Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1167129

57 (2016) 29104–29112
December

Performance evaluation of pressure reducing valves using statistical approach in water distribution system

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Received 29 December 2015; Accepted 8 March 2016

ABSTRACT

A pressure-reducing valve (PRV) regulates the outlet pressure regardless of the fluctuating flow and varying inlet pressure, thereby reducing leakage and mitigating the stress on the water distribution system. However, the operation of a PRV is affected by its mechanical condition and hydraulic operability. In this study, a statistical approach is proposed to assess the performance of a PRV by extracting hydraulic pressure noise from pressure data, and applying it to metered areas in the Goseong and Sungeuiwon districts of Goseong city. The proposed approach involves the application of Walsh's test to detect outliers in the pressure data at a significance level of 5%. The experimental results using field data showed that all measured data items were valid. A high-pass filter was then employed to extract white noise from the original pressure data for 24 h. The noise from standard PRVs remained relatively stable over time, ranging approximately ±0.2 kgf/cm^2, and the noise was found to be independent of the weighting parameter. On the other hand, it was found that noise from an abnormally operated PRV exceeded ±0.2 kgf/cm^2, with the magnitude of the scattering being proportional to the weighting parameter. The field test results show that the proposed approach is effective for assessing the performance of PRVs using a simple pressure measurement, an outlier test, and a noise filter.

Keywords: Pressure-reducing valve; Water distribution system; Statistical approach; Walsh's test; Noise filtering; Outlier test

1. Introduction

Leakage management is one of the most critical issues in a water distribution system (WDS) as it can provide several benefits, such as reduced treatment and investment costs, energy saving, and improved service to consumers. Pressure reduction in the distribution main may reduce the rate of water loss through leakage, as well as the strain on the pipe network, hence reducing the chances of damage due to fatigue at the joints. It has also been reported that pressure management is best undertaken in conjunction with metering district areas or establishing supply zones [1–6].

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Presented at the 6th IWA-ASPIRE Conference & Exhibition, Beijing, China, 20–24 September 2015

Pressure-reducing valves (PRVs) are widely employed in district metering areas (DMAs) that are sectored considering the distribution of elevation, pressure, and flow rate. A PRV is an automatic control valve that reduces the higher inlet pressure to a lower outlet pressure regardless of the fluctuations in flow and inlet pressure [1,7,8]. In practice, the following are the main problems that may occur when implementing a PRV: (1) erratic PRV performance can result from debris collecting in the mechanical parts after it has been dislodged from the main pipework owing to flow reversals caused by valve operations in the network, (2) pressure may be lower than expected because of an unknown pressure control valve, or it may be higher than expected because of an unidentified booster pump, and (3) PRV oscillation may occur around the set point during hydraulic transient events [3,9,10]. Therefore, all PRVs require continual monitoring and maintenance, unlike sluice valves that are typically installed and left alone. To minimize the risk of PRV failure or malfunction, most manufacturers recommend a program of periodic inspection and maintenance. However, the extent and frequency of the requisite inspection and maintenance varies significantly from one valve to another. Hence, determining the valves to be fixed or replaced is essential in the maintenance of WDSs [3,9–11].

The purpose of this study is to propose and test a method for determining the functional condition of a PRV that is likely to operate abnormally from the perspectives of mechanics and hydraulics. Two DMAs of Goseong (GS) and Sungeuiwon (SE) in GS city, located in the south of Korea, were chosen for a field study to assess the proposed method. These mountainous areas featured 14 PRVs to manage water pressure. The study began by investigating the condition of the PRVs, following which the one-minute pressure at the outlet of each PRV was measured using portable pressure loggers for 24 h. The pressure data were examined using the Walsh's test at a significance level of 5%, which led to the detection of natural, mechanical, and observational errors. A high-pass filter was then employed to determine the overall pattern of noise according to the operability of the PRVs; this approach shows advantages in practical applications through the simple prediction of the mechanical conditions as well as hydraulic operability.

2. Theoretical background

2.1. Pressure-reducing valve (PRV)

PRVs were manufactured to create head losses in fluid distribution systems that can reduce the pressure at the outlets of valves, which in turn reduces the excessive pressure on the DMAs. There are several variations in PRVs, depending on their structure and flow throttling type: globe-type, diaphragm-actuated valves, rolling diaphragm valves, direct acting spring-loaded valves, weight-loaded valves, and electronically controlled valves. Some valves reduce pressure by a fixed ratio, e.g. 3–1, regardless of the flow rate. Others can be fitted with pilot valves that alter the position of the valve such that it yields a fixed outlet pressure regardless of the inlet pressure or flow rate [3,11]. The type of PRVs employed—direct acting or pilot—depends on the function of the PRV in the distribution network. In other words, direct acting valves tend to be used on pipes with a small diameter, whereas pilot valves are popular for use with pipes having a large diameter. Typical problems in PRVs are (1) valves failing to open/close if there is a blockage at the inlet or outlet of the pipeline, (2) valves oscillating repeatedly owing to malfunction, and (3) valves splitting owing to wear or damage caused by debris. Therefore, the condition of PRVs must be regularly monitored by checking outlet gauge settings and logging the telemetry system.

2.2. Outlier test

The statistical outlier tests can be varyingly applied according to sample size, assumption of normal distribution, and detection of multiple outliers, as shown in Table 1. Typical methods include Dixon's test, the discordance test, Rosner's test, and Walsh's test [12,13].

Dixon's test, also known as the extreme value test, regards the highest and the lowest values of a data-set as greater and less than other values, respectively, within a sample size of 25. In this test, all values except the outliers are assumed to be normally distributed. The discordance test is applicable when an outlier only has the highest or the lowest value. This test is effective when all values except the outlier follow a normal distribution within a sample size of 50. Rosner's test is applicable for data-sets with multiple outliers for a sample size of greater than 25. All data items in this test, except outliers, are assumed to be normally distributed. By contrast, Walsh's test can be used for sample sizes greater than 60, is independent of probability distribution, and simultaneously verifies multiple outliers. To perform the Walsh's test, a set of n data items $X = \{x_\mathrm{i}\}_{\mathrm{i}=1}^{n}$ is rearranged in ascending order and set to a significance level according to the number of data items, as shown in Eq. (1):

Table 1
Comparison of outlier tests based on a statistical approach

Test type	Acceptable sample size	Assumption of normal distribution	Detection of multiple outliers
Dixon's test	$n \leq 25$	O	
Discordance test	$n \leq 50$	O	
Rosner's test	$n \geq 25$	O	O
Walsh's test	$n > 60$		O

$$\alpha = \begin{cases} 0.10 & (60 < n \leq 220) \\ 0.05 & (n > 220) \end{cases} \tag{1}$$

Under the significance level, the outlier test for the highest and the lowest values is performed using Eqs. (2) and (3):

$$\text{Lower outlier test: } x_r - (1+a)x_{r+1} + ax_k < 0 \tag{2}$$

$$\text{Upper outlier test: } x_{n+1-r} - (1+a)x_{n-r} + ax_{n+1-k} < 0 \tag{3}$$

where subscript r is the order of rearranged data in ascending order, and subscripts a and k are the variables that are defined as follows:

$$a = \frac{\left\{1 + b\left[(c-b^2)/(c-1)\right]^{1/2}\right\}}{c - b^2 - 1}, \text{ and } k = r + c \tag{4}$$

where $b = 1/\sqrt{\alpha}$, $c = \sqrt{2n}$, and the parenthesis { } denote rounding off to the nearest integer.

2.3. High-pass filter

In general, data collected from field observations, such as pressure measurements, may include various types of noise as outliers according to the measurement method and instruments. Data filtering removes noise from raw measured data, and has been widely applied to economics, statistics, engineering, and a variety of other fields. Typical data filtering methods include the moving average filter (which uses the average value in a continuous interval), the Kalman filter (which uses the covariance of error between measured and estimated values), and high- and low-pass filters (which use frequency analysis) [14].

The high-pass filter is a digital filter that permits signals with a frequency higher than a certain cutoff value and causes the attenuation of those with frequencies lower than the cutoff value. The extent of attenuation signal depends on filter design. A high-pass filter is usually modeled as a linear time-invariant system. It is sometimes called a low-cut filter or bass-cut filter [15]. The high-pass filter function of $G(s)$ can be expressed with the input signal of $Y(s)$ and the output signal of $U(s)$ to the high-pass filter, as shown in Eq. (5):

$$G(s) = Y(s)/U(s) \tag{5}$$

where s denotes the signal. The above equation can be converted by utilizing an arbitrary positive constant d and the reciprocal of τ as follows:

$$G(s) = \frac{s}{s+d} = \frac{s/d}{s/d+1} = \frac{\tau s}{\tau s + 1} \tag{6}$$

Inserting the values from Eq. (6) into Eq. (5):

$$(\tau s + 1)\ Y(s) = \tau s\ U(s) \tag{7}$$

By applying the Laplace's inverse transformation, the above equation becomes:

$$\tau \dot{y}(t) + y(t) = \tau \dot{u}(t) \tag{8}$$

Discretizing Eq. (8) over time step Δt, the measured noise from the input signal of y^k can be calculated in time k as follows:

$$\tau \frac{y_k - y_{k-1}}{\Delta t} + y_k = \tau \frac{u_k - u_{k-1}}{\Delta t} \tag{9}$$

$$\begin{aligned} y_k &= \frac{\tau}{\tau + \Delta t} y_{k-1} + \frac{\tau}{\tau + \Delta t}(u_k - u_{k-1}) \\ &= \beta y_{k-1} + \beta(u_k - u_{k-1}) \end{aligned} \tag{10}$$

where β is a weighting parameter ranging from 0 to 1.

3. Field investigation and pressure measurements

3.1. Field study area

The GS and SE DMAs are parts of the GS WDS located in the south of Korea in a topographically mountainous area and a heavily indented coastline.

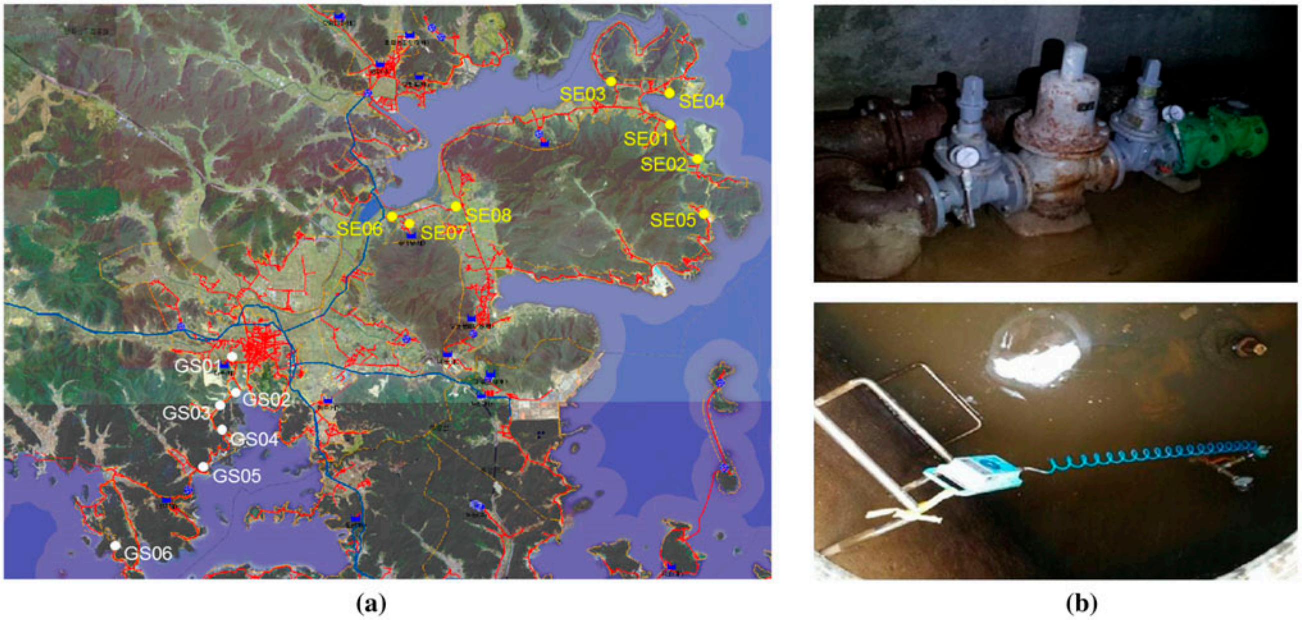

Fig. 1. Field investigation and pressure measurement at Goseong city: (a) water distribution network and (b) pressure test at the outlet of PRV.

The GS WDS supplies 15,300 m^3/d of drinking water to 17,600 service connections. The distribution network primarily has a dendritic pattern with several storage tanks in consideration of the geographical conditions. Because of the undulating topography, the water main retains a relatively high pressure of 5–10 kgf/cm^2, and regulates it through PRVs to prevent excessive leakage and supply water at an appropriate service pressure (see Fig. 1(a)). Therefore, the performance evaluation of PRVs is the first step for effectively and efficiently maintaining the WDS and reducing water loss. The conditions of the field areas are summarized in Table 2.

Table 2
Description of GS and SE DMAs

			PRV	
DMA	No. of taps	Flow (m^3/d)	Location	Type
GS	5,119	8,223	GS01–06	Direct acting
SE	2,222	3,719	SE01–08	Direct acting

3.2. *In situ investigation of PRV*

An *in situ* investigation was carried out for the 14 PRVs installed in the GS and SE DMAs. The investigation showed that the PRVs had diameters ranging from 80 to 150 mm, and were of the direct acting type with their own initial setting pressures. It was found that six PRVs—belonging to GS03, SE01, SE03, SE05, SE07, and SE08—were not operating normally owing to damage of their internal components, such as the disk, stem, or cylinder.

3.3. *Pressure measurement*

The PRVs were commonly installed along with pressure gauges at the inlets and outlets, as shown in Fig. 1(b). However, most pressure gauges installed in underground valve rooms are vulnerable to wetting and/or flooding, and hence, they can be rendered inoperable. With time, operators in water utilities are confronted with worn-out PRVs and/or pressure gauges. In case of old pipelines and valve rooms, operators of water utilities find it difficult to tap pipelines and reinstall pressure gauges because this damages the integrity of the pipe and causes leaks at the connection and the tapping hole. In this study, therefore, the only the outlets of PRVs were tapped to install logger-type pressure gauges (see Fig. 1(b)). A portable pressure logger was connected to the tapping connections, and an electronic signal transmitted by a pressure transducer was converted into a pressure reading [16]. The pressure logger could control the measurement interval, and was set to measure the pressure every minute for 24 h from 15 September 2014 for GS DMA and 22 September 2014 for SE DMA.

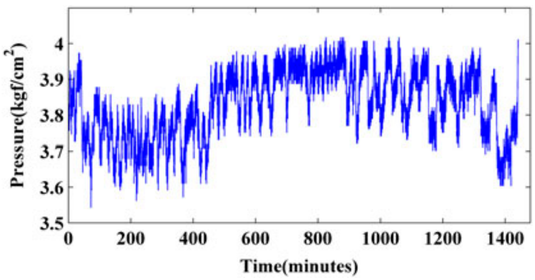

Fig. 2. Pressure data at the outlet of PRV GS01.

3.4. Basic statistics of measured pressure data

The pressure data exhibited high scattering because of unknown outliers and noise, as was expected (see Fig. 2). Prior to applying the outlier test and the digital noise filter, the basic statistics of the raw pressure data that was calculated are shown in Table 3.

4. Results and discussion

In this section, Walsh's test was performed to detect outliers in the measured pressure data at a significance level of 5%, with $\alpha = 0.05$ in Eq. (1), which was chosen considering the scale of pressure data and the variation in pressure data. A high-pass filter was then employed to eliminate unknown noise, following which the characteristics of the noise for normally and abnormally operated PRVs were analyzed.

4.1. Walsh's outlier test

The pressure data can contain four types of outliers, induced by natural error in the measurement of temperature, humidity variation in the measurement of pressure, mechanical error in the measuring instrument, and user error in measurement. Walsh's outlier test was carried out using Eqs. (2) and (3) after arranging the n measured (= 1,441) data items in ascending order. In applying the equations, the lower outlier test was performed for the r^{th} measured value and the upper outlier test for the $(n + 1 - r)^{\text{th}}$ measured value. Table 4 shows the result of Walsh's test, which showed that all 14 pressure data measurements at the outlets of the PRVs satisfied the minimum and maximum values within the fourth rank. This confirmed that the entire pressure data-set was appropriate for the statistical analysis of time-variable characteristics for 24 h.

4.2. High-pass filtering

The measured pressure data still contained unknown noise even though they had passed Walsh's outlier test. The noise needed to be separated from raw pressure data using a high-pass filter in order to better understand its statistical properties. To explain noise-related properties as reflective of the operability of PRVs, we analyze two instances of GS01 and GS 03 in terms of weighting parameters $\beta = 0.5$, 0.7, and 0.9. For the normally operating PRV of GS01, the noise was greater than 0.5 kgf/cm^2 during the first 60 min, and was subsequently irregularly distributed within ±0.2 kgf/cm^2 of that value independently of time vari-

Table 3
Statistical characteristics of measured pressure data

Date	# PRV	Statistics of pressure data (kgf/cm^2)			
		Avg.	Std.	Max.	Min.
15 September 2014 11:00–16 September 2014 11:00	GS01	3.8303	0.1001	4.0176	3.5427
	GS02	3.9818	0.0405	4.0980	3.9190
	GS03	5.4043	0.2599	5.8330	4.6960
	GS04	2.7529	0.0896	2.9410	2.4526
	GS05	2.7487	0.0687	2.8780	2.4890
	GS06	2.8190	0.0826	2.9610	2.2540
22 September 2014 11:00–23 September 2014 11:00	SE01	3.2672	0.1945	3.5900	2.6400
	SE02	3.2505	0.0334	3.3100	3.1100
	SE03	5.6272	0.1945	5.9500	5.0000
	SE04	4.2485	0.0733	4.3600	4.0200
	SE05	4.8998	0.8507	6.5100	3.3000
	SE06	3.9141	0.1560	4.3100	3.4800
	SE07	4.8329	0.1617	5.1300	4.4700
	SE08	3.2122	0.1945	3.5350	2.5850

Table 4
Walsh's test results for pressure data

# PRV	N	Lower outlier test			Upper outlier test		
		Data	Rank	Test value	Data	Rank	Test value
GS01	1,441	3.9250	4	0.0065	4.0176	1,441	−0.0040
GS02	1,441	3.9210	2	0.0001	4.0980	1,441	−0.0028
GS04	1,441	2.4526	1	0.0187	2.9410	1,441	−0.0054
GS05	1,441	2.4890	1	0.0162	2.8780	1,441	−0.0062
GS06	1,441	2.2540	1	0.0015	2.9510	1,440	−0.0028
SE02	1,441	3.1200	2	0.0083	3.3100	1,441	−0.0014
SE04	1,441	4.0200	1	0.0125	4.3500	1,440	−0.0028
SE06	1,441	3.4800	1	0.0094	4.3100	1,441	−0.0001
GS03	1,441	4.7250	2	0.0160	5.8330	1,441	−0.0026
SE01	1,441	2.6800	3	0.0164	3.5900	1,441	−0.0042
SE03	1,441	5.0400	2	0.0278	5.9500	1,441	−0.0042
SE05	1,441	3.3400	2	0.0347	6.4900	1,438	−0.0069
SE07	1,441	4.4700	1	0.0111	5.1300	1,441	−0.0042
SE08	1,441	2.6250	2	0.0278	3.5350	1,441	−0.0042

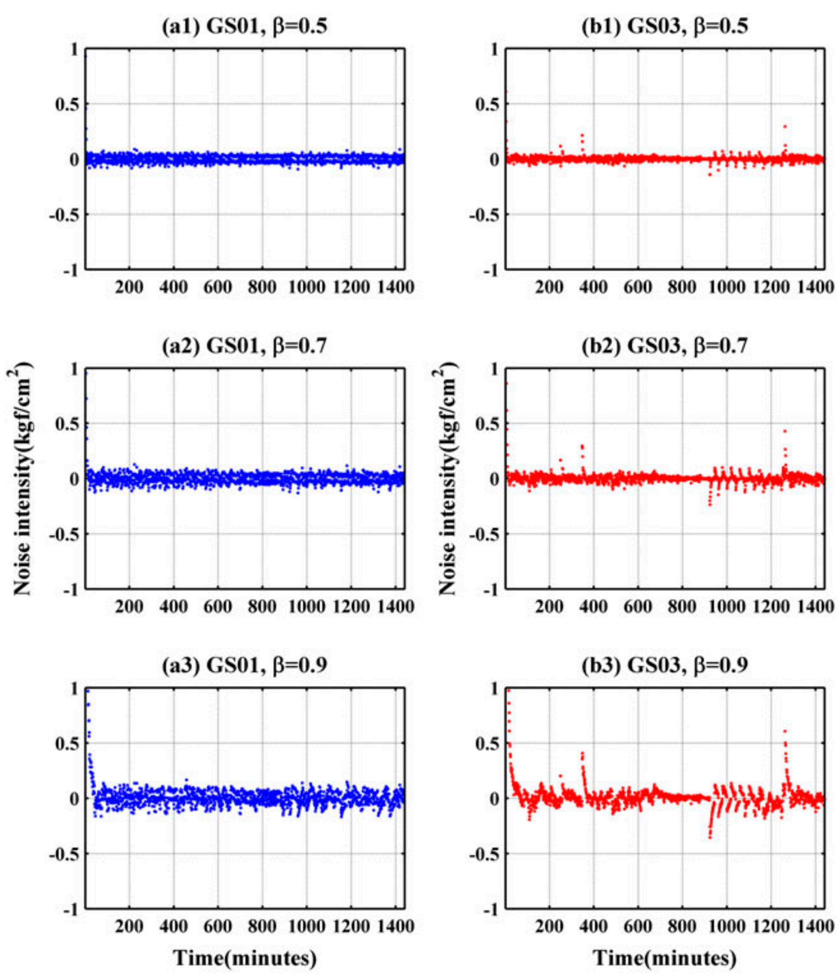

Fig. 3. Extracted noise from pressure data at GS01 for (a1)–(a3) and GS03 for (b1)–(b3).

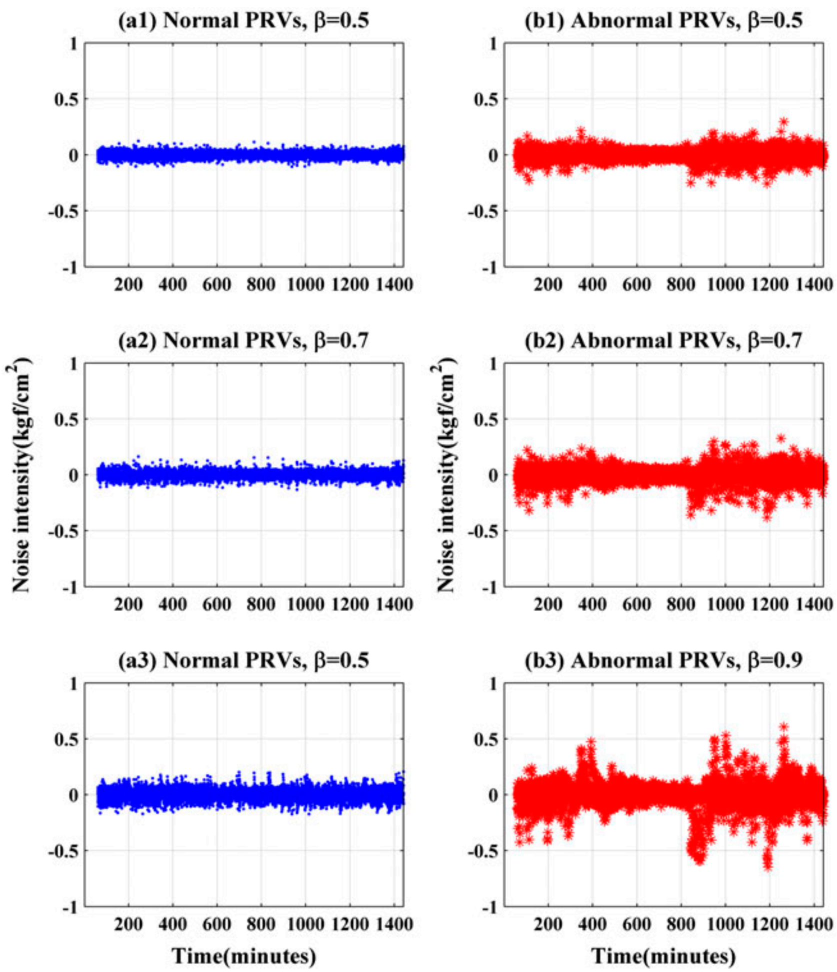

Fig. 4. Comparison of noise data of normally operated PRVs for (a1)–(a3) and abnormally operated PRVs for (b1)–(b3).

Table 5
Statistical characteristics of extracted noise from pressure data

	β = 0.5			β = 0.7			β = 0.9		
# PRV	Max.	Min.	Std.	Max.	Min.	Std.	Max.	Min.	Std.
GS01	0.0884	−0.0932	0.0312	0.1296	−0.1313	0.0423	0.2067	−0.1672	0.0593
GS02	0.0586	−0.0611	0.0159	0.1296	−0.1313	0.0423	0.1043	−0.0915	0.0322
GS04	0.1002	−0.1044	0.0254	0.1296	−0.1313	0.0423	0.1517	−0.1721	0.0516
GS05	0.0787	−0.0874	0.0203	0.1296	−0.1313	0.0423	0.1544	−0.1735	0.0429
GS06	0.0638	−0.0662	0.0148	0.1296	−0.1313	0.0423	0.1100	−0.1432	0.0433
SE02	0.0515	−0.0655	0.0114	0.0599	−0.0889	0.0166	0.0724	−0.1047	0.0232
SE04	0.0794	−0.0871	0.0218	0.1065	−0.1144	0.0312	0.1410	−0.1411	0.0430
SE06	0.1230	−0.0244	0.0170	0.1629	−0.0470	0.0290	0.2021	−0.1274	0.0604
GS03	0.2939	−0.1426	0.0221	0.4288	−0.2354	0.0365	0.6053	−0.3549	0.0711
SE01	0.1263	−0.1665	0.0300	0.1791	−0.2566	0.0426	0.2546	−0.4300	0.0623
SE03	0.1263	−0.1665	0.0300	0.1791	−0.2566	0.0427	0.2546	−0.4300	0.0623
SE05	0.2073	−0.2573	0.0578	0.3253	−0.3819	0.0885	0.5284	−0.6476	0.1571
SE07	0.1263	−0.0976	0.0263	0.1791	−0.1378	0.0363	0.2220	−0.1979	0.0501
SE08	0.1263	−0.1665	0.0300	0.1791	−0.2566	0.0427	0.2546	−0.4300	0.0624

ation due to the elimination of the low-frequency component. It was found that the overall pattern of noise had the same distribution independent of the value of β, as shown in Fig. 3(a1)–(a3). For the abnormally operating PRV of GS03, on the other hand, the measured noise exceeded the ± 0.2 kgf/cm^2 variation. Moreover, the degree of scattering increased with the value of β, attaining the level of initial noise values at $\beta = 0.9$ (see Fig. 3(b1)–(b3)).

Fig. 4 only plots noise from 60 min after the start of the measurement in order to compare the difference between the normal PRV and the abnormal PRV in terms of noise distribution. The normally operating PRVs recorded noise within the range ± 0.2 kgf/cm^2 independent of the weighting parameter β, as shown in Fig. 4(a1)–(a3). However, abnormally operating PRVs recorded highly scattered noise, the level of which increased proportionally to the weighting parameter β. Table 5 shows the statistical characteristics of noise extracted from the measured pressure data—minimum, maximum, and standard deviation. As for normally operating PRVs, the magnitude of noise ranged from –1.8 to 0.2 kgf/cm^2, with the standard deviation being approximately less than 0.06. Abnormally operating PRVs, on the other hand, recorded a maximum variation in noise of 0.2–0.6 kgf/cm^2 and a minimum variation of −0.3 to −0.7 kgf/cm^2 according to the weighting parameters. Their standard deviation values increased according to the weighting parameter, and exceeded 0.06 at $\beta = 0.9$.

5. Concluding remarks

In this study, a statistical approach was proposed and tested to evaluate the mechanical performance of PRVs using pressure data measured at their outlets. An in-depth field investigation was carried out for 14 PRVs installed at the two DMAs of GS and SE in GS city, Korea. Portable pressure loggers were connected to tapping connections to measure the pressure data at an interval of 1 min for 24 h. The measured data were subjected to Walsh's test to detect outliers, and to a high-pass filter to analyze the noise characteristics for normally and abnormally operating PRVs. The results of this study can be summarized as follows:

(1) From an *in situ* investigation of direct acting-type PRVs, it was found that six of the 14 PRVs had suffered mechanical damage in their internal components, such as the disk, stem, and cylinder.
(2) The results of Walsh's outlier test at a significance level of 5% showed that all measured data had a statistically effective distribution that reflected the temporal variation in pressure over 24 h. The proposed test is expected to be useful in detecting outliers and limiting their values.
(3) With the employment of a high-pass filter, white noise was successfully separated from time-dependent pressure data. The noise analysis showed that it is a useful tool for distinguishing normal PRVs from abnormally operating or defective ones: PRVs operating normally recorded evenly distributed noise, excluding an initial oscillating stage when low-frequency components were eliminated. On the other hand, the noise for abnormally operating PRVs showed a highly scattered distribution, which increased with the weighting parameter.

The PRV is a useful device for managing leakage and reducing pipeline breaks, but it should be periodically monitored and its mechanical operability should be maintained. In the practical implementation of PRVs, it is important for water utilities to distinguish normally operated PRVs from abnormally operated ones. Therefore, the proposed approach, which uses statistical methods for an outlier test and noise filtering, can be used when no information related to the mechanical performance and operability of PRVs is available. Moreover, the proposed approach is advantageous in practical applications because the tapping of pipelines can only be reduced by measuring the pressure at the outlets of PRVs.

Acknowledgments

This research was supported by the Korea Ministry of Environment under "The Eco-Innovation Project (Global Top Project)" No. GT-SWS-11-02-007-8, and the Korea Water Resources Corporation (K-water).

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