Predicting water pipe breaks using neural network

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Abstract The relationships between pipe breaks of service pipes and mains and several factors were examined. Also historical pipe breaks, and water and soil temperatures were modeled by an artificial neural network to predict pipe breaks for efficient management and maintenance of the pipe networks. It was observed that the breaks of pipes increased after the temperatures of water and soil crossed in spring and fall. The pipe breaks were closely related with water and soil temperature, especially mains were affected more than service pipes. The fittings and valves were susceptible to the temperatures and needed to take measures for preventing breaks. The prediction of the pipe breaks by the ANN model built had a good performance except that the sensitivity was not good when the pipe breaks rapidly increased or decreased. The ANN model gave a good performance and was to be useful to predict the patterns of pipe breaks on a seasonal basis.

Introduction

Water losses could occur in the process of supplying water from water treatment plants to the consumers' taps. Water losses are caused by pipe breaks, meter-reading errors, under-registration of meters, etc. In Europe and the USA, according to the latest directives, the water losses that occur in a network should not exceed 15 % and 10 % of the total water supply, respectively (Kanakoudis and Tolikas, 2001).

It is expected that pipe break occurrence is dependent on the pipe materials and the environmental conditions such as soil types, atmospheric temperature, traffic loading, and so on. Pipe breaks give rise to abrupt water shortage, traffic damages, flood, as well as water losses. Therefore prediction of water pipe breaks is important to improve water efficiency and decrease cost of water operation and maintenance in distribution systems.

O'Day (1982) showed that pipe breaks were not directly related to the age of pipes through the analysis of pipe sizes, pipe types, and environmental conditions. Kawakita (1986) studied relation of water temperature, soil temperature, and the number of breaks in water mains in Tokyo. The breaks of ductile iron, steel, and asbestos pipes were not dependent on the water temperature. In winter, when water temperature drops, cast iron pipe breaks increased, but joint breaks of the pipes did not. Harada (1988) defined the index below the freezing point for predicting service pipe breaks. This term means energy of the cold wave. Not only the conditions that service pipes are frozen in wide region, but also the prediction formula that predicts the number of damaged service pipes from the index below the freezing point, was obtained. Welter (2001) analyzed main breaks according to the water temperature at that time. The study provided evidence that stresses developed in the pipes and the drop in water temperature is a major cause of the main breaks in winter.

In this paper the relationship between breaks of service pipes and mains and soil and water temperatures were examined to reduce operation cost and enhance reliability in the distribution systems. Also historical pipe breaks, and water and soil temperatures were modeled by artificial neural network to propose a new methodology to predict pipe breaks for efficient management and maintenance of pipe networks.

Overview of waterworks system in Seoul city

Seoul city is located in the west central part of the Korean Peninsula. The city has a total area of 605 km^2 and 10 millions inhabitants. There are six intake stations along the Han River for the production of drinking water. The Han River basin comprises a total channel length of 497.5 km with a 26 km^2 basin area and 62 tributaries. The Han River basin receives an average of 1,289 mm of annual precipitation. Most of the rainfall is concentrated during the period from June to September, making it difficult to secure and manage water resources. Six drinking water treatment plants with a daily production capacity of 5.7 million tons, produce per day an average of 3.6 million tons of finished water. The average water supply is about 368 L per capita per day. The daily production has been reduced from 4.6 million m3 in 1998 to 3.6 million m3in 2003 thanks to the remarkable enhancement of revenue water. The city government has made an effort to enhance revenue water since 1999. Replacement of aged pipes, water loss detection in blocks, monitoring of minimum water demand in night time, and water saving campaign has conducted during the past 6 years and now on. In the year of 2003, the ratio of metered water reached 82.7%.

Analyses of the Pipe Breaks

The total length of pipe networks in Seoul city is approximately 17,000 km (Table 1). Ductile cast iron pipes (DCIP) and stainless steel pipes (SS) occupy 70 % in the total pipe length.

The average number of pipe breaks per km was 1.9 in the year of 2002. However we experienced 14 breaks per km for galvanized steel pipe (GSP) and 5 breaks for PVC, and 1.5 for cast iron in mains. 62 % of pipe breaks occurred in galvanized steel pipes despite the ratio of galvanized steel pipe length is 8 %. Though installation of galvanized steel pipe for drinking water supply had been prohibited since 1994, the pipes still remain as service pipes installed in the houses constructed more than 10 years ago.

Table 1. Characteristics of water pipes in Seoul City (2002)

	Total	Galvanized Steel	PVC	PE	Stainless Steel	Copper	Cast Iron	Ductile Cast Iron	Steel
Pipe length (km)	17,398	1,414	733	191	5,113	658	1,395	6,915	970
Ratio of pipe length (%)	100	8.1	4.2	1.1	29.4	3.8	8.0	39.7	5.6
Number of pipe breaks	33,475	19,875	3,788	439	3,927	650	2,124	536	732
Number of pipe breaks per km	1.92	14.06	5.17	2.30	0.77	0.99	1.52	0.08	0.75

Monthly water production and the number of pipe breaks were illustrated in Fig. 1 and 2. The lines indicate water production since 1998 in order. The water production of Seoul city has been reduced since 1998 thanks to the reduction of water loss and the increment of water revenue. As the result the daily production has been reduced 4.6 million m^3 in 1998 to 3.6 million m^3 in 2003. Water demand increases in summer seasons.

The bars indicate the number of pipe breaks occurred during 5 years on the monthly basis. Especially in January and March 2001 pipe breaks dramatically increased due to cold wave. On 15 January 2001 the sudden fall of atmospheric temperature, -18.6 ℃, occurred and the service breaks reached 4,000 occasions. Service pipes were largely influenced by cold wave due to the swallower depth of installation. On the other hand, the maximum number of main breaks occurred in March 2001 since the installation depth of mains is deeper than 1.5 m. Comparatively main pipe breaks in winter were fewer than the average. In addition, the breaks of service pipes in January and February were higher than those of mains due to the lower temperature and the difference in the installation depth. And the main pipe breaks in spring and fall were higher than those in summer and winter seasons.

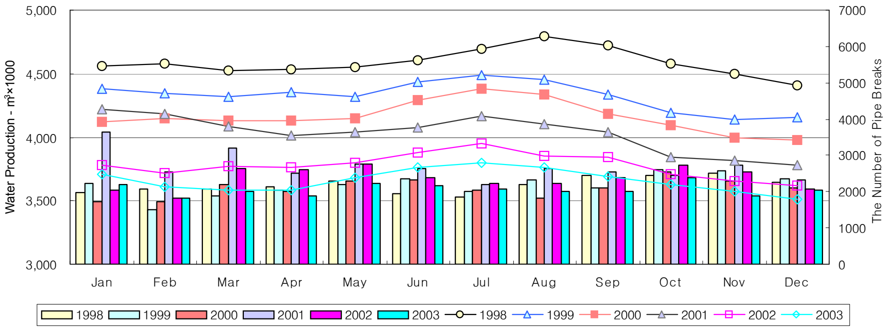

Fig. 1. Water production and breaks in service pipes (1998-2003)

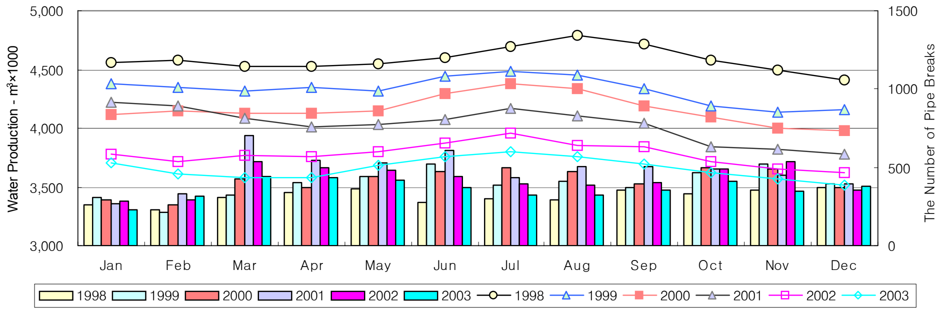

Fig. 2. Water production and breaks in mains (1998-2003)

Pipe breaks and the pipe materials

Service pipe breaks according to the materials in the year of 2002 and 2003 are illustrated in Fig. 3. Monthly average of the breaks in galvanized steel pipes was up to 1,530, and 327 in stainless steel, and in 257 PVC, respectively.

As shown in Fig. 4 pipe breaks in mains on a monthly basis, breaks in cast iron were the highest, 169. Those of steel pipe and ductile cast iron were relatively low as 50 and 48. Cast iron breaks were influenced by the seasonal change of temperature. In Korea galvanized steel and cast iron pipes are being replaced to stainless steel and ductile iron pipes. On the other hand breaks of steel pipes and ductile cast iron seemed not to be sensitive to the variation of temperature according to the seasonal change.

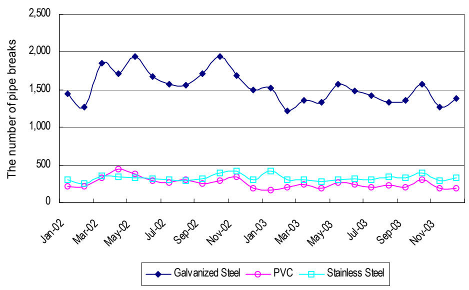

Fig. 3. Breaks in the service pipe

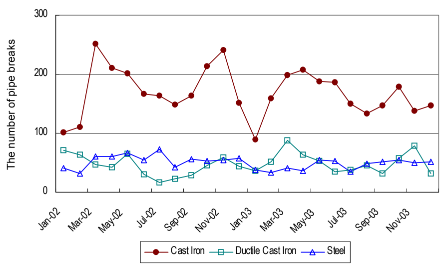

Fig. 4. Breaks in the mains

Pipe breaks and the pipe size

Service pipes and mains are divided by their diameter. Diameter of service pipes is 50 mm and smaller and that of water main is 80 mm and larger. Service pipes consist of 63 % of stainless steel and 17 % of galvanized iron. Mains consist of 75 % of ductile cast iron and 15 % of cast iron (CIP). The ratio of pipe breaks according to the pipe diameters was illustrated in Fig. 5. The highest break was observed in 15 mm pipes as 55%, and then in 20 mm and in 25 mm as 10 % and 8 %, respectively. As a result, the larger the pipe diameter, the fewer the pipe breaks occurred.

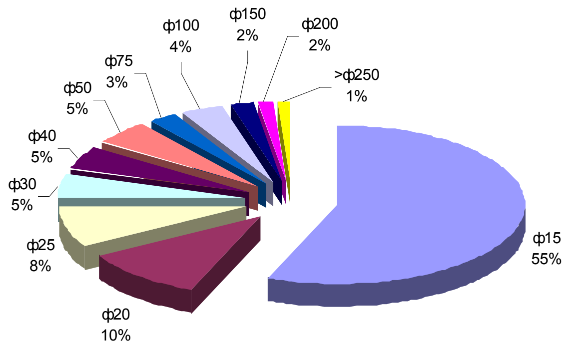

Fig. 5. Pipe breaks according to the pipe size (mm)
(2002-2003)

The causes of pipe breaks

The causes of pipe breaks during 1998 to 2003 are classified in Table 2. Ageing is the major factor of the pipe breaks. As galvanized steel and cast iron pipes are regarded as aged pipes to be replaced in the near future, the cause of breaks was classified as "ageing".

Table 2. The causes of pipe breaks during 1998-2003

Causes	1998	1999	2000	2001	2002	2003
Ageing	23,968	23,442	21,517	26,690	23,200	20,496
Vibration and shock	4,285	5,893	6,393	9,002	7,973	6,522
Unequal sinking	87	150	86	31	190	441
Insufficient depth	-	-	-	-	-	-
Poor materials	14	18	10	1	1	5
Poor construction	3	3	4	3	3	3
Electric corrosion	21	25	25	36	34	42
Others	1,623	1,371	2,159	2,507	2,074	1,531
Total	30,001	30,902	30,194	38,270	33,475	29,040

The major cause of breaks in service is ageing as illustrated in Fig. 6. The pipe breaks by ageing in service pipes mainly occurred in galvanized steel.

The pipe breaks by vibration and shock in service pipes occurred in stainless steel due to the molco (press fitting) joints. The molco joints of stainless steel are to be replaced to slip- in-joints for preventing leakage.

The breaks by ageing in mains mostly occurred in cast iron pipes (Fig. 7). Pipe breaks by vibration and shock occurred at fittings and valves attached in mains. The fittings and valves are susceptible to the change of their physical environment due to the seasonal variation of temperature.

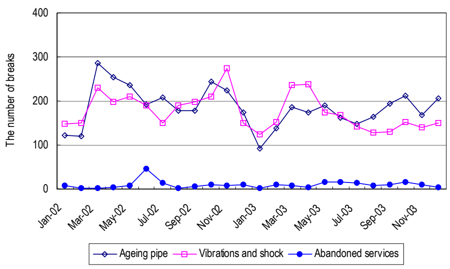

Fig. 6. Breaks in service pipes according to their causes (2002-2003)

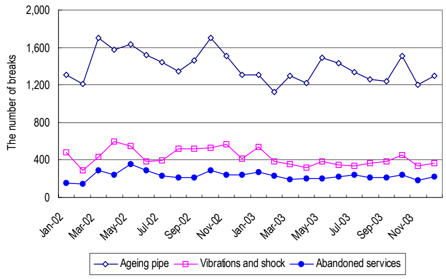

Fig. 7. Breaks in mains according to their causes (2002-2003)

Pipe break position and time

The pipe breaks were classified according to the break position and illustrated in Fig. 8 and 9. The pipe breaks were observed not only in the pipe bodies but also in the pipe parts such as valves, fittings, and others. Monthly average breaks in service pipes were reported 1,281 cases for valves and fittings, and 863 cases forbodies, respectively, and those in mains 151 cases for valves and fittings, and 131 cases for bodies. Since the pipe breaks were observed mainly in the valves and fittings of service pipes and mains, it is required to take measures for preventing breaks in the parts.

In Fig. 10 the number of daily pipe breaks is presented according to the occurrence time during 1 year. The accumulated occurrences of the pipe break 10 pm through 6 am in the next morning were 10 cases more or less. The occurrences increased 6 am to 12 am and reached the peak around 11 am as high as 400 cases. The patternof break occurrence reflects human activity time.

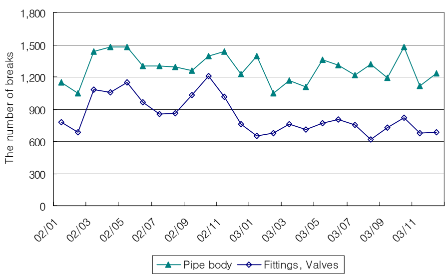

Fig. 8. Break position in service pipes (2002-2003)

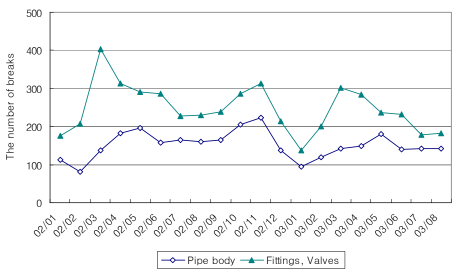

Fig. 9. Break position in mains (2002-2003)

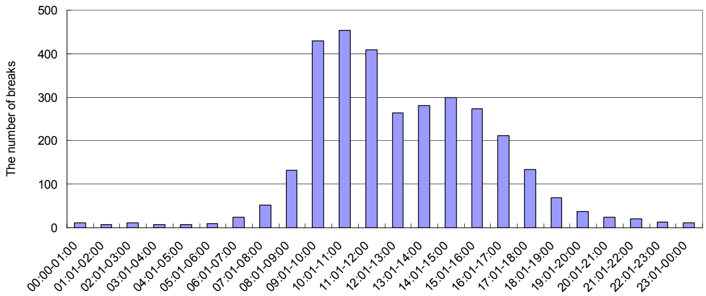

Fig. 10. Pipe breaks according to their occurrence time (2001)

Pipe breaks and temperature

Atmospheric, water, and soil temperatures are one of the parameters affect physical status of the pipes. The variation of temperature is atmospheric > water > soil temperature in order.

Water temperature

The average temperature of G plant effluent is illustrated in Fig.11. The maximum temperature ranges 20～25 ℃ June to September. The minimum occurs in January and February but is not below 1.5 ℃.

Soil temperature

Soil temperature is not severely changed even in winter season since ground is isolated from the atmosphere and geothermal heat is supplied.

The daily temperatures Courtesy of Korea Meteorological Administration. at 0.5 m, 1.5 m, 3.0 m under the ground in the year of 2003 are represented in Fig. 12. The minimum soil temperature at 0.5 m under the ground was 0.9 ℃ on 1st February and the maximum 25.8 ℃ on 5th August. The minimum soil temperature at 1.5 m under the ground was 6.0 ℃ on 28th February and the maximum 25.1 ℃ on 25th August. The minimum soil temperature at 3.0 m under the ground was 12.4 ℃ on 10th April and the maximum 18.6 ℃ on 20th September. The shallower the depth of pipe installation, the larger is the fluctuation of the soil temperature due to the susceptibility to the atmospheric temperature. The maximum and minimum temperatures according to the depth were shifted to the right side as shown in Fig. 12.

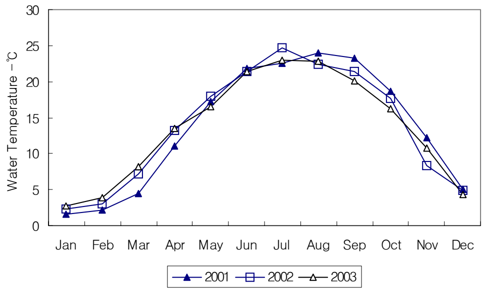

Fig. 11. Average water temperature of G plant effluent (2001-2003)

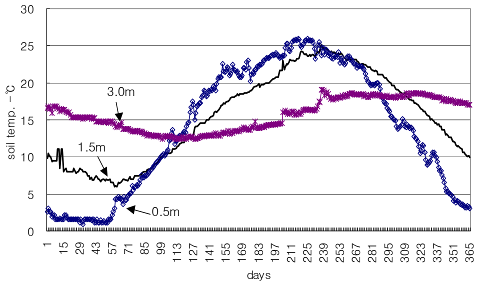

Fig. 12. Variation of soil temperature according to the depth (0.5 m, 1.5 m, and 3.0 m under the ground) (2003)

Influence of temperature on pipe breaks

Fig. 13 shows indices of pipe breaks during 6 years: 1998 through 2003. Water temperature of the effluent of a water treatment plant, and the soil temperature at 1.5 m under the ground in Seoul is illustrated also. Mains are installed deeper than 1.5 m underground for preventing freezing from a cold wave in winter. Soil temperature ranges 6.9 to 23.9 °C and water temperature 2.2 to 23.4 °C.

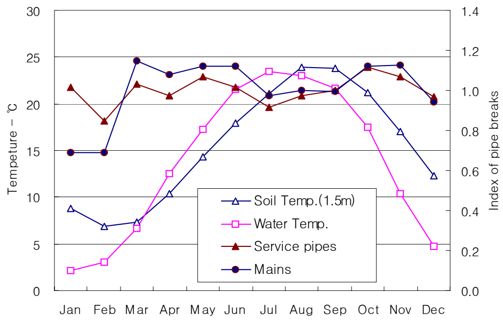

Fig. 13 shows indices of pipe breaks during 6 years: 1998 through 2003.

Main pipe breaks are lowest early in the year, mainly January and February. The pipe breaks increased after the intersection of water and soil temperature in spring and fall. However in some countries, Japan and the USA, pipe breaks occur highly in winter (Welter, G.J., 2001; Kawakita, K., 1986).

Fig. 14 shows the breaks of service pipes in 2002 and 2003. Temperature influence on the pipe breaks was relatively higher in 2002 than in 2003. The breaks of service pipes were more affected than those of mains by water and soil temperatures.

The breaks of mains and the water and soil temperature are illustrated in Fig. 15. The number of breaks of mains was 5,103 in 2002: 38 % of the break occurred in the pipe body and 62 % in the fittings and valves. The breaks of fittings and valves were more influenced by water and soil temperature than those of pipe body.

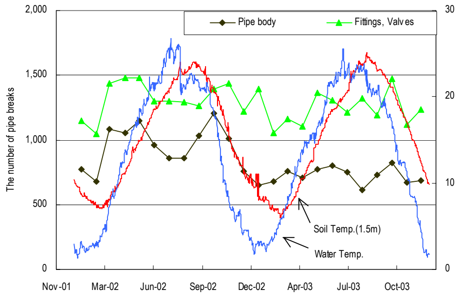

Fig. 14. Temperature of water and soil and the pipe parts in service pipes (2002-2003)

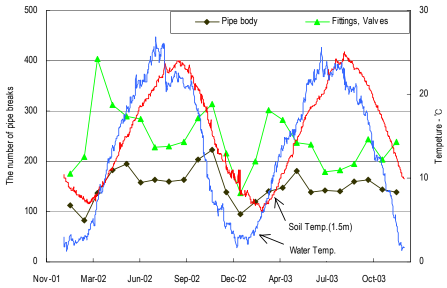

Fig. 15. Temperature of water and soil and the pipe parts in mains (2002-2003

ANN Modeling

The biological neuron represents the elementary unit of any biological nervous system, where, after an adequate learning period, they cooperate together to solve a high number of complex tasks.

The incoming neuronal fibers (the dendrites) receive electrical signals from the connected neurons via biochemical processes through the synapses. Depending on the synapse's chemical nature, each junction can enhance (excitatory synapse) or reduce (inhibitory synapse) the transmitted signal. If the sum of those incoming electrical signals reaches a threshold, an action potential is fired by the cell through the outgoing fiber (the axon) to other, usually a thousand, connected neurons. After firing the neuron has to wait for a time, called refractory period, before it can fire again. Neurons can differ from each other, regarding, for example, their refractory period, reaction time, synapses nature, and so on. This makes them play a particular role inside the biological neural structure to which they belong. (Berthold and Hand, 2003).

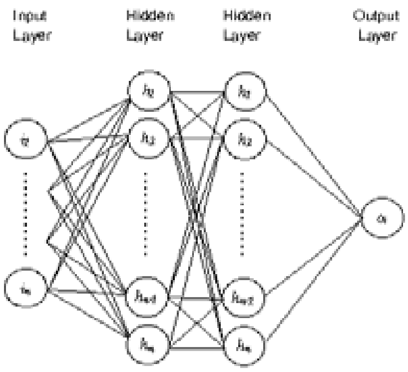

Fig. 16. Structure of ANN

The artificial neural network model highly simplified with respect to biological neuron. In most application of ANN, the backward error propagation algorithm is used to train the network. The basic structure of this algorithm is formed by (i) entering the specific inputs and outputs, (ii) comparing the determined output with the actual output and calculating a quantitative error, and (iii) iteratively minimizing the error by adjusting the weights of the connections in the network. To minimize the error, it is usual to begin at the output nodes and adjust their weights. Backward propagation to the hidden layer(s) adjacent to the output layer and recalculation of the errors are then performed, with weights adjusted accordingly (Leeuwen et al., 1999).

ANN approach focuses on finding a repeated, recognizable and predictable pattern(s) between the causes and the effects from the past operation data records. The ANN modeling approach does not require description of how the processes occur in either the micro or macro environments, only knowledge of important factors that govern the process. No mathematical algorithm is required to build the model. The network simply learns from the sample data and generates a black box type relationship (Stanley and Zhang, 1997).

In this study, ANN coded by C-language was a multilayered neural network structure with backward error propagation. The processing elements were structured into four layers: 1 input layer, 2 hidden layers, and 1 output layer (Fig. 16). The input data was normalized and sigmoid function was used. Optimal learning rates, momentum, and slopes showing predictive performance were determined using trial and error. The values of the parameters ranging from 0.1 to 0.9 were tried. The determination of ANN parameters was carried out using the mean absolute error (MAE) as performance criteria.

$$MAE = (1/n) \sum |(y_{observed} - y_{predicted}) / y_{observed}| \quad (1)$$

Application of ANN

Prediction of the pipe breaks is required to effectively manage and maintain pipe networks. ANN model was built based on the 9 units of input layer: maximum and minimum values of soil temperature at 1.5 m under ground, maximum and minimum values of finished water temperature, maximum and minimum values of atmosphere temperature, the ratio of stainless steel and galvanized steel of service pipes, the ratio of cast iron and ductile cast iron of mains in the distribution systems, the ratio of metered water. The units of 2 hidden layers were 18 and the unit of output layer was the corresponding number of pipe breaks of service pipe and mains.

The data were randomly separated into two sets on a monthly basis from January 1995 to May 2004: the training set with 91 observations, and the verification set with 22 observations as for service pipes and mains respectively. An experiment was carried out with variation of the learning rate, the momentums, slopes, and iterations. The experimentation process allowed an identification of an ANN model consisting of a learning rate of 0.5, a momentum of 0.9, and a slope of 0.9 after 500 iterations. The performance results of the ANN for service pipes were shown in Fig. 17 and 18.

The MAE for observed values and predicted values of training set by ANN were 147.4 (6.6 %) for service pipes, and that of verification set was 236.2 (10.0 %).

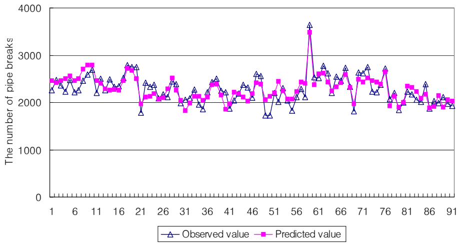

Fig. 17. Comparison of observed and predicted values for breaks of service pipes (training set)

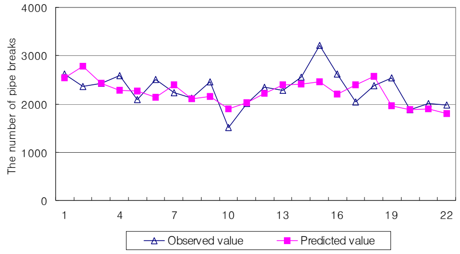

Fig. 18. Comparison of observed and predicted values for breaks of service pipes (verification set)

ANN model for prediction of main pipe breaks was the same as that for service pipes except that pipe materials in units of input layer were replaced stainless steel and galvanized steel with cast iron and ductile cast iron. As a result of the experiments for training set and verification set varying the learning rate, the momentums, slopes, and iterations, values of ANN parameters resulting minimum MAE showed a learning rate of 0.7, a momentum of 0.7, a slope of 0.9, and 900 iterations. The performance results of the ANN for mains were shown in Fig. 19 and 20. The MAE for observed values and predicted values of training set by ANN were 20.7 (5.5 %) for mains, and that of verification set was 44.5 (9.9 %).

As shown in Fig. 18 and 20, the sensitivity was not good when the pipe breaks rapidly increased or decreased. But the ANN model gave a good performance and was to be useful to predict the patterns of pipe breaks on a seasonal basis.

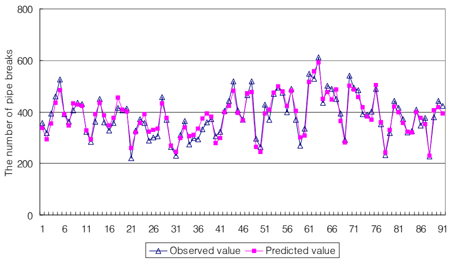

Fig. 19. Comparison of Observed and Predicted values for pipe breaks of mains (training set)

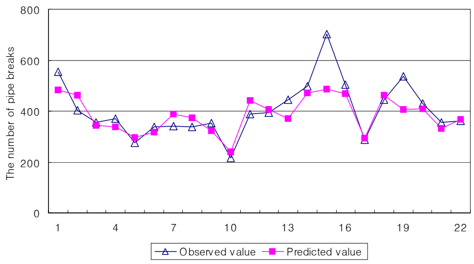

Fig. 20. Comparison of Observed Predicted values for pipe breaks of mains (verification set)

Conclusion

If there are pipe breaks in distribution systems, they give rise to water losses, failures of water supply, cross connection, etc. It is important that maintaining pipe networks in good performance to manage water amounts and water quality in the distribution systems. In this study, the relationship between pipe breaks of service pipes and mains and several factors was examined: soil temperature, water temperature with seasonal change for reducing operation cost and increasing reliability of distribution system. The data on historical pipe breaks, and water and soil temperatures were modeled by ANN to predict pipe breaks for contribution to the efficient management and maintenance of pipes.

It was observed that the breaks of pipes increased after the temperatures of water and soil crossed in spring and fall. The pipe breaks was closely related with water and soil temperature, especially Mains were more affected than Service pipes. The fittings and valves were more susceptible to the temperatures and needed to be reinforced.

The prediction of the pipe breaks by the ANN model built had a good performance except that sensitivity was more orless low when pipe breaks were rapidly changed. It was found that ANN model could predict the pipe breaks. If more input parameters are to be considered and the structure of ANN to be appropriately selected, ANN will be a predictive model of good performance.

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