Systematic Approach in Analysis of Pressure / Burst Frequency Relationship

Kristijan Iličić* and Jurica Kovač**

*Zagreb Holding, Water utility, Department of Development, Planning and Research, Folnegovićeva 1, HR-10000 Zagreb, Croatia, kristijan.ilicic@vio.hr
** IMGD d.o.o., A. Georgijevića 2, HR – 10430 Samobor, Croatia; jurica.kovac©imgd.hr

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Abstract

Purpose of this paper is to present for one representative segment of the water distribution network - DMA (District Metered Area) results and benefits of pressure reduction and control and effects on pipes burst frequency. Statistical analysis covered time frame of the last 4 years (2 years before pressure control was implemented and 2 years with pressure control) in one specific DMA.

This work is extensions of activities related with the pilot project for the DMA Knežija (16 km of pipelines) in the water distribution system of the city of Zagreb, capitol of Croatia, Europe [1].

Testing the influence of the introduction of regulation on the burst frequency

Introduction

Hydraulic systems of water supply are dynamic systems in which parameters change in time and space. In order to manage them, it is necessary to implement the prediction of physical phenomena, to estimate the specific values and make judgments about the necessary activities. Prerequisite for this is to gather and analyse large amounts of data, based on which conclusions are made. Monitoring and analysis of hydraulic systems of water supply are based on the measurements and statistical monitoring characteristic parameters of the system. It includes pressure and flow within the pipelines, and demand, length, profile, age, material pipelines, number of service pipes and frequency of failures on the system. The latter is usually considered as the value dependent of the previously mentioned values. Here, in the first place we investigated the behaviour of frequency failures on the part of the system of water supply after the introduction of regulation of pressure by the flow.

Under DMA (Figure 1.1) we considered a part of water supply system of the city of Zagreb, which was selected by taking into account several criteria. These criteria represent the basis that ensures that, in the first place, separation zone, and measuring are to be feasible (water supply needs of all consumers in the continuity and the condition that the water in the system maintain the prescribed quality), and further that these measurements are objective. In selecting zone is taken into account the following:

- The possibility of separating from the high objects zone, since these objects prohibiting the reduction of pressure without the consequence of suspension of water supply.
- Intensity of flow of water through pipes after reducing the number of entrances to the zone, to ensure satisfactory water quality
- Importance of loss of water due to leaking pipelines, to give priority to critical areas of water supply system
- The possibility of isolating zones from the rest of the system, to ensure the accuracy of data obtained by measurements
- Critical pressure in the pipelines, this is the cause of failures in the system and of excessive leakage of the water under the ground.

Water supply system of the city of Zagreb includes 2830 km of pipelines with pipe diameters from Ø50 to Ø1100, average age 40 years, which are made from several types of materials: Cast Iron, Steel, Nodular Cast Iron, PEHD (poly-ethylene high density), PVC (polyvinyl-chloride) and AC (asbestos cement). The total available capacity of water supply amounts to 5,000 l /s or 430,000 m^3 per day. Pressures in the pipelines near the water-plants are around 9.5 bars, while pressures in the demanding system are around 6-7 bars. On the whole system of water supply there are 90000 house connections.

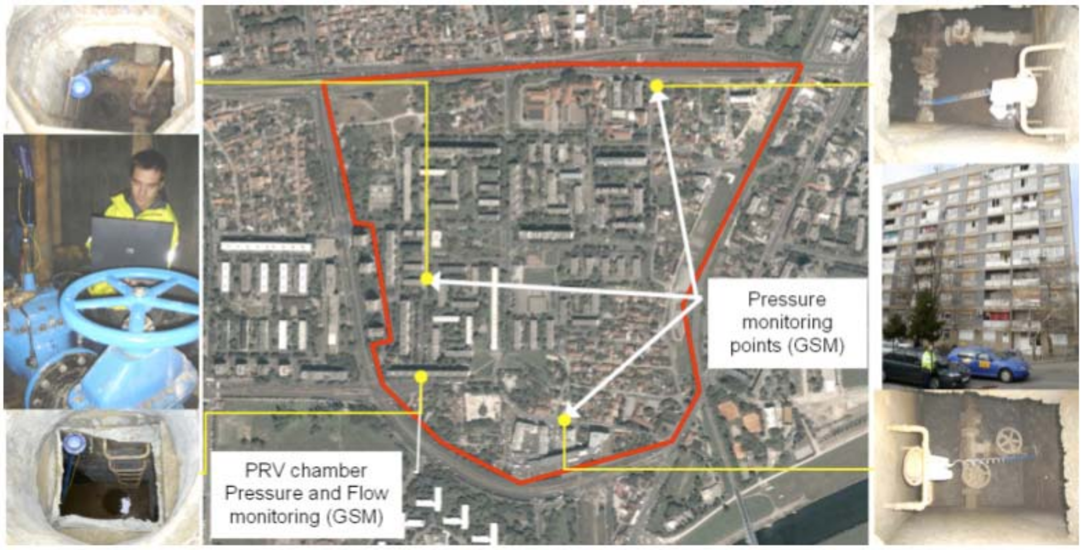

Figure 1.1 DMA Knežija

The observed total area has 16.811 km of pipelines, with the following portion of pipes by profiles: Cast Iron 85.21%, Steel 4.12%, Nodular Cast Iron: 0.65%, PEHD 4.97%, PVC 2%. The average age of the pipeline in the DMA is 45 years.

Number of installed house connections in the DMA is 653. Entrance of water into the system usually takes place through multiple input pipelines which are situated on the edge of DMA, which is, before the introduction of the condition of regulation, reduced to one input place that is located at the site Horvaćanska Street as shown in Figure 1.1. In that pipeline with diameter of Ø250 built-in measurement and regulatory equipment were installed. After that, and before and after the introduction of regulation of pressure the flow and pressure measurements were performed.

Before establishing the condition of regulation, maximum pressure at the entrance to the DMA was 7.6 bars and the average flow in the same place was 73 l/s. After the introduction of regulation, the maximum value of average pressure and flow at the entrance were 5.8 bars and 62.6 l/s. Along with these changes is important that the introduction of regulation reduced pressure oscillations and flow in time, which beside static mitigated dynamic stress pipelines, and hydraulic strikes which is known to significantly contribute to failures in the system of water supply.

Methods

In this work descriptive statistics and inferential statistics methods were used. With it, at first we tried to determine whether the frequency of failures on DMA fits theoretical Poisson distribution, which is to be expected, because we observe the appearance of the number of failures in one day, whose frequency is relatively rare (which is the most common case when the Poisson distribution occurs). Since the number of days in which the failure occurred is not very large, and the numbers of days with one, two, three, etc. failures rapidly decrease, instead of the frequency of failures in a year, it was considered the natural logarithm of the frequency of failures in a year. Therefore, the hypothesis H0 was tested which says that the value of natural logarithms of frequency failures appearing in the DMA during each of the observed period, i. e. periods with and without implemented regulation DMA, fits Poisson distribution. Testing hypotheses have been carried out Chi-square test.

After fit of the frequency of occurrence of failures on the DMA to Poisson distribution, it was tested whether the introduction of regulation of pressure and flow in the DMA influences significantly to the frequencies of occurrence of failures. In the first step, data on failures in the DMA by day were computed. Obtained data then were imported into a table with three columns. The first column is the observed date of measurement, the second number represents failures in that day and the third number indicates random sample. In the first case, that includes the period from January 1, 2005 to December 31, 2006, tags random sample is taking for each day the value of 1-21, which means that in one year, 21 selected a sample size of 35 elements were taken. In the second case that assumes the period from January 1, 2007 to September 7, 2008 number of samples of size 35 was 18.

Tests were conducted on F-test and t-test. These tests require that the observed frequencies are tested obey normal distribution. In order to facilitate the use of properties of the normal distribution, for each time period, i. e. for the period before and after the imposed regulation, it was necessary to structure data in the form of randomly selected samples (days) of 35 elements. With samples sized larger than 30 it was ensured that these samples follow a normal distribution, which is a prerequisite for conducting F-test (variance) and t-test (arithmetic mean).

The principal setting lays on consideration of two basic set of data of the number of failures in DMA, for which we assume, in the form of the hypothesis H0, that they are not significantly different from each other. The first set includes all the samples made from 35 days in 2005 and 2006 year, when the system was not under the strict supervision and regulation of pressure, with an appropriate number of failures. The second set includes samples of 35 days from 2007 and 2008 year, i. e. at the time when the system is located in the state of supervision and regulation of pressure with an appropriate number of failures.

Results and Discussion

In the first column of tables 1.1 and 1.2, and the Figures of 1.1 and 1.2 is shown the number of failures per day in the period 2005/2006 years, and 2007/2008 years. The minimum number of failures is 0 and the maximum number of failures that appeared in the DMA is 3. The second column shows the natural logarithm of the frequencies of appearance of these failures in each of the observed period. The third column is the product of these two values in order to implement Poisson distribution. The value λ that appears in the fourth column is the Poisson distributions parameter, which represents the average of logarithm frequency of failures by a observed period of time. With it the theoretical probabilities of the appearance of certain logarithm number of failures were calculated in the day shown in the fifth column. From this the theoretical frequencies values appear failures were obtained and shown in the sixth column. The goal was to determine whether the data from the second and sixth column, i. e. the practical and theoretical values differ significantly or accidentally. This was carried out chi-square test.

Table 1.1 Table of natural logarithm frequency of failures without regulation

x_i	f_i	$f_i x_i$	λ/x_i	$p(x_i)$	f_{ti}
0	6	0	-	0,33756	6
1	5	5	1,086	0,36659	6
2	3	7	0,543	0,19906	3
3	2	7	0,362	0,07206	1

Table 1.2 Table of natural logarithm frequency of failures with regulation

x_i	f_i	$f_i x_i$	λ / x_i	$p(x_i)$	f_{ti}
0	6	0	-	0,40723	7
1	4	4	0,898	0,36585	6
2	3	5	0,449	0,16433	3
3	1	3	0,299	0,04921	1

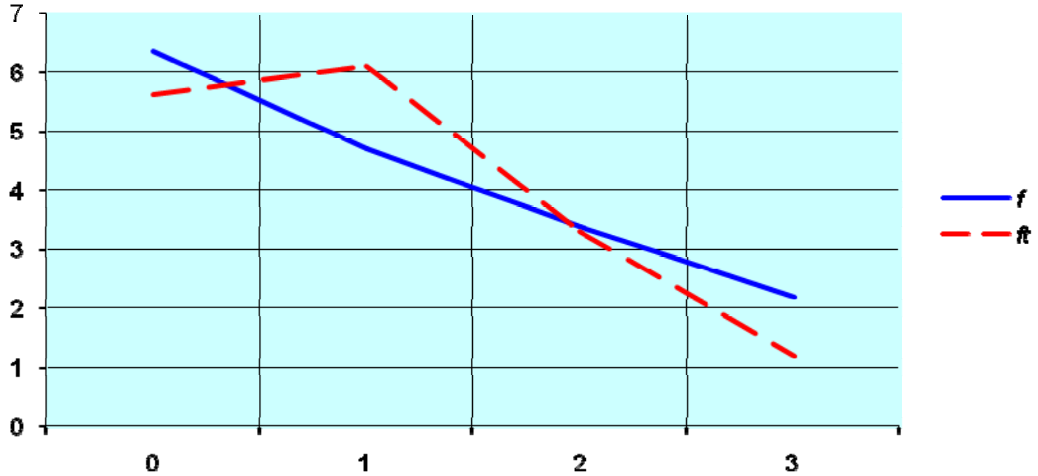

Figure 1.2 Line chart of the natural logarithm of empirical and theoretical frequency of failures without regulation

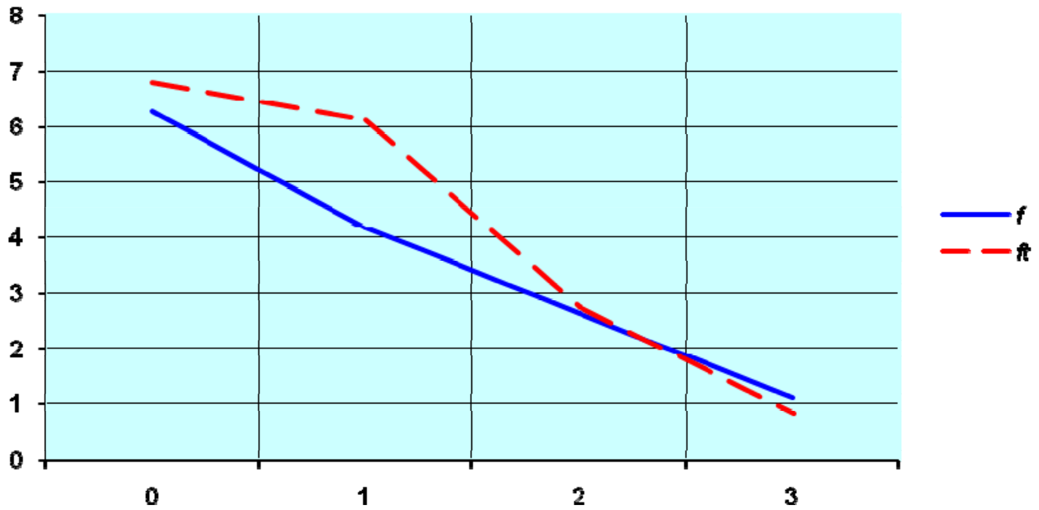

Figure 1.3 Line chart of the natural logarithm of empirical and theoretical frequency of failures with regulation

For the needs of chi-square tests of two basic sets, i. e. without regulation and with the regulation of pressure and flow, tables 1.3 and 1.4 were formed. In these tables fourth column is a key that shows quadratic deviation of the actual theoretical frequencies. Chi-square test would confirm the initial hypothesis H0 that the data followed the Poisson distribution if the sum of squared deviations in a given period for each value of x_i was less than the theoretically obtained value of chi-square distribution with degree of freedom n=2,, and with significance of α=0,05.

For DMA in the case without regulation, according to table 1.3, is valid

$$\chi_0^2 = 1{,}2 < \chi_\alpha^2 = 6 \, , \tag{1.1}$$

from which follows that the hypothesis H0 holds. It means that natural logarithms frequency failures in the period without regulation followed Poisson distribution. In the same way the hypothesis H0 for the time period after the introduction of regulation retains, because, according to table 1.4, we have

$$\chi_0^2 = 0{,}7 < \chi_\alpha^2 = 6 \, . \tag{1.2}$$

Table 1.3 Table of Chi-square test of natural logarithm frequency failures without regulation

x_i	f_i	f_{ti}	$(f_i-f_{ti})^2/f_{ti}$	
0	6	6	0,1	$N=$ 17
1	5	6	0,3	$n=$ 2
2	3	3	0,0	$\alpha=$ 0,05
3	2	1	0,8	$\chi_\alpha^2=$ 6,0
				$\chi_0^2=$ 1,2
$\chi_0^2<\chi_\alpha^2 \rightarrow$ Ne postoji signifikantna razlika između stvarnih i teorijskih frekvencija				

Table 1.4 Table of Chi-square test of natural logarithm frequency failures without regulation

x_i	f_i	f_{ti}	$(f_i-f_{ti})^2/f_{ti}$	
0	6	7	0,0	$N=$ 14
1	4	6	0,6	$n=$ 2
2	3	3	0,0	$\alpha=$ 0,05
3	1	1	0,1	$\chi_\alpha^2=$ 6,0
				$\chi_0^2=$ 0,7
$\chi_0^2<\chi_\alpha^2 \rightarrow$ Ne postoji signifikantna razlika između stvarnih i teorijskih frekvencija				

Checking whether the frequency of failures in years 2007 and 2008 is less than the frequency of failures in years 2005 and 2006 is based on checking whether the arithmetic mean of arithmetic means of samples from 2007 and 2008 was significantly different from the arithmetic mean of arithmetic means of samples from years 2005 and 2006 (Table 1.5). Since the sizes of all samples are greater than 30, it implies that the arithmetic means of samples follow a normal distribution. On this basis it is possible to conduct testing variance and arithmetic means using the F-test and T-test.

Table 1.5 Arithmetic means of samples

Regulation	Number of failures in the samples of 35 days								
No	6	4	8	10	8	5	4		
	4	18	10	13	11	18	9		
	6	13	9	13	10	11	9		
Yes	3	4	6	3	5	5	7	6	5
	7	3	5	4	10	15	6	9	6

Basic parameters of arithmetic means of samples from the 2005/2006 and 2007/2008 needed for the implementation of F-test and t-test are:

Test significance

$$\alpha = 0{,}05\,, \qquad (1.3)$$

Number of samples of basic sets

$$n_1 = 21;\ n_2 = 18\,, \qquad (1.4)$$

Mean values arithmetic means of samples

$$\hat{\mu}_1 = 9{,}5\,;\ \hat{\mu}_2 = 6{,}1\,, \qquad (1.5)$$

Variances of arithmetic means of samples

$$\hat{\sigma}_1^2 = 17{,}2\,;\ \hat{\sigma}_2^2 = 9{,}2\,, \qquad (1.6)$$

Degrees of freedom F-distribution

$$k_1 = n_1 - 1 = 20\,;\ k_2 = n_2 - 1 = 17\,, \qquad (1.7)$$

Degree of freedom T-distribution

$$k = n_1 + n_2 - 2 = 37\,. \qquad (1.8)$$

To enable comparison of two arithmetic means using T-test, an essential requirement is that those two sets have variances that are mutually not significantly different. That is checked by F-test, which therefore has to be carried out first. It includes the calculation of the variable in a form

$$F = \frac{\hat{\sigma}_1^2}{\hat{\sigma}_2^2} = 1{,}877\,. \qquad (1.9)$$

Obtained result belongs to the F-distribution with degrees of freedom $k_1 = 20$ and $k_2 = 17$. For the same degrees of freedom, with significance of $\alpha = 0{,}05$ it can be calculated critical value F_t of which 5% of the value of random variables falls right:

$$F_t\left(k_1, k_2, \alpha\right) = 2{,}23 . \qquad (1.10)$$

Comparing (1.9) and (1.10) we see that

$$F < F_t , \qquad (1.11)$$

so that the hypothesis of equality of variance of 2005/2006 and 2007/2008 holds.

In order to implement T-test on equality of arithmetic means of arithmetic means of samples taken from the set 2005/2006, and the same variable taken from the set of 2007/2008, it is necessary to calculate the value of

$$S_{d1,2} = \sqrt{\frac{(n_1-1)\hat{\sigma}_1^2 + (n_2-1)\hat{\sigma}_2^2}{n_1+n_2-2}}\sqrt{\frac{n_1+n_2}{n_1 n_2}} = 0{,}041 . \qquad (1.12)$$

Based on the obtained value can be calculated t-test variable in the form

$$t = \frac{\left|\hat{\mu}_1 - \hat{\mu}_2\right|}{S_d} = 2{,}899 . \qquad (1.13)$$

Key assumption is that the calculated value belongs Student T-distribution with degree of freedom of $k = 37$. With the same degree of freedom and significance of $\alpha = 0{,}05$, theoretical value of t-variable is

$$t_\alpha\left(k_1, k_2, \alpha\right) = 2{,}026 . \qquad (1.14)$$

Criteria for holding the hypothesis, which means that the basic sets with the estimated arithmetic means $\hat{\mu}_1$ and $\hat{\mu}_2$ are mutually not significantly different, is the condition that the actual value of the variable t is less than the theoretical limit value t_α of the same distribution. Since the

$$t > t_\alpha , \qquad (1.15)$$

this criterion is not fulfilled, so the initial hypothesis is rejected, i. e. with the likelihood of errors of 5% we can claim that the basic sets of the arithmetic means differ each other significantly.

Conclusions

First part of the analysis showed that the probability nascence of failures in the periods before and after regulation following Poisson distribution, assuming that the frequency of failures considered as natural logarithms failure rate within the considered period. This conclusion is very important in order to monitor and predict the trend of failures in the formation of DMA.

In the second part of the analysis is statistically proven that with the 95% certainty may assert that the regulation of pressure in the system caused the change in the frequency of failures on the network. Shown that the establishment of regulation of pressure reducing the annual number of failures from about 100 to 60, which is on average about 40%. From these data can easily be calculated what the savings achieved in maintaining the water supply network. Iterations of this practical-theoretical work on further DMA can reach significant conclusions allowing adoption of objective decisions on the functioning of the system.

It should be noted that the regulation of DMA was introduced in March 20, 2006. If we considered the boundary of the sets according to this date instead of considered date December 31, 2006, it seemed that we couldn't prove that there was a significant change of failures frequency occurred. This is very indicative, since if the boundary between sets has been taken according to day from eight to nine months later, the changes became significant. It is assumed that this phenomenon follows from the fact that in the DMA Active Leakage Control (ACL) has not be implemented, and in takes eight to nine months to leakage that occurred before introduction of regulation appears visible.

This confirms the fact that the observed maximum number of DMA failures related to the leakage manholes and hydrants, while the number of pipe bursts that can be quickly visually detect poorly represented. Further studies on the appearance of failures in the system of regulation under the influence of pressure, it is necessary to focus research on the causes of failures. On the basis thus obtained data, it is possible to make objective decisions when determining the priority activities in the system.

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