Failure mechanisms and condition assessment of PVC push-fit joints in drinking water networks

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ABSTRACT

This paper presents and discusses the significant role played by joints in the failures registered in drinking water distribution networks. The three most important failure mechanisms related are presented and a procedure to detect them through the visual measurement of the gap between pipes inside a joint is proposed. The procedure is proved to be a valuable source of information on joint condition after the assessment of a 600-m DN500 PVC pipe.

Key words | CCTV, condition assessment, field inspections, joints, PVC

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INTRODUCTION

Background information

Millions of kilometres of pipes are used everyday to supply drinking water to customers around the world. Occasionally these pipes burst and in some countries burst-related data are systematically registered in databases. In the Netherlands, the data included in the growing national mains failure database (USTORE) cover the period 2009–2011. Five water companies participate in the project and the length of the network available on the database is above 50,000 km, almost 50% in polyvinyl chloride (PVC) (Geudens 2010). Of all failures, around 29% are detected at joints (irrespective of pipe material), and over 9% of all failures are detected at PVC joints. USTORE is thoroughly discussed in Vloerbergh & Blokker (2010). Other authors have also presented results that underline the important role played by joints in the failures registered in drinking water networks.

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Dingus *et al.* (2002) discussed data from 46 of the largest AwwaRF (now Water Research Foundation) member utilities. The companies filled in a questionnaire. For the transmission systems, the number one problem was joint leaks/failures (35%), irrespective of the pipe material. For the PVC distribution systems less than 15% of the total number of problems was due to a problem in a joint.

Burn *et al.* (2007) discussed data collected through a survey from utilities in Australia (nine utilities), Canada (four utilities) and the USA (four utilities). The total length of pipes in the collective networks was above 97,000 km, of which around 12,000 km was PVC. For the PVC networks, the percentage of failures registered as joint leak ranged from 1% up to 38%, averaging 16%.

The data analysed by Reed *et al.* (2006) were obtained from a questionnaire to seven utilities from the UK (one), the USA (four) and Canada (two). The total mains population was 33,247 km, being cast iron dominant (40% of length) and PVC the fourth most used material (11%). PVC joint failures were dominated by gasket/seal failure (55%). The primary cause of joint failure for mechanic joints in non-metallic pipes (asbestos cement, reinforced concrete and PVC) was ground movement.

Arai *et al*. (2010) surveyed the Japanese water companies and obtained information on leakages related to water distribution pipelines that occurred during 2004 and 2005. The Japanese network is composed of approximately 600,000 km of water pipelines. More than 40% of the total number of failures were detected at joints. When focusing on PVC, more than 60% of the failures were detected at joints.

These results indicate that joints play a major role in PVC network failures. Given the focus of the literature on pipe barrel deterioration this role might have been overlooked in the past.

Recently, Liu *et al*. (2012) argued that 'information on the current structural condition of individual water mains [and joints], combined with a good understanding of failure modes and deterioration models, can greatly enhance the ability of water utilities to manage their assets in a cost-effective manner'. It could be added that this information should be as accurate as possible, and that this can only be obtained from in-line inspections with non-destructive evaluation (NDE) equipment. During an NDE inspection and/or afterwards during analysis, operators and analysts should focus on detecting distress indicators on the pipes or joints. According to Rajani & Kleiner (2004) these are forms of deterioration that have not yet led to pipe or joint failure. Among the distress indicators presented by the authors are cracks, corrosion pits and broken prestressing wires. However, no distress indicators were defined for PVC joints. This might be explained by the fact that PVC has only been used on a large scale since 1960 and that long-term deterioration mechanisms are not well documented for PVC mainly because they are very slow (Rajani & Kleiner 2001). Breen *et al*. (2004) also argued that the lifetime of PVC material that is well processed, well installed and applied under relative mild service conditions will exceed 50 years and possibly 100 years. Therefore, the objectives of the present work are to identify the appropriate distress indicators – failure mechanisms – for PVC joints and develop an NDE inspection procedure to detect them.

CONCEPTS

The Dutch jointing system

Around the world the bell-and-spigot jointing system is used in PVC networks. In the Netherlands, PVC pipes are connected with double-socket PVC joints. These are standalone pieces that have two rubber gaskets and connect two pipes. While the rubber gaskets keep the system sealed, the pipes are separated inside the joint by a ring. This ring can be part of the joint or, in smaller diameters, a separate piece. This ring creates a gap between the pipes (Figure 1).

Ideal and threshold conditions of a joint

A PVC joint is designed to bend. The ideal condition or alignment of a joint can be defined as the alignment inside the joint that minimizes the occurrence of stress within the joint and allows for a certain movement of the pipe. In this situation, the pipes inside the joint are perfectly aligned along their axis and are not touching each other or the joint's inner-wall (Figure 2). Reversely, the threshold

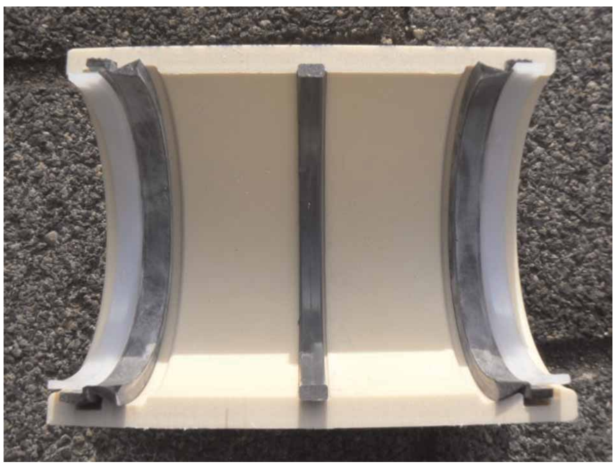

Figure 1 | Longitudinal cut of a double-socket DN110 PVC push-fit joint. At the centre a ring (black) separates both the two pipes inside the joint. At each end a rubber gasket (black) keep the system sealed.

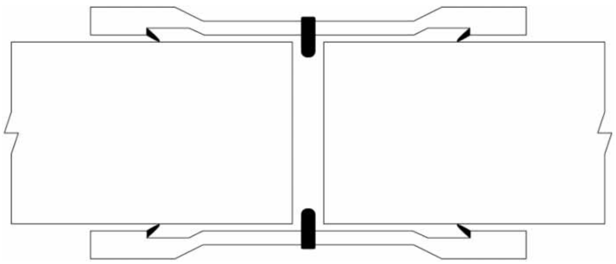

Figure 2 | Ideal joint condition (not to scale).

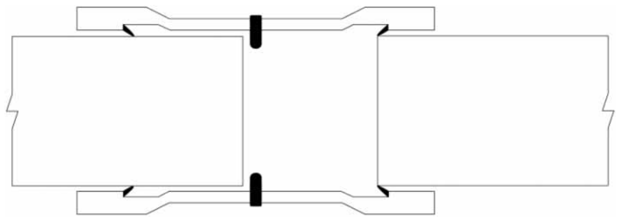

Figure 3 | Alignment of a joint during axial displacement. The pipe on the right-hand side is almost pulled out from the rubber gasket (not to scale).

condition of a joint is an alignment inside the joint for which a slight variation in the joint's alignment leads to a failure.

Joint failure

A joint is considered to have failed only in the following situations: (1) the joint is broken (circular or longitudinal break), (2) the rubber gaskets are leaking, or (3) a part of the pipe wall inserted in the joint is broken.

Failure mechanisms

Arsénio *et al*. (2009) discussed thoroughly failure in push-fit joints and presented failure mechanisms obtained from the literature. The three most important failure mechanisms related to joints.

Axial displacement

Longitudinal tensile stresses in water mains causing axial movements may be induced through temperature changes, ground movements and tensile forces. For example, water mains will contract (axially and to a minor extent circumferentially) upon a subsequent drop in water and ground temperatures (Rajani *et al*. 1996). The same authors showed that the axial strain due to the contraction or expansion of pipes is not constant throughout the pipe length. As expected, the portion of the pipe near the joint is freer to move than the centre of the pipe. Axial displacement can also occur due to the Poisson effect or due to installation procedure (Figure 3).

In fact, with an axial contraction of the pipe, a complete pull-out of the pipe from the inside of the rubber ring can occur. This leads to joint leakage. The pipes can also move towards each other (e.g., pipe expansion due to temperature increase) and this may lead to contact between pipe and joint and between the two pipes and to joint/pipe breakage. The length of a 10-m PVC barrel can vary 8 mm over a temperature variation of 10–25 °C, considering a linear expansion coefficient for PVC of 54 μm/m.K (AWWA 2002).

Joint bending

Underground structures (pipes and joints) are compelled to move with the surrounding soil. Some of the major causes of axial bending or beam action in a pipeline are as follows (Moser & Folkman 2008):

- Uneven bedding support. This can result from unstable foundation materials, uneven settlement due to overexcavation and non-uniform compaction and scouring, for example, due to a leaking joint (Rajani & Tesfamariam 2004).
- Differential settlement. This effect is especially important in wastewater networks when a pipe is rigidly connected to a manhole and both structures settle at different rates.
- Ground movement. This can happen due to earthquakes or expansive soils. Frost heave can also play a role.

Usually, soil movement can be mitigated with an appropriate selection of the pipe material most appropriate to a specific soil, proper preparation and compaction of the foundation and bedding materials of the pipe to be installed. In fact, the soil properties used in the embedment and compaction of the backfill are the most important factors and the highest deflections are expected in subsiding sensitive backfills such as peat and clay (Lange 2003). If the movement of the soil is uniform, no problem will arise with the pipe since the whole pipe will move as a single structure. However, in the presence of differential soil settling, different sections of the pipe will experience different levels of settlement. When the bending angle exceeds a threshold value, contact points arise between the pipe and the joint or, in extreme situations, between the two pipes inside the joint. Figure 4 presents some contact points inside a joint. These contact points lead to high bending moments longitudinal tensile stresses in the pipe, which may induce pipe or joint burst (Rajani *et al*. 1996).

Push-fit joints allow a slight bending of the pipes connected to it. The maximum bending angle depends on the material type and on the inner shape of the joint. This inner shape depends on the manufacturer, on its pressure rating and on its diameter. Special types of PVC joints also allow higher bending angles due to their inner conformation. To the knowledge of the authors, no laboratory tests have been performed to determine the maximum bending angles for PVC push-fit joints. The standard procedure to test PVC joints (ISO 13783: 1997) is not aimed at determining the maximum limit condition of a joint (e.g., maximum bending angle) before breakage/leakage, but the minimum tolerable conditions (e.g., minimum applied bending force) without leakage.

Pipe bending

Pipe bending is not a failure mechanism for joints but may be related to joint bending. Two consecutive bent joints may be connected through a bent pipe.

Longitudinal bending of a long tube in a horizontal plane will produce vertical ring deflection due to the bending moments created (Reissner 1959). The level of this deformation is mainly governed by the installation procedure and is related to the material used in the embedment and its

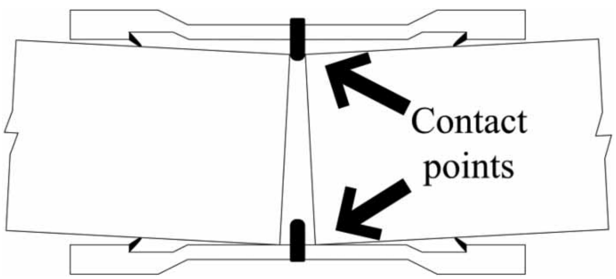

Figure 4 | Alignment of a joint during bending (not to scale).

compaction. With pressurization, the pipe tends to reacquire its round shape with decrease of the deflection (Lange 2003).

Typically, tensile hoop strains would be anticipated when a pipe is subjected to water pressure. However, large hoop stresses can arise either as a result of radial internal, external loads, temperature change and axial stress (Rajani *et al*. 1996). External pressure is caused by soil or traffic (Rajani & Kleiner 2001). Freezing of moisture in the soil causes an increase of the ring stress, due to the expansion of the soil (Rajani & Kleiner 2001). Another cause of increased hoop stress is the response of water mains to pressure surge (Rajani *et al*. 1996).

Due to the increase in hoop stress, longitudinal breaks can occur in the pipes and in the joint (Rajani *et al*. 1996; Lange 2003; Bailey & Kaufmann 2006). Due to the differences in stiffness between the pipe and the joint, hoop stress will have more influence on the pipe than on the joint, which may lead to leakage of the joint.

MATERIALS AND METHODS

Joint angle

All aforementioned failure mechanisms can be detected by analysing the alignment of the pipes inside a joint. Other failure mechanisms (e.g., slow crack growth) cannot be detected using this approach. Inside a joint there is a gap. For a double-socket PVC joint the gap is the separation between the two pipes connected inside a joint. Different alignments of the pipes will correspond to different shapes of the gap. By measuring the width of a gap at four different locations (12 h, 3 h, 6 h and 9 h), its three-dimensional orientation can be determined with the help of simple trigonometry. One angle is obtained for the pair of gap widths '12 h–6 h' and another for the pair of gap widths '9 h–3 h'. The angle between positions '*i*' and '*j*' is given by the following expression:

$$\text{Angle}_{i-j} = 2 \times \arcsin \times \left(\frac{\text{Gap width}_i - \text{Gap width}_j}{2} \middle/ \text{OD} \right) \quad (1)$$

In this expression, OD is the outside pipe diameter in mm. To use this expression it is assumed that both pipes ends were cut perfectly perpendicular to the pipe's axis. Therefore, for the pipe alignment inside a joint, several situations are hypothesized:

- Ideal alignment: the joint will show the same gap at the four measured points.
- Axial pull-out: the angle for the pair 12 h–6 h and for the pair 9 h–3 h is equal to zero. The threshold distance depends on the joint's dimensions.
- Joint bending: the angle calculated with Equation (1) is not equal to zero. For the 12 h–6 h pair, a positive angle is obtained when the gap at 12 h is wider than the gap at 6 h. For the 9 h–3 h pair, a positive angle is obtained when the gap at 3 h is wider than the gap at 9 h. Joint bending can be decomposed into pure bending and axial pull-out.
- Pipe bending: a pipe can be considered to be bent when both the joints to which it is connected have the angles with the same signal.

Field inspection

The objective of the inspection was to gather information on the present condition of the PVC joints, and to test the inspection procedure in real life. For each joint the gap width at 12 h, 6 h, 3 h and 9 h was registered.

According to Dingus *et al.* (2002) the most promising idea at the time of their research was an ultrasonic system mounted on a pig. However, ultrasound inspection requires the pipe to be filled with water. Therefore, for the present work, CCTV was selected because the pipe to be inspected was empty. An IBAK Modular II system with an Argus 4 camera was used. Arsénio *et al.* (2010) present a comparison between CCTV and ultrasound inspection of PVC push-fit joints. A DN500 PVC pipe was inspected. The pipe was installed in 1975 in sand and in 2011 a burst occurred. After the burst, the pipe was taken out of service and emptied. Access to the pipe's interior was made through the burst section. In total, approximately 600 m of pipe were inspected. The inspection took 4 h and 54 joints were inspected. For each joint the gap widths for the crown, invert and both springlines were obtained (Figure 5).

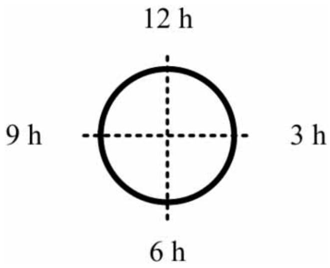

Figure 5 | Schematic drawing of a pipe (cross-section in which the pipe positions 12 h (crown), 6 h (invert), 3 h and 9 h (springlines) are given).

Root mean squared errors

The pipes at a joint can have deviations from an ideal alignment and the gap at one point (e.g., 12 h) can be higher/lower than the gap at the opposite side (e.g., 6 h). In order to quantify which one of the pairs (12 h–6 h or 9 h–3 h) deviated more from a perfect alignment, the root mean squared errors (RMSE) is calculated. The minimum value for the RMSE is zero when all the joints are perfectly aligned along either:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (\mathrm{pred} - \mathrm{obs})^2} \quad (2)$$

In this equation 'pred' is the predicted value [mm], 'obs' is the observed value [mm]. The observed value is the gap width measured with CCTV and the predicted value is obtained considering that the gaps at opposing locations (e.g., gap at 6 h = gap at 12 h) have the same value. n is the number of samples and i refers to the ith sample. RMSE will have the same units as the measurements [mm].

RESULTS

Figure 6 presents the gap width at the pipe's crown (12 h) plotted against the gap width at the pipe's invert (6 h) – a black circle (•) represents an inspected joint. With the exception of two joints, all joints align below the $x = y$ dashed line. This indicates that the gaps at 6 h are larger than the gaps at 12 h – the pipe is sagging at the joints.

Figure 6 also plots the gap width at one springline (9 h) plotted against the gap width at the opposite springline

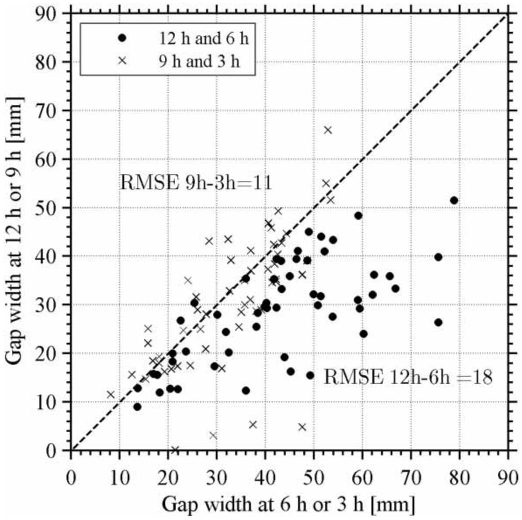

Figure 6 | Joint gap at one position (9 h or 12 h) vs. the joint gap at the opposite position (3 h or 6 h). The dashed line represents $x = y$. For the pair 12 h–6 h a value below the line indicates that the gap at 6 h is wider than the gap at 12 h. For the pair 9 h–3 h a value below the line indicates that the gap at 3 h is wider than the gap at 9 h. The RMSE is given both for the pairs 12 h–6 h and 9 h–3 h in mm.

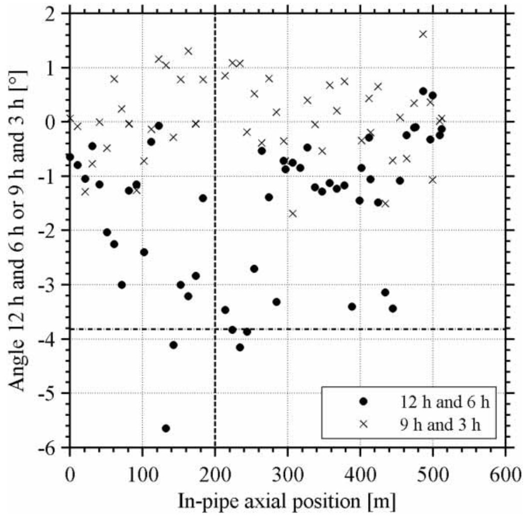

Figure 7 | Angle values for each inspected joint using the CCTV (Equation (1)). The vertical dashed line ($x = 200$ m) represents the point where the burst occurred. This was the CCTV's access point. The AWWA guideline for installing a PVC pipe is presented as a horizontal dashed line (pipe angle = 3.82°).

(3 h) – a cross (×) represents one inspected joint. As can be seen, with the exception of four joints, the values of gap width for all joints are nearly aligned along the $x = y$ dashed line. This indicates that the pipe moves more along the vertical plane than along the horizontal plane. This is confirmed by the RMSE that is lower for the 9 h–3 h pair (11 mm) than for the 12 h–6 h pair (18 mm) by more than 60%. No explanation was found for the four unaligned joints, these values are distributed over the pipe length.

Figure 7 gives the joint angles for the pair 12 h–6 h. A negative angle indicates that the gap at 6 h is bigger than the gap at 12 h, or that the gap at 3 h is bigger than the gap at 9 h. The vertical dashed line ($x = 200$ m) represents the point where the burst occurred.

The AWWA guideline dotted line was calculated using Equation (3) (AWWA 2002). It calculates the maximum bending angle that is permitted when two consecutive barrels are installed. During installation, the system will not be stressed if the bending angle is below this limit:

$$\beta = \frac{57.3 \times L}{300 \times D} \quad (3)$$

in which L is the length of a pipe barrel (10 m), D is the outside pipe diameter (0.5 m). β is the recommended installation angle (3.82°). It should be mentioned that β gives no information about allowable bending angles throughout a pipe's life. However, since no threshold conditions for pipes are available, the AWWA guideline value is used to characterize the angle values obtained from the pipe's inspection.

For the 12 h–6 h pairs, two angles were positive, the remaining were negative. Five joints have bending angles below the AWWA guideline. These joints are located in the vicinity of the burst point. Considering that most joint angles were negative (joint gap at pipe invert wider than gap at crown), the pipe would be above ground, assuming that the barrels were not bent (deformed). However, since this situation was not detected, it is concluded that the pipe was sagging below the joints and that the barrels were bent along the length. No extreme values are detected for the 9 h–3 h pair and no angle has a value close to the AWWA guideline limit. Angle values are larger for the 12 h–6 h pair than for the 9 h–3 h pair.

DISCUSSION

The inspected pipe was shown to be sagging at the joints. Little lateral movement was detected. In fact, for the

9 h–3 h pair there is no joint angle with an absolute value above 2°. For the 12 h–6 h pair, close to the burst point ($x = 200$ m), a total of five joints with angles below the AWWA limit were detected, one angle is $-5.8°$ (Figure 7). Bending may create contact points between the joint's inner wall and the pipe and even between the two pipes inside a joint. Both the contact points and the bending create stress on the pipe. Excessive stress leads to a joint or pipe barrel failure.

For the present situation, the extreme bending angles detected close to the burst point indicate several barrels close to the burst point were bent and, therefore, subjected to stress. It is hypothesized that the pipe failed due to extreme stress and that a pre-emptive inspection would have detected the extreme bending angles and a decision to replace part of the pipe/the whole pipe could have been made, avoiding the failure of the pipe.

An attention point with the utilization of NDE is the access to the pipe's interior. This requires adapting the existing network. In the present case the pipe was accessible through the burst point. In the future, important transport mains can be equipped from installation with access points for inspection. Despite the present work being focused on PVC networks and on the Dutch push-fit joints, the principles discussed here can be applied to all push-fit joints irrespective of material type. Other NDE tools can also be used.

Considering that it is difficult to access a pipe for inspection, the presented procedure can be used optimally in the following situations:

- Inspection of a burst pipe (the present case)
- Inspection of important pipes (e.g., large transport mains)
- Inspection of a problematic pipe before deciding on replacement.

The three aforementioned situations minimize the problems of accessing the pipe and/or maximize the importance of the obtained data.

In the present work, it is considered that the current shape of the gap is indicative for the condition of the joint. This procedure can be used to periodically inspect pipes. The development of the gap, observed with repeated inspection, is a measurement of its degradation and can be indicative for the lifetime expectancy of the joint.

The next step will be characterizing both the accuracy and reproducibility of CCTV for this kind of application. Future work will also involve defining the threshold condition of PVC push-fit joints with destructive laboratory tests – threshold bending angle and threshold push-out distance – before extreme stress within the joint arises. With this information it will be possible to detect, during inspection, joints that are at risk of leaking or bursting. This information will replace the use of the AWWA guideline threshold that is intended for installation and not for in-service pipes.

CONCLUSIONS

The data obtained from failure registration databases demonstrate the important role that joints play in the total number of failures in PVC networks worldwide. The effect of these failures can be mitigated through pro-active asset management and, more specifically, condition assessment.

Joints are considered to be particularly affected by bending, that can originate, for example, from differential soil movement. Bearing this in mind, the spatial alignment can be used as a surrogate measure for joint condition. Following this principle, a CCTV inspection was performed on a PVC pipe that burst in order to gather information on the spatial alignment of its joints. A cluster of joints with extreme bending angles was detected close to the burst point. It can be hypothesized that a pre-emptive inspection of this pipe could have detected this situation before the failure.

This work also further underlines the importance of condition assessment in the context of modern pro-active asset management where good managerial decisions can be made from good information.

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