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MODELLING PRESSURE - LEAKAGE RESPONSE IN WATER DISTRIBUTION SYSTEMS CONSIDERING LEAK AREA VARIATION.

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ABSTRACT.

Research has shown that area of leak openings varies linearly with pressure under both elastic and viscoelastic conditions. However, hydraulic modelling of water distribution systems currently uses a power function that does not explicitly take into account leak area variation with pressure. This function is commonly known as the N1 power equation.

This paper investigates the possibility of explicitly incorporating leak area variation into hydraulic modelling of water distribution systems. The FAVAD (Fixed And Variable Area Discharges) equation, which takes into account leak area variation with pressure, was incorporated into the widely used Global Gradient Algorithm (GGA) in EPANET.

A stochastic model was developed to generate and distribute leaks in a standard water distribution system. It was based on existing theories about leakage in water distribution systems, taking into account physical properties of the system. Thereafter, hydraulic simulations were run using both FAVAD and N1 equations.

The results show that the N1 power equation estimates the total system leakage with an error of up to 20%. On a specific junction, the leakage estimation error was found to be as high as 60%.

Keywords: Pressure, Leakage, N1-Equation, FAVAD-Equation, Pressure Management.

1 INTRODUCTION

1.1 N1 Power Equation

Hydraulic modelling tools, such as EPANET, model pressure-dependent demands using an emitter function, which is a power function:

$$Q = Ch^{N1} \quad (1)$$

Q = leakage flow rate,

C = leakage coefficient,

h = pressure head and,

$N1$ = leakage exponent.

Pressure management is the application of techniques to reduce excess pressure in an isolated zone of a water distribution system, with the aim of reducing leakage levels. The above function, which is also commonly known as the N1 power equation, is used widely by water utility practitioners when implementing pressure management.

The N1 power equation has the following disadvantages:

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

1.2 FAVAD Equation

Hydraulically, leaks are orifices and therefore should adhere to the orifice equation with fixed exponent of 0.5:

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

Q = leakage flow rate,

C_d = discharge coefficient,

A = leak area,

g = acceleration due to gravity and

h = pressure head.

Using finite element analysis under linear elastic deformation, Cassa & Van Zyl (2013), showed that leak area varies linearly with pressure irrespective of leak type, loading conditions, pipe material and section properties. Some experimental studies like Ferrante et al., (2012 and 2013), have also confirmed these results. Ssozi et al (2015) also investigated the impact of viscoelasticity on pressure – leakage relationship using finite element analysis and found a linear relationship. Thus, the relationship between leakage area and pressure may be described with the equation;

$$A = A_0 + mh \quad (3)$$

where A = leak area at head h ,

A_0 = initial leak area (area of leak under zero pressure conditions) and

m = head-area slope (potential of pipe to increase leak size under pressure).

Replacing the leak area (A) in equation 2 with equation 3, results in the FAVAD (Fixed And Variable Area Discharges) equation;

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

The FAVAD equation was first introduced by May (1994). The first term of equation 4 is identical to the orifice equation and describes leakage flow rate through the initial leak area, while the second term describes leakage flow rate through the portion of the leak area that has expanded due to pressure. FAVAD equation provides more realistic description of leakage behaviour for both individual and system leaks than N1 power equation, although it has never been incorporated into any standard hydraulic modelling tools. In this study, the FAVAD equation was incorporated into the widely used implementation of Global Gradient Algorithm (GGA) in EPANET.

Schwaller & Van Zyl (2014), developed a stochastic model for generating and distributing leaks in a water distribution system. These leaks adhere to FAVAD behaviour with the two FAVAD parameters, initial leak area (A_0) and the head -area slope (m). The same model was used as the basis for this research.

2 METHODOLOGY

2.1 Incorporating FAVAD concept into standard hydraulic modelling

The GGA in EPANET's hydraulic solver uses an emitter function, equation 5, to model pressure dependent demands like leakage;

$$Q_e = k(h)^{E_e} \quad (5)$$

Q_e = emitter flow rate

E_e = emitter exponent

k = emitter coefficient

h = pressure head.

This emitter function, was utilised to incorporate the FAVAD concept into standard hydraulic modelling. According to the FAVAD concept, total leakage through a leak is the sum of leakage through both the initial and expanding leak areas. Therefore, a second emitter function was added to the existing one (see equation 6), in which case the first/original emitter function models leakage through fixed leak area while the second/added one models leakage through expanding leak area.

$$Q_t = k_1(h)^{0.5} + k_2(h)^{1.5} \quad (6)$$

Q_t = total junction leakage flow rate

k_1 = first emitter coefficient ($C_d * \sqrt{2g} * A_0$)

k_2 = second emitter coefficient ($C_d * \sqrt{2g} * m$)

h = pressure head.

2.2 Stochastic model for generating and distributing leaks to a standard water distribution system

A stochastic model was used to generate and distribute FAVAD leaks with random parameters to a standard water distribution system. From this random but realistic distribution of leaks, 200 systems with different leak distributions were generated.

One of International Water Association's water distribution system performance indicators, the ILI (Infrastructure Leakage Index) was used to model leakage level. The ILI is defined as the ratio of current annual real loss to unavoidable annual real loss (Lambert, 2009). In this study, an ILI of 16 was considered realistic for a typical water distribution system.

The parameters that were statistically generated or calculated are; discharge coefficient, initial leak area, and head-area slope. Because the leak generation process is described in detail in Schwaller & Van Zyl (2014), only the main points are highlighted below:

- discharge coefficient (C_d) was modelled using a normal distribution.
- initial leak area (A_0) was modelled using lognormal distribution bounded by zero for background leaks, and a normal distribution for potentially detectable leaks since they can be easily found and repaired quickly in a system.
- head-area slopes (m) for background leaks with N1 close to 1.5 were calculated using equation 7. These background leaks have initial areas that close completely under zero pressure and their leakage number is 100, Cassa & Van Zyl (2013). Given the fact that it is not clear what percentage of background leakage could be due to this type of leaks, a fraction of 20% was used.
- head-area slopes of remaining background leaks plus potentially detectable leaks were calculated using a generalized power function of initial leak area, based on finite element study by Cassa and Van Zyl (2013).

$$m = \frac{L_N * A_0}{h} \quad (7)$$

Numerous leaks equivalent to an ILI of 16 were generated. Although the generating process was random, it was ensured that an accuracy of plus or minus 0.001% was archived. A leak was then randomly picked and allocated to a pipe. The allocation of leaks to pipes took into account system physical properties. A pipeline with high length was considered to have high probability of having leaks. Cumulative length of all pipes in the system was calculated, and a number between zero and the final cumulative length was randomly generated and used to identify the pipe on which to allocate the leak.

2.3 Modelling leakage flow rate with both FAVD and N1 equations

2.3.1 Before applying pressure management

Leakage was first modelled before applying pressure management, using both FAVAD and N1 equations. As the distributed leaks adhere to the FAVAD approach, each one of the 200 randomly generated systems, was simulated first using the

FAVAD approach, and then N1 approach. This was done by converting from the FAVAD to N1 format. Junction leakage and pressure were obtained in both approaches.

The conversion of leaks from FAVAD to N1 approach was done in the following steps:

- Calculate system leakage exponent (N1 value) at MNF (Minimum Night Flow) conditions,
- Calculate junction leakage coefficients at MNF conditions,
- Calculate the emitter coefficient and exponent and model it using the first emitter in the system (the second emitter is set to zero).

In order to calculate system leakage exponent, at MNF conditions, a data set of system leakage and AZNP (Average Zone Night Pressure), were determined. Pressure in the system was then reduced slightly and another set of system leakage and AZNP determined. From the two data sets, system leakage exponent (N1) was calculated using equation below;

$$N_1 = \frac{\log\left(\frac{Q_1}{Q_2}\right)}{\log\left(\frac{AZNP_1}{AZNP_2}\right)} \quad (9)$$

where Q_1 and Q_2 are system leakages and $AZNP_1$ and $AZNP_2$ are average zone night pressures before and after pressure reduction respectively.

With system leakage exponent and leakage at each junction during MNF conditions, junction leakage coefficient was calculated using equation below;

$$C = \frac{Q}{h^{N_1}} \quad (10)$$

where Q is the junction leakage flow rate at MNF conditions, h is the corresponding junction pressure head and N_1 is the system leakage exponent.

With leaks converted to N1 approach, an extended period hydraulic simulation was done and leakage flow rates plus pressure heads were determined.

2.3.2 After applying pressure management

Pressure management was then applied by reducing the level of water in the reservoir, from 125 to 75m, for both FAVAD and N1 approaches. An extended period hydraulic simulation was done and leakage plus pressure heads determined at each of the junctions.

2.4 Description of standard water distribution network used in the study

The network used in this study was adapted from EPANET's "Net3.net". The original "Net3.net" system has two sources, and it operates under pumping conditions. In this study the pumps were removed and only one source maintained, as shown in *Figure 1*. The head at the source, was adjusted to ensure that the range of pressures in the system under gravity were close enough to the original system that operated under pumping conditions. Total length of pipes in the system is 60 km, with pipe diameters ranging from 200 to 800mm.

2.4.1 Critical node

Before leaks were distributed into the standard water distribution system, a node was identified whose pressure was minimum during peak demand conditions. This node is referred to as a "critical node", and it is used in this study to give a representation of how leakage varies on an individual junction.

3 RESULTS AND DISCUSSION

3.1 Modelling FAVAD and N1 leakage at varying pressure values

A single period simulation was run during peak demand conditions, with both FAVAD and N1 approaches. Leakage was then modelled before and after applying pressure management. Different levels of pressure management were considered. Calculation of system N1 was done at the highest pressure, before pressure management. It is therefore evident that at the same pressure where the N1 calculation was done, leakage modelled with both FAVAD and N1 are close enough, as shown in *Figure 2*. However, as pressure is reduced further, significant differences in leakage are observed. This is because the N1 formulation is an empirical formulation that works in a given range of data set. If used outside the calibrated range of data set, the solution will be erroneous.

3.2 Volumetric percentage error in system leakage modelling after pressure management

An extended period simulation was done with both FAVAD and N1 approaches after applying pressure management. The error in system leakage was expressed as a percentage. Negative sign indicates that N1 approach underestimates leakage flow rate.

In about 30% of the systems simulated, the N1 approach was found to underestimate system leakage flow rate in the range of 11.2 to 9.6%. Some systems had a percentage error of up to 20%, see *Figure 3*.

3.3 Volumetric percentage error at individual junction

In order to understand the volumetric error on individual junctions, leakage on the critical node was considered in both FAVAD and N1 approaches. *Figure 4*, shows the percentage of networks with corresponding volumetric percentage errors. Also in this graph, the negative sign means that the N1 approach underestimates leakage flow rate. About 56% of the systems simulated, indicated that the percentage error is in the range of 46.25 to 33.75%. Some systems showed an underestimation of 60% while others showed an overestimation of up to 56%.

4 CONCLUSION

This paper investigated the possibility of incorporating leak area variation with pressure into standard hydraulic modelling. This was achieved through implementation of the FAVAD concept into the widely used global gradient algorithm in EPANET.

Simulation results showed that using N1 equation outside a pressure range used in calculating the N1 value, results in leakage estimation error. FAVAD and N1 equations gave similar leakage flow rates, when pressure was very close to the one used to calculate system N1. With further reduction in pressure, which is always the case in pressure management, the percentage error between the two approaches increased significantly.

The use of N1 equation in estimating leakage reduction by pressure management, should therefore be done with caution. This is because pressure management always involves reducing pressure, while the N1 value is calculated at high pressure.

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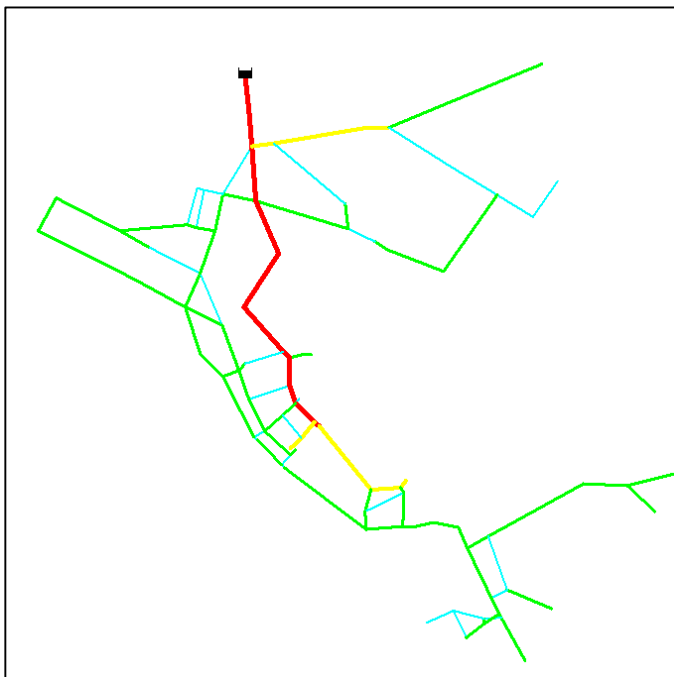


Figure 1: Pipe layout for adapted Net3

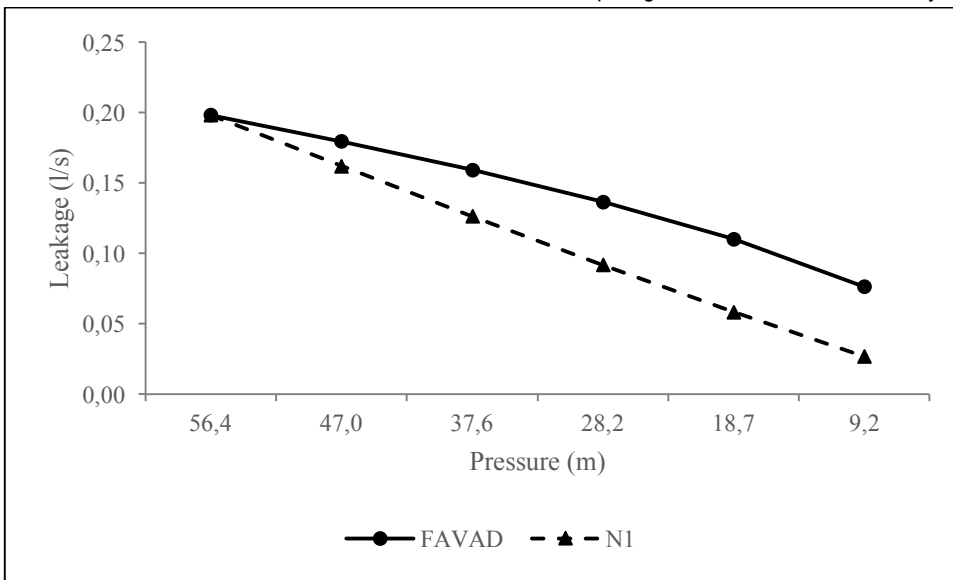


Figure 2: Leakage variation at critical node with varying pressure heads

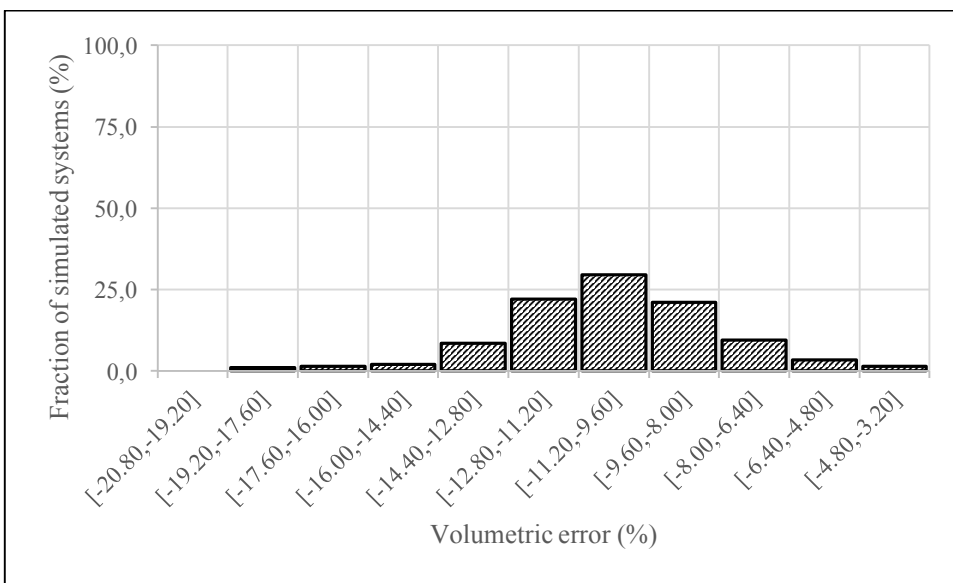


Figure 3: System volumetric error in leakage modelling

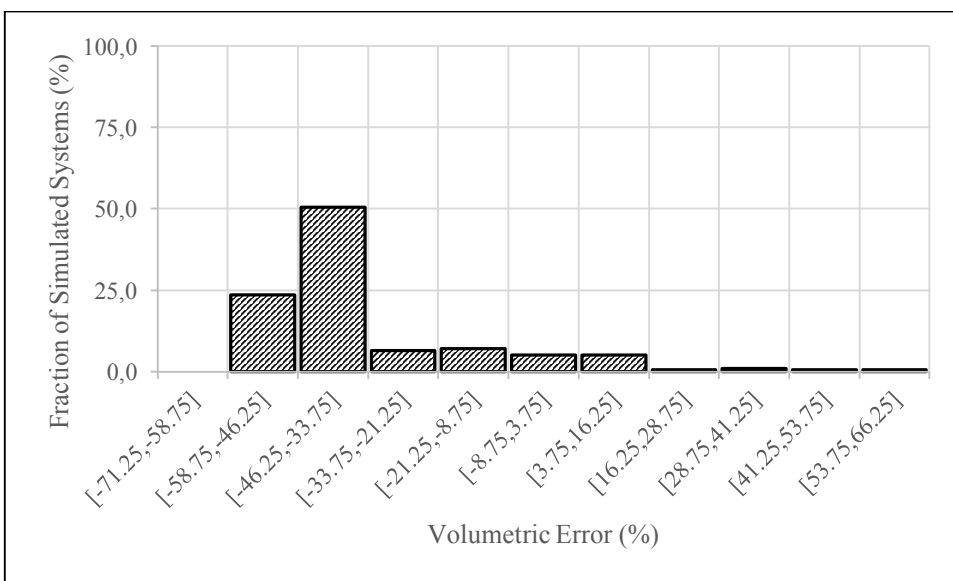


Figure 4: Volumetric error in leakage modelling at the critical node