Determination of the corresponding roughness height in a WDS model containing old rough pipes

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ABSTRACT

The aim of the paper was to determine the influence of irregular pipe wall roughness on the flow velocity in a water distribution system (WDS) containing old pipes. Field studies have shown that due to pipe wall build-up, the shape of the inner pipe surface can vary temporally and spatially. This will lead to unrealistic pipe roughness values when calibrating the WDS model using nominal pipe diameters. Therefore, in this study, three types of pipe wall build-up were investigated using EPANET2 and computational fluid dynamics to estimate the velocity correction coefficients for EPANET2 calculations. It was shown that in old rough pipes, the mean velocities are higher than expected, indicating that in water quality estimation in a WDS, actual pipe diameters with reasonable roughness need to be defined.

Key words | CFD, old pipes, pipe wall build-up, roughness, WDS modelling

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INTRODUCTION

The determination of the roughness height in engineering pipelines, e.g., water distribution systems (WDSs) that contain old rough pipes, is essential to calculate the corresponding pressure drop in the system. In addition, information about real pipe diameters and flow dynamics is very important for estimating the propagation rate of the contaminated zones in a WDS at various threats, including natural disasters, pollution accidents and malicious actions (Boxall *et al.* 2004; Annus & Vassiljev 2015; Vassiljev & Koppel 2015; Kanakoudis & Tsitsifli 2017; Tsitsifli & Kanakoudis 2018). Therefore, models and methods capable of accurate prediction of turbulent flows over rough surfaces are needed. Most correlations of roughness are restricted to surfaces whose geometry is easily described and unable to cope with irregular surfaces (Jimenez 2004). The typical calibration of a numerical model of an existing WDS that contains old pipes is usually based on the roughness estimation of the pipes using nominal pipe diameters. Alternatively, the estimated water consumption at nodes can be adjusted (e.g., Kanakoudis & Gonelas 2015a, 2015b). However, due to build-up, the shape of the inner wall can vary significantly over the pipe length, resulting in non-homogeneous cross-sections. In the calibration procedure, the pipe wall build-up is compensated by adjusting the roughness value (Lansey *et al.* 2001). This approach does not take into account that the developed irregular wall roughness elements greatly complicate the flow dynamics (Christensen *et al.* 2011). Therefore, the usage of nominal pipe diameters in the modelling process is not always justified.

In a number of review articles (e.g., Jimenez 2004; Flack & Schultz 2010), different methods and approaches regarding the surface roughness in fluids engineering have been analysed. The works of Nikuradse (1933), Colebrook & White (1937), Colebrook (1939) and Moody (1944) are well known and widely used but somewhat limited in their applications. The question remains how pressure drop in piping systems relates to the particular roughness topography and more importantly to the irregular pipe cross-sectional shape. Over the years, a number of experimental and numerical studies have been conducted using pipes with regular roughness (corrugated pipes) to analyse the flow

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dynamics (e.g., Vijiapurapu & Cui 2007, 2010; Stel *et al.* 2010, 2012; Calomino *et al.* 2015), but just a few of these used pipes with irregular surface elements (e.g., Christensen *et al.* 2011). At regular wall roughness, the distinction between *d*-type and *k*-type roughness can be made, indicating whether the grooves sustain stable circulation vortices that isolate the outer flow from the roughness or form recirculation bubbles that reattach ahead of the next rib, exposing it to the outer flow (Jimenez 2004). This enables the use of different methods for deducing the corresponding roughness height. But real old pipe surfaces generally have a range of roughness scales. Moreover, the shape of the pipe inner wall is often distorted, leading to misjudgement of the effective pipe diameter (or effective pipe cross-section) and the corresponding mean velocity. Therefore, the hydraulic diameter concept is used to take into account different shapes of the cross-section. Based on the literature, Herwig *et al.* (2008) listed three different approaches on how to determine the hydraulic diameter D_h of a rough pipe. Because of the limitations, they proposed an additional option where D_h could be measured without opening the channel or pipe. This would mean that one has to determine the real volume V of the pipe segment, e.g., by measuring how much fluid it takes to fill the rough pipe. This is not applicable to an operational WDS as the pipes are laid underground.

Different studies carried out in Tallinn, Bergen and Athens WDSs (e.g., Kändler 2002; Kanakoudis 2004; Vreeburg & Boxall 2007; Vreeburg *et al.* 2009) have shown that the build-up of pipe inner surface is not only time-dependent, but it is also affected by the water quality, the cross-sectional area, how sensitive is the pipe material towards corrosion, the concentration of carbon dioxide in the water and the velocity in the pipes. Typically, the roughness is not evenly distributed over the perimeter and length, making it hard to estimate the average roughness. Inspections in water systems in Bergen, Norway and Tallinn, Estonia have shown that the nominal pipe diameter can be reduced up to 50%. Flow variations in WDSs could lead to sedimentation in pipes (Vreeburg *et al.* 2009), and velocity changes cause sediment settling in the lower half of the horizontal pipe (at low velocities) or settling on the entire pipe wall (at higher velocities) (Vreeburg & Boxall 2007). Carrying capacity failures due to pipe wall build-up may prevent the network from constantly satisfying customers water needs and cause poor quality of the delivered water (Kanakoudis 2004).

Analyses of the pipe specimens taken from the real WDS have indicated that three types of roughness build-up can occur (Figures 1(a)–1(c)) – evenly distributed roughness where roughness height is up to 10 mm (representative to areas where ground water is used), unevenly distributed roughness where roughness height can be up to half a diameter and sometimes even block the flow (representative to areas where surface water is used) and sediment settling in the lower half of the pipe (representative to areas with a low flow velocity).

In this study, three typical pipe wall build-up cases were investigated numerically using EPANET2 and computational fluid dynamics (CFD) to determine the effect of roughness and pipe diameter on the pressure drop and flow velocity. EPANET2 is a common tool for modelling WDS, but the

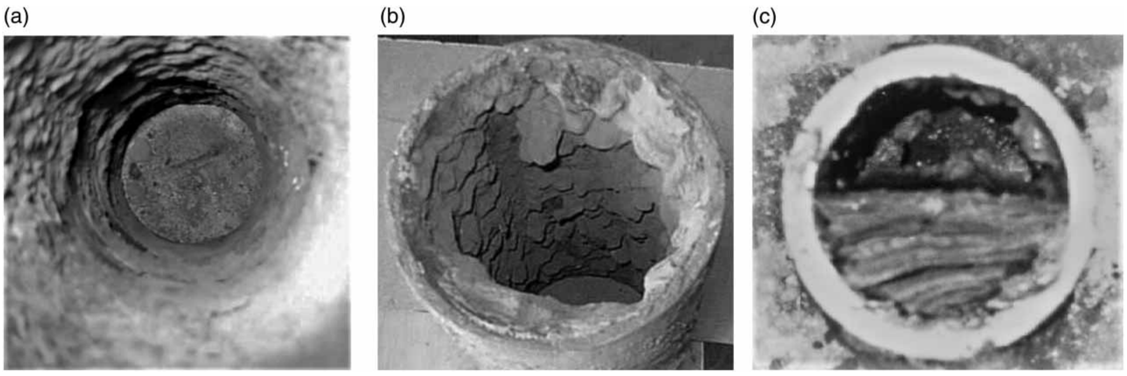

Figure 1 | Typical pipe wall build-up: (a) evenly distributed roughness; (b) unevenly distributed roughness; and (c) sediment settling. Samples from Tallinn WDS (Kändler 2002).

software does not enable to simulate pipes with non-homogeneous cross-section and/or pipe wall build-up. Therefore, the focus was on the improvement of the EPANET2 simulation procedure of a WDS that contains old rough pipes. CFD results were used to deduce the velocity correction coefficients for EPANET2 water quality analysis. The paper is based on the results obtained in Kaur *et al.* (2018) but with a substantial extension of the CFD analysis. The data analysis in this study is more comprehensive.

MATERIALS AND METHODS

Pipe wall build-up (regardless of the type) will always result in a decrease of the actual effective diameter. The change in the pipe wall build-up may be the same along the length of the pipe section, but the shape of the cross-section remains round (evenly distributed pipe wall build-up) and may vary along the pipe length, but the shape of the cross-section remains round (unevenly distributed pipe wall build-up) or the shape of the pipe cross-section changes along the pipe length (sediment settling). In this study, all three typical pipe wall build-up scenarios were considered. In reality, the pipe wall build-up is a mixture of these three cases. The investigation of all typical cases enables to generalize and apply the results in any given old rough pipe.

Type 1. Pipe diameter decreases due to the pipe wall build-up evenly along the pipe length. This case can be solved very easily using EPANET2. If the flow rate and pressure drop are known, the pipe roughness can be estimated using a simple optimization procedure. Typically, this will lead to quite large roughness values. Therefore, it is more appropriate to estimate the corresponding pipe diameter at the same flow rate and pressure drop if the pipe roughness is 1 mm. This roughness value represents a typical pipe wall build-up of a cast iron pipe at evenly distributed roughness (Idelchik 2008).

Type 2. Pipe diameter decreases due to the pipe wall build-up unevenly along the pipe length. This leads to an irregular pipe inner wall surface and cross-section. In this study, a CFD model of a circular pipe was used, and a random pattern was created (Figure 2), which was 'bruised' into the pipe wall to mimic the inner surface of a typical old rough pipe. The random surface pattern was applied to the test pipe surface at 2, 4, 6 and 8 locations over the pipe length both on the top and bottom side (Figure 3). Pipes

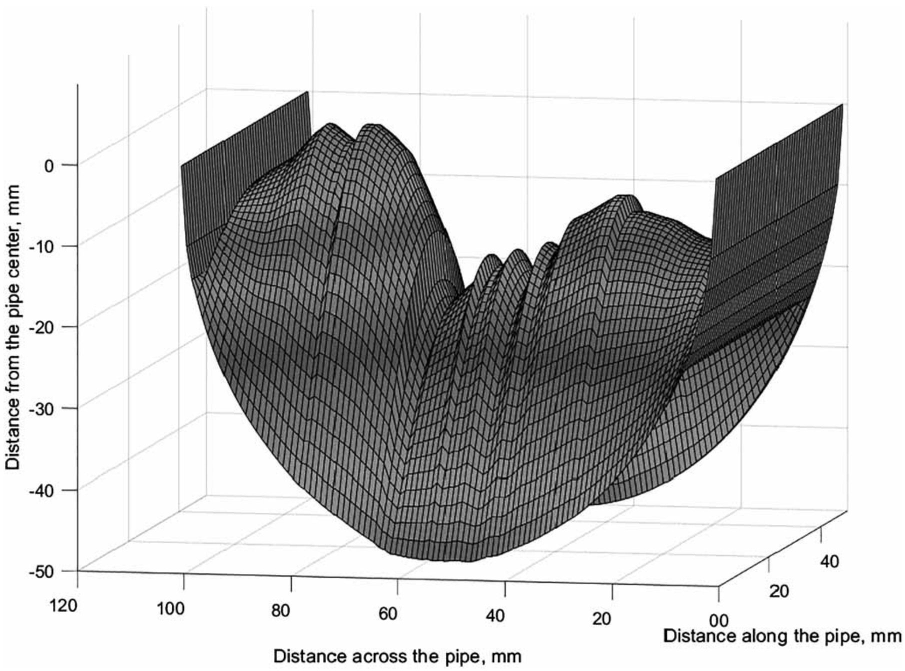

Figure 2 | 3D visualization of a random surface pattern.

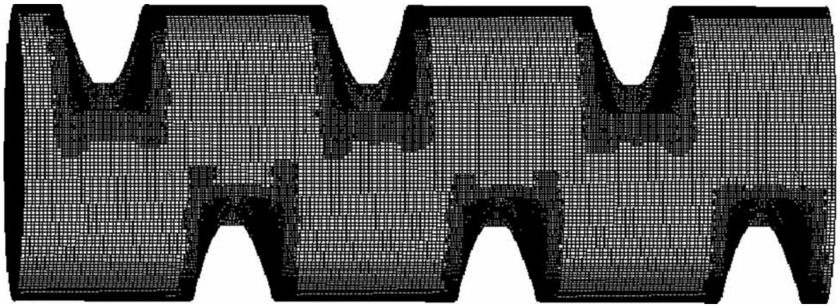

Figure 3 | Locations of the changed pipe inner wall shape over the pipe length (pipe length 0.5 m, diameter 100 mm).

with a nominal inner diameter of 100 and 200 mm were analysed. In the case of a larger pipe, the test segment length, the distance between the patterns and the patterns height were increased two times. CFD was used to deduce the corresponding flow rates at different pressure drops.

Type 3. The shape of the pipe cross-section was not circular and remained the same along the pipe length. CFD was used to deduce the corresponding flow rates at different pressure drops. In total, eight different pipe configurations were studied – settlement height at the pipe bottom was 0.15, 0.34, 0.5 and 0.75 of the pipe diameter for pipes with the nominal inner diameter of 100 and 200 mm (Figure 4). It was assumed that the settlement height is constant along the pipe length.

3D analyses of the flow dynamics were conducted in OpenFOAM v1712 using a pressure-based solver with a segregated solution algorithm and a two equation RANS model for turbulence. In two of the most commonly used RANS turbulence models, two extra transport equations for turbulent properties of the flow are solved. The transported variables are the turbulent kinetic energy k and the turbulent dissipation ϵ or the specific turbulence dissipation rate ω, depending on the model chosen. The two transport equations are solved to determine the scale and energy of turbulence. As described in detail by Wilcox (1998), for boundary-layer flows, the k–ω model is superior both in its treatment of the viscous near-wall region and in its accounting for the effects of streamwise pressure gradients. More specifically, the advantages of using the ω equation instead of the ε equation are: (i) the second is easier to integrate (more robust); (ii) it can be integrated through the sublayer without a need for additional damping functions and (iii) it performs better for flows with weak adverse pressure gradient. One of the weak points of the Wilcox model is the sensitivity of the solutions to values for k and ω outside the shear layer (free stream sensitivity).

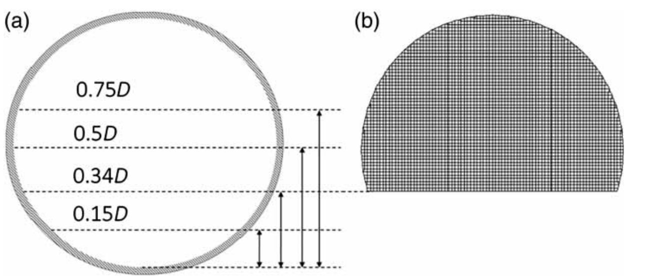

Figure 4 | (a) Numerically tested settlement heights 0.15*D*, 0.34*D*, 0.5*D* and 0.75*D* as measured from the pipe invert and (b) computational domain cross-section of a pipe representing settlement height 0.34*D*.

In Annus *et al.* (2016), different turbulence models were compared with experimental results gained in a pipe with a sudden change in diameter, using 2D particle image velocimetry (PIV). The measured and the modelled velocity and kinetic energy distributions over the pipe segment length and perimeter were analysed. The standard k–ω model showed the best qualitative and quantitative correlation with the experimental results when using standard turbulence model coefficients. Therefore, in this study, the CFD analyses were performed using the standard k–ω model.

Description of the pipe models

In the CFD calculations, models of a 0.5 and 1 m long pipe segment with a nominal inner diameter of 100 and 200 mm were used. The models were modified to mimic the irregularity of the pipe inner surface (type 2) or the change in the shape of the pipe cross-section (type 3). In the case of type 2, a random surface pattern was created (Figure 2) and 'bruised' into the pipe wall in 2, 4, 6 or 8 locations over the pipe length. The random pattern was applied to the test pipe surface both on the top and bottom side (Figure 3). In the case of type 3, the shape of the pipe cross-section was changed to mimic a pipe with the settlement at the bottom (Figure 4). Four different settlement heights were used in the analysis.

The computational domain was divided into ~750,000 mesh cells. The mesh consisted of hexahedrons with a minimal mesh size of 1.2 mm and a maximal mesh size of 2.4 mm. The grid distribution over the cross-section was uniform. Different mesh sizes and distributions were used to study the sensitivity of mesh parameters and the stability of the solutions. A special method that converts a volume mesh into a predominantly Cartesian mesh (i.e., the mesh consists of mostly hexahedral elements, with faces that are aligned with the coordinates axes) was used. In the case of local complex geometry, smaller elements were used, and the interfaces between the different size elements were non-conformal. The convergence criteria for x-, y- and z-velocity components, ω and k, were set to 0.0001.

The calculations for all three cases were performed at 11 different pressure drops between the pipe segment inlet and outlet, varying from 50 to 2,500 Pa over the 0.5 or 1 m long pipe specimen. This corresponds to typical average velocities in WDS, ranging from 0.25 to 2.5 m/s. The pipe surface roughness of type 1, 2 and 3 models was set to 1 mm. CFD was used to calculate the corresponding flow rates at different pressure drops for different pipe types. Thereafter, a simple optimization procedure was used in EPANET2 to estimate the pipe wall roughness at the same flow rates and pressure drops. Results of the CFD and EPANET2 calculations are presented in the next section.

RESULTS AND DISCUSSION

In this section, the CFD and EPANET2 calculation results are presented for all three pipe types. An overall idea was to deduce the velocity correction coefficient for each pipe type based on the estimated roughness value gained using EPANET2.

For type 1 pipe, the analysis was conducted in EPANET2 for pipes with an initial inner diameter of 100 and 200 mm. Flow rates were calculated for 11 different pressure drops at six different pipe wall roughness values (Table 1). The initial values of the pipe wall roughness were selected randomly taking into account the range of the roughness values gained in the case of calibrating models of the real working WDS in Tallinn, Estonia. A simple optimization procedure was developed to deduce the corresponding pipe inner diameter; in case, the pipe roughness would be 1 mm for each of the pipe wall roughness value. This enabled to find a relation between the EPANET2 estimated pipe roughness and the corresponding velocity correction coefficient:

$$v_{\mathrm{cor}} = \frac{A_{\mathrm{in}}}{A_{\mathrm{c}}}$$

where A_{in} is the pipe cross-section calculated using the nominal inner diameter and A_{c} is the corrected pipe cross-section using the estimated pipe diameter.

Results for the pipe with a nominal diameter of 100 mm are given in Table 1.

The dependence of the velocity correction coefficient and relative roughness for pipes with even pipe wall build-up is given in Figure 5.

Table 1 | Velocity correction coefficients for type 1 pipes

Pipe wall roughness (mm)	Nominal pipe diameter (mm)	Initial pipe cross-section (mm^2)	Estimated pipe diameter in case of 1 mm roughness (mm)	Corrected pipe cross-section (mm^2)	Velocity correction coefficient
1.46	100	7,853.98	97.6	7,481.51	1.05
6.2	100	7,853.98	87.3	5,985.75	1.31
22.6	100	7,853.98	75.8	4,512.62	1.74
50	100	7,853.98	66.9	3,515.14	2.23
100	100	7,853.98	57.1	2,560.72	3.07
200	100	7,853.98	43.2	1,465.74	5.36

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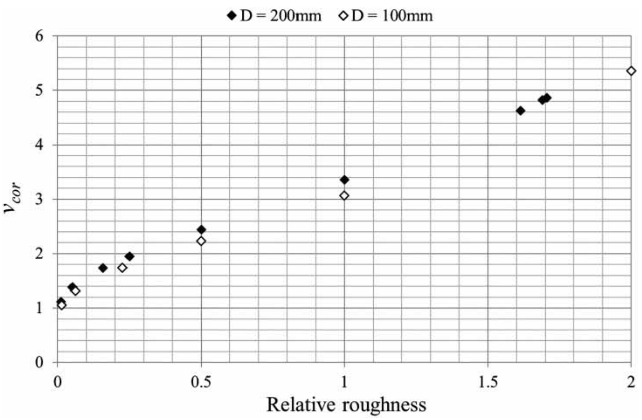

Figure 5 | Dependence between the velocity correction coefficient and the relative roughness (type 1).

In the case of type 2, CFD was used to calculate the corresponding flow rate at different pressure differences for eight random pipe surface patterns. The pressure drop between the pipe inlet and the outlet was changed from 50 to 2,500 Pa. Calculations were performed for pipes with an initial diameter of 100 and 200 mm. The number of pipe wall deformations for both pipes was 2, 4, 6 and 8. The complex pipe inner wall shape leads to complex flow dynamics and different interactions between the developing vortices near the deformed wall elements. The flow rate in the pipe segment depends both on the shape and the number of pipe wall deformations and the distance between them. Therefore, a set of eight different pipe segment configurations were analysed to generalize the results.

The calculated flow rates at different pressure drops were used as input data in EPANET2 to estimate the corresponding roughness values. In order to estimate the average effective diameter in CFD calculations, eddy convections were excluded from the overall volume (Figure 6).

This enabled to calculate the corresponding velocity correction coefficient at different relative roughness values. For each pipe configuration, one average velocity correction coefficient was deduced (Figure 7).

In the case of type 3, the shape of the pipe cross-section was changed due to the bottom settlement. Therefore, it was necessary to use CFD in order to estimate the effect of the settlement on the flow rate. Calculations were performed at 11 pressure differences using two nominal pipe diameters (100 and 200 mm) and four settlement heights. In the first step, CFD was used to calculate the flow rates at different

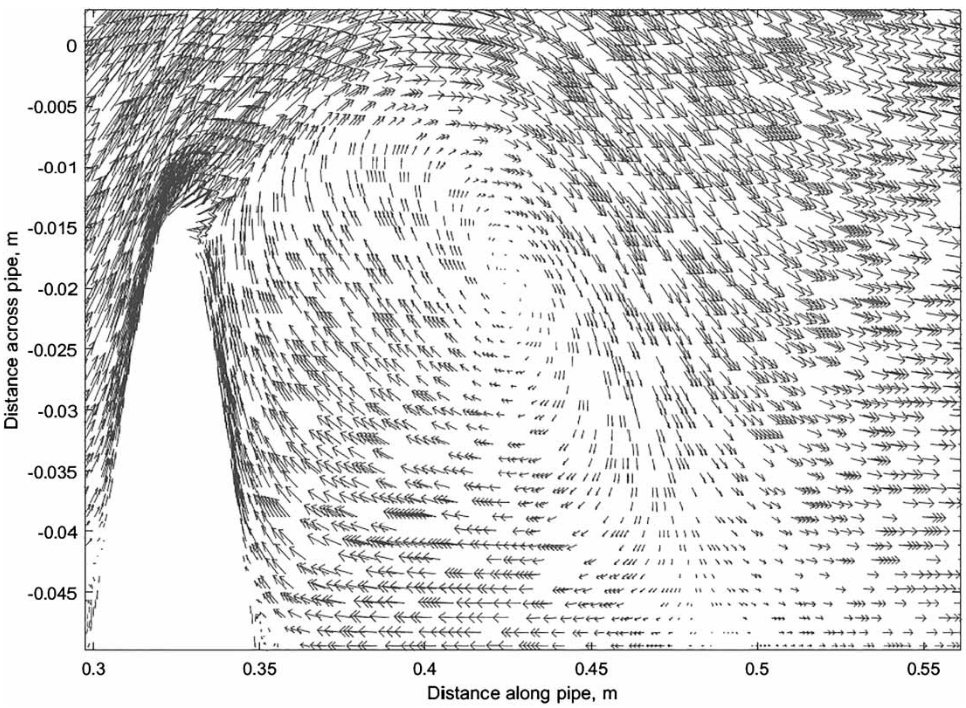

Figure 6 | Eddy convections near the roughness elements.

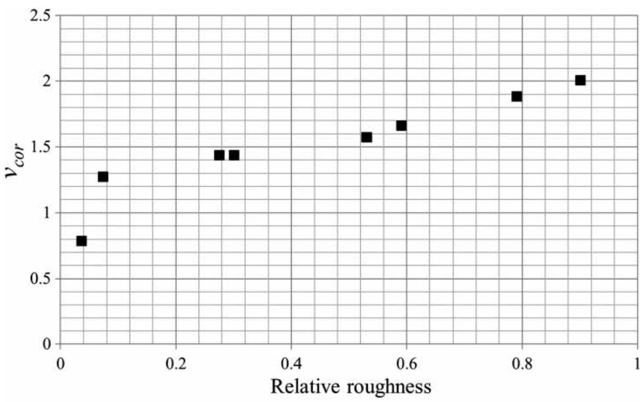

Figure 7 | Dependence between the velocity correction coefficient and the relative roughness (type 2, $D = 100$ mm and $D = 200$ mm).

pressure differences. Then, the flow rates were used as input in EPANET2 to find the corresponding roughness values at the same flows and pressure differences. In the third step, a simple optimization procedure was used in EPANET2 to estimate the corresponding pipe diameter of a circular pipe (to calculate A_c) at the same flow and pressure conditions at the wall roughness of 1 mm. The analysis showed that the dependence between the relative roughness and the velocity correction coefficient is similar to type 1 pipes (Figure 8).

The analysis of different pipe wall build-up types revealed that in the case of old rough pipes, the estimated roughness values in EPANET2 can lead to unrealistic results where pipe wall roughness is larger than the nominal radius of a pipe. This is caused by the restriction that the shape of the pipe cross-section and/or the diameter are fixed and changes in the pressure drop are compensated only by the change in the pipe wall roughness value. Therefore, the roughness values calculated in EPANET2 at the same pressure drop and flow rate were up to 200 times higher than in the CFD model. Moreover, the roughness values at the same pipe configurations and different flow rates were not constant. This will lead to significant errors in WDS water quality modelling. Therefore, it is suggested that in the case of old rough pipes, it should be taken into account that roughness is dependent on the Reynolds number ($Re = vd/\nu$), and real pipe diameters should be estimated while keeping the roughness values in a physically reasonable range (Annus & Vassiljev 2015). This can be achieved by reducing the pipe diameters. Reduction in pipe diameters leads to an increase in flow velocities, which is crucial when estimating, e.g., the propagation of contamination in the WDS. Therefore, it is necessary to adjust the flow velocities according to the relative roughness values gained during the calibration procedure in EPANET2. In reality, the pipe wall build-up shape is a mixture of the three cases analysed in this study. The trend of the velocity correction coefficient is similar regardless of the build-up shape (Figure 9), which makes it possible to generalize the results for any given wall build-up configuration.

The determination of real flow velocities in old rough pipes remains a challenge, as even with extensive data collection, it is impossible to determine the pipe roughness values for all links (Mallick *et al.* 2002). Echávez (1997) reported that in galvanized iron pipes, the roughness can

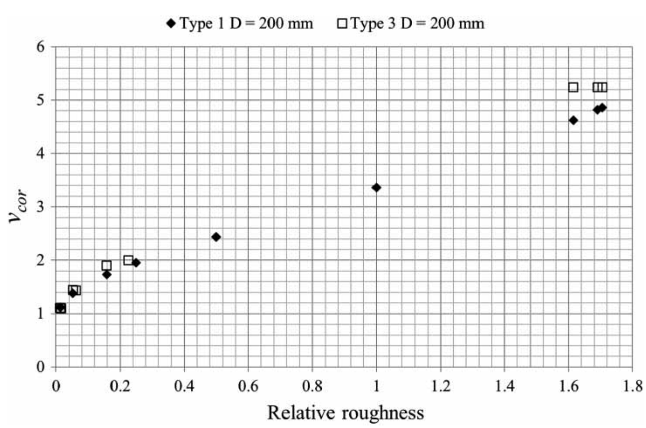

Figure 8 | Comparison of the dependence between the relative roughness and the velocity correction coefficient for type 1 and type 3 pipes.

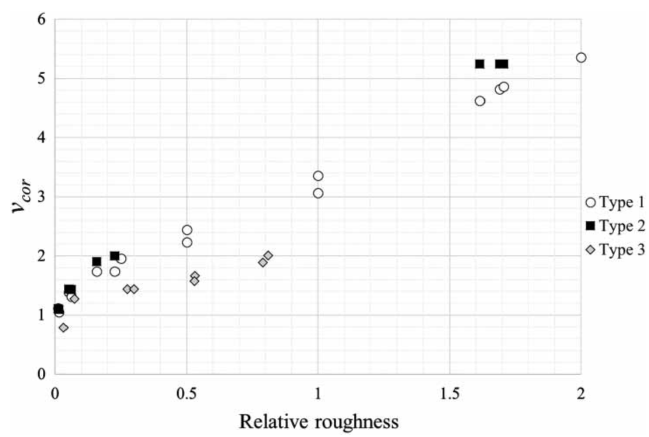

Figure 9 | Dependence between the velocity correction coefficient and the relative roughness (for all pipe types, $D = 100$ mm and $D = 200$ mm).

increase as much as 2.13 mm/yr leading to a considerable increase in loss coefficients and a decrease in actual diameter that eventually can close the pipe completely. Volumetric measurements of pipes that varied in age from 25 to 50 years and in nominal diameter from 20 to 100 mm indicated that the largest reduction in flow area was estimated to 23% as compared to a new pipe. Modelling this pipe without accounting for changes in flow area would result in modelled flow velocities being 23% lower than actual velocities (Christensen 2009). This would lead to considerable errors in water quality modelling.

Therefore, the ageing process of pipes should rather be described by the reduction of their diameter and the increase of their absolute roughness than by the increase of absolute roughness only. It is especially important in water quality modelling and defining flow parameters in extreme conditions (e.g., fire flows). Thorough CFD modelling carried out in this study revealed that in the case of pipes with uneven pipe wall build-up, the streamlines in a pipe with the deformed cross-section curve and the effective pipe diameter decreases compared to the nominal diameter. This is confirmed by the experimental investigation carried out in a pipe with a sudden change in diameter (Annus *et al.* 2016, 2019) and experimental and numerical investigations carried out in real old pipes (e.g., Christensen 2009; Christensen *et al.* 2011). Calculations showed that the mean velocity in EPANET2 is underestimated up to 200%. This is of significance when modelling the propagation rate of the contamination in a WDS. The diameter of old pipes is not homogeneous along its length and the flow conditions in the conduits should be taken into account while calibrating the WDS model.

CONCLUSIONS

Field studies have shown that the pipe wall build-up can be classified into three types. In this study, the effect of different roughness and pipe wall shapes was taken into account to estimate the velocity correction coefficients for EPANET2 calculations. The study showed that in old rough pipes, the mean velocities are higher than expected, indicating that in the modelling of the propagation of contamination in a WDS, actual pipe diameters with reasonable roughness need to be defined. When using nominal diameters, it has to be reckoned that pipe wall roughness is not constant at different flow rates (Re numbers). This will enable decrease of modelling errors in EPANET2 or other WDS modelling software.

It was shown that in type 1 pipes, the roughness value estimated by EPANET2 can exceed the pipe radius. This corresponds to a pipe with a diameter reduction of 57% and roughness of 1 mm. In such a case, EPANET2 underestimates the real flow velocity more than five times. In type 2 pipes, the velocity correction coefficient is dependent both on the shape and the number of local disturbances that generate local vorticities and reduce the effective pipe diameter. The analysis showed that the flow velocity can be underestimated up to two times. In type 3 pipes, the dependence between the relative roughness and the velocity correction coefficient is similar to type 1 pipes, indicating that the influence of secondary flows developing in non-circular pipes was insignificant.

Pipe wall build-up and sedimentation settling may reduce the pipe nominal diameter of more than 50%, which will lead to unrealistically large roughness values in WDS model calibration. Actual pipe diameters should be estimated and used in the WDS calibration, which will lead to more realistic roughness values and average flow velocities. The latter is very important in water quality modelling and risk assessment. In addition, proper restoration actions like systematic pipe flushing and/or scraping have to be implemented to remove settled materials from the pipe walls and to prevent carrying capacity failures.

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