A Comprehensive Analysis of PVC Pressure Pipelines' In-Service Performance

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ABSTRACT

Pipe infrastructure is the underpinning of our health, safety, and economy. With proper design, polyvinyl chloride (PVC) pipes have withstood a wide range of operating pressures, ground motions, and exposure to aggressive environments. Corrosion-free durability, broad in-service success, and cost effectiveness have made PVC pipe a very popular choice for water distribution and transmission. While the in-service failure rates for PVC pipe are relatively low, all pipe products experience failures. To keep PVC pipe infrastructure working better, safer, and longer, it is important to understand PVC pipe's service life factors and the underlying causes for in-service failures. In this research, previous studies and investigations which were carried out to predict the lifetime and/or mechanical failures in buried PVC pressure pipelines are comprehensively reviewed. The existing publications are analyzed and discussed regarding PVC pressure pipe failure rates and the causes for mechanical failures are delineated. Determining whether a particular failure is isolated, or indicative of a larger problem, requires accurate identification of the root cause. The aim of this research is to examine and classify the results from previous investigations. Different causes and types of mechanical failures are explained. The findings developed from this review indicate advantages, limitations, and research gaps in this area. Finally, recommendations for improving in-service performance and future research directions are presented.

INTRODUCTION

The installation of PVC pipe in water and sewer systems has steadily increased since the 1960s. PVC pipelines have become the mainstay for most municipalities' water and wastewater pipelines. According to a market study, "U.S. Municipal Pipe Markets: Trends, Opportunities and a Changing Competitive Landscape in Water", municipal utilities and engineering firms have a strong preference for PVC water and sewer pipe (Bluefield 2017). In Figure 1, the study projected a continuing increase in municipal utility purchases of PVC pipe with U.S. municipal PVC pipe sales topping $7 billion annually and surpassing that of all alternative pipe products combined.

The strong preference for PVC water and sewer pipelines is a result of PVC pipe's unrivaled resistance to corrosion, resistance to chemical oxidation/degradation, high strength-to-weight ratio, excellent strain capacity (flexibility), and low hydraulic friction (Burn 2005, Balkaya 2009). All these favorable properties; combined with PVC pipe's affordability, simple maintenance, compatibility with traditional pipes/pipe appurtenances, and extensive track record of in-service resiliency spanning more than 70 years have led to PVC pipe's prominent share of the U.S. municipal water and sewer pipe market.

In 2017 Utah State University (USU) conducted a large survey of municipal and private water utilities across the U.S. and Canada to obtain data on water main failures. More than 300 utilities provided responses and 281 utilities, serving a population of 52,477,346, provided water main break data for 170,569 miles of pipe or about 12.9% of the estimated total length of water mains, excluding those with diameters under 4 inches, in the U.S. and Canada. The responses measured pipe failures over a recent 12-month period and was broken down by pipe material. Recorded failure rates for all the commonly used pipe materials – Asbestos Cement (AC), Cast Iron (CI), Concrete Steel Cylinder (CSC), Ductile Iron (DI), Polyvinyl Chloride (PVC), Steel, and Other (HDPE, Fiberglass, Copper, and some Galvanized Steel) are shown in Figure 2. The first two, AC and CI, are older pipe materials that are no longer used. PVC pipe had the lowest number of breaks per 100 miles per year (Folkman 2018).

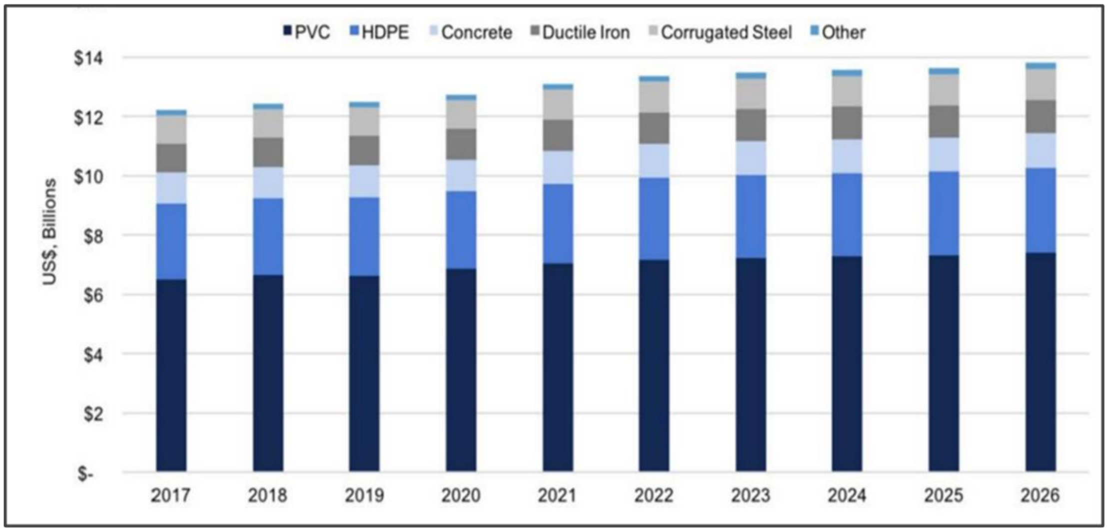

Figure 1. Total U.S. municipal water and sewer pipe investments by material type,2017-2026 (Bluefield 2017)

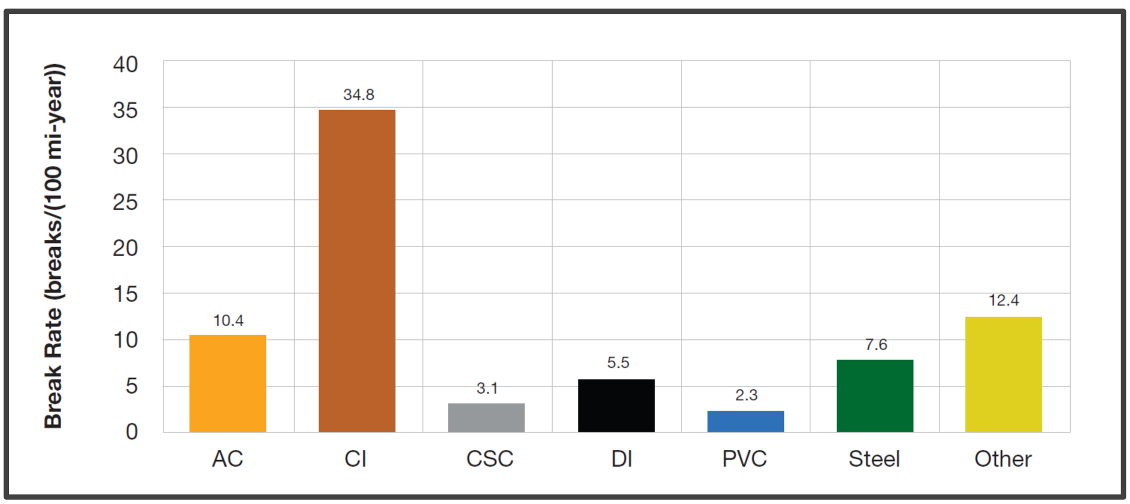

Figure 2. Break Rates Reported for Each Material (Folkman 2018)

While the recorded break rate for PVC water pipe is the lowest, the predominant use of PVC pipe justifies lowering them further. As PVC pipe use increases, the economic and social consequences of premature breaks also increase. Hence, further reductions in the already low

PVC pipe break rate will significantly improve the overall performance and sustainability of municipal water and sewer pipelines.

In this study, failure behavior and fractures of in-service PVC pipes were reviewed based on studies and articles from scientific databases. The aim of this research was to examine and classify the results from previous investigations and outline failure mechanisms of PVC pressure pipes. The findings should be used to improve the in-service performance and longstanding resiliency of PVC pressure pipe.

Review of Factors That Influence Pipe Failure

The fundamental parameters that influence utility pipe failure are as follows (AWWA M23 2020, Burn 2005, Folkman 2013, Rahman 2005, Winn 2018):

- *Degradation*: With the passage of time, pipe materials can deteriorate from exposure to chemicals that cause oxidation and/or electrical currents that impart galvanic corrosion. PVC pipes are immune to galvanic corrosion and not susceptible to oxidative degradation from chlorinated drinking water. However, higher concentrations of petrochemical solvents and/or very strong oxidizing chemicals can compromise material properties and lead to premature failure.
- *Joining methods*: Most underground PVC water mains joints are unrestrained and sealed with compression gaskets. A variety of mechanical means or thrust blocks are used when restraint is warranted. Other PVC pipe joining methods include fully restrained heat fusion welding and welding with appropriate solvent cements. Each method offers advantages with limitations. The type and quality of the joining method have influence on a pipeline networks capabilities and life expectancy.
- *Manufacturing Defects/Imperfections*: As with any pipe, PVC pipe failures are more likely to occur at locations where manufacturing defects and imperfections are present. Defects may cause micro-cracks and elevated stresses that can eventually lead to failure.
- *Improper Storage and Handling*: Damage can result in the form of gouges, scratches, and/or cracks caused by poor handling. Unprotected outdoor storage in direct sunlight for long periods of time are associated with reduced resistance to impact loads.
- *Improper Tapping*: When making direct connections to a pressurized pipeline, it is important that the tapping equipment and procedures are well suited and recommended for the pipe material. Otherwise, failures have occurred.
- *Internal Pressures*: Sustained operating pressure that exceeds the long-term stress capacity of the pipe material or pressure fluctuations/surges that collectively exceed the pipe material's stress capacity can cause failure.
- *External Loads*: When the combination of earth and traffic loads exceeds the stress capacity of a pipe, failure can be expected in the form of collapse or fracture.
- *Residual Pipe Wall Stresses*: It is worth noting residual stresses, which result from the cooling phase in the pipe manufacturing process, may contribute to thermoplastic pipe failure.

The above factors, singularly or in combination, will nearly always explain the circumstance(s) that resulted in a premature water or wastewater pipe break.

Brief Overview of PVC Pressure Pipe's Lifespan Expectation

The performance, resiliency, and longevity of any pipeline depend on the pipe material properties (e.g., tensile strength, stiffness, toughness, flexibility, and resistance to degradation), together with the joint system used, proper installation, operating conditions, and margins of safety required in the pipeline design (AWWA M23 2020, Burn 2005, Folkman 2014, Rahman 2005).

A minimum of 100 years is the established, conservative life expectancy for PVC water and wastewater utility pipelines. It is based on the inherent properties of PVC and evaluations of PVC water and sewer pipelines after extended years in service. (AWWA M23 2020, Burn 2005, Folkman 2014) These evaluations have documented minimal changes in the physical and mechanical properties occurring in PVC pipe underground.

Examinations of In-service PVC Pipe Breaks

Breaks with in-service PVC water and sewer pressure pipe have been exhumed and examined over nearly six decades. Scanning electron microscope examinations of PVC pipe fracture surfaces have indicated that most PVC pipe fractures include local ductility and are not purely brittle (Burn 2005). These examinations also revealed that nearly all fractures initiated at or near the inside surface of the pipe and then propagated through the wall to the outer surface. Complete pipe wall fractures, generally result in cracks that run longitudinally a few feet in both directions. On a very few occasions, excessive amounts of entrapped air provided enough stored energy to drive longer fractures following a break.

Early on, some PVC pipe breaks were due to poor manufacturing and inadequate quality controls. This has not been the case more recently. Nearly all PVC pipe breaks in the last four decades have been a result of improper installation, third-party damage, and a few to extreme operating conditions. These breaks occurred in different forms. In some cases, they have been isolated while others have been multiple along a length of pipe (Burn 2005).

Almost invariably, in-service PVC pressure pipe breaks are a result of elevated stress regions in the pipe wall (Burn 2005).

Localized Elevated Stress is the Primary Cause for In-service PVC Pipe Failures

Buried PVC pipelines have a well-established record of resistance to significant degradation from external and internal environments. PVC pipe is not prone to galvanic corrosion or oxidation. The operating conditions that often degrade traditional water and wastewater pipe products have negligible effect on buried PVC pipe performance. That is, PVC pipe breaks have very rarely been attributed to material degradation (Burn 2005, Winn 2018).

Absent significant material degradation, PVC pipe breaks are nearly always the result of localized elevated stresses that greatly exceed the stresses caused by the anticipated internal operating pressures (AWWA M23 2020, Burn 2005, Shumard 2006, Winn 2018, Youssef 2008). Figure 3 depicts in-service PVC pipe break rates over 110 years (Burn 2005). PVC pipe's asymptotic failure rate pattern has substantiated the product's inherent resistant to in-service degradation and supports that failures are primarily caused by localized high stresses.

In the US and Canada, the long-term stress capacity for PVC pressure pipe compounds is based on the widely accepted hydrostatic testing and extrapolation methodology published in ASTM D2837. The extrapolated long-term hydrostatic stress (LTHS) defines a PVC pipe compound's Hydrostatic Design Basis (HDB) category, also defined in ASTM D2837. Since the tests to determine HDB do not include localized elevated stresses that are present in actual installations and operations, recommended long-term design stresses are generally limited to half of the PVC pipe compound's HDB. Likewise, design engineers conservatively limit short-term surge stresses to no more than half of the pipe's required minimum quick-burst test stress. These recommended design criteria provide a safety margin of 100 percent or a safety factor of 2.0 (AWWA M23 2020, AWWA C900 2022).

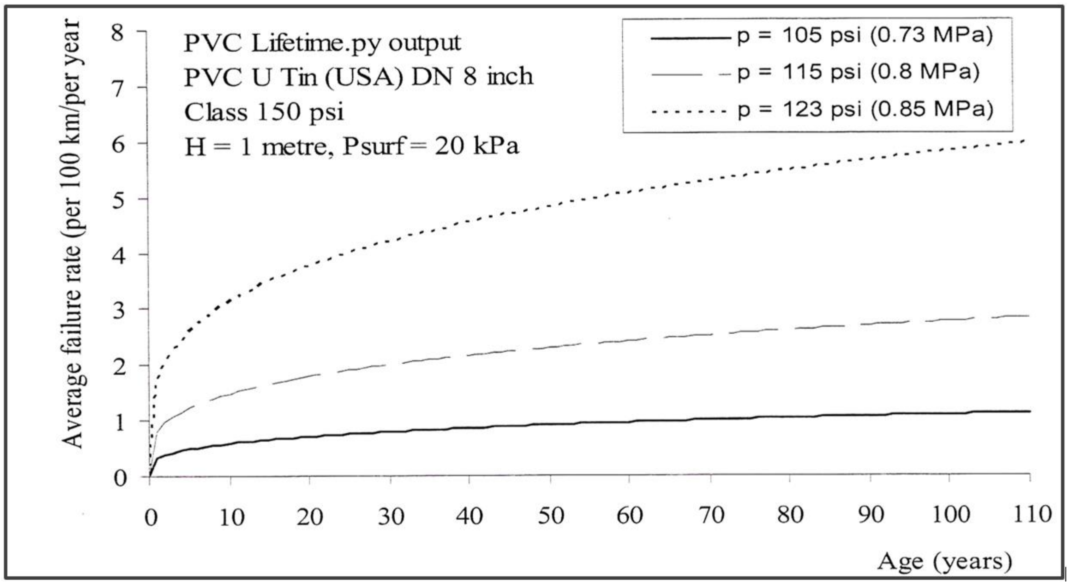

Figure 3. Average Failure Rate Versus Age for Class 150 psi, PVC Pipe (Burn 2005)

Analyses of Excessive Stresses and Their Causes

Gasketed joints are the most common method for joining PVC pipes for buried applications. While this method has proven to be very reliable over the years, investigations of PVC pipe breaks reveal that spontaneous fractures nearly always originate from these joints. When spigot ends are over-inserted into the gasketed pipe bell end, elevated stresses arise at the regions of contact. The likelihood for over-insertion increases when mechanical means (such as backhoes) are used to assemble pipe joints in the field (AWWA M23 2020, Burn 2005, Shumard 2006, Winn 2018, Youssef 2008).

PVC pipe spigot ends include maximum insertion indicators, but controlling the insertion depth can be difficult and some installers have not been trained to avoid over-insertion. Over-insertion stresses alone have been tied to premature PVC pipe fractures, particularly in pressure pipelines (AWWA C605 2021, AWWA M23 2020, Rahman 2005, Uni-Bell 2013, Winn 2018).

Fractures that originate at gasketed joints have also been attributed to excessive axial deflections. This results when installers over-deflect gasketed joints to avoid using fittings to accommodate vertical or horizontal changes in alignment. While some PVC pipe manufacturers allow a small amount of joint deflection, usually 1/3° up to 3° degrees, installers occasionally exceed the manufacturer's limits to adjust an otherwise straight alignment or to accommodate a curvilinear alignment (AWWA C605 2021, AWWA M23 2020, Winn 2018). Per AWWA C900, PVC pipe manufacturers are required to include the maximum allowable axial joint deflection, in degrees, on their pipe marking (AWWA C900 2022). Joint over-insertion takes away any axial deflection tolerance and amplifies the stresses imparted by joint deflection (AWWA M23 2020, Rahman 2005, Shumard 2006, Uni-Bell 2013, Youssef 2008).

Experience has shown that joint over-insertion, over-deflection, or the combination of both has been the leading cause for premature breaks in PVC pipe (Shumard 2006, Rahman 2005, Uni-Bell 2013, Youssef 2008, Winn 2018)*)* To quantify and more fully understand the effect of these loads on pipeline integrity, tests have been performed together with finite element (FE) analyses. Three load conditions have been reproduced in multiple testing facilities to assess the resulting stresses in gasketed PVC pipe joints. (*3 references*) Figures 4 – 6 depict cross-section views of elevated Von-Mises stress distributions for over-insertion, over-deflection, and the combination of both (Youssef 2008).

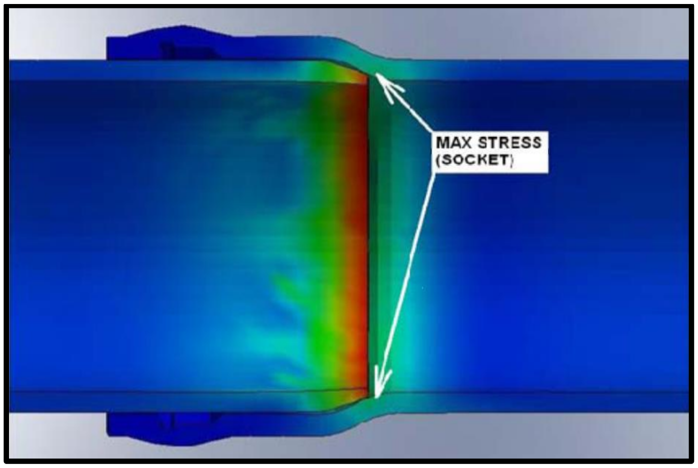

Figure 4. Stress distributions when a PVC pipe spigot-end is over- inserted to push against the adjoining bell neck (Youssef 2008)

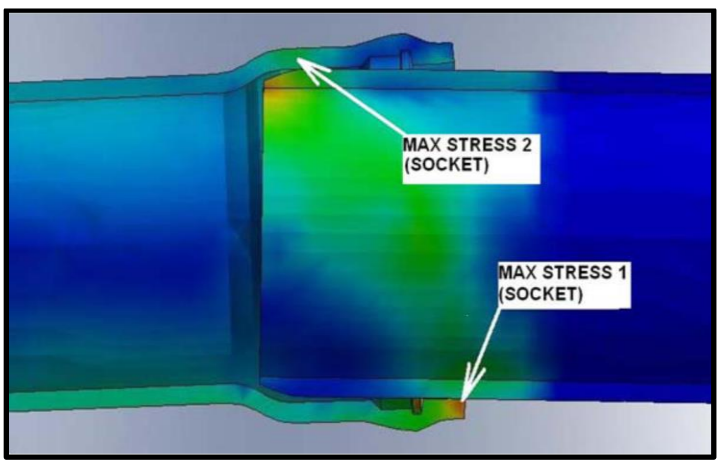

Figure 5. Stress distributions when a PVC pipe spigot-end is over-deflected to make contact with the inside of the adjoining bell and socket lip (Youssef 2008)

The elevated stressing caused by joint over-insertion and/or over-deflection is very rarely high enough to instantly break PVC pipe (Youssef 2008). However, it is well known that these elevated stresses have sometimes been severe enough to cause fractures after installation and after the installer's warranty has expired. A typical time window has been about 5-7 years (Winn 2018).

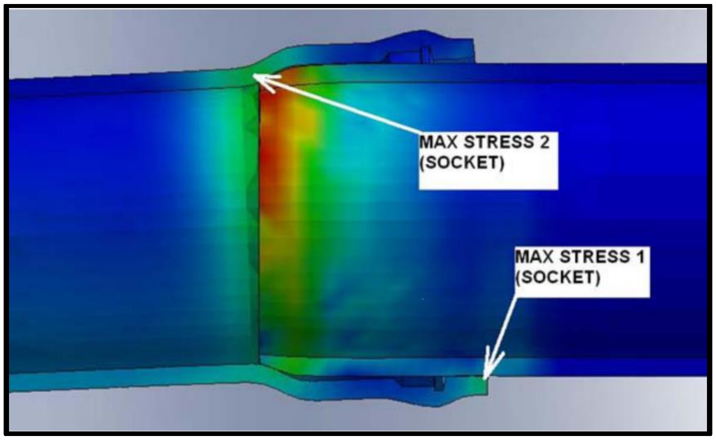

Figure 6. Stress distributions when a PVC pipe spigot-end is over-inserted and axially over-deflected (Youssef 2008)

Requirements and Recommendations for Eliminating Gasketed Joint Fractures

Water and sewer utilities' recognition of the potential for premature PVC pipe breaks due to elevated stress points at their joints has prompted them to make important changes to pertinent requirements and recommendations. The following is a list of recommended restrictions and limitations, including those from AWWA M23 2020, AWWA C605 2021, Uni-Bell 2013 and Winn 2018. When followed, these can substantially lower the already low in-service break rates for PVC pipe.

- The safe allowable axial joint deflection depends upon the joint type, dimensions, and insertion depth. The print line on PVC pipe manufactured to ANSI/AWWA C900 includes the allowable axial joint deflection angle. Axial joint deflection limits must be obtained from the manufacturer for PVC pipe products not manufactured per ANSI/AWWA C900. The manufacturer's insertion depth and axial joint deflection angle limits must not be exceeded.
- Deflection couplings axial limits also vary and need to be established by the coupling manufacturer. When larger changes in alignment are needed, fittings should be used.
- Suitable fittings or high deflection couplers should be required whenever axial joint deflection, horizontal or vertical, exceeds that printed on the pipe or the limit obtained from the manufacturer.
- Depending on pipe size and joint design, the allowable axial deflection for gasketed PVC pipe joints generally fall within the range of 1/3° up to 3°. The allowable axial joint deflection requires that after assembly the insertion mark, provided around the circumference near the pipe spigot end, remain visible near the bell of the adjoining pipe.
- In a properly assembled PVC joint the pipe spigot is pushed into the bell until the insertion line is nearly flush with the lip of the bell, shown in Figure 7. This leaves a gap to accommodate some axial deflection and thermal expansion without elevated stressing.
- The pipe spigot end should not be "homed" or fully inserted because when the leading edge of the spigot end contacts the tapered neck of the adjoining bell, the allowable deflection angle is reduced to zero. (AWWA M23 2020, Uni-Bell 2013)
- Bending segmented (elastomeric gasket-joined) PVC pressure pipe larger than nominal 6-inch (150 mm) is not recommended because of the higher forces required to bend larger

pipe. Keeping joints straight is difficult, highly dependent on the installer, and there are no proven methods able to maintain straight alignment after installation.

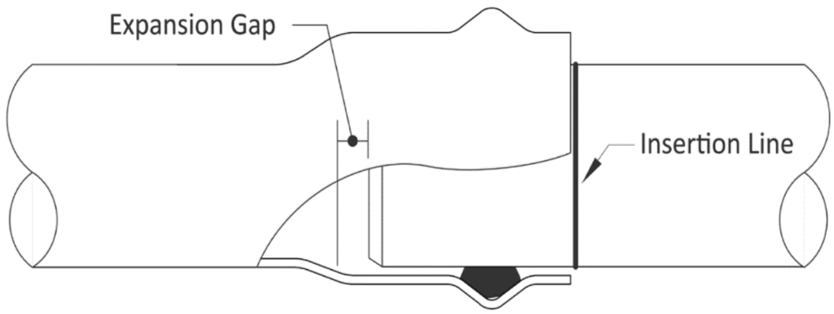

Figure 7. Gap indicative of proper PVC pipe joint assembly (Uni-Bell 2013)

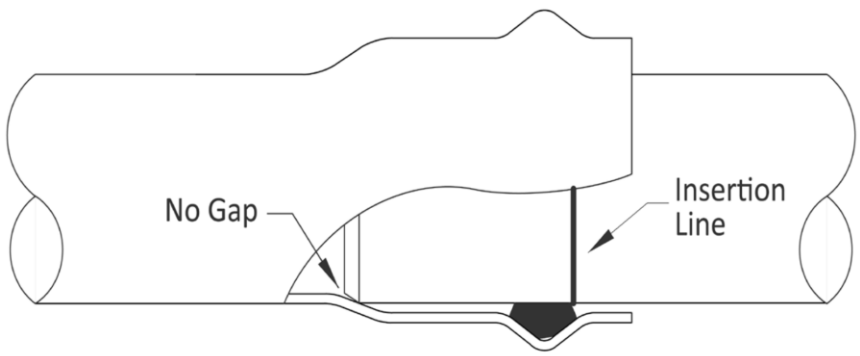

Figure 8. No gap indicative of improper PVC pipe joint assembly (Uni-Bell 2013)

- For PVC pipe larger than nominal 6-inch (150 mm), bending is only permitted when joints are continuous, e.g., thermally fused together. Bending across thermally fused PVC pipe joints is consistent with that of the pipe barrel and not subject to concentrated point stresses.
- Specify a method of measuring joint deflection and require qualifying that method for accuracy via repeatability and reproducibility procedures per ASTM E2782.
- Specify a minimum allowable joint deflection of 1/3° to handle unplanned incidents such as ground movement, settling, pressure surges, and loss of soil-bearing capacity because of saturation or physical disturbances.
- Do not allow the elimination of any fittings or couplings without approval of the design engineer.

CONCLUSIONS

PVC has become the most popular product for new and replacement buried water and wastewater pipelines. The year-over-year demand for PVC pipe continues to grow. Consequently, further reductions in the already low PVC pipe break rate will provide significant improvements to the overall performance and sustainability of underground water and sewer pipe systems.

This study has presented a review of in-service pipe breaks and discusses the primary causes. The over-stressing that can cause PVC pipes to fail is explained. Further, various approaches for eliminating or at least reducing break rates have been included.

The two most common causes for untimely, in-service PVC pipe failures are improper joint assembly and/or excessive axial joint deflection. Insertion of a pipe spigot end into and beyond the neck of the adjoining pipe bell, or coupling, produce elevated stresses and is generally considered the most egregious installation issue. Insertion marks included on the pipe spigot ends need to remain visible following joint assembly. Axial joint deflections that exceed the manufacturer's limits also produce elevated stress points. To achieve curvilinear alignments that require higher axial deflections, fittings should always be required. In addition, quantitative joint deflection measurement during and following installation can be implemented to prevent excessive axial deflection and the associated elevated stresses.

These issues do not impugn the value of PVC pressure pipe. Test results of material properties after decades of service indicate that PVC pipe is inherently long-lasting and should provide reliable service far beyond 100 years (Folkman 2014).

The most purposeful conclusion to be drawn from this study is that there is opportunity for change in the way utilities manage their use of PVC pipe that will enable them to lower maintenance costs and reduced upward pressure on water and sewer rates – a goal that everyone can support.

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