AUT Journal of Civil Engineering

AUT J. Civil Eng., 4(4) (2020) 437-448
DOI: 10.22060/ajce.2019.16234.5575

A Proposed Method for Locating of Leaky Areas in Water Distribution Networks Based on the Flow Hydraulic Grade Line

R. Moasheri[1], J. Ghazizadeh[2*]

[1] PhD Student, Faculty of Civil, Water, Environmental Engineering, Shahid Beheshti University, Tehran, Iran.
[2] Associate Professor, Faculty of Civil, Water, and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

ABSTRACT: Leaks in water supply networks cause problems such as water loss and contamination. Due to the difficulties of the current leak detection methods, some methods are recently being developed that use network field data (in the form of flow or pressure) and the hydraulic simulation to determine the location of leaks. In this paper, a new method is proposed for locating the leaky areas in water supply networks, based on the results of field pressure measurements and investigation on the hydraulic grade line. Suggestions on the number and arrangement of pressure meters in the network were also recommended. The obtained results for three scenarios in a looped water network with 30 junctions were presented. The results showed that this method can correctly identify the leak areas with no limitation on the number of simultaneous leaks in the network. In this methodology, if the number of field pressure meters increases, the reported leaky areas become smaller. As an example, by increasing the number of pressure meters from 3 to 4, the reported area gets halved. The proposed method can be utilized by operators of water dsupply networks.

Review History:

Received: Feb. 15, 2019
Revised: Apr. 25, 2019
Accepted: Apr. 28, 2019
Available Online: Apr. 29, 2019

Keywords:

Hydraulic Grade Line
Water Supply Network
Pressure Metering
Leak Detection
Flow Hydraulics

1- Introduction

Due to the reduction of annual renewable water level, preventing water losses during various stages of water transmission and distribution is purposed as one of the main strategies to measure this problem. Controlling and reducing water losses is an important issue in the global management of distribution networks [1]. Preventing leaks in water distribution networks reduces operating and maintenance costs. It also helps to reduce the investment costs for the development of new water resources, increases the efficiency and income of water and wastewater companies, and satisfies customers [2]. At the same time, leaks are also an environmental issue, since they are a potential entrance for secondary pollutions to get into the water network [3].

The amount of leak in water distribution networks varies widely between different countries and is reported from 3–7% to 50% in some undeveloped countries [4]. Sometimes it has accounted for more than 70% of total losses [5].

The leak detection methods can be divided into physical and analytical methods. Methods such as acoustic equipment, thermography, ground-penetrating radar, tracer gas, and video inspection [6] are considered as physical leak detection methods. Considering the need for an expert force, timing, and costliness of the mentioned methods, recent studies have attempted to determine the location of the leak by analytical methods. In these methods, the leak locations are determined by using the network field data and the results of the hydraulic analysis of the network. Among these methods, can be mentioned to the network calibration process, using artificial intelligence methods such as artificial neural networks and transient analysis. In the following, some studies that have been done with the mentioned methods are presented.

Wu and Sage [7] detected the leak with the genetic algorithm (GA) optimization-based model calibration. They examined this method in different scenarios including uniformly distributed leak at all demand nodes, a big leak at a node, and uniform leak at the rest of the nodes, and an increase of pipe diameter to simulate the leak in the hydraulic model. Their results showed that this method is effective to detect water loss of the network model. Faghafur Maghrebi et al. [8] detected leaks and their rates at network nodes using the genetic optimization algorithm and ant colony optimization algorithm. In their work, network field data were pressure and flow. They concluded that the ant colony optimization algorithm had a better performance than the genetic optimization algorithm in detecting network leaks. Candelieri et al. [9] located a leak in water systems using the graph optimization method. This method involves creating leak scenarios and analyzing them by Normalized Laplace Matrix. It was proposed that the combination of graph-based analysis and conventional machine learning methods (such a as regression) to estimate leak intensity would improve water distribution network management. Faghafur Maghrebi et al. [10] determined the amount and location of leaks in

*Corresponding author's email: email

water supply networks using a neural network improved by the bat optimization algorithm. Their results showed that the use of the bat algorithm had better results than the conventional neural network training algorithms. Boostani and Khodashenas [11] studied pressure-leak relationship-based leak detection methods in pressurized water networks. They treated leaks as extra consumption of the network nodes. They made all the possible conditions for leaks and assessed them by an objective function (that it was mean square errors and their field parameters were pressure measurements for nodes). They investigated this for single and two simultaneous leaks. Their results revealed that node pressure difference before and after the leak could be an effective parameter for detecting leaks at nodes. Asgari and Faghafur Maghrebi [12] devised a method for locating a single leak in water distribution networks. In this method, find the location of the leak by calculating equations such as leak index and real relative leak index. This method was investigated on the Poulakis network [13]. Results indicated that their methodology is not so sensitive to the amount of leak.

Ebrahimi and Jalili Ghazizade [14] by defining a matrix as the leak indicator and using flow meters, detected a leak in water distribution networks. This method can use only when there is one leak. Wu and Liu [15] studied a method to detect burst in water distribution systems based on a two-stage framework of classification/prediction. Stage 1 is a prediction model involving an artificial neural network, Kalman Filter, and polynomial regression, which is used to predict ideal data based on pipe network normal conditions. Then, stage 2 i.e. classification is used to assess the difference between the predicted and actual values to detect burst. Results of apply uncertainty to locate burst showed that non-stationary monitoring data and limitations present in these methods challenge the reliability of results. Attari and Faghafur Maghrebi [16] introduced a method to detect leaks in water networks using artificial neural networks. This method was investigated for 2 and 4 simultaneous leaks. Their results showed that this method can detect nodes leak and their rate by minimum hydraulic information of pressure types.

Using inverse transient analysis, Rahmanshahi et al. [17] detected leaks in viscoelastic pipelines. For this purpose, they first developed a model of inverse transient analysis using genetic optimization algorithm for calibration and leak detection. Then, to assess the model, they built an experimental model to collect the required data and used a set of leaks data in two locations with different sizes to evaluate the inverse transient analysis method. The results indicated that considering the nature of the genetic metaheuristic algorithm, different implementations of the inverse transient analysis model give different results of decision parameters. Moasheri and Jalili-Ghazizadeh [18] presented a two-step algorithm for identifying the location and the number of leaks in the water distribution systems. In this research, the first step determines the location of leaks by a stepped algorithm and the second step determines the number of leaks using the firefly algorithm (FA). This method was applied for a maximum of two simultaneous leaks in the Poulakis network [13]. Results showed that the mentioned method can detect a very low leak (below 0.3%). Hajibandeh and Nazif [19] proposed a method for leak detection in water distribution networks. In this method, first, the networks are divided into three pressure zones based on the results of field pressure metering. Then, the node pressures and demands are calibrated by the multi-objective ant colony algorithm. This method was investigated in the Rossman networks [20]. In this paper, the proposed optimization algorithm was compared to the multi-objective genetic algorithm (NSGA II) and it was concluded that the multi-objective ant colony algorithm presented better results from the NSGA II for investigating the leaks in the water networks. Wu et al. [21] using the results of pressure sensors in district metering areas (DMAs) detect the location of bursts in water networks. This method was studied in a DMA network with four pressure sensors in the presence of large bursts with a flow greater than 40% of the input flow. The results showed that this method can detect relatively big bursts.

The use of the calibration to detect leaks that in recent studies have done with metaheuristic algorithm does not guarantee to obtain optimal and correct solutions since there is no appropriate scientific proof for it. The use of artificial neural networks requires suitable and comprehensive data in its training stage and if the input data is not in its training stage data range, it may result in errors in the output solution. The use of inverse transient analysis to detect leaks is difficult with executive problems in practice. Moreover, the mentioned methods can detect a certain number of leaks in a network, while the number of simultaneous leaks is not clear in the practice. Furthermore, most of the methods report the leak locations precisely and usually in the network nodes, while the leaks cannot be in the nodes in practice and this requires a completely calibrated hydraulic model of the network. Also, some methods can be used only when we deal with DMA networks, while many networks are not designed in this manner. Therefore, these methods cannot be used in these cases. In general, despite the researches done on analytical leak detection, it appears that more studies need to be conducted to achieve a scientific and practical method to detect leaks.

In the present paper, a new method is proposed for locating leaky areas in water supply networks. In this method, the hydraulic grade line of some points in water networks is drawn in leak mode (with performing field pressure measurements) and non-leak mode (based on hydraulic results in the computer simulator model made by software such as EPANET). Then, by analyzing the slope changes of the hydraulic grade diagram, the leakiest area is detected. The proposed method can scientifically be proved and thus, it is reliable to a great degree. Moreover, there is no limitation on the number and location of simultaneous leaks. Additionally, reports of leak areas, instead of precise location, reduce uncertainty effects on items such as measurement device errors and the network hydraulic model parameters.

2- Materials and methods

Consider a water supply network with J nodes, M source nodes, N consumption nodes ($M + N = J$), and C loops. We have a total of $C + J - 1$ equations (including energy and continuity equations) [22]. If there is a leak in this network and it is considered as extra node consumption, the total number of unknowns becomes $X + J - 1$. Thus, the total number of the parameters that have to be found by field data (in the form of flow or pressure) so that all the hydraulic equations are satisfied will be $X - C$. This number of field data is time-consuming and costly to collect. Therefore, we will introduce a method to detect leaks by a limited number of field data and the analysis of the hydraulic flow grade line.

Consider the branched network shown in Fig.1. It has a reservoir and four nodes. In this network, all the pipes have the length of L and the diameter of D along with the same roughness. The consumption demand of all the nodes is q, reservoir hydraulic grade is H, and all the nodes are on the base-ground (0). According to flow continuity law, if the hydraulic grade is known for all the nodes, the flow in pipe P-1 is the total node demand (4q), and since all the pipes are the same in geometry, the hydraulic grade line slope from the reservoir to node 1 (J-1) is maximum according to the pressure loss equations. The flow in pipe P-2 is 3q according to continuity law. Thus, the hydraulic grade line slope from node 1 (J-1) to node 2 (J-2) is lower than that of pipe P-1. With the same argument, it can be concluded that the hydraulic grade line slope in pipe P-3 is lower than in pipe P-2 and higher than in pipe P-4. As a result, the hydraulic grade line slope declines from the initial to the end of the network. Hence, its hydraulic grade line is the one in Fig. 2. Assume that the leak of node 2, for example, is Q_L in this network. According to flow continuity law, this leak increases the flow of pipes P-1 and P-2 by Q_L, thereby increasing the hydraulic grade line slope in the two upstream pipes, that is, pipes P-1 and P-2, while it is the same in pipes P-3 and P-4.

Thus, the hydraulic grade line will be as in Fig.3. It should be noted that velocity head changes are ignored in the two given profiles (Fig.2 and 3) as they are very low. Thus, in general, the leaks can be detected from a change in hydraulic grade line slop from the state without leaks to a leaky state.

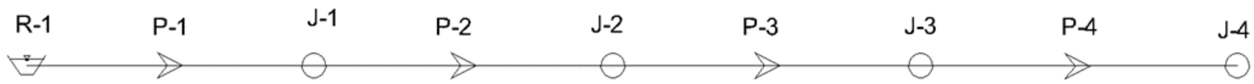

Fig. 1. The investigated branched network.

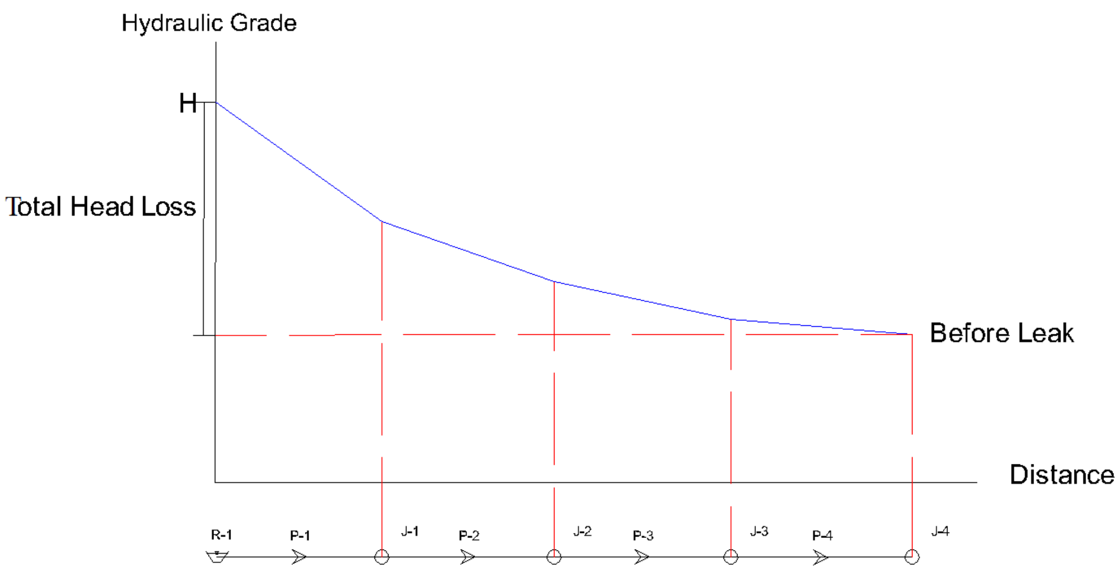

Fig. 2. Hydraulic grade line of the branched network without the leak.

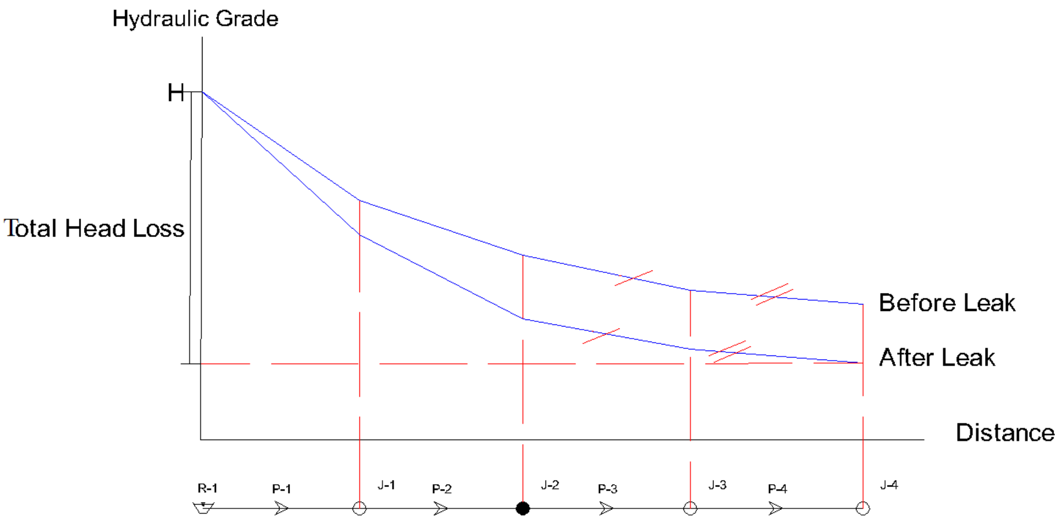

Fig. 3. Hydraulic grade line of the branched network with a leak at node J-2.

As already mentioned, it is very difficult and costly to determine the hydraulic grade for all the nodes as it requires field pressure measurements in them. The purposed method for a water supply network with any dimension is as follows:

1. Selecting at least three nodes of the water network in a given branch (first, internal, and end nodes in that branch) as field pressure measurement locations. A branch refers to a set of nodes connected by pipes in a certain path.
2. Calculating the absolute value for the slope of the hydraulic grade line based on the computer simulation of the water network in non-leak mode between the two successive locations (or nodes) that were selected as the field pressure measurement locations. At this stage, a matrix is formed which is called the computed hydraulic grade line slope matrix ($A((r-1)\times 1)$). In this matrix, r is the total number of locations in which the water pressure measurements will be performed.
3. Performing pressure metering operation at the field pressure measurement locations.
4. Calculating amounts of the hydraulic grade with stage 3 field data.
5. Calculation of absolute the hydraulic grade line slop value, based on the results obtained from stage 4, between the two successive locations of the field pressure measurement. As a result, a matrix called the field hydraulic grade line slope is formed ($\mathrm{B}((r-1)\times 1)$).
6. Calculation ratio of the changes in the slope of hydraulic grade line with and without leak for the pipes in the highlighted branch (branch 1) between two consecutive field pressure measurement locations (Eq. (1)).

$$K_i = \frac{S_{(A.L)_i}}{S_{(B.L)_i}} = \frac{\sum_{j=1}^{P_i} R_{(A.L)_{i,j}} Q_{(A.L)_{i,j}}^{\;n}}{\sum_{j=1}^{P_i} R_{(B.L)_{i,j}} Q_{(B.L)_{i,j}}^{\;n}} \tag{1}$$

Where

K_i : The parameter that denotes the increase of the flow in the branch between two consecutive field measurement locations ‘i’ due to the leak(s),

i : The counter of two consecutive field measurement locations (i=1:p that the minimum p is 2 and maximum p is the total number of the network pipes for measuring the pressures of all the network nodes),

j : The counter of the pipes in the branch between two consecutive field measurement locations,

P_i : The total number of the pipes in the branch between two consecutive field measurement locations i,

$S_{(A.L)_j}$: Hydraulic grade line slope for the pipes in the branch between two consecutive field measurement locations i with the leak(s),

$S_{(B.L)_j}$: Hydraulic grade line slope for the pipes in the branch between two consecutive field measurement locations i before the leak(s),

$R_{(A.L)_{i,j}}$: Resistance of pipe j in the given branch between two consecutive field pressure measurement locations i with the leak(s),

$Q_{(A.L)_{i,j}}$: The flow of pipe j in the branch between two consecutive field pressure measurement locations i with the leak(s)

$R_{(B.L)_{i,j}}$: Denotes resistance of pipe j in the branch between two consecutive field pressure measurement locations i before the leak(s),

$Q_{(B.L)_{i,j}}$: The flow of pipe j in the branch between two consecutive field pressure measurement locations i before the leak(s),

And n is the energy loss equation exponent which is dependent on the type of the equation used (n=2 for Darcy-Weisbach and Manning head loss equations and n=1.85 for Hazen-Williams head loss equation).

Then, a matrix is formed which is called hydraulic grade line slop ratio matrix (K(sum(i)×1)) where sum(i) is the sum of the counter 'i' (number of paired field pressure measurement locations).

7.As mentioned in section 6, each element of matrix K denotes the ratio of the flow in the branch pipes between two consecutive pressure measurement locations with and without leak(s). If this parameter reduces between two consecutive locations, it implies the presence of leak(s) in one of the two pressure measurement locations. Also, an increasing or constant trend in it shows the presence of leaks in other locations in the network. By considering the results obtained from the diagram of the hydraulic grade line slope in the water leak mode, the following results can be recognized:

7.1.In two successive elements of the matrix K, if the ratio of the second matrix element to the first element is less than 1, then the corresponding area of the first element can be specified the area of the leak(s).

7.2.If the last element value of matrix K is greater than 1, then the water network leaks (s) in the area corresponding to the last element of the matrix K or in the area outside of the given branch from the last node of the network.

7.3.If the network leaks (s) but the value of the element of matrix K is equal to 1, then the leak(s) area of the network is outside of the area defined to the first node.

If the existing water network is branched and there is no uncertainty about any of its hydraulic parameters (such as pipes roughness, demands, measured pressures, etc.), then the area of all leaks in the given branch (stage 1) is determined by using the proposed method; but, if some uncertainty exists about the mentioned parameters or in looped or composite networks due to hydraulic complexity of the network, the leakiest area can be determined in the defined branch. That way, the nodes suspected for the leak(s) (according to the points mentioned) which corresponds to two successive elements in the matrix K that the change value of the second element compare to the value of the first element, or the change value of the last element (in its value is greater than 1) to 1 is greater, will determine leakiest area in the given branch. But in the following, using the proposed method, one can similarly detect other leak locations after precisely detecting leaks by physical leak detection methods.

It should be noted that the more number of the network nodes have pressure meters, the smaller the leak area(s) will be and in practice, leak detection will be easier and cost lower. If pressure is measured for all the nodes in a branched network, the proposed method will precisely locate the leaks (assuming that the leaks happen only for the network nodes). However, with pressure metering in the network step by step, the precise locations of leaks can be detected by a lower number of pressure meters.

2.1. Required Number and Arrangement of Pressure meters

As mentioned for the proposed method, the hydraulic parameter of pressure is required to be measured in the network by a field operation. To determine the number and arrangement of the pressure meters, the following is recommended:

2.1.1. Branched Network

In branched networks with any dimensions, the branch where pressure is measured is the main branch. Assuming a location for the initial node, a location for the end node, and a location in one of the internal nodes in that branch, the minimum number of the pressure measurement nodes is 3.

2.1.2. Looped and Compound Networks

For looped or compound networks with any dimensions, an analysis can be made based on the proposed method. The minimum number of pressure measurements in each branch of a looped or compound network is three – i.e. pressure measurement for nodes in initial, internal, and end locations of each branch. As a result, the total number of pressure meters is 3 times the total number of the branches defined in the network according to stage 1 for the proposed method.

For looped networks that have crosshatch patterns, such as the Poulakis network [13] (Figure 4), since all the nodes are connected by the pipes in short distances, if leaks take place in a short distance of up to 2 nodes from each branch, leak area(s) can be detected by implementing the proposed method as the branch is affected by the leak. In a $m \times n$ fully crosshatch looped network, Eq. (2) is proposed to calculate the minimum number of pressure measurements:

$$\mathrm{MNLP} = 3 \times \left\lceil \frac{\min(m,n)}{5} \right\rceil \tag{2}$$

Where

$MNPL$: The minimum number of the pressure meters required in a fully crosshatch looped network,

m : The number of the rows in the fully crosshatch looped network,

n : The number of columns in the fully crosshatch looped network.

For this case, the following arrangement is proposed for the pressure meters:

In case min (m, n) =2, if n= min (m, n), the pressure meters are in column n, and if not, they are in row m;

In case min (m, n) =3, if n=min (m, n), the pressure meters are in column n-1, and if not, they are in row m-1;

In case $\min(m,n) \geq 4$, if n=min (m, n), the pressure meters are in columns with the maximum distance of two nodes from each other, and if not, in rows with the maximum distance of two nodes from each other.

It is evident that the above-mentioned statements are proposed to minimize the number of the pressure meters based on the shape and hydraulic state of all the fully crosshatch looped networks and it cannot necessarily be proved to work.

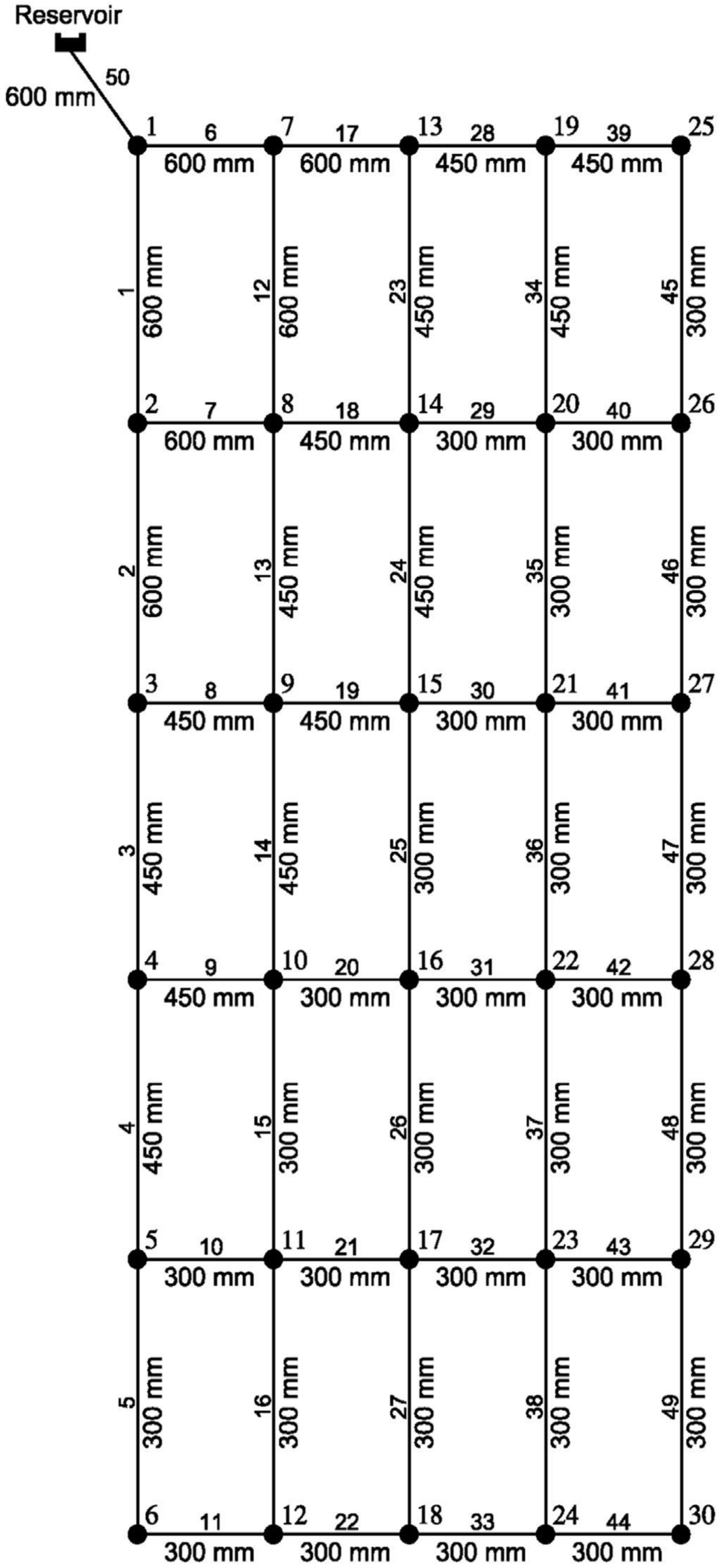

Fig. 4. The case study network [13].

Table 1. Hydraulic grade values and nodes' distances from each other in the pressure meters branch of the study network (without leaks).

Node	Hydraulic Grade [m]	Distance [m]
13	30.35	0
14	28.92	2000
15	27.07	4000
16	22.02	6000
17	19.12	8000
18	18.10	10000

Table 2. Computed hydraulic grade line slope values in the proposed pressure meters arrangement for the case study network (without leaks).

Initial and end hydraulic grade line node	Hydraulic grade line slope
13, 16	0.001388
16, 18	0.000980

2.2. Case Study

To investigate the mentioned methodology, the purposed method has been implemented on the Poulakis network [13]. In the network shown in Fig.4, the lengths of horizontal and vertical pipes are 1000 and 2000m, respectively, and the mean absolute roughness of each pipe is 0.26mm. This network has 20 loops, 30 nodes, 50 pipes, and a reservoir with 50m of water level. The diameters of the pipes are indicated in Figure 4. Nodes demand is considered to be 30 L/s. It should be noted that it is a fully crosshatch looped network, which is much more difficult to hydraulically analyze than real networks. To detect the leak(s) by writing and solving hydraulic equations, 30 field measurements (of either pressure or flow metering) are required ($X - C = 50 - 20 = 30$), which costs a lot. Thus, the biggest leaks area are detected by the proposed method in the following.

Given that this network is a 6×5 fully crosshatch looped network, the minimum number of the required pressure gauges is 3 (according to equation 2) and they should be placed in the column with a maximum distance of two nodes from other nodes. Thus, in this network, the middle vertical branch (consisting of nodes 13, 14, 15, 16, 17, and 18) is selected. According to the above-mentioned statements, there has to be at least one pressure meter in the initial node, one in the end node, and one in the internal node of this branch. Therefore, pressure meters locations are selected to be at nodes 13, 16, 18.

Table 1 gives hydraulic grade and node distance values for the branch where pressure meters are located. It should be noted that node hydraulic grade values were derived from EPANET 2.0 in this case study. Table 2 represents the calculation results for the computed hydraulic grade line slope matrix (matrix A) based on the values given in Table 1.

3- Results and Discussion

This section provides the results of three different leak scenarios in the study network. In them, leak scenarios were created by the hydraulic model of the network in EPANET 2.0.

3.1. Investigating Single Leak

In this scenario, 20 L/s (approximately 2.22% of the input flow) was added to the demand of node 26. After simulating the network, pressures of nodes 13, 16, and 18 were measured as 29.42, 21.00, and 17.07m, respectively, as the field, measured pressures. It should be noted that their hydraulic grade values are almost the same as their pressure head as all the nodes are at the basic height of zero in the Poulakis network [13].

The results of applying the proposed method are given in Table 3 and their hydraulic grade line graph before and after the leak is represented in Fig.5. As it is seen in Table 3, the ratio of the second to the first element and the ratio of 1 to the last element value of matrix K is less than 1. But the difference value between the second to the first element (that is 0.008) is greater than the difference value between the last elements to 1 (which is 0.0003). Thus, according to the above-mentioned statements, the area represented by the first element in the matrix can have a leak(s) and as this branch where pressure meters are installed represents other vertical branches in the network, the rectangular area whose angles are at nodes 1, 25, 4, and 28 indicates the leakiest area. As it is seen, the main leak node (node 26) is located in this area. Thus, the leak location is detected correctly.

Table 4 shows the calculation results for the case where four pressure measurements are done for nodes 13, 14, 16, and 18 in this example. As it is seen in this table, the ratio of the second to the first element, the third to the second element, and the ratio of 1 to the last element value of matrix K are less than 1 but the difference value between the second to the first element (that is 0.038) is greater than the rest. Therefore, the rectangular area whose angles are at nodes 1, 25, 2, and 26 represents the greatest leak(s) area and the location of the main leak node (node 26) is in this area.

3.2. Investigating Three Simultaneous Leaks

In this scenario, 5 L/s to the demand of node 8, 20 L/s to the demand of node 9, and 15 L/s to the demand of node 21 are added, and after hydraulic simulating the network, pressures of nodes 13, 16, and 18 was measured (28.59, 19.78, and 15.86 m, respectively), as the field measured pressures. The results of the proposed method are presented in Table 5.

According to the results in this table, just the second to the first element of matrix K is lower than 1. Thus, according to statements in stage 7.1, theleakiest area is a rectangular area that its angles are at nodes 1, 25, 4, and 28. As it is seen, all the network leaks are located in it. Therefore, their area is successfully detected. Fig.6 shows their hydraulic grade line graph before and after the leaks.

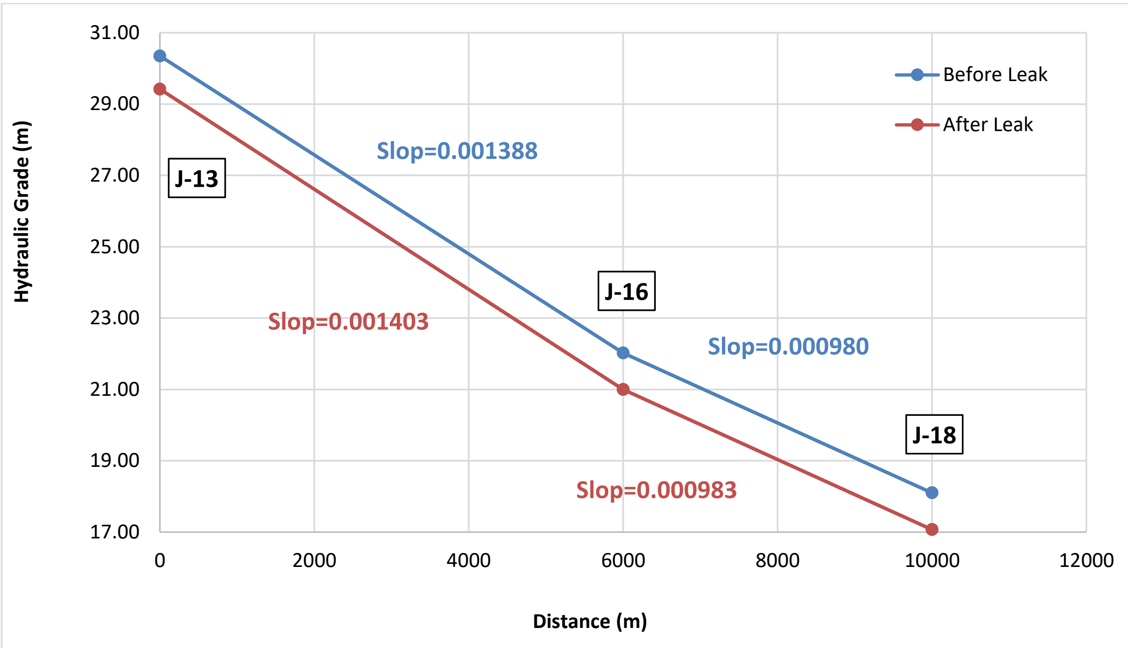

Fig. 5. Hydraulic grade line before and after leak (scenario 3-1 with 3 field pressure measurements).

Table 3. Suspected leaky areas estimation results for scenario 3-1 with 3 field pressure measurements.

Initial and end nodes of hydraulic grade line	Computed hydraulic grade line slope matrix (A)	Field hydraulic grade line slope matrix (B)	Hydraulic grade line slope ratio matrix (K)
13 , 16	0.001388	0.001403	1.011
16 , 18	0.000980	0.000983	1.003

Table 4. Suspected leaky areas estimation results for scenario 3-1 with 4 field pressure measurements.

Initial and end nodes of hydraulic grade line	Computed hydraulic grade line slope matrix (A)	Field hydraulic grade line slope matrix (B)	Hydraulic grade line slope ratio matrix (K)
13 , 14	0.000715	0.000745	1.042
14 , 16	0.001725	0.001733	1.004
16 , 18	0.000980	0.000983	1.003

3.3. Investigating Six Simultaneous Leaks

In this scenario, 15 L/s to the demand of node 12, 18 L/s to the demand of node 30, 10 L/s to the demand of node 24, 10 L/s to the demand of node 10, 5 L/s to the demand of node 9 and 10 L/s to the demand of node 20 are added and after hydraulic simulating the network, pressures of nodes 13, 16, and 18 was measured (27.11, 17.08, and 11.59 m, respectively), as the field measured pressures. The results of the proposed method are presented in Table 6. Also, its hydraulic grade line graphs before and after the leaks are demonstrated in Fig.7.

As it is seen in column 4 in Table 6, just the last element value of matrix K is greater than 1. Afterward, according to stage 7.2, the leakiest area is represented by the last element in the matrix and according to the nature of fully crosshatch looped networks, their area, the rectangular area, involves nodes 4, 28, 6, and 30. As it is seen, the greatest leaks are located in this area (15 L/s at node 12, 10 lL/s at node 24, and 18 L/s at node 30). Thus, the area of the greatest leaks in the network is correctly detected. After performing the leak detection in this area, the proposed method can be applied again to detect other leaky areas if needed.

Table 5. Suspected leaky area estimation results for scenario 3-2.

Initial and end nodes of hydraulic grade line	Computed hydraulic grade line slope matrix (A)	Field hydraulic grade line slope matrix (B)	Hydraulic grade line slope ratio matrix (K)
13 , 16	0.001388	0.001468	1.058
16 , 18	0.000980	0.000980	1.000

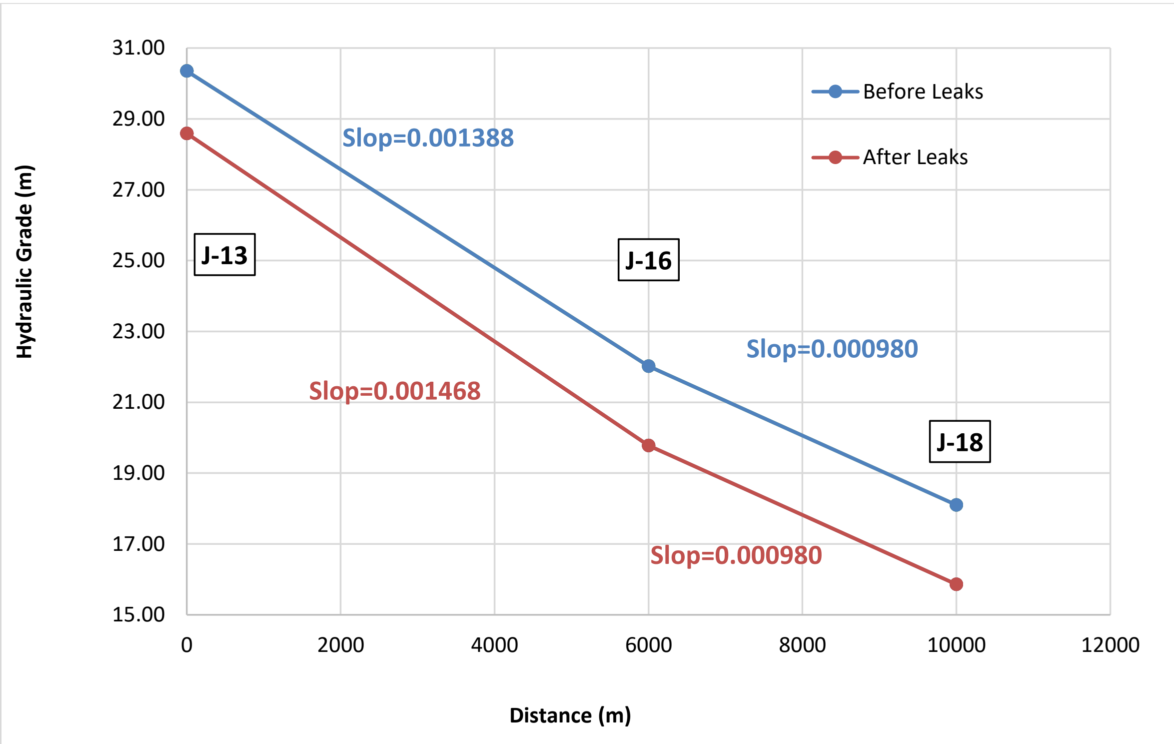

Fig. 6. Hydraulic grade line before and after leaks (scenario 3.2).

Table 6. Suspected leaky area estimation results for scenario 3-3.

Initial and end nodes of hydraulic grade line	Computed hydraulic grade line slope matrix (A)	Field hydraulic grade line slope matrix (B)	Hydraulic grade line slope ratio matrix (K)
13 , 16	0.001388	0.001672	1.204
16 , 18	0.000980	0.001373	1.401

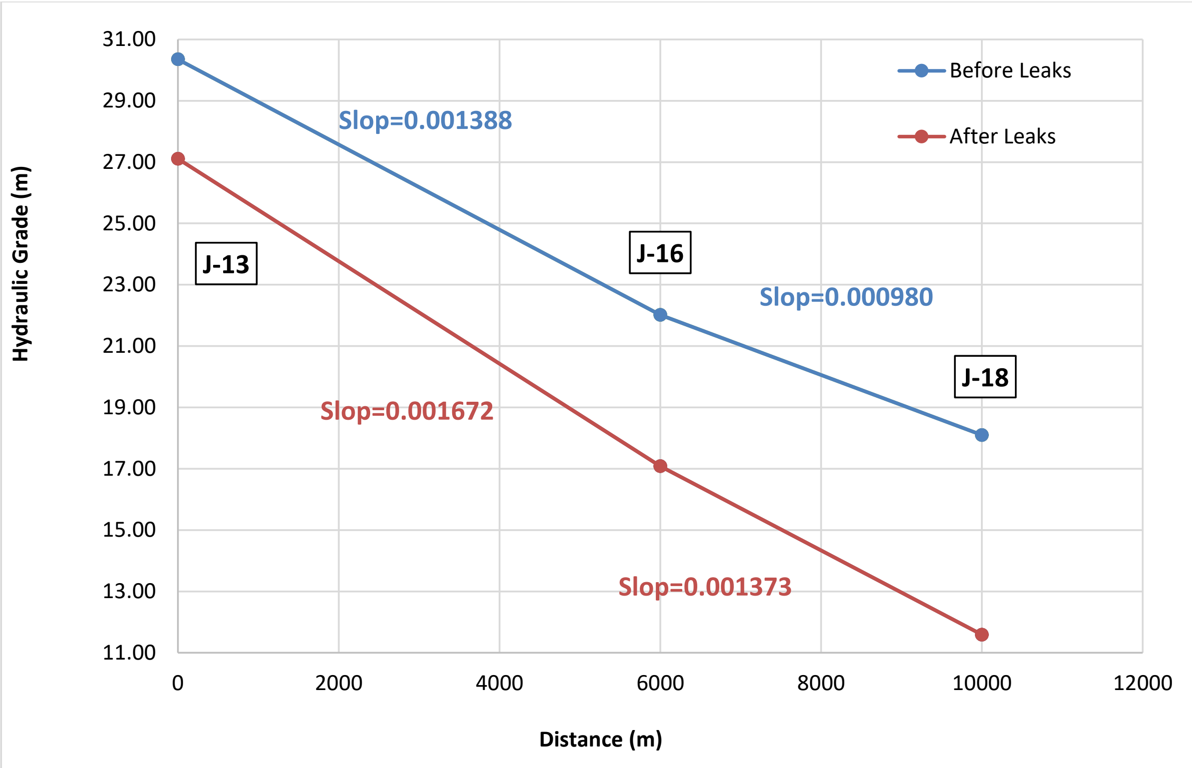

Fig. 7. Hydraulic grade line before and after leaks (scenario 3-3).

4- Conclusions

In this paper, a new method was purposed for locating the biggest leak area in water supply networks, which is based on the flow hydraulic of the water network. Some advantages of this method include: practically provable (unlike commonly used analytical methods such as metaheuristic algorithms), no limitation on the number of simultaneous leaks, and their location in the network.

In addition, some equations were recommended to determine the number and arrangement of the required pressure meters to use the proposed method for branched and looped networks. It was also concluded that more pressure measurements, will be reduced the reported leaky area, and leak detection costs. This method was investigated on the Poulakis network, as a complex network in terms of hydraulic. The proposed method was studied on the scenarios of one, three, and six simultaneous leaks. In all of these cases, only by performing three pressure meters on the network, the area of theleakiest area correctly identified.

References

[1] G. Mazzolani, L. Berardi, D. Laucelli, R. Martino, A. Simone, O. Giustolisi, A Methodology to Estimate Leakages in Water Distribution Networks Based on Inlet Flow Data Analysis, Procedia Engineering, 162 (2016) 411-418.

[2] Vice Presidency for Strategic Planning and Supervision, The Guide to Recognizing and Investigating the Effective Factors in Unaccounted-For Water the Unaccounted and Approaches to its Reduction, 2012 (in persian).

[3] J. Sousa, L. Ribeiro, J. Muranho, A.S. Marques, Locating Leaks in Water Distribution Networks with Simulated Annealing and Graph Theory, Procedia Engineering, 119 (2015) 63-71.

[4] R. Puust, Z. Kapelan, D.A. Savic, T. Koppel, A review of methods for leakage management in pipe networks, Urban Water Journal, 7(1) (2010) 25-45.

[5] N. Samir, R. Kansoh, W. Elbarki, A. Fleifle, Pressure control for minimizing leakage in water distribution systems, Alexandria Engineering Journal, 56(4) (2017) 601-612.

[6] D. Covas, H. Ramos, Case Studies of Leak Detection and Location in Water Pipe Systems by Inverse Transient Analysis, Journal of Water Resources Planning and Management, 136(2) (2010) 248-257.

[7] Z.Y. Wu, P. Sage, Water Loss Detection via Genetic Algorithm Optimization-based Model Calibration, in: 8th Annual Water Distribution Systems Analysis Symposium, Cincinnati, Ohio, USA, 2006.

[8] M. Faghafur Maghrebi, Y. Hasanzadeh, S. Yazdani, Calibration of Water Supply Systems Based on Ant Colony Optimization, Journal of Water and Wastewater; Ab va Fazilab (in persian), 24(1) (2013) 101-111 (in persian).

[9] A. Candelieri, D. Conti, F. Archetti, A Graph based Analysis of Leak Localization in Urban Water Networks, Procedia Engineering, 70 (2014) 228-237.

[10] M. Faghafur Maghrebi, M. Aghaebrahimi, H. Taherian, M. Attari, Determining the amount and location of leakage in water supply networks using a neural network

improved by the bat optimization algorithm, Journal of Civil Engineering and Urbanism, 4(3) (2014) 322-327.
[11] A. Boostani, S.R. Khodashenas, Studying a leakage detection method in pressurized water networks based on the pressure–leakage relation (Presentation of Optimization Code for Locating Leakage), Journal of Water and Sustainable Development, 2(1) (2015) 59-66 (in persian).
[12] H.R. Asgari, M.F. Maghrebi, Application of nodal pressure measurements in leak detection, Flow Measurement and Instrumentation, 50 (2016) 128-134.
[13] Z. Poulakis, D. Valougeorgis, C. Papadimitriou, Leakage detection in water pipe networks using a Bayesian probabilistic framework, Probabilistic Engineering Mechanics, 18(4) (2003) 315-327.
[14] S. Ebrahimi, M. Jalili Ghazizadeh, Identification of the leakage location in water distribution networks using flow-meter, in: 1th National Conference on Water Loss & Consumption Management, Iran, Shahid Beheshti University 2017 (in persian).
[15] Y. Wu, S. Liu, A review of data-driven approaches for burst detection in water distribution systems, Urban Water Journal, 14(9) (2017) 972-983.
[16] M. Attari, M. Faghfour Maghrebi, New Method for Leakage Detection by Using Artificial Neural Networks, Journal of Water and Wastewater; Ab va Fazilab (in persian), 29(1) (2018) 14-26 (in persian).
[17] M. Rahmanshahi, M. Fathi-Moghadam, A. Haghighi, Leak Detection in Viscoelastic Pipeline Using Inverse Transient Analysis, Journal of Water and Wastewater; Ab va Fazilab (in persian), 29(5) (2018) 85-97 (in persian).
[18] R. Moasheri, M. jalili Ghazizadeh, Identifying the Location and Amount of Two Simultaneous Leaks in Water Supply Networks by a Two-step Algorithm, Amirkabir Journal of Civil Engineering, 52(5) (2020) 1-10 (in persian).
[19] E. Hajibandeh, S. Nazif, Pressure Zoning Approach for Leak Detection in Water Distribution Systems Based on a Multi Objective Ant Colony Optimization, Water Resources Management, 32(7) (2018) 2287-2300.
[20] L.A. Rossman, EPANET users manual, version 1.1, Cincinnati: US Environmental Protection Agency, 1994.
[21] Y. Wu., S. Liu., X. Wang., Distance-Based Burst Detection Using Multiple Pressure Sensors in District Metering Areas, Journal of Water Resources Planning and Management, 144(11) (2018) 06018009.
[22] T.J. McGhee, Water supply and sewerage, 6th Edition ed., McGraw-Hill Book Company, 1991.Offictur siti

HOW TO CITE THIS ARTICLE

R. Moasheri, J. Ghazizadeh, A Proposed Method for Locating of Leaky Areas in Water Distribution Networks Based on the Flow Hydraulic Grade Line ,(2020). AUT J. Civil Eng., 4 (4) (2020) 437-448

DOI: 10.22060/ajce.2019.16234.5575