

A Parametric Evaluation of Leakages in Water Distribution Networks [†]

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Abstract: One of the main problems of water distribution systems is the management and the evaluation of water losses. At the Laboratory of Hydraulics and Maritime Constructions at the Università Politecnica delle Marche, experimental research on this topic was conducted to measure the water volume exiting from a known shape and size hole at fixed hydraulic conditions. The obtained results were also used as input data for the Evolutionary Polynomial Regression (EPR) analysis for the construction of prediction models that could be employed for the management of water leakages in pressurized networks.

Keywords: water distribution network; leakages; experimental setup; Evolutionary Polynomial Regression (EPR)

1. Introduction

Leakage reduction in water distribution systems (WDSs) is a fundamental aspect for water utilities as it is one of the macro-indicators of the technical conditions for providing the service [1].

It is widely known that one of the main parameters influencing water leakage is the internal pressure head (P) of the pipe, and it is important to define a relationship that links this parameter to the water flowing from a hole (QL) for controlling leakages and limiting breakages in WDSs. The general equation describing this phenomenon is

$$QL = aP^b \quad (1)$$

where a and b are the coefficient and the exponent, respectively, in the water loss model. The values of exponent b derived from experiments and field studies are between 0.5 and 2.79 (e.g., [2]), and factors influencing its value are the material, type of rupture, soil characteristics, flow rate and nature of the phenomenon. Regarding the discharge coefficient a , it has been observed that its value increases as the leak area increases.

The aim of this paper is the definition of two different aspects: the first is an evaluation of water volume lost from circular holes in a cast iron pipe, measured in a pressurized system simulating a water distribution system, and the description of this phenomenon through Equation (1) and an estimation of the parameters describing the equation (a and b); the second is the use of the Evolutionary Polynomial Regression (EPR) method for the construction of prediction models for the validation of the experimental results, investigating if other parameters are influential in this process.



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2. Materials and Methods

2.1. Experimental Setup

The pressurized hydraulic system used for water leakage measurement consists of DN110 PN16 PVC pipes with a total length of 20 m, on which a DN100 spheroidal cast iron pipe 6 m long is mounted (Figure 1a). The circuit is fed by a 3 m³ free surface tank, while the flow rate and pressure conditions are guaranteed by a vertical multistage radial impeller pump with a power of 5.5 kW and a nominal frequency of 50 Hz. The performance of the system in pressure and flow terms is regulated by the presence of a three-phase inverter connected to the electric pump that allows a variation in the number of motor revolutions in terms of frequency (from 35 Hz to 50 Hz) and a spheroidal cast iron DN100 PN16 flow valve installed at the end of the circuit before the outlet into the discharge tank. The operating conditions are measured by two electromagnetic flowmeters and two pressure gauges.

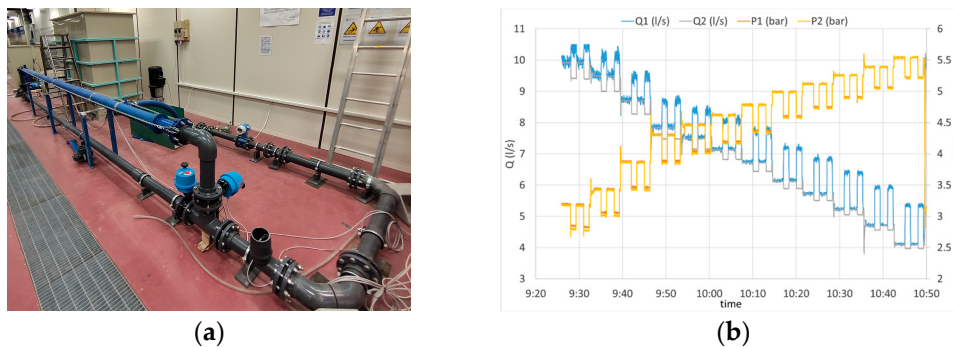


Figure 1. (a) Hydraulic plant used for the experiments; (b) example of test performance.

Water leakage is simulated from the cast iron pipe through the drilling of circular holes on it. Normally, water flows in the PVC pipeline (e.g., the bypass line), but through the presence of three motorized valves, water reaches the cast iron pipe, located 80 cm above the PVC circuit.

The water leakages have been measured at different hydraulic conditions and for different hole sizes; holes with a diameter from 3 to 12 mm were tested, while the hydraulic conditions, imposed with a variation in the pump frequency (35 Hz, 40 Hz, 45 Hz and 50 Hz) and the gradual shutting of the flow valve, were in the range of (3–7.7) L/s and (12–56) m for flow and pressure, respectively (Figure 1b). Each measurement was performed multiple times to verify the repeatability of the data. The discharge lost during the test was evaluated as the difference between the flow rate measured by the flowmeter upstream and downstream of the leak, respectively. In the analysis of this phenomenon, for simplicity's sake, two different conditions are defined: “closed circuit” represents the flow in the bypass line and no water losses are present; “open circuit” is the condition in which water flows in the cast iron pipe and water losses are registered (this phase is characterized by a time interval of 60 s).

2.2. EPR Setup

The EPR technique is a data-driven modeling strategy that integrates the best features of numerical regression with genetic programming and symbolic regression [3]. This technique can be roughly described in two steps: the first is the selection of exponents for polynomial expressions and the second is the use of numerical regression for the evaluation of coefficients for the above polynomial terms.

In this specific case, the experimental data obtained with the laboratory tests were used as input data for the determination of the polynomial equations, and specifically, 5 parameters were considered: hole area (A), water velocity in the condition of “closed circuit” (v_c) and “open circuit” (v_a), and pressure head in “closed circuit” (P_c) and in “open circuit” conditions (P_a).

Within the polynomial structure of the equation, no functions were selected, and a statistical regression method was imposed since the data were not arranged according to time series. The analysis was carried out with different numbers of the equation terms and assuming for the exponents the following values: 0.47, 0.48, 0.49, 0.50, 0.51, 0, 1, and -1 .

Lastly, the non-negative least squares method was imposed as a regression model to determine the polynomial coefficients values. Finally, the accuracy of the candidate models is defined through the Coefficient of Determination (COD).

3. Results

3.1. Experimental Results

The results obtained from the laboratory tests are reported in Figure 2, where the relationship between the water leakage and the pressure head in a logarithmic scale is shown (Figure 2a) and the values of coefficient a and exponent b are plotted (Figure 2b). The values of coefficient a are in the range 0.022–0.41, increasing as the hole area increases; the values of coefficient b are between 0.4 and 0.52, which are slightly different to the theoretical one of 0.5. Figure 2a shows that the hole area seems to influence only the values of coefficient a , while the values of exponent b are almost constant, resulting in the parallelism of the trend lines. Also, the tendency for the leakage to increase as the operating pressure in the pipeline increases is confirmed.

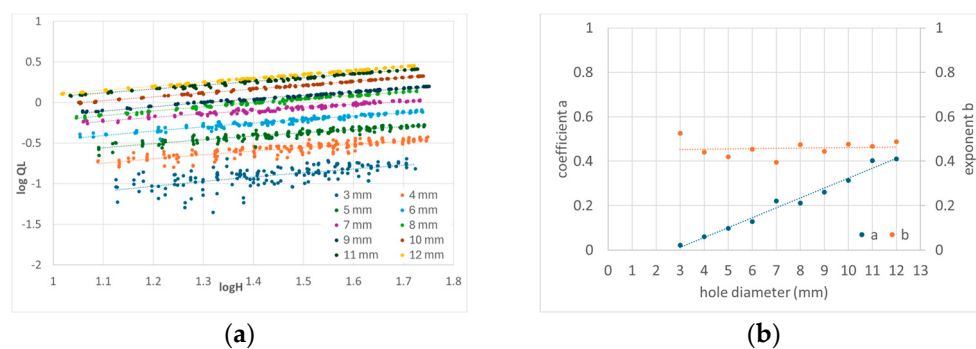


Figure 2. (a) Water loss–pressure head relationship for cast iron pipe; (b) coefficient a and b values.

3.2. EPR Results

The results obtained with the laboratory tests were used as input data for the construction of prediction models with the EPR method. Many simulations were performed, and it was decided to consider only three parameters out of five for the definition of the predictive equations, hole area (A), “open circuit” velocity (v_a) and “open circuit” pressure head (P_a), since these were the most recurrent parameters determined by the EPR software (V.1) simulations. The number of equation terms was set equal to three to highlight the influence of the largest number of parameters on the leakage. The obtained models are shown in Table 1.

Table 1. Prediction models by EPR.

Equation Model		COD
$QL = 1.0463$	(1)	0.176254394
$QL = 0.019388A + 0.047377$	(2)	89.17354241
$QL = 0.0037899AP_a^{0.48} + 0.041421$	(3)	99.21249723
$QL = -0.82268(1/A) + 0.0034105AP_a^{0.5} + 0.10893$	(4)	99.291084
$QL = 0.052874A^{0.5} - 0.0041606A + 0.0039875AP_a^{0.47} - 0.11632$	(5)	99.31090183

The optimal model is number 3, since it is the one with a higher value of the COD and a lower number of terms; moreover, this prediction equation is very similar to the one obtained with the experimental tests. It can be noticed that the values of the COD

of Equation Models (3)–(5) are very similar, but model 3 is a less complex equation. The results of the EPR simulations are plotted in Figure 3.

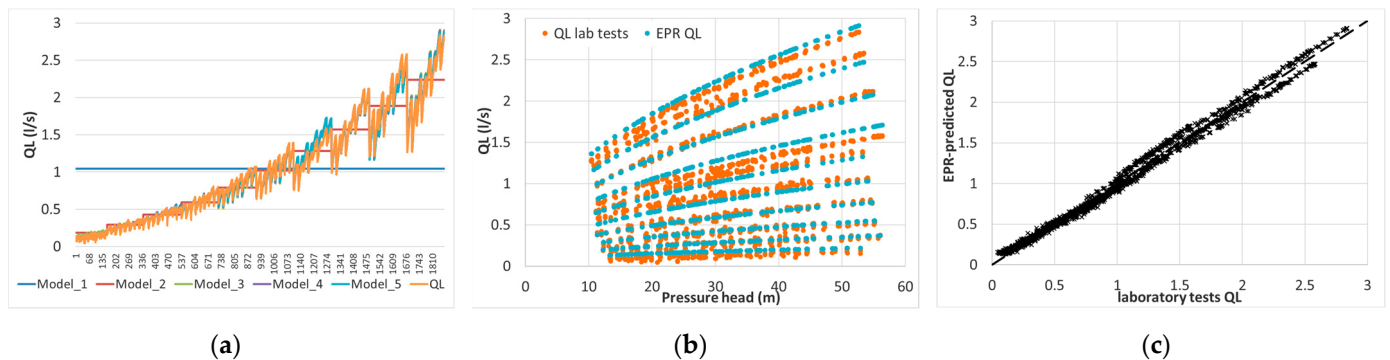


Figure 3. Results from EPR simulation. (a) EPR output model plot; (b) comparison between EPR model 3 and QL values from laboratory tests; (c) correlation plot between EPR-predicted and lab test QL (cross-marks) with perfect agreement (dashed line).

4. Conclusions

At the Hydraulic and Maritime Construction Laboratory of the Università Politecnica delle Marche, an experimental investigation was carried out, in which water leakages from a hole in a pressurized system were simulated, varying the operative conditions (flow and pressure) and the size of the holes.

The first results obtained are the values of the coefficients a and b , which are part of the general equation describing this phenomenon: coefficient a is characterized by an increasing value as the hole area increases, while exponent b assumes values that are slightly different from the theoretical value of 0.5 with a certain level of confidence (between 0.4 and 0.52). Also, the increasing tendency of the water flow from a hole as the pressure head increases is confirmed. These results were validated with the EPR methodology, with which a prediction equation was defined; an equation very similar to the theoretical one was obtained, characterized by a Coefficient of Determination (COD) equal to 99.21%.

Further studies and laboratory experiments are still ongoing, with particular reference to the role of pipe materials.

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