Systematic estimation of discharge water due to transmission mains failure by the means of EPANET2

D. Fuchs-Hanusch*, M. Möderl, R. Sitzenfrei*** F. Friedl**** and D. Muschalla***

*Graz University of Technology, Institute of Urban Water Management and Landscape Water Engineering, Stremayrgasse 10/I, 8010 Graz, Austria; email: fuchs@sww.tugraz.at

**Province of Tyrol, BBA Innsbruck, Valiergasse 1, 6020 Innsbruck, Austria

***University of Innsbruck, Institute of Infrastructure, Technikerstraße 13, 6020 Innsbruck, Austria;

****Water distribution company, Grenzland Südost, Bahnhofstraße 20b, 8350 Fehring, Austria

Keywords: leakage outflow calculation, orifice equation, risk analysis

Introduction

Transmission water mains (TWM) are of high relevance for every water supply system. If leakage occurs, high amount of water can be lost and the consequences of such irregular conditions may be enormous. The impacts which are generated by TWM-failure make it necessary to understand the occurrence-probability of different failure modes (e.g. longitudinal crack, corrosion) as well as the associated consequences. The discharged amount of water, until the failure is identified and valves are closed, influences the TWM failure consequences. Therefore, the analysis described in this paper focuses on estimating discharge water due to different failure modes. The analysis is part of a research project funded by Vienna Waterworks which has the aim to develop a risk assessment methodology for (large-diameter) transmission mains (Friedl et al., 2012).

The water losses for different failure modes can be modelled with the orifice equation.

$$Q = ce.h^{ee} \tag{1}$$

It describes the relation between flow and pressure with a leakage-coefficient (ce) and a leakage-exponent (ee) with (ce) being a function of the orifice area (A) and the discharge coefficient (cd).

$$ce = cd * A * \sqrt{2g} \tag{2}$$

Various studies about the leakage-exponent (ee) can be found in literature (Lambert, 2001; Thornton and Lambert, 2005; van Zyl and Clayton, 2007, among others). On the contrary, investigations about material specific failure modes and orifice area are scarce. Hence, a detailed investigation on data of TWM failure origin from several Austrian supply systems was part of the research described in this paper.

In the following, a systematic approach for calculating failure mode dependent discharge rates by the means of EPANET 2 (Rossmann, 2000) is described. Therefore, a comprehensive literature review on emitter exponents is given. The results of a detailed investigation on typical failure modes and sizes in a case study area are shown. On basis of these investigations, the most probable discharge rates due to TWM failure in the case study area are calculated, described and interpreted in the results section.

Materials and Methods

Different information about an Austrian transmission mains system were available, to analyze the material, diameter, failure mode and specific average orifice area (A). Those were failure documentation forms, in situ examinations of pipe parts and expert opinions. The target was to derive material and failure mode specific “ce” values to be used in a systematic way within a hydraulic model. As the pipe specific information, like diameter and material type is determined in the hydraulic model or an underlying GIS, with a matrix for typical failure sizes of different failure modes, a suitable value of the parameter “ce” can be provided for each pipe in the entire system. Table 1 shows such a matrix for the case study system.

Table 1: Orifice area A (cm²) for different failure modes for an Austrian transmission mains system (amended from Friedl, et al. 2012)

failure mode	poly-ethylene	polyvinyl-chloride	asbestos-cement	concrete	cast Iron	ductile Iron	steel
circumferential crack	4-20 10[*]	4-20 10[*]	4-40 25[*]	-	8-50 25[*]	-	-
longitudinal crack	20-80 40[*]	20-80 40[*]	20-80 40[*]	-	20-80 40[*]	-	-
corrosion cluster	-	-	-	5-20 15[*]	5-20 15[*]	5-20 15[*]	10-80 50[*]
leaking joint	-	-	5-20 15[*]	5-20 15[*]	5-20 15[*]	1-5 5[*]	1-5 5[*]

[*] used for risk analyses

The discharge coefficient (cd) was generally set to 0.6. We derived this value from the results of Trout (1986), who defined the range for the size of the discharge coefficient cd between 0.438 and 0.673, depending on the geometry of the orifice area. Further, we took into account the results provided in Lambert (2001), where a relation between the size of cd and the Reynold´s number was demonstrated.

Based on work from Lambert (2001), Thornton and Lambert (2005), Van Zyl and Clayton (2007) and Cassa et al, 2010 a matrix with emitter-exponents (ee) for different materials and failure modes to be used for the calculations with EPANET 2 was derived. For material and crack types where no literature studies were found values of similar crack/material types were chosen.

Table 2: Emitter exponents for different failure modes derived from literature (amended from Friedl et al., 2012)

failure mode	poly ethylene	polyvinyl chloride	asbestos cement	concrete	cast iron	ductile iron	steel
circumferential crack	0.5[5]	0.4-0.5[1] 0.5[5]	0.5[4,5]	-	0.5-0.68[4] 0.5[5]	-	-
longitudinal crack	1.4-2.0[2] -2.0[3] 1.5[5]	1.4-1.9[1] 1.4-2.0[2] 1.5[5]	0.8-1.0[1,3] 0.9[5]	-	0.5-0.85[4] 0.85[5]	-	-
corrosion cluster	-	-	-	1.5[5]	1.5[5]	1.5[5]	0.7-2.3[1] 1.5[5]
leaking joint	-	-	0.61-1.26[2] 1.0[5]	0.61-1.26[2] 1.0[5]	0.61-1.26[2] 1.0[5]	0.61-1.26[2] 1.0[5]	0.61-1.26[2] 1.0[5]

[1]van Zyl und Clayton, 2005, [2]Lambert, 2001, [3]Thornton und Lambert 2005, [4]Cassa et al., 2010
[5]used for risk analyses

As an average time for the water discharge, 2 hours were defined. This is assumed to be the time window from the occurrence of the transmission pipe break to the closing of all relevant valves. It is assumed that the time between occurrence and discovery of big events is neglectable, as, due to the high discharge rates, such breaks are reported quickly.

Results

The discharge estimations of TWM according to specific failure modes have been realized by means of a one at a time sensitivity analysis of water distribution systems (Möderl et al., 2011). For one node after the other, pressure-dependent discharge rates are modelled with the emitter-function of the software EPANET 2. The failure modes longitudinal crack and circumferential crack, corrosion cluster and leaking joint can be investigated with this method with the purpose to identify the most vulnerable pipes on these specific failure modes.

As the chosen emitter exponent is expected to have a significant influence on leakage outflow, the sensitivity of the simulation results on the emitter exponent was analyzed first. Longitudinal cracks and leaking joints were of special interest as the literature values for ee vary significantly for these failure modes (see Table 2). To analyze the input parameter sensitivity, the leakage outflow of each node was first simulated with the lower boundary of the parameter range and afterwards with the upper boundary. The leak size was set similar in both simulations.

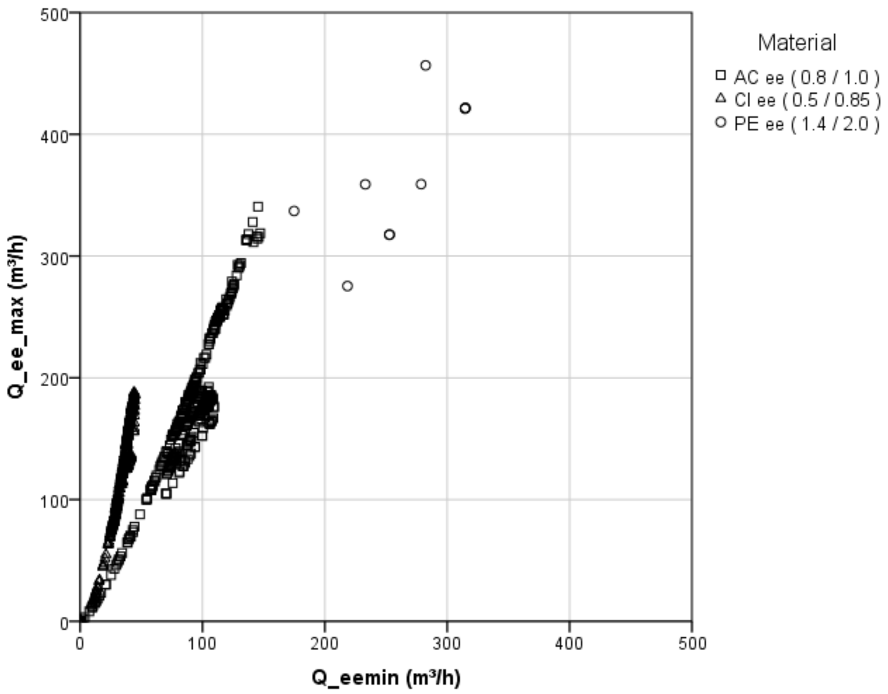

Figure 1: Comparison of leakage outflow for longitudinal cracks (width=2mm; length = 1m; A = 20cm²) and different emitter exponents (ee) in a partial transmission mains system of Vienna

Figure 2 shows that for polyethylen (PE) pipes, where the literature values for ee range between 1.4 and 2 the difference in the calculated leakage outflow of the longitudinal crack is not as severe as for cast iron pipes, where ee values between 0.5 and 0.85 are suggested in literature. On basis of these results, the emitter exponents for further systematic leakage outflow calculations were set as follows (see also Table 2 values x[5]**Table 1**):

- For cast iron (CI), to be on the safe side, ee was set 0.85;
- for PE the value ee is set to 1.5
- for asbestoscement (AC) ee is set 0.9 again with the purpose to be on the safe side for pipe burst consequences calculations.

Besides the dependency of leakage outflow on the emitter exponent, it is obvious that the orifice area, respectively the size of the crack, is of high significance too. Hence, for the case study transmission pipe systems the parameter range of already occurred pipe bursts was analyzed in previous work (Friedl, et al 2012 and Table 1). Again, simulation runs were undertaken for as well the lower as the upper boundary of the value range. The emitter exponent was fixed as defined in Table 2.

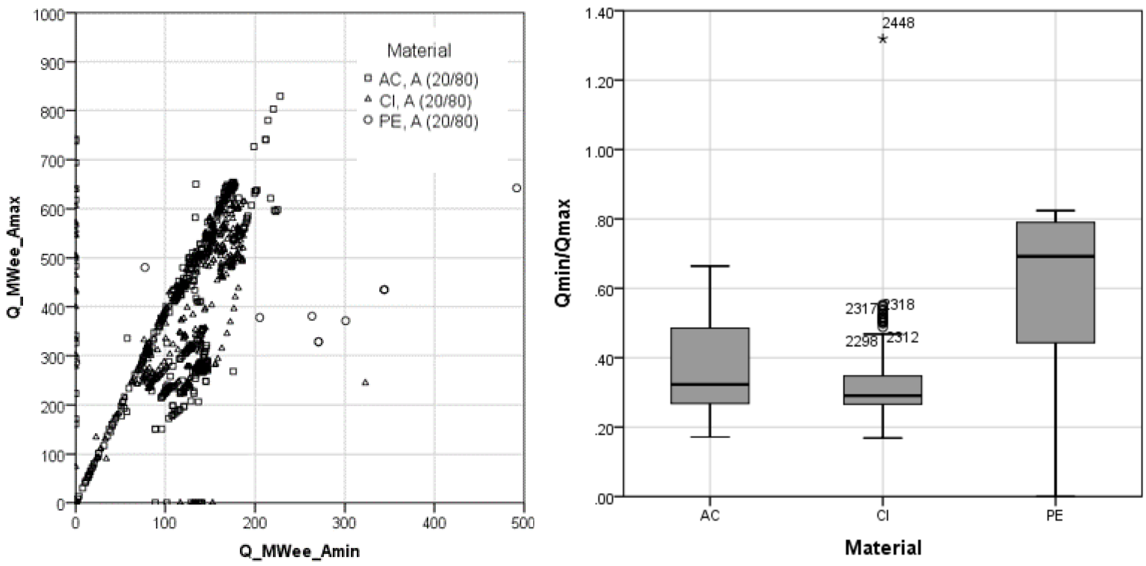

Figure 2: Leakage outflow for longitudinal cracks of different leak size (Amin = 20cm²; Amax = 80cm²) and fixed emitter exponents in a partial transmission mains system of Vienna

Figure 2 shows that for AC and CI, the influence of the crack size on leakage outflow for many of the pipes is linear (e.g. a 4 times as big leak size causes 4 times as big leakage outflow). This results from the power law as the value of the emitter exponent for CI and AC is near “1”. On the contrary for PE pipes, the variation of the leak sizes causes lower variations in leakage outflow (see box plot in Figure 2). The findings according to leak sizes and the corresponding leakage outflow were discussed with responsible engineers at Vienna Water. For the risk analyses the leak sizes were afterwards defined as given in Table 1 (values x*).

Figure 3 shows the final leakage outflow map for the failure mode “longitudinal crack” in a of the case study transmission system.

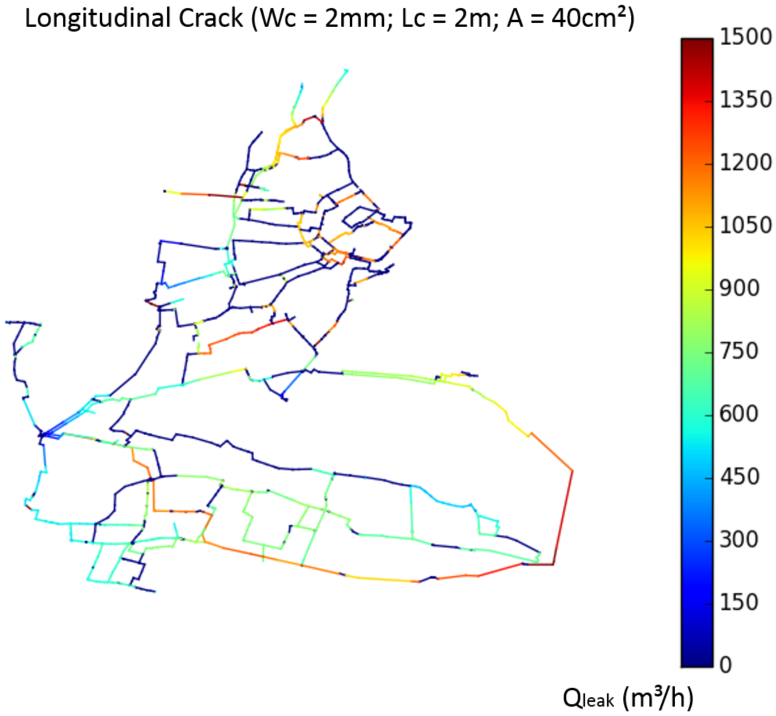

Figure 3: Pressure and material specific leakage outflow (m³/h) for the failure mode "longitudinal crack" in a partial transmission mains system of Vienna.

By using spatial overlay with failure mode probability maps (Friedl et al., 2012) failure mode specific risk maps can be derived (Figure 4). Those can be used as a basis for maintenance and rehabilitation measures.

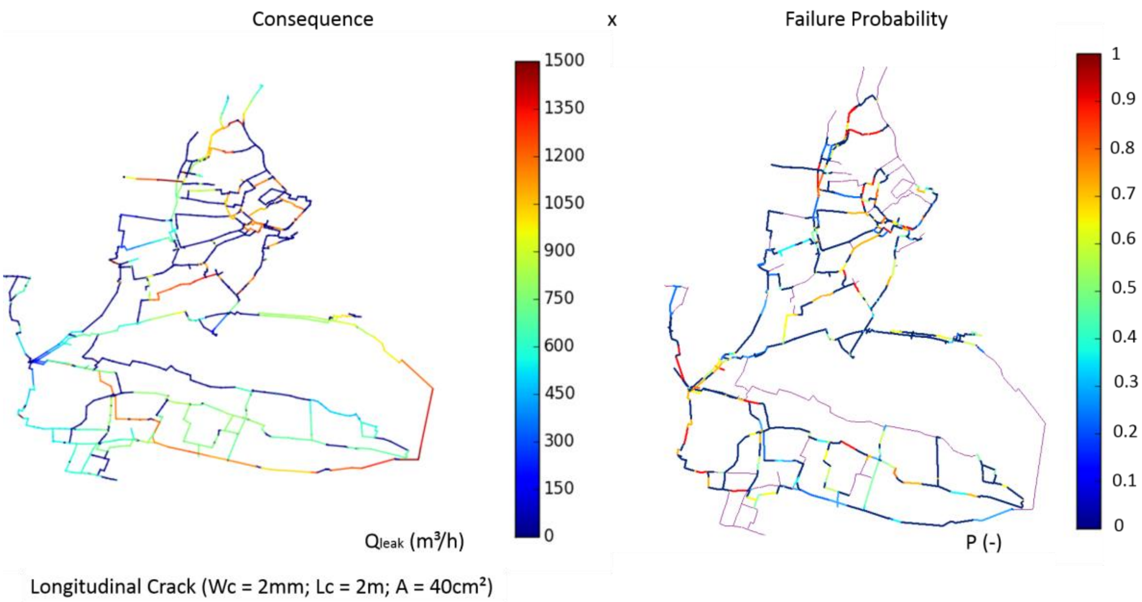

Figure 4: Example for a risk analyses based on leakage and failure probability estimation to identify pipes with as well high failure probability as high leakage outflow

Summary and Outlook

Water loss, third party damage and health risks caused by TWM failure force not only to understand the probability of such failures, but also the associated consequences. The consequences of a pipe burst have a strong relation to the discharge rate of the burst. Failure mode, pipe material, orifice area and pressure are the main influences on the discharge water of leakage. Therefore, failure and material type specific matrices were derived for the main parameter of the orifice equation (equation 1), which are the emitter exponent (ee) and the emitter component (ce) to be used in the hydraulic simulations with EPANET 2. These matrices allow modeling the failure mode and pipe specific leakage outflow for further use in e.g. rehabilitation or maintenance planning.

To derive proper values for the matrices a sensitivity analyses helped to identify the influence of the input parameter on the leakage outflow. According to the definition of significant crack areas, detailed investigations in the supply system of interest were essential. Therefore in the case study area of Vienna Water the most relevant crack sizes for different failure modes and material types were derived from expert opinion and failure reports. For this case study area, pipe burst risk maps could be generated by spatial overlay of leakage outflow maps with failure mode probability maps, which were derived in additional research (Friedl, et al. 2012). The maps were finally used by Vienna Water to select pipes for internal inspections.

Finally an outlook on our ongoing research on this topic involves resent findings of van Zyl et al., 2014, where the dependency of pressure driven leakage outflow on not only material parameter and crack type but also on the initial crack area size is shown. The bigger the initial crack area the higher the additional pressure dependent crack area slope. As modelling leakage with EPANET 2 so far is limited to the power law in further steps of our research an implementation of the findings of van Zyl et al., 2014 into our systematic leakage modelling tool was of interest and will be presented in Fuchs-Hanusch, et al., 2014.

References

Rossman L.W. (2000), EPANET 2 Users Manual, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH 45268.

Cassa, A. M., J. E. van Zyl and R. F. Laubscher (2010). "A numerical investigation into the effect of pressure on holes and cracks in water supply pipes." *Urban Water Journal 7(2)*: 109-120.

Fuchs-Hanusch, D., Günther, M., Steffelbauer, D. and D. Muschalla (2014): Impact of pressure, failure mode and crack size on leakage outflow, World Environmental and Water Resources Congress, 1.6.2014 - 4.6.2014, Portland, USA

Friedl, F., Möderl, M., Rauch, W., Liu, Q., Schrotter, S. and Fuchs-Hanusch, D. (2012). Failure Propagation for Large-Diameter Transmission Water Mains Using Dynamic Failure Risk Index. EWRI 2012, ASCE - American Society of Civil Engineering, Albuquerque, USA.

Lambert, A. (2001). What do we know about pressure-leakage relationships in distribution systems? Systems approach to leakage control and water distribution system management, Brno, Czechoslovakia.

Möderl, M., Hellbach, C., Sitzenfrei, R., Mair, M., Lukas, A., Mayer, E., Perfler, R., and Rauch, W (2011). GIS based applications of sensitivity analysis for water distribution models. *EWRI 2011 ASCE - American Society of Civil Engineering Palm Springs*, California, USA.

Trout, T.J. (1986): Orifice Plates for furrow flow measurements,1. Calibration. *Transactions of the Asae*, Vol. 29(1), p. 103-106

Thornton, J. and Lambert, A. (2005). Progress in practical prediction of pressure: leakage, pressure: burst frequency and pressure: consumption relationships. Leakage Conference 2005.

Van Zyl, J. E. and Clayton, C. R. I. (2005). The effect of pressure on leakage in water distribution systems. *Proceedings of the Institution of Civil Engineers-Water Management 160 (2)*, 109-114.

van Zyl, J. and A. Cassa (2014). "Modeling Elastically Deforming Leaks in Water Distribution Pipes." *Journal of Hydraulic Engineering 140(2)*: 182-189