowledge database" and the "test database", 2030 simulations were run for each scenario earthquake. 2000 simulations were randomly selected and taken as the "knowledge database", with the remaining 30 simulations being assigned to the "test database". By applying the localization technology procedure to the two databases, their effectiveness can be assessed. Table 2 lists the percentage ( $\eta$ ) of pipes in the MLGW's water system for which the damage state was correctly identified, where  $\eta$  is defined as follows:

$$\eta = \frac{\sum_{i=1}^{N} \delta_{i}}{N}$$
(2)

Where N is the total number of pipes in the water system that need damage detection  $\delta_i$  is the i<sup>th</sup> pipe damage identification status. It can be computed as follow

 $\delta_i = 1$  if i<sup>th</sup> pipe damage status was determined correctly

=0 if  $i^{th}$  pipe damage status was not determined correctly



Figure 7. Water Pressure Distribution (M=6.5 Earthquake at Marked Tree, Arkansas)



Figure 8. Water Pressure Distribution (M 7.0 Earthquake at Marked Tree, Arkansas)

Marked Tree	M=6.5	M=7.0	M=7.5	M=6.5	M=7.0	M=7.5	
Test Data Sets	Number of	pipes with da	amage state	Percentage of pipes with damage state			
	со	rrectly identifi	ed	correctly identified			
1	1205	1145	1113	91.2%	86.7%	84.3%	
2	1192	1115	1116	90.2%	84.4%	84.5%	
3	1196	1149	1108	90.5%	87.0%	83.9%	
4	1209	1142	1116	91.5%	86.4%	84.5%	
5	1195	1137	1116	90.5%	86.1%	84.5%	
6	1191	1139	1097	90.2%	86.2%	83.0%	
7	1196	1141	1107	90.5%	86.4%	83.8%	
8	1201	1131	1117	90.9%	85.6%	84.6%	
9	1194	1133	1104	90.4%	85.8%	83.6%	
10	1180	1136	1125	89.3%	86.0%	85.2%	
11	1207	1126	1110	91.4%	85.2%	84.0%	
12	1194	1123	1120	90.4%	85.0%	84.8%	
13	1198	1143	1119	90.7%	86.5%	84.7%	
14	1261	1152	1125	95.5%	87.2%	85.2%	
15	1195	1142	1110	90.5%	86.4%	84.0%	
16	1199	1150	1097	90.8%	87.1%	83.0%	
17	1193	1140	1115	90.3%	86.3%	84.4%	
18	1206	1156	1132	91.3%	87.5%	85.7%	
19	1185	1131	1115	89.7%	85.6%	84.4%	
20	1186	1133	1095	89.8%	85.8%	82.9%	
21	1183	1146	1135	89.6%	86.8%	85.9%	
22	1194	1117	1108	90.4%	84.6%	83.9%	
23	1191	1123	1124	90.2%	85.0%	85.1%	
24	1203	1321	1124	91.1%	100.0%	85.1%	
25	1186	1117	1133	89.8%	84.6%	85.8%	
26	1184	1141	1121	89.6%	86.4%	84.9%	
27	1190	1130	1098	90.1%	85.5%	83.1%	
28	1183	1122	1084	89.6%	84.9%	82.1%	
29	1185	1116	1109	89.7%	84.5%	84.0%	
30	1261	1141	1115	95.5%	86.4%	84.4%	
Mean	1198	1141	1114	90.7%	86.4%	84.3%	

Table 2. Effectiveness of Damage Localization Techniques for the Study Case With Multiple Pipes Damaged

The results show that the correlation analysis is also efficient for identifying damaged pipes when more than one pipe is damaged. It should be noted that this test case consisted of 2000 different water pressure distribution patterns; a number that is probably insufficient for many cases of multiple pipes damaged. With more information obtained for the "knowledge database", the inverse analysis results will be improved significantly.

## **CONCLUSION AND FUTURE RESEARCH**

The purpose of this study was to develop a methodology to identify the location and determine the severity of damage in a water delivery system by monitoring water pressure on-line at selected locations

within the system. A correlation analysis-based inverse analysis method is developed for the stated purpose. The method is based on on-line water pressure variation before and after water system damage, and provides a quick, effective, and practical analysis tool to serve the purpose.

The future study will be focused on (1) minimizing and optimizing the monitoring stations number and locations; (2) refining the methodology to achieve more accurate results and (3) consideration of the variation of demands and water heads in different time periods.

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## REFERENCES

- Nishio, N. (1994) "Damage Ratio Prediction for Buried Pipelines Based on the Deformability of Pipelines and the Nonuniformity of Ground ," J. of Pressure Vessel Technology, ASME, 116, 459-466.
- 2) Tanaka, S., Shinozuka, M., and Hwang, H. H. M. (1993) "LIFELINE-W(2) User's Guide: a Program for Connectivity and Flow Analysis of a Water Delivery System Under Intact and Seismically Damaged Conditions." Technical Report, Princeton University.
- Yamazaki, F., Katayama, T., and Yoshikawa, Y. (1994) "On-Line Damage Assessment of City Gas Networks Based on Dense Earthquake Monitoring." Proc. 5th U.S. Conf. on Earthq. Engrg., EERI, Vol.4, 829-837.
- 4) Eguchi, R. T., Chrostowski, J. D., and Tillman, C. W., (1994) "Early Post-Earthquake Damage Detection for Lifeline System." EQE Research Report prepared for National Science Foundation.
- 5) Shinozuka, M., and Liang, J. (1999) "On-Line Earthquake Damage Identification of Water Supply Networks." Research Report, International Institute of Innovative Risk Reduction Research on Civil Infrastructure Systems, University of Southern California. (in print)
- 6) Takada, S., and Ogawa, Y. (1994) "Seismic Monitoring and Real Time Damage Estimation for Lifelines." Proc. 4th U.S. Conf. on Lifeline Earthq. Engrg., ASCE, 224-231.