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A Laboratory Based Study of Hydraulic Simulation of Leakage in Water Distribution Networks

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Abstract

It is obvious to all people the importance of water as an essential element for life, hence, water loss is a life-threatening and alarming predictor of the future. Leakage problem is one of the most important causes of water loss in water systems; therefore, it was and is still a matter of attention of many researchers, who are in search of the most effective methods to solve this problem using many techniques. These techniques vary with one another in terms of accuracy, cost and speed of obtaining results. This research paper presents a part of an extensive research work, which aims to develop a geospatial approach for solving the leakage detection problem in water systems using an integrated geospatial system. This paper will show a sample of the results that has been obtained through a lab experiment, which explains the changes in hydraulic behavior of the network due to the change in leakage size and leakage location as a step for validating the mentioned approach.

Keywords: Leakage detection, water distribution networks, GIS, Hydraulic modeling.

1. Introduction

1.1 Background

Leakage in water distribution networks has become an important and urgent problem that involves a lot of cost yearly. The difficulty of the problem is further worsened, particularly when the location of leakage is hidden in nature (Farley, 2001; Farley, 2003). There is clear evidence that this problem of water loss is a very complex issue, and has an impact on water systems worldwide through some statistics. Based on the statistics, more than 32 billion cubic meters of water is lost annually from the distribution networks because of the leakage problem, while more than 16 billion cubic meters of water is consumed by users. There is also unmetered or not correctly metered volume of water due to theft and robbery (Kingdom, 2006).

The significant reliance on expensive leakage detection devices which are required in field works for a long-term network age is unacceptable, especially when the problem continues to recur. Hence, there is an extensive research attempts to find out an effective approach for detecting water leakage by conducting some hydraulic analysis scenarios using some measurements, which can be obtained from the field in real time using SCADA system. However, this remains a matter of research about their effectiveness, unless they are accompanied with verification of their effectiveness through laboratory and field experiments.

This research paper addresses a part of practical stage for validating the geospatial approach for leakage detection in water distribution networks, which has been carried out through laboratory experiments as the first phase. As the next futuristic step, there will be another phase to verify the results of this approach in the field using readings from existing water network.

1.2 Research Aim

This laboratory experiment is a part of an extensive research study aimed at developing a geospatial approach for leakage detection and location in water distribution networks in real time with high accuracy and low cost. For this purpose, an integrated system has been suggested to conduct this task. In addition, this laboratory experiment attempts to study the changes in the hydraulic behavior of the network due to the changes in leakage size and leakage location, which helps later in validating the proposed approach in this extensive research study. The laboratory experiment results contribute to planning the field work and applying the approach in an existing water network later.

2. Literature Review

The most important characteristics of leakage detection techniques in water systems are the ease of application, cost of implementation, as well as the accuracy and speed of getting the results through them. Some leakage detection techniques rely on hardware and equipments to detect leaks in limited pipes, as well as the other theoretical and analytical methods which used to identify some hot spots which are expected to be leakage points (Bentley, 2006). So far, researchers cannot find a method that can detect the exact location of leakage in the distribution networks, it's just an estimate of the leakage location with an unacceptable error rate. Sometimes, the problem is exacerbated when there are leakages in more than one location in the network at the same time, as well as the presence of some noise arising from water loss because of the illegal consumption of water. It may be difficult for the current methods of leakage detection to reach the location of leakage accurately as a result of wrong inputs of distance or changes in pipe materials, which leads to costly and unsatisfactory results. In addition, it is also difficult to make an overall monitoring for the network because the leakage detection only covers a specific area at a time.

Currently, the main approach of detecting and locating leaks is based on the methods of investigating the sound waves in the network, called as the acoustic methods. In these methods, the emissions of acoustic signals caused by the leakage in the pipes are monitored to determine its location in the network (Burn, 1999). The non-acoustic techniques of leakage detection in water distribution systems include these methods as follows:

i. Injection of tracing substances for tracking and investigation in water stream.
ii. Electromagnetic inspection of pipes from the inside.
iii. Analysis of quasi-static signals detected by the sensors installed into the pipe, such as pressure, flow rate and temperature.
iv. Analysis of transient signals detected by the sensors installed into the pipes, such as the pressure wave.
v. Analysis of changes in temperature resulting from the leakage by using the infrared thermography of sensors located outside the pipe system.
vi. Identification of frequencies emitted by radio or radar transmitters installed inside the pipes which permeate through the pipe cracks.

Some of these techniques including the techniques in items ii, v and vi are relatively expensive, while other techniques such as in items i, ii and vi intrude into the fluid stream, which increases the risk of contamination. Although there are some research-based development methods based on the analysis of transient methods as mentioned in item iv, such as the inverse transient method, it is not straightforward in their application beyond the trivial pipe networks. The method in item iii relies on the status of the pipe system based on some measured parameters, such as pressure, flow rate, and sometimes, the temperature at various points and time within the pipeline system (De Silva, 2009).

As the process of field survey using special devices for leakage detection requires a long time to perform the task, as well as high cost resulting from the expensive devices, apart from the expenses of the field survey itself, therefore, the field survey was excluded in this research. Thus, all methods based on the field survey no longer meet the required purpose due to their limitations in terms of time, cost and accuracy. Although there are some analytical methods that rely on hydraulic analysis of the network hydraulic parameters to detect the leakage, they are still unable to determine the location of leakage accurately. Their abilities stop at finding a group of hot spots that are likely to be the location of leakage among them (Bentley, 2006), which requires the necessity of field survey in a limited area of the network in order to locate the leakage location more accurately. Therefore, these methods have contributed to reducing the time needed to locate the leakage with a little reduction of cost. Even though this seems good, it is not enough. The ideal solution is to find a method that is able to detect the location of leakage accurately in real time and at the lowest cost.

3. Methodology

3.1 Introduction

3.1.1 Research Concept

The research concept shown in (Figure 1) depends on the assumption of asymmetry of pressure values over the time in all network nodes, so that it can be presumed that each node has its own pressure footprint at every moment during water flow over the network. Furthermore, it can also rely on measuring these pressure footprints in the field at certain points on the network and compare them with the values of pressure obtained theoretically through the hydraulic modeling at the same points, which are expected to be close to one another significantly.

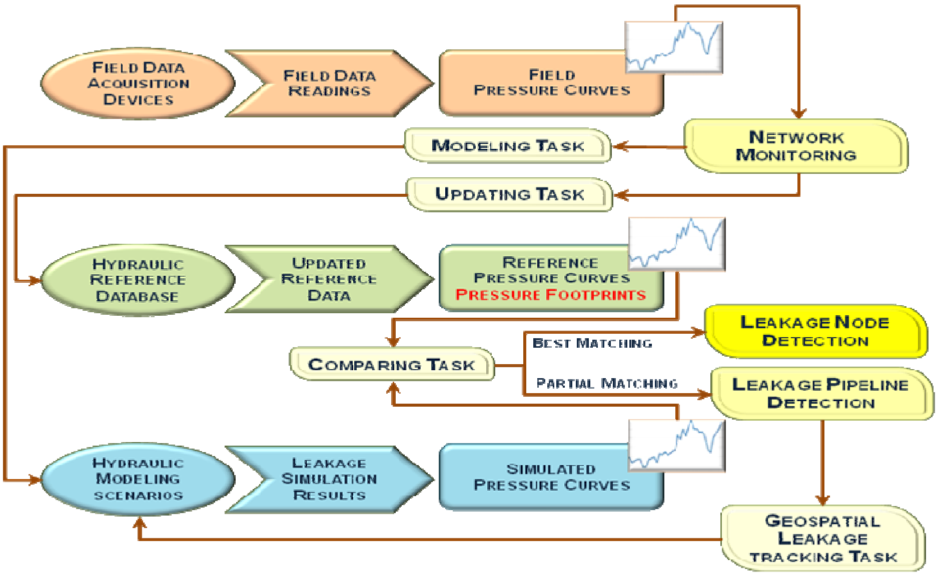

Figure 1. Research Concept

In case of a leakage, the leakage volume can be known by monitoring the flow rate over the time. On the other hand, the leakage location can be detected by conducting some hydraulic modeling scenarios and representing the leakage as a water demand in all the nodes of the network one by one, which is then compared with the field pressure readings obtained by the pressure transmitters at specific nodes in the field with the pressure results obtained from the hydraulic modeling scenarios at the same nodes in each case. By comparing the results, it can be concluded that the node which has matching results among the field readings and hydraulic modeling results can be considered as the Leakage Node, while the pipe which is after that node in the downstream direction can be considered as the Leakage Pipe. After identifying the leakage pipe, the spatial capabilities of GIS can be used for generating a virtual node at the middle of the leakage pipe. The hydraulic modeling steps are repeated to determine whether the new leakage pipe here is located before the virtual node or after it. By continuing repeating the steps to decrease the length of leakage pipe to the minimum will help detect the leakage location to a more accurate location. The chart shown in (Figure 2) illustrates the procedures undertaken for identifying the leakage location.

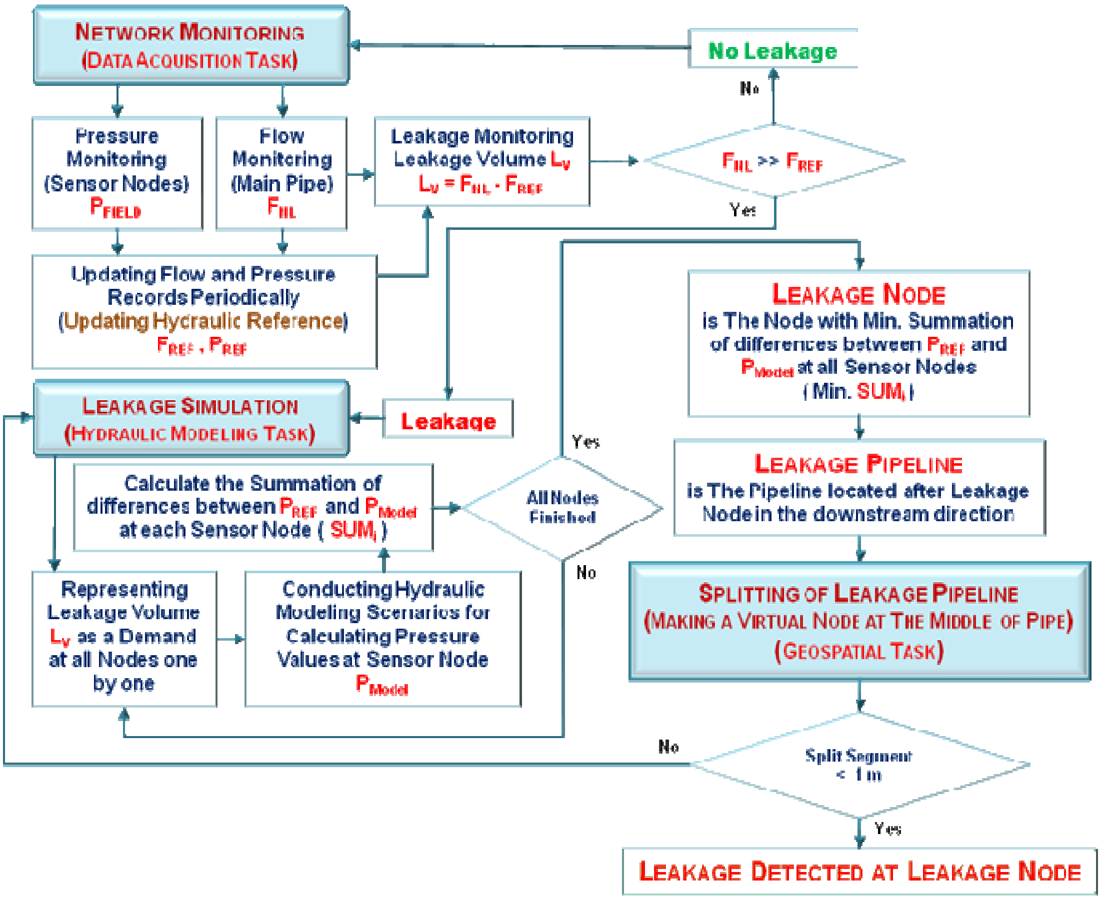

Figure 2. Procedures for leakage detection and location

3.1.2 *Integrated System*

The idea of this research takes advantage of the features of three systems in order to build a geospatial approach by integrating the following systems:

i. Geospatial Information System (GIS): works as a base system and helps in the generation of a virtual network of nodes along the pipelines; this process is needed for the hydraulic system to perform the hydraulic analysis along the pipelines.

ii. Hydraulic Modelling System (WaterGEMS): conducts hydraulic analysis processes and calculates the values of pressure at the nodes, which are needed to detect the leakage location.

iii. Data Acquisition System (SCADA): monitors the network devices, such as flow meters and pressure transmitters, and transfers field data to the hydraulic modelling system in real time.

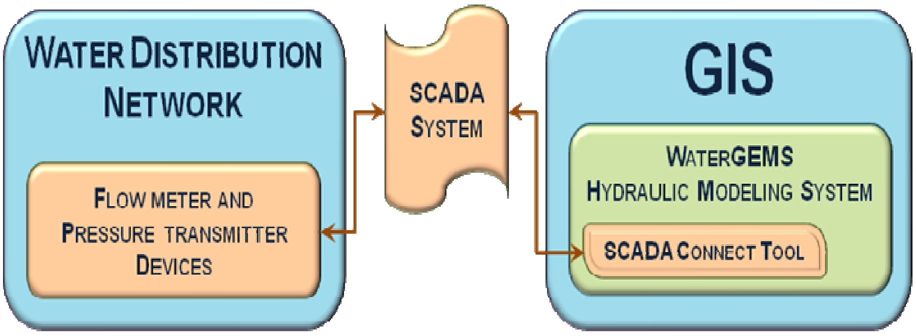

Figure 3. The Integrated System Components

3.1.3 Stages of the Extensive Research Work

This research is conducted in four main stages:

First Stage: Theoretical Stage. This stage is for studying the research principle through its application on some water networks. It is carried out by conducting some theoretical hydraulic scenarios that represent the application of research principle steps, and for retrieval of theoretical results.

Second Stage: Practical Stage. This stage is divided into two phases, as follows:

Phase I : Laboratory Study – this phase involves a lab experiment to verify the theoretical results using a small network model.

Phase II : Field Study – this phase engages field activities for applying the same procedures on an actual existing water networks in order to check the possibility of using the approach practically.

Third Stage: Validation Stage. This stage is for studying the theoretical and practical results, as well as conducting the necessary comparisons and realistically confirming the approach and its applicability.

Fourth Stage: Real Time Stage. This stage is for proposing and designing the outlines of the real time system.

Although this extensive research includes four referenced stages, this research paper only focuses on the first phase of the practical stage, which is the laboratory experiment

3.2 Laboratory Experiment

3.2.1 Model Materials and Instrumentation

The experiment network model consists of two square loops of 0.5in PE pipes with a dimension of 1m x 1m. Water is pumped into the network using a 0.5hp pump from a small tank to the network. There are two ball valves, in which one is fixed at the end of the network to control the initial pressure inside the network pipes (V01), while the second one is used to control the size of leakage (V02). The following images show the general descriptions of the network components:

The network model is equipped with two pressure transmitters (BCM Model 130C) to measure the values of pressure within the range of 0-4 bar in two certain nodes [PT(A) and PT(B)], and three digital flow meters (GPI Model TM050) to measure the flow rate within the range of 0-35 L/min at inflow point (FM01), out flow point (FM02) and leakage location (FM03) (see Figures 4, 5 and 6).

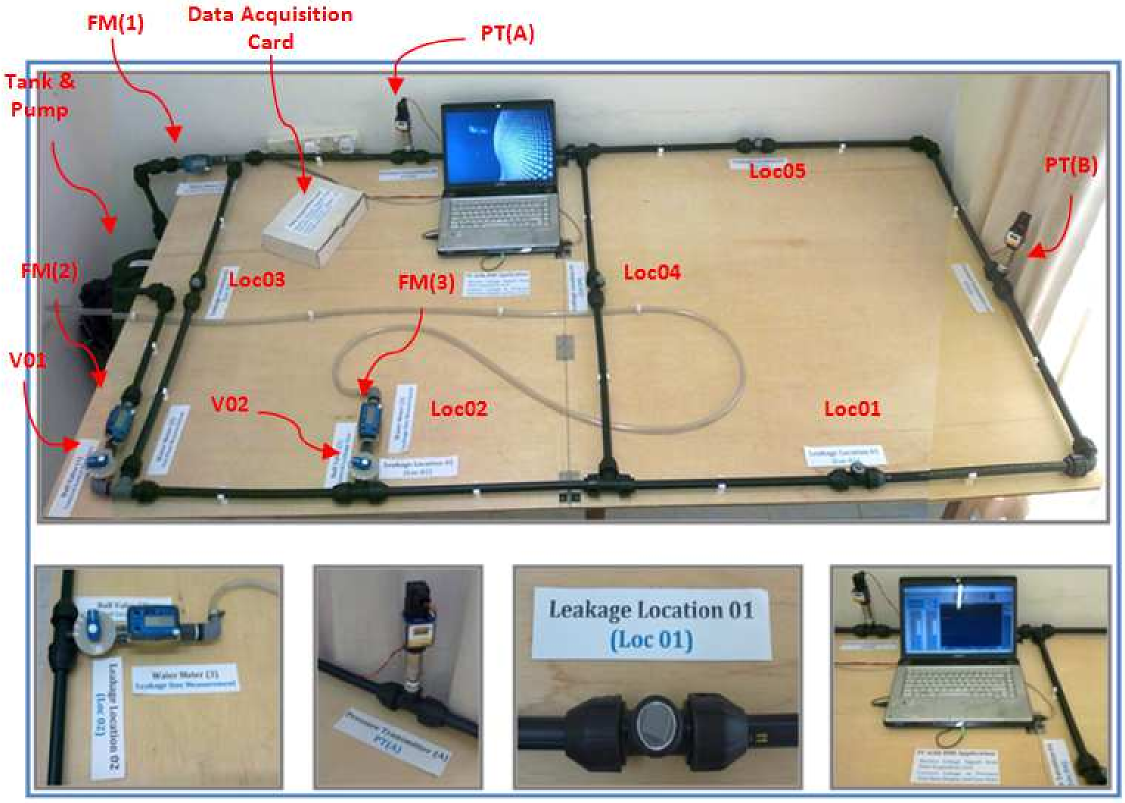

Figure 4. The Designed Network Model with Several Leakage Locations

Figure 5. Pressure Transmitter

Figure 6. Digital Water Meter

3.2.2 Procedures and Scenarios

a)Practical Scenarios

This phase aims to reach the results which give the impression that there are clear differences among the pressure values at all network nodes due to any change in the network flow distribution map, and thus, a change in the node pressure distribution map. The experiment is designed to study the effects of both initial pressure changes and leakage volume at the leakage location. Therefore, there are three key factors that have changed during the experiment, and their impact has also been investigated on others. The factors are as follows:

1. The initial pressure in the network. Four cases have been changed as the initial pressure, named as Case I, Case II, Case III and Case IV.
2. Leakage volume. Besides the no-leakage stage, the leakage volume has been changed to another three stages based on the valve slot which is used to control the leakage volume. The stages are named as Stage01,

Stage02 and Stage03. Therefore, the leakage volume in each case depends on the changes of the initial pressure.

3. Leakage location. Five locations have been selected as the location for the fabricated leakage. These locations are named as Loc01, Loc02, Loc03, Loc04 and Loc05 (see Figure 4).

First Scenario: During this scenario, all the four stages of leakage volume have been applied with all four cases of initial pressure, whereby the pressure readings have been obtained using the pressure transmitters in real time every second for a period of three and half minutes. This scenario has been applied at all selected five leakage locations. In addition, this scenario aims to study the relationship between the initial pressure and the leakage location, with the changes in leakage volume depending on the initial pressure. It also attempts to study the extent and clarity of the differences in pressure among the different points on the network, specifically the nodes where the pressure transmitters have been installed on them.

Second Scenario: Despite the fixation of the valve slot at the same stage of leakage volume, the value of the leakage volume varies with the changes of the initial pressure. Therefore, in this scenario, the value of leakage volume is stabilized by changing the initial pressure between two cases (Case I - Low Pressure) and (Case IV - High Pressure). The pressure readings are recorded using the pressure transmitters in real time for every second for a period of one minute. This scenario has been applied at all five leakage locations. This scenario also aims to study the relationship between the initial pressure and the leakage location without any effects due to the changes of leakage volume.

b) Hydraulic Modeling Scenarios

This phase aims to verify the possibility of matching the theoretical results of hydraulic analysis with the readings obtained from the experimental model, and thus, verifying the possibility of using the research concept as explained in paragraph 3.1.1.

Bentley WaterGEMS software has been selected for conducting the hydraulic modeling scenarios because of its high efficiency in hydraulic modeling and compatibility with GIS. The software is run within the GIS environment and also to take advantage of its potential in linking and communicating with the SCADA system, which will provide the required field data of the integrated system for the hydraulic analysis in real time. Furthermore, the WaterGEMS software has been used to build the hydraulic model of the network and fabricate the leakage as a demand in the specified locations one by one. It also conducts a hydraulic analysis in each case to determine how the pressure results match with those pressure readings obtained from pressure transmitters practically in the same circumstances. These procedures are then repeated in each scenario of the practical scenarios.

Figure 7 shows the schematic diagram of the network model, noting that the junctions (J-8, J10,J-15, J-16 and J-4) were used as leakage locations (Loc01,Loc02, Loc03, Loc04 and Loc05) respectively.

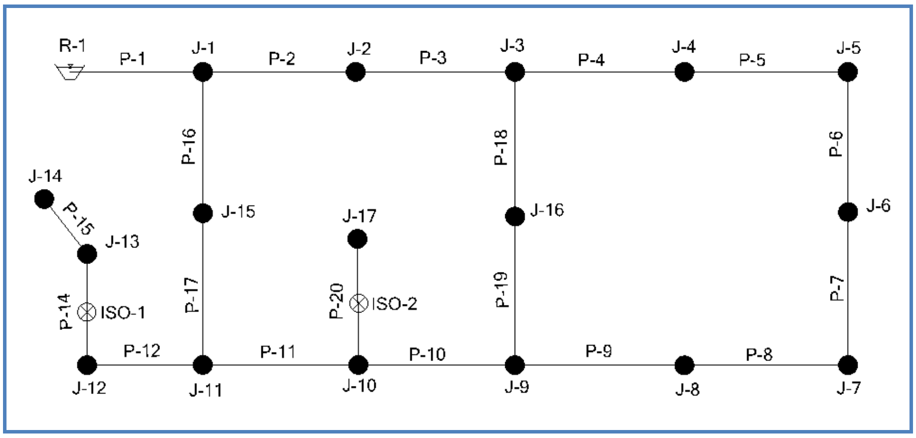

Figure 7. Schematic Diagram of the Network Model

4. Results and Discussion

4.1 Results

The results obtained from the lab experiment phase have been used to create a set of comparison curves that show the changes in pressure values in the network over a period of short time. The sample results show the changes of the pressure values in the network as a result of the leakage volume change due to the changes in initial pressure values and leakage volume stability (6 L/min). The chart sample in Figure 8 shows the changes in pressure readings at the pressure transmitters nodes PT(A) and PT(B) in the case of no leakage, and then after fabricating a leakage at the first leakage location (Loc01). The leakage volume has been changed gradually from Stage01 to Stage03 in three cases in all the cases of initial pressure (i.e. Case I, Case II, Case III and Case IV).

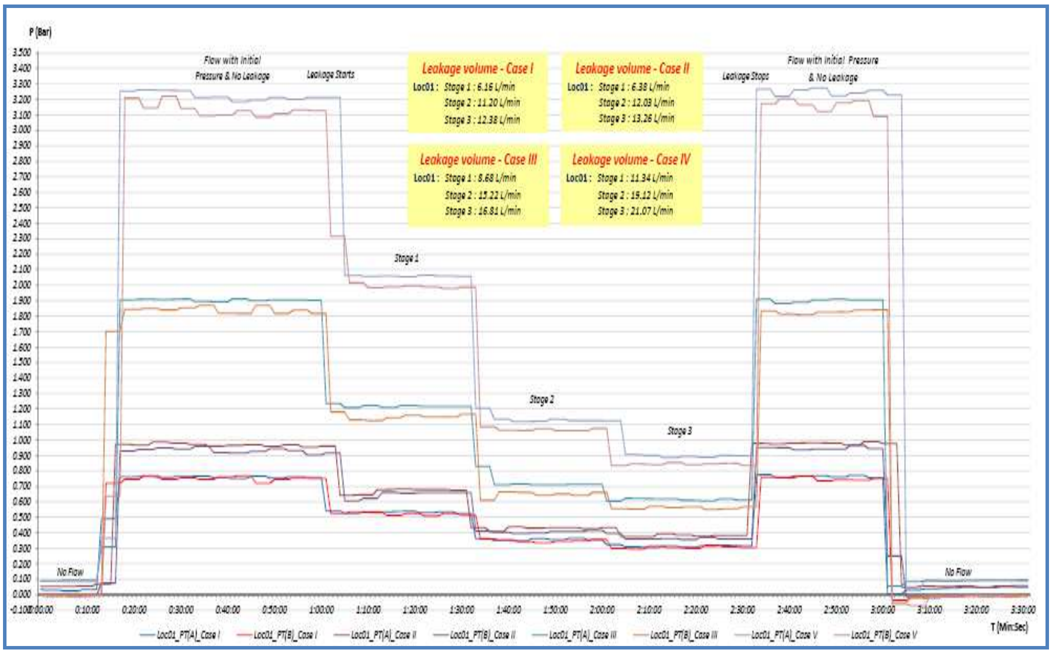

Figure 8. Pressure behaviour due to the changes of initial pressure and leakage volume at the leakage location (01)

The results are similar in the case of fabricating the leakage at the other leakage locations (i.e. Loc02, Loc03, Loc04 and Loc05). To study the effect of initial pressure in determining the leakage location without the impact of the change in leakage volume, the leakage volume has been specified to an appropriate value (6L/min) in each case of previous cases. The following charts (Figs. 9 and 10) show the changes in pressure values at P(B) node - which is one of the pressure transmitters locations - due to the changes at the leakage locations (Loc01, Loc02, Loc03, Loc04 and Loc05) in the cases of low initial pressure (Case I) and high initial pressure (Case IV). Note that the same interval has been used in the pressure column in order to ease the comparison between the two cases.

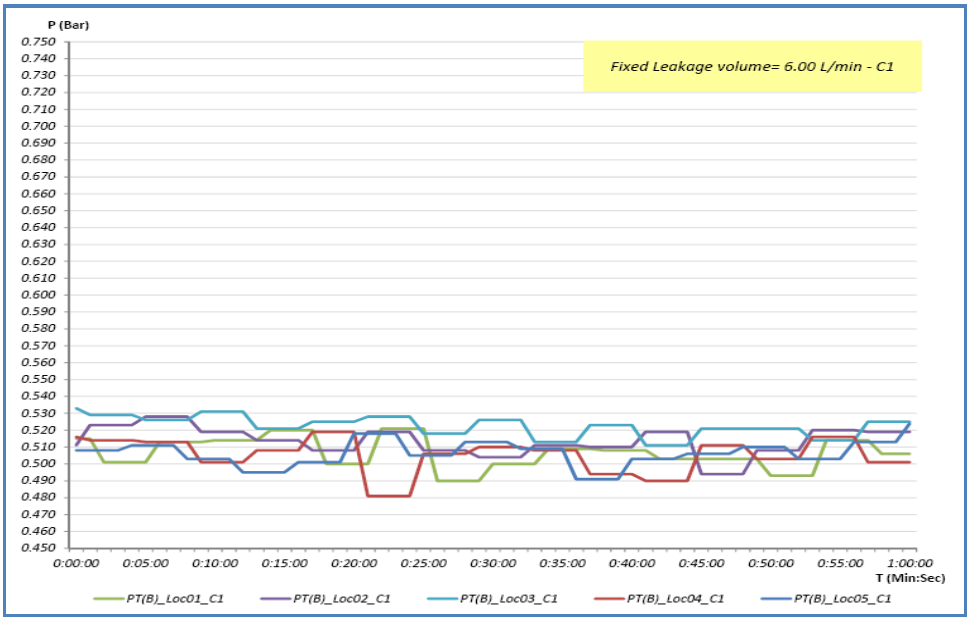

Figure 9. Pressure changes at pressure transmitter PT(B) due to the fixed leakage volume at different leakage locations [Low Initial Pressure (Case I)]

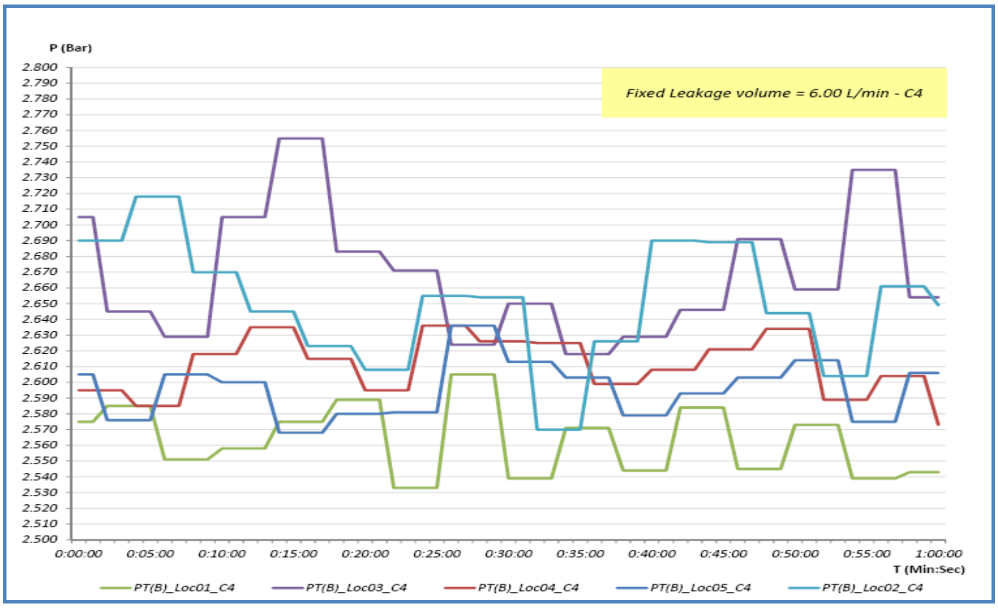

Figure 10. Pressure changes at pressure transmitter node PT(B) due to the fixed leakage volume at different leakage locations [High Initial Pressure (Case IV)]

4.2 Discussion

During the review of the results obtained from the practical scenarios, it is noted that there are significant changes in the node pressure at monitoring locations despite they are close to each other, particularly when the initial pressure is increased and the leakage volume is decreased. This is obvious from the pressure readings obtained by one of the pressure transmitters in both cases of initial pressure, as shown in Figs. 9 and 10, it can be considered that the five curves are the pressure footprints for the node of pressure transmitter PT(B) at the five leakage locations (Loc01, Loc02, Loc03, Loc04 and Loc05) as an example of results. Despite the constant value of leakage volume in all scenarios with changing of leakage location, but the differences in the pressure values was significant and measurable, which allows to conduct comparisons among the pressure values in each case to reach the real leakage location even if the comparison between two nodes close to each other.

By using hydraulic modeling analysis, can get pressure results at the all network nodes in all cases of changing leakage location by applying a leakage - as a node demand - with the same constant leakage volume which used in the laboratory experiment (6.0 l/min) at all nodes one by one in different scenarios, then conduct comparison among hydraulic modeling pressure results at all nodes with the laboratory pressure measurements for all cases. Through the process of comparing the differentiated laboratory pressure measurements and pressure results obtained by hydraulic modeling analysis, it show that the minimum difference in pressure between modeling results and laboratory experiment measurements is always at leakage node, thus it is possible to detect the leakage location by determine the node where the pressure differences are minimum, at this node there is the best matching among laboratory pressure measurements and hydraulic modeling pressure results in all cases.

5. Conclusion and Recommendations

The laboratory experiment results have shown significant differences in pressure measurements at the monitoring nodes, which facilitate the process of comparison in studying the match between the laboratory pressure measurements and simulation results obtained from the hydraulic modeling processes. This help to prove that the geospatial approach undertaken in this extensive research work will have promising and encouraging results. Therefore, future studies need to use the outcomes in the field study in order to establish more accurate validation. To get more accurate results in detecting leakage locations, SCADA sensors require precise calibration, as the accuracy of results depends on the accuracy of input data and the model itself, which needs to be well calibrated.

Considering that actual field conditions vary relatively with the laboratory experiment conditions, it is recommended to do some field work to validate of laboratory results, this what is planned as a second step of the practical stage of the overall research project for development of a geospatial approach for detecting leaks in water distribution networks.

In addition, the behavior of leakage in the network do not really represented actually by outflows from the ball valve as it used in the laboratory experiment, which affects in any way on the obtained pressures, it may be needed in the future to represent leakage more realistically through fabricated holes or cracks with various sizes in the pipe, which would give the study more credibility and realism.

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