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Theoretical Modeling of Pressure and Leakage in Water Distribution Systems

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Abstract

The purpose of this paper is to summarize the latest theoretical developments on the pressure-leakage relationship in water distribution systems. It is clear that the high leakage exponents often found in field studies are mainly caused by leak areas varying with system pressure, and a good understanding of the response of leaks deforming elastically has been developed. Other factors that are briefly discussed include leak hydraulics, soil hydraulics and the way individual leaks combine in pressure management zones.

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Keywords: Pressure, leakage, leakage exponent, leakage number, water distribution systems, theory, models, FAVAD

1. Introduction

Recent years have seen significant developments in the understanding of the relationship between pressure and leakage based on the results of theoretical, numerical, experimental and field studies. In 2007, van Zyl and Clayton [1] proposed four factors that may be responsible for the observed high sensitivity of leakage to pressure, i.e. leak hydraulics, pipe material behavior (causing leak areas to vary as a function of pressure), soil hydraulics and water demand. A fifth factor, the way that the distribution of individual leaks in a pressure management area affect the leakage exponent was later added [2].

The purpose of this paper is to summarize the theory of the impact of pressure on leakage for each of the factors above. Water demand is not included since it is not a direct component of leakage.

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2. Background

A leak in a distribution system pipe can be considered as an orifice. Orifice hydraulics is well understood, and the orifice equation describes the flow rate Q through an orifice as a function of the orifice area A and pressure head h as:

$$Q = C_d A\sqrt{2gh} \tag{1}$$

Where C_d is the discharge coefficient, accounting for energy losses and jet contraction, and g is acceleration due to gravity.

However, leakage practitioners uses a more general form of the equation to describe the relationship between pressure and leakage [3]:

$$Q = Ch^{N1} \tag{2}$$

Where Q is the leakage flow rate, C the leakage coefficient, h the average zonal pressure (AZP) and $N1$ the leakage exponent. While the orifice equation Eq. (1) predicts the leakage exponent to be 0.5, values as high as 2.9 have been reported in field studies, although the vast majority of leakage exponents are between 0.5 and 1.5 [4].

3. Leak hydraulics

While orifice hydraulics dictates that the leakage exponent should be 0.5 for an orifice with fixed area, this is only true for turbulent flow. For laminar flow, the relationship between flow rate and pressure becomes linear, and thus laminar flow can explain a leakage exponent of one. The flow regime is determined by the Reynolds number (Re), and flow through orifices is typically laminar at Re below 10 and turbulent at Re above 4000 to 5000 [5].

For a fixed Reynolds number, the maximum velocity that orifice flow will be laminar or transitional is only a function of the wetted perimeter of the leak and, to a lesser extent, the viscosity of the water, which is mostly influenced by temperature [1].

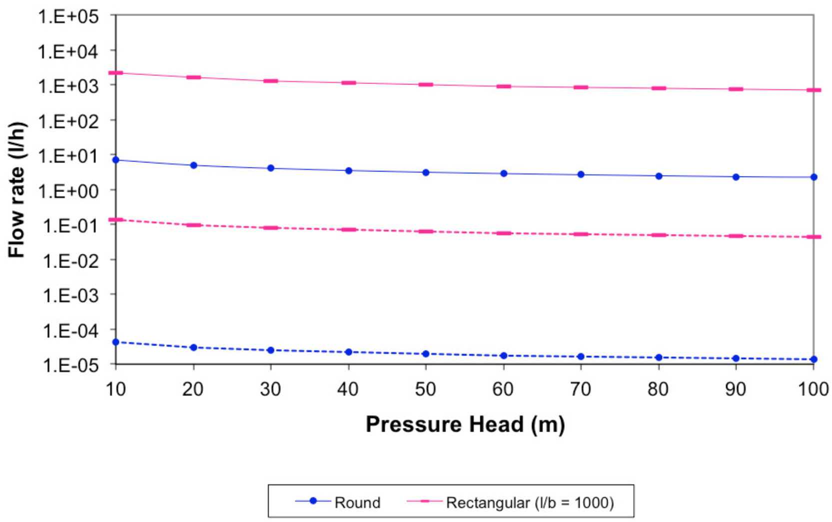

Fig. 1. Maximum laminar (dotted line) and transitional (solid line) flow for round holes and cracks with a length to width ratio of 1000.

Fig. 1 shows the maximum laminar and transitional flow possible for a round hole and a crack with a length to width ratio of 1000. At a pressure head of 50 m, the crack is able to provide a maximum laminar flow rate of 0.06 L/h and a maximum transitional flow rate of 1000 L/h.

Based on these results, it seems unlikely that a significant fraction of the leakage in a distribution system can be laminar. Transitional flow can be much larger, but the larger the flow rate is, the lower the effective leakage exponent will be down to a value of 0.5 at the limit of transitional flow. It thus seems also unlikely that transitional flow will have much impact on the leakage exponent of a system.

4. Pipe material behavior

May [6] introduced the FAVAD concept in 1994 by assuming that some leaks are rigid, while others will expand with increasing pressure. He assumption that leak area varies linearly with pressure, and this was later confirmed by Cassa et al [7] in a finite element study on the behavior of holes and cracks in various pipe materials (uPVC, cast iron, steel and asbestos cement) under two loading states. This study found that under elastic conditions, leaks areas vary linearly with pressure, and that the head-area relationship can thus be described by the initial area A_0 and head-area slope m in the form:

$$A = A_0 + mh \tag{3}$$

The head-area slope is a function of the properties of the leak, as well as the pipe material and section properties. For round holes, m is very small and for longitudinal, spiral and circumferential cracks, formulae for m have been proposed based on CFD studies [8]. The assumption of elastic deformation inherent in Eq. 3 is considered reasonable for general analysis, although it is known that leaks in plastic pipe are also affected by hysteresis and plastic deformation [9].

Replacing Eq. 3 into Eq. 1 results in the FAVAD equation:

$$Q = C_d \sqrt{2g}\left(A_0 h^{0.5} + m h^{1.5}\right) \tag{1}$$

Van Zyl and Cassa [10] defined the dimensionless leakage number L_N as the ratio between the expanding and fixed leakage terms in Eq. 4 as:

$$L_N = \frac{mh}{A_0} \tag{5}$$

They found a one-to-one relationship between the leakage number and leakage exponent as shown in Fig. 2 and described by the following equation:

$$L_N = \frac{N1 - 0.5}{1.5 - N1} \tag{6}$$

This relationship, in combination with equations to predict the head-area slopes (see [8]) can be used to predict the head-area slope of individual leaks, and predict changes in the leakage exponent when measured at different pressures.

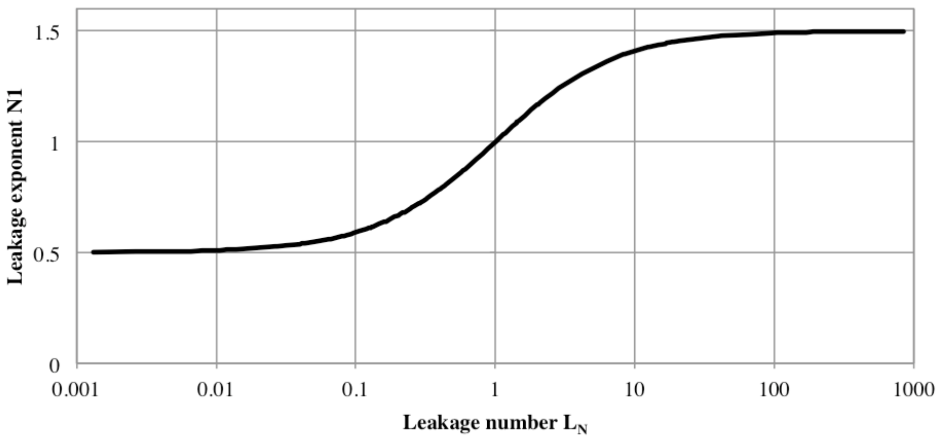

Fig. 2. Relationship between the leakage number and leakage exponent.

5. Soil hydraulics

Soil hydraulics is characterized by a linear relationship between pressure and leakage as described by the Darcy equation. However, soils are not generally able to handle the high flow energies of water jets from leaks in water distribution pipes, and non-Darcy flow is likely to occur close to the leaks, possibly in the form of hydraulic fracture and piping. A 'suspended zone' of soil-leak interaction has been observed in experimental studies based on an idealized soil, and there are indications that the suspended zone acts as an energy dissipation mechanism [11].

While soils around a leak may have some impact on the pressure-leakage relationship, it is unlikely that any soil will be able to contain the pressures that are commonly found in water distribution systems, and thus the impact of soils on the pressure-response of leakage is likely to be small.

6. Combined effect of many leaks

For the combined response of many leaks, Schwaller and van Zyl [2] showed that the FAVAD model can also be used to describe the behavior of pressure management zones with many leaks, and that the parameters of the FAVAD model are strongly related to the sum of all the individual leak areas and head-area slopes in the system.

7. Conclusion

This paper summarized the main theory of factors that influence the pressure-leakage relationships in water distribution systems. Pipe material behavior (i.e. expanding leak areas with increasing pressure) is the main factor responsible for the high leakage exponents observed in field studies, but leak hydraulics, soil hydraulics, water demand and the way individual leaks combine in a pressure management zone can also influence this relationship.

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