CHARACTERISING THE PRESSURE-LEAKAGE RESPONSE OF PIPE NETWORKS USING THE FAVAD EQUATION

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KEY WORDS

FAVAD; pressure management; leakage; leakage number; water distribution systems

ABSTRACT

This study investigated the feasibility of characterising the pressure-leakage response of water distribution systems using the FAVAD (Fixed and Variable Area Discharges) equation, instead of the conventional $N1$ power equation. The study was based on 300 network models with randomly distributed leaks and 35 networks generated through a sensitivity analysis. It was found that the leakage rate and average zone pressure head (AZP) before and after pressure reduction may be used in conjunction with the FAVAD equation to estimate the initial leakage area (A_{0S}) and head-area slope (m_S) of any system. In addition, A_{0S} and m_s were shown to provide good estimates respectively of the sum of the initial areas and head-area slopes of all the individual leaks in the system. The study found that a dimensionless leakage number may be calculated for any system and used to characterise the pressure-leakage response. Finally, the study showed that it is possible to convert between $N1$ and the leakage number using a simple equation.

LIST OF SYMBOLS

A	Leakage area
A_0	Initial leakage area (leakage area at zero pressure)
A_{0S}	Initial leakage area of a system.
AZP	Average zone pressure head
C	Leakage coefficient
C_d	Discharge coefficient
C_{dS}	System discharge coefficient

FAVAD	Fixed And Variable Area Discharges
g	Acceleration due to gravity
h	Pressure head
h_{AZP}	Average zonal pressure head before reduction
h_{AZP_1}	Average zonal pressure head before reduction
h_{AZP_2}	Average zonal pressure head after reduction
L_N	Leakage number
L_{NS}	System leakage number
m	Head-area slope
m_S	System head-area slope
$N1$	Leakage exponent
PMA	Pressure management area
Q	Leakage rate
Q_1	Total system leakage rate before pressure reduction
Q_2	Total system leakage rate after pressure reduction

INTRODUCTION

Pressure management is applied internationally as an effective method to reduce leakage from water distribution systems (Farley & Trow, 2003; Lambert et al., 2013), and has also been shown to produce other benefits such as reduced pipe failure rates, extend pipe service life and lower consumption (Lambert et al., 2013).

Pressure management refers to the practice of reducing excess pressures in an isolated network zone called a pressure management area (PMA) using a pressure reducing valve. Leakage in a PMA or in DMA is estimated by first measuring the minimum night flow and then subtracting the estimated consumption from it.

Estimates of system leakage and average zone pressure head (AZP) before and after pressure management can be used to estimate the leakage coefficient *C* and leakage exponent *N1* in the equation:

$$\mathrm{Q} = \mathrm{C}h_{AZP}^{N1} \qquad (1)$$

where Q is the leakage flow rate and h_{AZP} the AZP. Equation 1 is also called the N1 power law or the N1 equation. The latter term will be used in this paper.

The *N1* exponent is widely used to characterise the pressure-leakage response of water distribution systems. Applying Equation 1 to conditions before and after pressure management, and dividing one equation by the other, allows *C* to be eliminated and *N1* obtained from the equation:

$$\frac{\mathrm{Q_1}}{\mathrm{Q_2}} = \left(\frac{\mathrm{h_{AZP\_1}}}{\mathrm{h_{AZP\_2}}}\right)^{\mathrm{N1}}$$

Where h_{AZP_1} and Q_1 are the AZP and leakage flow rate before pressure management, and h_{AZP_2} and Q_2 the AZP and leakage flow rate after pressure management.

The link between pressure and leakage is dependent on both C and $N1$, but since the exponent has a much greater influence on the relationship, only $N1$ is used in practice.

Despite its wide use in practice, the N1 equation has a number of disadvantages:

- It is an empirical equation not founded on fundamental fluid mechanics theory.
- The values of C and $N1$ for a given system are not constant, but are functions of the pressures at which they are estimated (Van Zyl & Cassa, 2014).
- It is dimensionally awkward, since the units of C include the variable $N1$.

Hydraulic theory predicts $N1$ to be 0.5 for an orifice, but field studies on water distribution systems in the UK, Japan, Brazil, Cyprus and Malaysia have reported leakage exponents ranging from 0,36 to 2,79 (Lambert, 1997). Greyvenstein and Van Zyl (2007) found $N1$ values between 0.4 and 2.3 for individual leaks in an experimental investigation. The following reasons have been proposed for the leakage exponent differing from the theoretical value of 0.5 (May, 1994; Van Zyl & Clayton, 2007; Schwaller & Van Zyl, 2014b):

- Leakage areas are not constant, but vary with pressure.
- The leak flow regime may be laminar, transitional or turbulent.
- Darcy laminar flow may occur in the soil surrounding buried pipes.
- Impact of pressure variation on the water consumption component of the minimum night flow.
- The combined effect of many leaks with different properties and at different elevations in a PMA.

It has been demonstrated in numerous individual leak studies that varying leakage areas may result in a wide range of $N1$ values, and this is widely accepted as the main reason for the observed variability in $N1$ (Lambert, 2000).

Finite element studies under both linear elastic (Cassa & Van Zyl, 2013) and viscoelastic (Ssozi, under review 2014) conditions have shown that leakage areas vary linearly with pressure, irrespective of leak type, loading conditions or pipe material and section properties. Some experimental studies have also confirmed these results (Ferrante et al., 2012 and 2013). Thus the relationship between leakage area and pressure may be described with the equation:

$$A = A_0 + mh \qquad (2)$$

where A is the leakage area at head h, A_0 the initial leakage area (defined as the leakage area under zero pressure conditions) and m the head-area slope.

In a hydraulic sense, leaks are simply orifices and thus their hydraulics can be described by the orifice equation (for instance, see Idelchik, 1994):

$$Q = C_d A \sqrt{2gh} \qquad (3)$$

where C_d is the discharge coefficient.

Replacing Equation 2 into Equation 3 results in the FAVAD (Fixed and Variable Area Discharges) equation, first introduced by May (1994):

$$Q = C_d \sqrt{2g} (A_0 h^{0.5} + m h^{1.5}) \qquad (4)$$

The first term in the FAVAD equation is identical to the orifice equation and describes the flow through the initial portion of the leakage area (i.e. the area of the leak at zero pressure), while the second term describes the leakage flow through the expanded portion of the leakage area.

It should be noted that practitioners often refer to the FAVAD concept when really using the N1 equation, sometimes describing *N1* as the ‘equivalent FAVAD *N1*’ or ‘FAVAD *N1*’. In these cases, the FAVAD concept is invoked as motivation for the leakage exponent not being the theoretical value of 0.5, rather than a different equation. In this paper the N1 equation will strictly refer to Equation 1 and FAVAD equation to Equation 4.

Van Zyl and Cassa (2014) defined a dimensionless leakage number L_N as the ratio of the flow through the expanded leak area to the initial leak area as:

$$L_N = \frac{mh}{A_0} \qquad (5)$$

For instance, a leakage number equal to one means that the initial and expanded portions of the leakage area contribute equally to the leakage flow, while a leakage number less than one means the initial portion has a greater contribution than the expanded portion.

While the pressure-leakage relationship of individual leaks has been shown to adhere to the FAVAD equation (Cassa & Van Zyl, 2013; Van Zyl & Cassa, 2014), the application of this equation to systems with many leaks has been limited. May and Lambert (Lambert, 2014) considered systems with many leaks, with individual leaks either fixed (with N1 = 0.5) or flexible (with N1 = 1.5) and little variation in-between. Ferrante et al (2014a, b) investigated the application of both the N1 and FAVAD equations to a system with several leaks. The two equations were perturbed and the results compared with simulations of 100 districts with 100 leaks each. When using the N1 equation they found that the system N1 is often higher than the mean local leak exponent. For the FAVAD equation they found that the effects of parameter perturbation were much less evident, and global and local leak laws show the same functional relationship between leakage and pressure.

The purpose of this study was to investigate the use of the FAVAD equation to characterise the pressure-leakage response of systems (or PMAs) with many leaks. The PMA leakage model is described in the next section, followed by an evaluation of the FAVAD equation to characterise its pressure-leakage behaviour, an investigation into the accuracy of the FAVAD parameters and the link between the FAVAD parameters and system *N1*. Finally, the implications for practical leakage management are discussed.

NETWORK LEAKAGE MODEL

Schwaller and Van Zyl (2014b) proposed a statistical model of the distribution and parameters of elastic leaks in a network based on current best knowledge. Their study showed that a large number of individual leaks, each adhering to the FAVAD equation, can explain the range of *N1* values reported in most field studies. The same model was used as the basis for this study. Since a full description of the development and parameters of the model is available in Schwaller and Van Zyl (2014b), only a brief overview is provided here.

A typical PMA consisting of 40 km of pipes and 2 500 service connections was used as basis for the model. A spread sheet leakage model was developed consisting of different numbers of leaks at random positions and with randomly distributed properties. The following statistical distributions were used for individual leak parameters in the PMA:

- The discharge coefficient C_d was modelled using a normal distribution.
- The initial leakage area A_o was modelled using a lognormal distribution bounded by zero for background leaks. Since it is more likely that large and potentially detectable leaks in the network were found and repaired quickly in the network, a normal distribution was chosen for potentially detectable leaks.
- The FAVAD head-area slope of individual leaks were modelled as a generalized power function of the initial leakage area A_0, based on finite element study by Cassa and Van Zyl (2013).
- The distribution of the pressure head was modelled as a uniform statistical distribution to represent a PMA with a constant elevation.

For each model, a typical parameter value was estimated, ranging from very low, to very high values as defined in Schwaller and van Zyl (2014b) in an attempt to represent realistic parameter ranges found in the field. Individual leak behaviour was modelled using the FAVAD equation. A summary of the parameters used in the model is provided in Table 1.

The parameters of a typical system were used to generate 100 random networks each comprising 100, 1000 and 10 000 leaks based on the ‘typical’ column in Table 1. In addition, a sensitivity analysis was conducted by varying each parameter in the typical network to its very low, low, high and very high values respectively. This resulted in a total of 335 network leakage models that were used both in Schwaller and Van Zyl (2014b) and this study.

It should be noted that the range of leakage generated through the above process extended well beyond that observed in practice. However, the purpose of this study was to evaluate the proposed method over a large range of conditions, and thus networks with excessive leakage generated through the method described above were included in the study.

The study assumed minimum night flow conditions, which implies negligible head losses and static nodal pressures. The total leakage rate was calculated as the sum of all the individual leakage rates in the system.

Table 1: Summary of the leakage parameters used in this study

Variable	**Component**	**Very low**	**Low**	**Typical**	**High**	**Very high**
Pressure head	Mean (m)	20	30	45	60	75
	Range (m)	0	±5	±10	±20	±45
Discharge coefficient	Mean (-)	0.5	0.575	0.65	0.725	0.8
	Standard deviation (-)	0	0.026	0.030	0.035	0.039
Background leaks	Number	550	550	550	550	550
	Standard deviation (mm^2)	3.7	3.4	3.2	3.1	2.9
Potentially detectable (PD) leaks	Percentage PD leaks	0.1%	0.4%	1%	3%	12.5%
	Number	0.5	2	5.6	17.2	69.8
Pressure variation	Practice values (m)	5	15	25	35	50
	Modelling values (m)	0.001	0.01	0.1	1	10

SYSTEM FAVAD PARAMETERS

To characterize the pressure-leakage behaviour of a system, the leakage and AZP were estimated before and after a uniform reduction of the pressure at all points. This resulted in two data points: (Q_1; h_{AZP_1}) and (Q_2; h_{AZP_2}), where Q is the total system leakage, h_{AZP} the AZP, and subscripts 1 and 2 refer to the system before and after the change in pressure respectively.

In Schwaller and Van Zyl (2014b) the conventional approach was followed by using the two data points in the *N1* equation (Equation 1) to determine *C* and *N1* for the system. However, in this study, the same two data points were used to determine the coefficients of the FAVAD equation (Equation 4). To do this, the FAVAD equation was first written in the form:

$$Q = C_{dS}\sqrt{2g}(A_{0S}h^{0.5} + m_S h^{1.5}) \qquad (6)$$

Where A_{0S} is the system initial leakage area, m_S the system head-area slope and C_{dS} the system discharge coefficient. In this study, C_{dS} was assumed to be equal to the average leak C_d in the model (0.65), which then allowed the other two parameters to be estimated using the equations:

$$m_S = \frac{h_2^{0,5}Q_1 - h_1^{0,5}Q_2}{C_{dS}\sqrt{2g}(h_1{}^{1.5}h_2^{0,5} - h_2{}^{1.5}h_1^{0,5})} \qquad (7)$$

$$A_{0S} = \frac{Q_1}{C_{dS}\sqrt{2gh_1}} - m_S h_1 \qquad (8)$$

The FAVAD parameters were determined for each of the 335 generated networks with leakage and then analysed. Good correlations between the system and individual FAVAD leakage parameters were observed as follows:

- The system initial leakage area A_{0S} was found to be approximately equal to the sum of the individual leak initial areas as shown in Figure 1.
- The system head-area slope m_S was found to be approximately equal to the sum of the individual head-area slopes as shown in Figure 2.

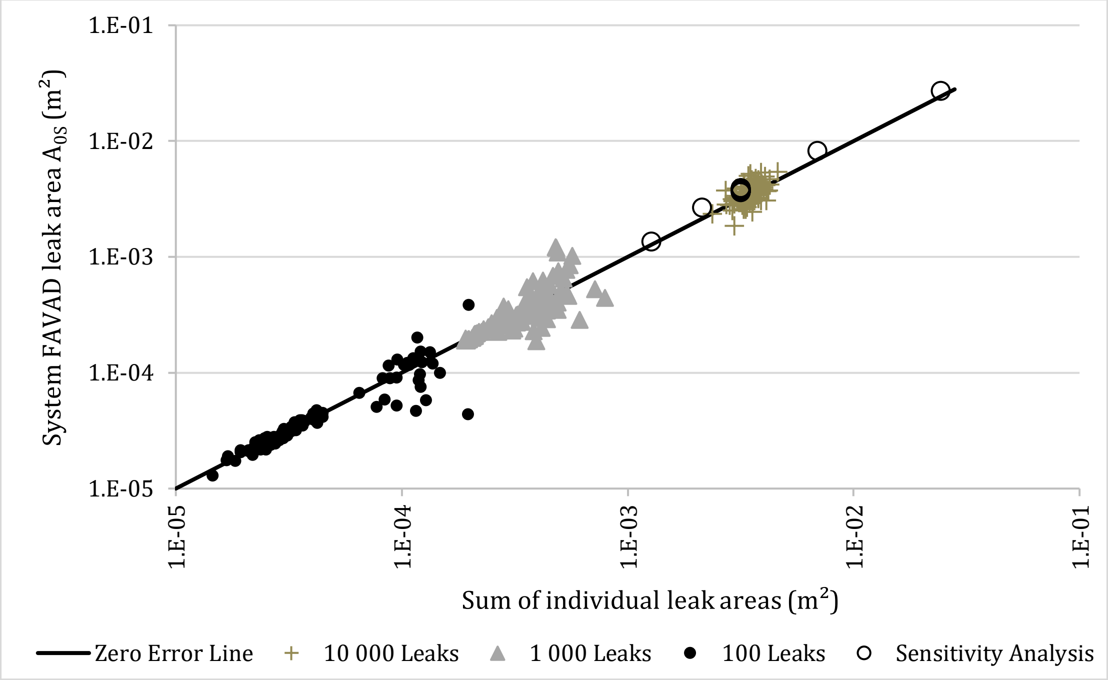

Figure 1 Comparison between the system initial leakage area A_{0S} and the sum of the individual leakage areas for 335 networks.

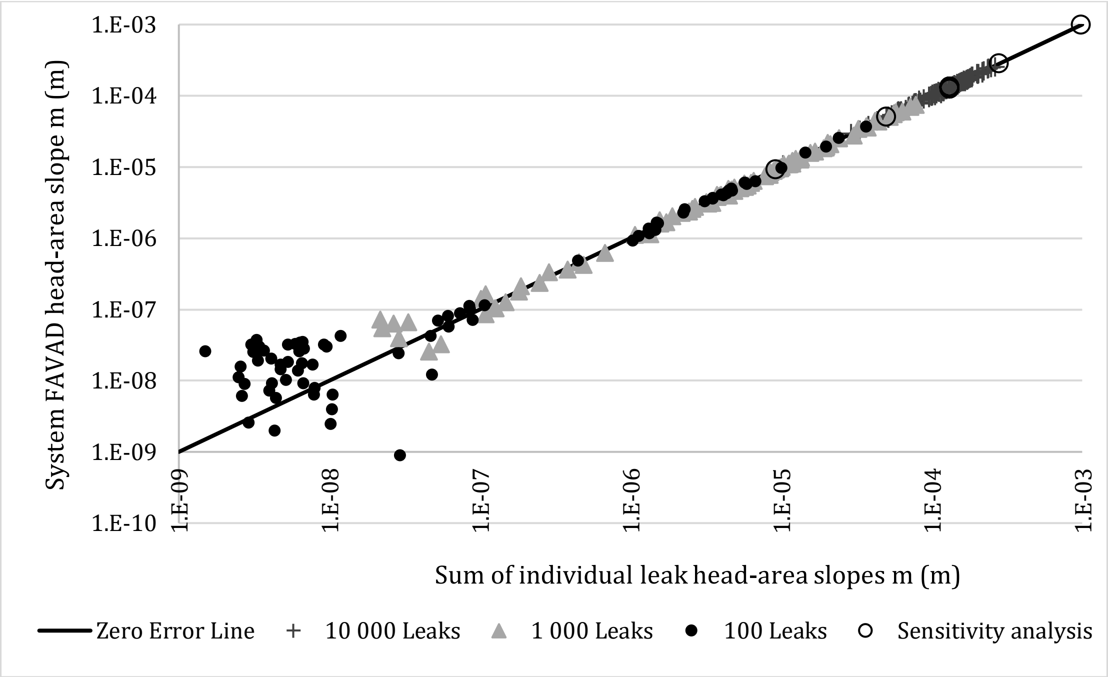

Figure 2 Comparison between the system FAVAD head-area slope m_S and the sum of the individual leak head-area slopes for 335 networks.

The results show that pressure management data can be used in the FAVAD equation to provide information on the physical properties of leaks in a system. The total initial areas of all the leaks provide a meaningful measure of the physical integrity of the system. Also, since Cassa & Van Zyl (2013) showed that the head-area slope of a leak can be linked to the properties of the pipe (diameter, material, wall thickness) and leak (type and size), the system head-area slope provides insights into the type of leaks present.

ACCURACY OF FAVAD PARAMETERS

The model used in this study allows information on the leaks to be known perfectly, and thus errors in the system FAVAD parameters can only result from two factors:

- Differences in proportional variations in leak pressures. While the absolute pressure change in the model was identical for all leaks, the proportional change in pressure varied due to the random variations in leak elevations (and thus static pressures).
- Variations in the individual leak discharge coefficients.

To illustrate this, the impact of pressure and discharge coefficients on the accuracy of the system initial area was investigated by doing a sensitivity analysis on a typical system (which happened to have an estimation error of 16 %). The parameters used for this analysis are given in Table 1 and the results are shown in Figure 3.

The figure shows that variations in the discharge coefficient and mean system pressure have little impact on the system initial area estimate, but that the error is highly sensitive to the range of pressures (i.e. slope) of the system. For a horizontal system the estimation error reduces to 1%, but increasing the range of leak elevations to a very high value (90 m) increased the error to almost 100 %.

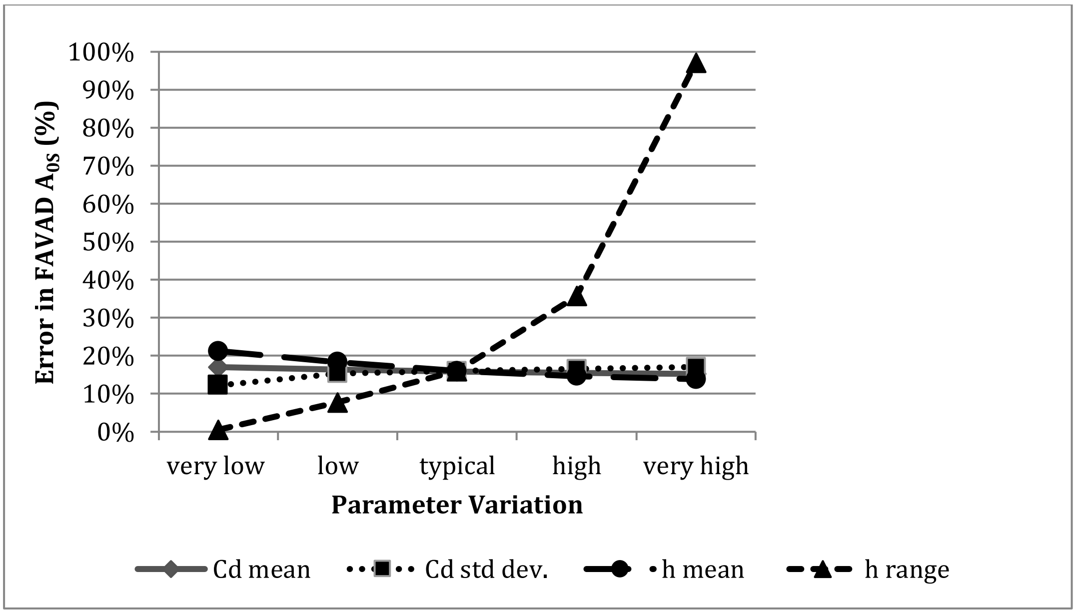

Figure 3: Sensitivity of the system initial area estimate to variations in pressure and discharge coefficients.

Further work was done to investigate the errors in the system FAVAD parameter estimates. One way of improving the accuracy of the estimate would be to include the unknown discharge coefficient in the FAVAD parameter estimation rather than assuming an average value in advance. This can be done by modifying Equations 6 and 7 to estimate the effective area ($C_{dS}A_{0S}$) and effective head-area slope ($C_{dS}m_S$) respectively. This approach may be particularly useful in field applications where the mean and range of discharge coefficients are unknown.

To investigate the effect of elevation differences on the system initial leakage area estimate, the absolute errors for the 300 random networks were calculated for the typical, low and very low pressure ranges in Table 1. These correspond to variations of ± 10 m, ± 5 m and 0 m (i.e. a horizontal system) respectively. Cumulative distributions of the absolute values of the errors are shown in Figure 4.

The results confirm the sensitivity of the system initial area error to the pressure range: the median error for the typical, low and very low (horizontal) pressure ranges were found to be 8.7%, 4.6% and 0.8% respectively. Using the effective system area produced only marginal improvements for the typical and low pressure ranges. However, for no elevation variation the error reduced to zero for all systems when using the effective area.

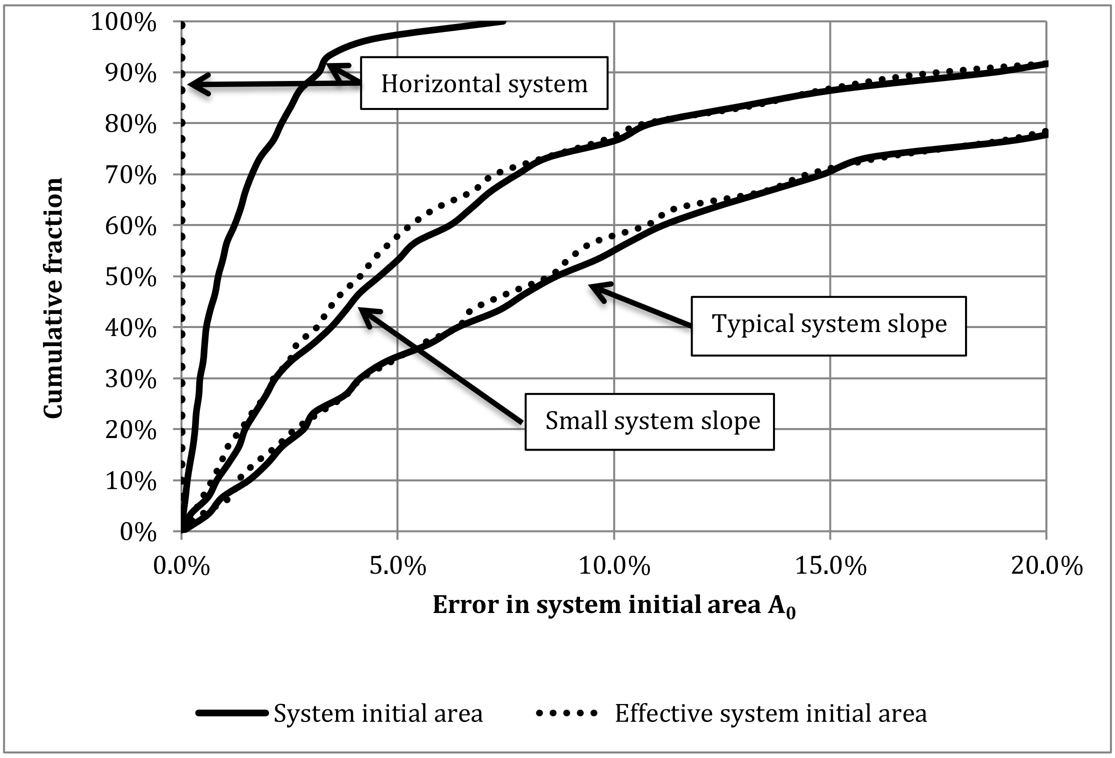

Figure 4: Cumulative error in the FAVAD system area for different system slopes.

While significant errors in the initial system area occurs throughout the range modelled (Figure 1), it can be seen from Figure 2 that the error in the system head-area slope is only significant for small head-area slopes. Further analysis showed that for a system with typical pressure range the errors are generally below 10 % when the total head-area slope is above 10^{-6} m and below 5 % when the total head-area slope is above 10^{-5} m. For systems with head-area slopes below 10^{-7} m, the estimation error can be substantial.

The system with a small slope shows only a minor improvement in accuracy. However, for horizontal systems, the errors were substantially smaller with a median error below 3 % even for systems with the lowest head-area slopes.

As with the system initial area error, using the equivalent head-area slope only produced marginal improvements in accuracy for the typical and small slopes, but reduced the error to zero for all horizontal systems.

While the errors in the system FAVAD parameters can be significant as discussed above, it should be noted that these errors are still small when compared with the range of values that the parameters may adopt: in this study the system initial areas and head-area slopes varied by three and six orders of magnitude respectively. Thus even in the worst cases, the system FAVAD parameters still provide good order-size estimates of the actual system values.

LEAKAGE NUMBER

Working with individual leaks, Van Zyl and Cassa (2014) showed that there is a one-to-one relationship between the leakage number and N1 in the form:

$$L_N = \frac{N1-0.5}{1.5-N1} \qquad (9)$$

or $N1 = \frac{1.5L_N+0.5}{L_N+1}$

It can be shown from these equations that *N1* is equal to one when the leakage number is one. Van Zyl and Cassa (2014) demonstrated that in practical terms *N1* is 1.5 when the leakage number is greater than 100, and 0.5 when the leakage number is less than 0.01 (but greater than 0).

The leakage number concept was applied to the systems in this study by rewriting Equation 5 in the following form:

$$L_{NS} = \frac{m_S\, h_{AZP}}{A_{0S}} \qquad (10)$$

where L_{NS} is the system leakage number. The physical meaning of the system leakage number is that it describes the ratio of the leakage flow through the expanded to the initial portions of all the leak openings in the system.

The relationship between the leakage number and *N1* was found to be also valid for systems with many leaks as shown for the 335 systems used in this study in Figure 6. The figure shows that the data points plot on or close to the theoretical relationship (Equation 9).

The two points on the left hand side of the figure both had very large leaks at elevations very different to the AZP. It suggests that the FAVAD equation may result in *N1* values greater than 1.5 under certain conditions. However, this will require further investigations and falls outside the scope of this study.

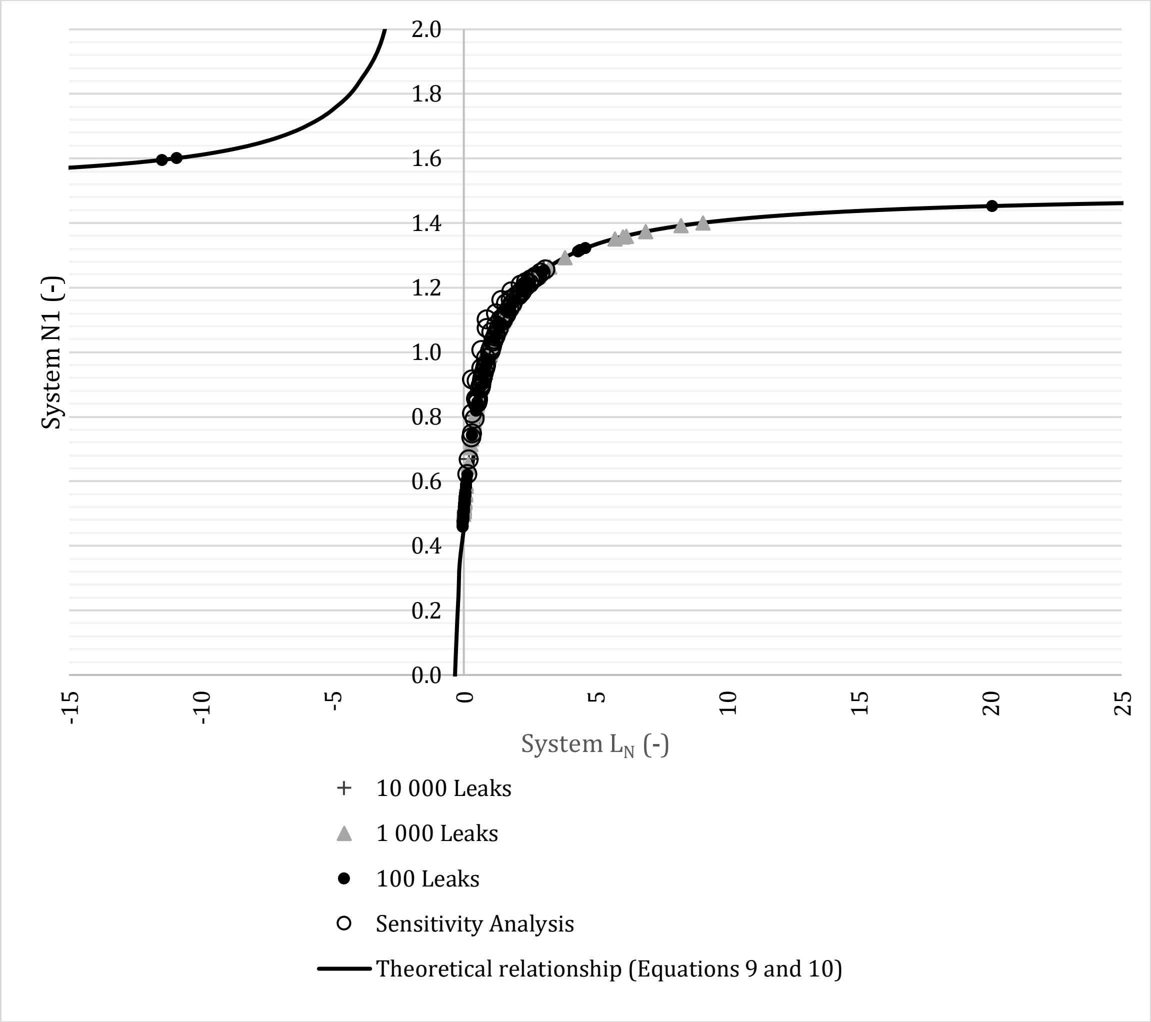

Figure 5: Relationship between the system leakage number L_{NS} and N1 for 335 systems.

APPLICATION IN PRACTICE

The findings of this study have several implications for characterising the pressure-leakage relationship of systems in practice. The main assumption underlying the FAVAD concept is that individual leak areas, and thus also system leakage areas, expand linearly with pressure. Thus it is necessary to evaluate the validity of this assumption for real systems.

Changing the system pressure, and thus the stresses in the pipe wall, can only result in the leakage area deforming in one of the following ways:

- Negligible deformation (fixed areas)
- Elastic deformation
- Viscoelastic deformation
- Plastic deformation

- Fracture

The leakage areas of the first three categories have been shown to expand linearly with pressure (Cassa & Van Zyl, 2013; Ssozi, under review 2014) and will thus satisfy the requirement for FAVAD behaviour.

The last two categories are likely to result in non-linear area variations with pressure. However, both plastic deformation and fracture are unlikely to occur when the pressure is reduced, as in the case of pressure management. Consequently the assumption of linear pressure-area behaviour seems reasonable for real systems.

Applying the FAVAD concept to systems in practice is feasible since no additional data is required beyond that currently used to estimate *N1*. The benefit of the FAVAD approach is that the system initial area and head-area slope provide physically meaningful properties that are independent of pressure.

Knowing the initial leakage area and head-area slope for a system allows its leakage number to be calculated, which provides the ratio of leakage through the expanded to the initial portions of the leakage areas. Variations in the leakage number with pressure can be directly calculated due to the inclusion of pressure in Equation 10. In addition, Equations 9 may be used to convert between the system leakage number and *N1*. This, in turn, may be used to estimate how *N1* will vary with system pressure.

It is recommended that the effective initial leakage area and head-area slope are used in field applications, since this avoids errors introduced by assuming a leak discharge coefficient. The leakage number is not affected by this, and the initial leakage area can always be estimated at a later point by assuming an average leakage coefficient.

Finally, the results show that the accuracy of system FAVAD parameters are sensitive to the slope of the system and that horizontal systems will provide the most accurate values. However, even for a system with a significant slope the error is likely to be small compared to the range of possible values, and thus the system FAVAD parameters will still provide a good estimate of the state of the system.

CONCLUSIONS

This study used a stochastic model of leaks in a typical pressure management area to investigate the application of the FAVAD equation for characterising the pressure-leakage response of systems with many leaks.

Applying the FAVAD equation to a system provides estimates of the total initial areas of all the leaks as well as the sum of all the head-area slopes in the system. These are physical properties of the network that are independent of pressure and can be used to evaluate and monitor the extent and type of leaks present.

FAVAD parameters are sensitive to the slope of the system, and horizontal systems will have the lowest errors. However, even for large slopes, the estimation errors will be small compared to the several orders of magnitude the FAVAD parameter values may adopt in practice. Thus the FAVAD parameters of the system will still provide a good estimate of the physical state of the system.

The FAVAD parameters can be used to calculate the system leakage number, which is the ratio of the leakage flow through the expanded to the initial portions of all the leak openings in the system. A simple equation (Equation 9) may be used to convert between the system leakage number and *N1*.

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REFERENCES

Cassa, A. M., and Van Zyl, J. E. 2013 Predicting the pressure-leakage slope of cracks in pipes subject to elastic deformations. *J. Water Supply Res. Technol. AQUA*, 62(4), 214–223.

Farley M. and Trow S. 2003 *Losses in Water Distribution Network*. London: IWA Publishing.

Ferrante, Marco. 2012. "Experimental Investigation of the Effects of Pipe Material on the Leak Head-Discharge Relationship." *Journal of Hydraulic Engineering, ASCE 138 (8): 736-43. doi:10.1061/(ASCE)HY.1943-7900.0000578.*

Ferrante, Marco, Christian Massari, Bruno Brunone, and Silvia Meniconi. 2013. "Leak Behaviour in Pressurized PVC Pipes." *Water Science & Technology: Water Supply 13 (4): 987. doi:10.2166/ws.2013.047.*

Ferrante, Marco, Bruno Brunone, Silvia Meniconi, Caterina Capponi, and Christian Massari. 2014a. "The Leak Law: From Local to Global Scale." *Procedia Engineering 70: 651-59. doi:10.1016/j.proeng.2014.02.071.*

Ferrante, Marco, Silvia Meniconi, and Bruno Brunone. 2014b. "Local and Global Leak Laws." *Water Resources Management 28 (11): 3761-82. doi:10.1007/s11269-014-0708-x.*

Greyvenstein B. and van Zyl J. E. 2007 An Experimental Investigation into the Pressure-Leakage Relationship of some Failed Water Pipes. In: *Journal of Water Supply: Research and Technology—AQUA*, vol. 56, no. 2.

Idelchik I. 1994 *Handbook of Hydraulic Resistance*. Begell House.

Lambert A. 1997 Pressure Management: Leakage Relationships. Theory, Concepts and Practical Application, Paper presented at *IQPC Seminar*, London.

Lambert A. 2000 What Do We Know About Pressure: Leakage Relationship in Distribution System? In: *System Approach to Leakage Control and Water Distribution Systems Management*, Brno, Czech Republic.

Lambert, A., Fantozzi, M., and Thornton, J. 2013 Practical approaches to modeling leakage and pressure management in distribution systems–Progress since 2005. In: *Proc., Int. Conf. on Computing and Control for the Water Industry.*

Lambert, A. 2014 PressCalcs pressure management concepts software, Version 5b, User documentation, ILMSS Ltd, www.leakssuite.com/software/presscalcs/.

May J. H. 1994 Leakage, Pressure and Control. In: Proceedings of the BICS International Conference Leakage Control Investing In Underground Assets, The SAS Portman Hotel.

Schwaller, J, and J. E. van Zyl.(2014a). Implications of the Known Pressure-Response of Individual Leaks for Whole Distribution Systems. In: *Procedia Engineering 2014 (70): 1513-17.*

Schwaller J. and van Zyl J.E. (2014b) Modeling the Pressure-Leakage Response of Water Distribution Systems Based on Individual Leak Behavior. In: *ASCE, J. Hydraul. Eng.*

Ssozi, E.N., Reddy, B.D. and Van Zyl, J.E. (under review) Effect of viscoelastic deformation on the pressure-leakage behavior of plastic pipes. In: *ASCE, J. Hydraul. Eng.*

Van Zyl J.E. and Cassa A.M. 2014 Predicting the pressure-leakage relationship : technical paper. In: *Water & Sanitation Africa*, vol. 9, no. 2

Van Zyl J.E. and Clayton C.R.I. 2007, The effect of pressure on leakage in water distribution systems, In: *Proceedings of the ICE-Water Management*, 160 (2), 109-114