The location of the following investigation is a southern Arizona desert environment. Much of Pima County is the service domain of Tucson Water, an enterprise fund of the City of Tucson. The city is surrounded by mountain ranges on four sides. The water infrastructure includes a central system and a number of independent systems at elevations from 1,891 to 3,855 ft above mean sea level. It is divided into 19 pressure zones in approximately 100 ft increments of elevation and has a diverse portfolio of water sources that include surface water, groundwater, remediated water, and reclaimed water. Water main sizes range from 3 to 96 in. Main materials include cast iron, ductile iron (DI), steel, steel-reinforced concrete, asbestos–cement (AC) composite, high-density polyethylene, and polyvinyl chloride (PVC). Tucson Water’s potable water component alone is arguably one of the most complex water infrastructures in the world.

To promulgate a vision for the future, the Tucson Water 2020 Strategic Plan addresses five relevant business values:

- Reliable water services, calling for highly reliable water pipes employing a data-driven maintenance approach to reduce and prevent failures
- Exceptional customer service to get help to customers when they have an interrupted-service problem (relevance derives from minimizing the frequency of needed maintenance, ease of maintenance, and minimizing leakage with its associated energy losses)
- Increasing efficiency and conservation by identifying and pursuing increases in efficiency, comprehensive energy management, and maintenance management (relevance derives from minimizing the frequency of needed maintenance, ease of maintenance, and minimizing leakage with its associated energy losses)
- Transparency and communication, including action that describes why staff is proposing a specific policy
- Sound financial management, requiring a water utility that is financially strong and self-supporting, and is sensitive to the hardships of large or unexpected rate increases (relevance derives from minimizing maintenance costs)

Failure Data Analysis Results

Tucson Water collects maintenance data for 12 material types (including “other” and “unknown”). This article discusses the dominant three in detail: DI, AC, and PVC. The data are expressed in terms of main breaks per mile, a main being any public water conveyance of at least 3 in. diameter. A break is considered to be a leak large enough to surface for visual reporting. The number of
breaks in pipe of a specified material in a given year is normalized by the number of miles of installed pipe of that material extant in the specified year. The resulting parameter is herein referred to as breaks per mile (breaks/mi) in pipe of a given age. “Breaks per mile per year” would be more orthodox but less descriptive of process, which compares favorably with that used previously (Burn et al. 2005).

Overall this analysis considers 5,447 main breaks in 4,519 mi of pipe over 11 years, from 2003 to 2014. AC pipe (2,415 mi of it, representing 53% of the system) accounted for 3,506, or 64%, of main breaks reported in the Oracle Work and Asset Management database. AC is the principal legacy material, no longer used but prevalent in the older parts of the central system. In Figure 1, a plot of breaks per mile against age in years shows an approximately Gaussian-looking failure distribution with almost no breaks in the first 20 years and almost none after 60 years, but up to 0.04 breaks/mi in between. Many of the breaks appear at joints that have been penetrated by the aggressive roots of mature Sonoran Desert trees, typically mesquite or palo verde. It is logical to speculate that the highest failure rates in AC pipe occur during the life span of a typical desert tree, which grows to maturity in about 20 years. At that point it has roots deep enough (up to 14 ft) and spread widely enough (more than 50 ft) to reach water mains, typically at only 44 to 60 in. below the surface. Joints in AC pipe are straight couplings with two seals each, twice as many as the bell-and-spigot design typical of iron or plastic pipe. In addition, the standard pipe length for AC is 13 ft, versus 20 ft for most other materials. Since root penetration occurs at seals, vulnerability to it is proportional to the number of seals. Therefore, under the best of conditions, such pipe would be three times \((20 ÷ 13) \times 2 = 3.077\) as vulnerable to root penetration as other types. AC pipe in the urban core, blocks away from any tree, has been found to be in good to excellent condition after nearly 80 years in one case. DI pipe, with 363 breaks (7% of those reported) over 291 mi (6% of the system), has a maximum failure rate of around 0.06 breaks/mi in the first 30 years, falling to 0.02 breaks/mi after that (Figure 2). One might describe the distribution as characteristic of an early failure mode. In Tucson, DI pipe is currently

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**FIGURE 1** Incidence of breaks per mile in asbestos–cement pipe versus pipe age in Tucson Water’s system

Asbestos–cement is included here as representative of a legacy pipe material.
installed with a polyethylene wrap as a corrosion-preventative construction standard, but that has not always been the case. Also, DI pipe that has been in the ground longer may have thicker walls as a result of the transition of pipe classification standards from wall thickness to pressure class (Rajani et al. 2011). Because of the similarity of external appearance, DI pipe and the thicker-walled cast-iron pipe may be conflated in this study, and that could account for the appearance of an early failure mode.

PVC, with 1,913 breaks (35%) over 1,396 mi (31%), has an infant mortality failure mode (Figure 3). The failure rate peaks at more than 0.10 breaks/mi at 10 years and drops rapidly after that. In general, infant mortality describes a reliability distribution characterized by a precipitous decline in failure rate soon after operations begin. They are highly undesirable, and always the effect of design or assembly errors (Wilkins 2002). This distinguishes them from early (left-skewed) distributions, which may have multiple causes.

FIGURE 2 Incidence of breaks per mile in ductile-iron pipe versus pipe age in Tucson Water’s system

Ductile iron is a fairly common choice for pipe material in Tucson, Ariz. The distribution, skewed to the left, is typical of an early-failure mode, but it is more likely due to changes in pipe manufacturing and installation practices.

ENGINEERING ANALYSIS RESULTS

Tucson Water has permitted the longitudinal bending of PVC pipe within industry-prescribed limits but has become aware by measurement, as will be shown, that field practice is exceeding manufacturers’ recommended angular joint deflection. It is also clear that there exists no credible long-term bracing technique to limit deflection in joints due to bending forces. Curiously, manufacturers recognize the bending feature as a selling point for real estate developers, but pipe bending produces a joint offset (i.e., angular deflection) issue.

In considering curvature of longitudinally bent PVC, AWWA Manual of Water Supply Practices M23 (AWWA 2002) calculates stress in the pipe barrel assuming the entire barrel length is bent in a circular arc. Pipe length as it applies to longitudinal bending includes only that portion of the length that is actually curved, a feature controlled by installation technique.

To fix ideas, if pipe were bent in a full circle (2π radians), its length would be 2πR and the alignment change per
unit length would be $2\pi \div 2R = 1 \div R$ radians/ft, alignment change per unit length being the definition of curvature. The curvature of a circle is uniform by definition, so the radius of a section of pipe with constant curvature is given by $R = L_c \div \theta$, where $L_c$ is the curved length (at maximum, the pipe length without the bell) and $\theta$ is the alignment change over that length in radians.

If the installer attempts to follow industry advice to compact fill around the joints to prevent deflection, that compacted region will require some length, say 3 ft on either side of a joint, of potentially straight pipe. Only 14 ft is then available to be bent. For a 20 ft length of pipe that is braced 3 ft from each end, $L_c = 20 \text{ ft} - 6 \text{ ft} = 14 \text{ ft}$, and the pipe length available to accomplish the fixed change of alignment is $14 + 20 \times 100\% = 70\%$ of the nominal length, requiring a proportionately tighter radius. The actual bending radius of each pipe will be 0.7 of that specified on the plan because of the straight sections at the ends. In practice, the pipe will have unknown, but higher than nominal, stresses because we cannot know what the behavior of the pipe is at the joints under fill.

Not covered in the literature is how to deal with compound curvature, in which a horizontal bend is combined with a roll to follow terrain or change in depth of cover. One way is to recognize that curvature is a vector quantity. The curvature of horizontal and vertical circular arcs may be represented as

$$\kappa_h = \frac{1}{R_h} \quad \text{and} \quad \kappa_v = \frac{1}{R_v}$$

where $R_h$ and $R_v$ are the respective radii (Petrunin 2004).

Since vertical and horizontal vectors are orthogonal by definition, vector addition results in the easily recognized Pythagorean formula, symbolized as compound curvature:

$$\kappa_c = \sqrt{\kappa_h^2 + \kappa_v^2}$$

Substituting and inverting, one obtains

$$R_c = \frac{1}{\sqrt{1 \div R_h^2 + 1 \div R_v^2}}, \quad \text{where} \quad R_c = \frac{1}{\kappa_c} \quad (1)$$

The distribution, with a massive peak early in life, is termed “infant failure mode.”

**FIGURE 3** Incidence of breaks per mile in polyvinyl chloride pipe versus pipe age in Tucson Water’s system

<table>
<thead>
<tr>
<th>Pipe Age (years)</th>
<th>Breaks/Mile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>1</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.08</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>7</td>
<td>0.00</td>
</tr>
</tbody>
</table>

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This derivation is not rigorous, but it has three intuitively satisfying and expected features. First, it does not ignore the often-occurring field event of concurrent horizontal and vertical bending of PVC pipe. Second, we can readily see that non-zero vertical bending radius decreases the compound radius, thus increasing stress. Finally, in the limit as $R_v$ goes to infinity (zero curvature), $R_c = R_h$, as expected.

The current installation procedure in Tucson is to bend pipe about a fulcrum of compacted fill. The result approaches the deflection of a simply supported beam with central loading. Using that as a conservative model, the author has calculated stresses and curvatures using the accepted results of beam theory (Lindeburg 2003) and differential geometry (Petrunin 2004). These are summarized in Table 1. The results are in complete agreement with tabular data in AWWA Manual M23 for loads associated with specific bending radii ($R_{avg}$), in the tabulated case for 8 in. C900.

**Joint deflection metrics are under development.** Alignment change accomplished by joint deflection is one approach considered acceptable for rigid pipe. Figure 4 shows the geometric relationship between deflection angle and arc radius.

Eq 2 gives the trigonometric forms for calculating $R$ and $L$. Note that length $L$ is the lay length, not the end-to-end length of the pipe. Note, too, that an angular deflection of the joint, $\theta$, is identically equal to the angle subtending the lay length, $L$.

$$R = \frac{L}{2 \tan \left( \frac{\theta}{2} \right)} \Rightarrow \theta = 2 \tan^{-1} \left( \frac{L}{2R} \right) \tag{2}$$

The measurement of joint deflection angles under field conditions is largely unexplored territory. Some detail as to existing processes is available in a white paper from Tucson Water (Winn 2016).

### Table 1: Comparison of curvature and stresses for pipe bent in accordance with practice versus AWWA Manual M23 (constant curvature)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe lay length—ft</td>
<td>$L$</td>
<td>Input</td>
<td>20</td>
</tr>
<tr>
<td>Young's modulus—kbf/in.$^2$</td>
<td>$E$</td>
<td>Input</td>
<td>400</td>
</tr>
<tr>
<td>Pipe outer diameter—in.</td>
<td>$D_o$</td>
<td>Input</td>
<td>9.05</td>
</tr>
<tr>
<td>Pipe diameter ratio$^b$</td>
<td>$D_R$</td>
<td>Input</td>
<td>14</td>
</tr>
<tr>
<td>Location—ft</td>
<td>$x$</td>
<td>Input</td>
<td>10</td>
</tr>
<tr>
<td>Average radius$^c$—ft</td>
<td>$R_{avg}$</td>
<td>Input</td>
<td>189.0000</td>
</tr>
<tr>
<td>Load—lbf</td>
<td>$P$</td>
<td>$1000 \times E \times I / (18 \times L \times R_{avg})$</td>
<td>932.0752</td>
</tr>
<tr>
<td>Moment of inertia—in.$^4$</td>
<td>$I$</td>
<td>$(\pi + 64) \times (1 - ((DR - 2.12) + DR)^4) \times Do^4$</td>
<td>158.5460</td>
</tr>
<tr>
<td>Deflection coefficient—1/ft$^2$</td>
<td>$C__2$</td>
<td>$P / (48 \times E \times I)$</td>
<td>0.0003</td>
</tr>
<tr>
<td>Slope coefficient—1/ft$^2$</td>
<td>$a$</td>
<td>$12 \times C__2$</td>
<td>0.0037</td>
</tr>
<tr>
<td>Slope @ $x = 0$—radians</td>
<td>$S_0$</td>
<td>$-P \times (12 \times L)^2 + (16 \times 1000 \times E \times I)$</td>
<td>-0.0529</td>
</tr>
<tr>
<td>Slope @ $x = L$—radians</td>
<td>$S_L$</td>
<td>$P \times (12 \times L)^2 / (16 \times 1000 \times E \times I)$</td>
<td>0.0529</td>
</tr>
<tr>
<td>Alignment change/stick—radians</td>
<td>$D_T$</td>
<td>$SL - S_0$</td>
<td>0.1058</td>
</tr>
<tr>
<td>Slope @ $x$—radians</td>
<td>$S$</td>
<td>$-P \times ((12 \times L)^2 - 4 \times (12 \times x)^2) + (16 \times 1000 \times E \times I)$</td>
<td>0.0000</td>
</tr>
<tr>
<td>Moment @ $x$—lbf-ft</td>
<td>$M$</td>
<td>$-P \times x + 2$</td>
<td>-4660.3761</td>
</tr>
<tr>
<td>Constant moment—lbf-ft</td>
<td>$M_C$</td>
<td>$(1 + 144) \times (1000 \times E) \times I + R_{avg}$</td>
<td>2330.1880</td>
</tr>
<tr>
<td>Curvature @ $x$—1/ft</td>
<td>$K$</td>
<td>$2 \times a \times x + (1 + S^2)^{3/2}$</td>
<td>0.0735</td>
</tr>
<tr>
<td>Constant curvature—1/ft</td>
<td>$K_c$</td>
<td>$1 / R_{avg}$</td>
<td>0.0053</td>
</tr>
<tr>
<td>Radius of curvature @ $x$—ft</td>
<td>$R$</td>
<td>$1 / K_c$</td>
<td>13.6080</td>
</tr>
<tr>
<td>Maximum tensile stress SS/CL—psi</td>
<td>$T_{max}$</td>
<td>$12 \times AB(M) \times (Do + 2) + 1$</td>
<td>1596.1199</td>
</tr>
<tr>
<td>Maximum tensile stress circular—psi</td>
<td>$T_{maxC}$</td>
<td>$(12 \times M_c) \times (Do + 2) + 1$</td>
<td>798.0600</td>
</tr>
</tbody>
</table>

ABS—absolute (unsigned) value, SS/CL—simply supported/centrally loaded

$^a$Tabulated in AWWA C900

$^b$Tabulated in AWWA C900

$^c$The radius of the circular arc having the same angular deflection at the ends and the same cord as the deflected shape from a concentrated load.
**Inconsistent standards drive high costs.** In Tucson Water’s case, the internal engineering standard for PVC (no bending) is usually applied to larger-diameter pipes per AWWA standard C905 rather than the C900 standard of 12 in. and smaller, typical of subdivisions. However, it is also true that internal engineers have worked with smaller PVC pipes, usually after their premature failure, and new area development has overseen the installation of curved 16 in. PVC. The new-area-development standard is less expensive in the short term because it focuses on initial cost, not life cycle cost. However, it requires high levels of maintenance to support, as will be shown, and therefore must be considered a subsidy when employed by developers.

**Ambiguity must be avoided.** Tucson Water’s *Standard Specifications and Details Manual* has restricted the installation of PVC pipe in an ambiguous and easily abused manner. The manual states, “PVC pipe bell and spigot joints shall be assembled/installed with no deflection...” (Tucson Water 2011). The language results in a split between the Tucson Water’s internal design policy (no deflection of PVC joints) and its politically influenced new-area-development policy that permits “the manufacturer’s allowable longitudinal pipe bending” and ignores the question of how the pipe bending moment is reacted at the joints.

**APPLICATION, RESULTS, AND DISCUSSION**

AWWA Manual M23 addresses the installation of PVC pipe with the following statements:

- Curving pipe is to be avoided because it increases the likelihood of failure during tapping. The manual gives the specific advice, “Do not tap curved pipe if the radius of the bend is less than 300 times the pipe outside diameter” (AWWA 2002 at 34).
- If curvature is allowed, curved pipe should be tapped on the inside of the curve only. Manual M23 for PVC pipe tells us that “known changes in alignment and
grade should be accomplished with high-deflection couplings or fittings” and that “curving of PVC pipe may increase the possibility of failures during tapping under pressure” (AWWA 2002 at 34).

• Unstressed joint offset capability varies with size and design from $\frac{1}{3}^\circ$ to $5^\circ$ (AWWA 2002 at 34). The author’s search of the marketplace via the Internet did not substantiate this claim. The range of tested capability, not design recommendation, was found to be $1^\circ$ to $2^\circ$.

• All offset allowance is predicated on correct installation, specifically insertion to the marked location (“stab” mark) only. “Homed” assemblies (fully inserted to the stop) allow zero joint offset. In homed assemblies, any radius of curvature will deform the spigot and promote leakage (AWWA 2002 at 34).

In the Handbook of PVC Pipe Design and Construction (Uni-Bell 2012), one finds the statement, “When PVC pipe is bent longitudinally, its joint must be blocked or braced to ensure its straight alignment and to prevent axial deflection in the gasketed or mechanical joint.” Chapter 10 deals with the specifics (author’s comments follow each recommendation):

1. **Keep the spigot in straight alignment with the bell.** The limits of “straight” are left undefined. For reference, a 1/32 in. variation in axial displacement around an 8 in. pipe’s insertion ring results in 0.2° of joint deflection. Measurement (Winn 2016) has demonstrated installed joint deflections from 0.8 to 1.6°. Time allowed for only three measurements, so no statistical significance is implied. That one of the joint deflections had the sense opposite that of the overall pipe curvature indicates a lack of control, however.

2. **Place compacted backfill around the assembled joint to restrict its movement while the curvature is being made.** Deflection cannot be measured once the operation is complete, so the joint’s actual condition is unknowable. What small deflection limits are allowable should probably be left to handle incidental shifts, and not be used in design. In any case, Tucson Water inspectors have stated that they need the joints to be exposed for leak checks. The process of bracing joints in curved pipes as recommended here is not consistent with that need.

3. **Place compacted backfill at the inside of the curve, at the midpoint of the pipe length, to form a fulcrum.** In Tucson, we have seen this done by covering the center of a pipe stick with uncompacted fill (Winn 2016). It is assumed in the stress calculation from which minimum bending radius is derived that the bent length of pipe conforms to a circular arc (AWWA 2002 at 35). As this approaches the condition of a centrally loaded, simply supported beam, curvature will not be constant, but will be concentrated at the fulcrum (Table 1). The local bending radius will be shorter and the stress higher than supposed. The length used in the calculation is the bent length of the pipe (AWWA 2002 at 36), which may well be shorter than the nominal pipe length as it depends on installation technique. The foregoing considerations, in combination with the stress concentration factor (roughly 3.0) for a service tap and potentially high water temperature in some areas, may eliminate the safety factor and create a hazardous condition.

4. **Using only manual effort, move the leading bell of the pipe length to be curved by no more than the offset distance shown in the following table.** As pointed out earlier, this technique will not result in constant curvature. Also, the soil of the “fulcrum” may not be able to bear the bending loads without creep. A better approach might be to form a circular arc with compacted fill and bend pipe to conform to that shape. If this shows anything, it is that the referenced standards and recommendations are not followed. It is likely they cannot be followed. Something else is needed from the industry if longitudinal bending is to be considered benign. Note that the recommendations apply in the context of horizontal deflection only. Vertical deflection is ignored.

**Specifications provide augmentation and context.** ASTM D3139, “Standard Specification for Joints for Plastic Pressure Pipes Using Flexible Elastomeric Seals” (ASTM International 2011), is the pipe joint deflection test, which loads the joint with a few feet of pipe on either side until the spigot contacts the inside of the bell, and then pressure testing is performed to determine how that affects the seal. This is the basis for claims of joint deflection capability. AWWA C900-89 section 2.4 requires that assembled bell and spigot joints be tested in accordance with ASTM D3139. C900, section 3.2, requires that manufacturers make test data available to the purchaser on request.

AWWA C605-5, “PVC Pipe Installation,” section 5.6 (Pipe Bending and Gradual Alignment Change), instructs to “block or brace pipes to ensure that the joint deflection (angular misalignment) does not exceed manufacturers’ recommendations.” It recommends against bending pipe larger than 12 in. because of the force required.

**Field experience weighs in as well.** The central problem with curved PVC is high life cycle cost because of increased need for maintenance activity and the increased difficulty of performing maintenance when PVC pipe curvature is involved.

Tucson Water by and large accepts the following maintenance issues as sound arguments for change:

• PVC pipe failures in the bending mode require replacement of an entire length of (usually split) pipe.

• If pipe is bent or deflected, cost-effective repairs cannot be made easily because new sections and existing joints do not align.
• At least some excavated C900 pipe failures exhibit stain marks on deflected joints where water has leaked past seals.
• Service taps are being specified on the tension side of curved PVC pipe in the design phase, potentially leading to split pipe failures and higher maintenance costs.

The Tucson Water construction staff agrees that it is an unacceptable cost burden for inspectors to support two different sets of design standards—one for developers and one for Tucson Water projects.

The development community resists higher initial costs. Developers, who must provide the water systems to serve their projects, are most concerned about initial costs. They are not motivated to consider maintenance and replacement costs, which are the realm of the water utility and its rate payers.

Contractors will be necessarily reluctant to accept exposure to the unknown cost and schedule effects of new practices. In some cases, they have worked out a cost saving when pipe can be rolled, eliminating the expense and labor associated with fittings called for in plans.

Manufacturers make varied claims. JM Eagle (formerly PW Eagle), a manufacturer of PVC water transmission and distribution Pipe, allows 1.5° angular deflection. JM Eagle’s technical bulletin TB-D4 says, “It is sometimes possible to accomplish this (restraint from excessive angular deflection) by backfilling over the joint before bending the pipe body” (PW Eagle 2005). A pressure pipe installation guide from North American Pipe states a 1° joint deflection limit (tested capacity, not a design limit). Pacific Western’s PVC pipe installation guide offers a 2° maximum joint deflection (again, that is a leak limit). Diamond Plastics’ installation guide states that “neither the pipe nor the joint should be axially deflected in any manner to cause stress on the joint” (Diamond Plastics n.d.). Diamond C900 will accommodate a 1° joint deflection.

One industry authority (Fassler 2011) writes, “Because of the compactive effort required to isolate the joint from radial bending of the pipe barrel we normally recommend using fittings to achieve changes of direction.”

Another authority (Glasgow 2014) says,

> I do not recommend attempting to bend gasket jointed pipe because:

• I am not aware of any method to keep the joints straight when bending the pipe during installation that has been proven to be consistently effective. The performance of any attempt is highly dependent on the installer.

The time dependent stress-strain properties of PVC are such that failures due to over-deflection of the bell joints typically do not occur until sometime after the installation has been completed, often after the installer’s warranty period has expired. A typical time window appears to be about 5-7 years after installation but will vary based on conditions. Occasionally we see bells broken by over deflection during installation but these are infrequent.

• The cost of the fittings needed to obtain the required alignment changes on a typical project are much less than the potential expenses if the system begins to fail after installation.

Allowing bending of the pipe in your specifications opens your company to potential conflicts with your installers and possible liability.

Utility policies lean toward restrictions. Tucson Water’s construction unit has conducted a review of municipal water utility specifications online. Following is a list of the utilities checked (favored material in parentheses):

• Albuquerque, N.M. (PVC)
• Corona, Calif. (PVC)
• Denver, Colo. (no preference)
• Las Cruces, N.M. (PVC)
• Las Vegas, Nev. (PVC)
• Maricopa County (which includes Phoenix), Ariz. (DI)
• Portland, Ore. (DI)
• San Diego, Calif. (DI)
• San Francisco, Calif. (PVC)
• Santa Fe, N.M. (PVC)
• St. George, Utah (no preference)
• Washington, D.C. (PVC)

The findings reflect a broad acceptance of PVC but frequently with restrictions.

Three utilities specify DI, seven PVC, and two do not favor a specific material. Of the seven utilities that specify PVC, four refer to existing standards and/or “manufacturers’ recommendations.” Three that show a preference for PVC impose their own restrictions on bend radius and/or joint deflection. The remaining two jurisdictions specify bend fittings and limit joint deflection regardless of pipe material.

Case studies reveal control issues. Historically in Tucson, there has been little control of PVC pipe curvature because bend fittings were allowed to be deleted in the field. The changes occurred without revision review, and possibly without designer knowledge, each being documented with an as-built sketch that did not include a record of the resulting layout’s radius of curvature. The effects of such changes on life cycle costs have not typically been a feature of the builder’s thought process—hence the need for control via standard specifications. Examples are available only by happenstance. The author can name three:

• Culver’s PN 2-012-2014 design was changed in the field by the deletion of two 45° vertical bends. An 8 in. PVC main was rolled about 2.33 ft vertically (up) between stations 10+90 and 11+50 (60 ft), resulting in a radius of curvature of 380–390 ft. That implies a high likelihood of joint deflection exceeding the...
utility’s then-current policy tolerance (1° of joint deflection, corresponding to a radius of 1,146 ft). It also takes the main substantially off profile, but not off plan. As Tucson Water does not require profile drawings for pipe smaller than 12 in., it is not likely that the casual viewer would realize that the plan is off profile. As the pipe remained in its easement, one can speculate that the change was thought to be inconsequential.

- Las Nubes subdivision, PN 2-081-2007, is similarly stressed as a result of horizontal curvature as a consequence of field substitution of rolled pipe for bend fittings. As can be seen in Table 2, that outcome produced radii of curvature that are, in some cases, below even the manufacturer’s minimum bending radius recommendation without service taps, 189 ft for 8 in. DR14 pipe under ideal conditions (Uni-Bell 2012).
- Entrada Segunda subdivision, PN 085-1996, failed as a result of deleting horizontal bends for a change of alignment that resulted in a 60 ft radius of curvature in 4 in. PVC pipe. The affected pipe was replaced in 2011 at ratepayer expense.

Concerning the Las Nubes subdivision, more detail is available. Curvatures were estimated from the as-built plan after construction. One example of unplanned curvature (out of four in this plan) appears in Figure 5. The effect of vertical curvature is available from profile information and Eq 1. Removed were

- four 11¾° bends × $200 ea = $800,
- six 22½° bends × 200 ea = $1,200, and
- corresponding restrained lengths.

A rough estimate of cost of pipe for the entire project derives from the 1,796 ft of (mostly) 8 in. pipe × $35/ft = $62,860.

This project merits closer examination than some others because it includes an example of planned curvature as well as the unplanned outcomes. We can therefore examine costs from two perspectives: that of replacing existing bend fittings and that of an existing curve replaced with bends and straight sections. The results are shown in Table 1, a spreadsheet with calculated cells (shaded) based on Figure 4.

Table 1 uses costs for fittings as provided by local retailers. The numbers for restrained flex couplings and flange coupling adaptors are 2016 list prices from Romac (Romac Industries Inc. 2016).

Expressed in terms of percentage of construction costs, we have

- +8% to stay within 0.31 ft of a curved pipe center-line,
- +3% to stay within 0.69 ft of a curved pipe center-line, and
- +3% to stay within 2.75 ft of a curved pipe center-line.

Taking a look at a larger radius of curvature, we consider the Tucson Water–financed Aerospace Parkway 12-Inch Main Extension project, PN 3-012-2016. It is an Aerospace Corridor project of Tucson Water along a mile-long curved roadway. Its design avoids the use of longitudinal bending at minimal incremental cost. The author used the detailed construction cost estimate of the consulting design agency to focus on the financial impact of installing fittings instead of longitudinal bending of the PVC pipe barrel. The line has a minimum inscribed radius of approximately 1,800 ft. It uses eight fittings and six flange coupling adapters (FCAs) to accomplish a reverse-bend (s-curve) horizontal alignment change in a little less than a mile of pipe. The estimated cost of the fittings and FCAs was $8,700 for the estimated $812,280 project. The added fittings avoided designed-in bell-and-spigot joint deflection at an additional cost of 1.1% of the total.

PVC that is bent in storage or during transport is a related, though separate, issue. The fact that it occurs so easily has been raised in defense of bending PVC pipe by design. But the problems are durability of pipe in the bent condition and stress in the joints required to react the bending moment for an indefinite period (much longer than 10 years). The author is not aware of any industry authority that recommends allowing PVC pipe to be stored or transported in a bent or stressed condition.

**CONCLUSIONS, RECOMMENDATIONS, AND FUTURE DEVELOPMENTS**

The most likely causes of early C900 PVC pipe failure include improper installation and incorrect system design, the design issue being curvature. In strictly manufacturing terms, the failure mode described is indicative of an over-constrained joint design, with little tolerance for angular deflection and no accepted way to measure or control it in the field.

This result does not necessarily impugn the value of PVC as a pipe material. Dig-up test results of material properties indicate that PVC pipe should provide reliable service in excess of 100 years (Folkman 2014). However, the Folkman report does point to installation issues and vulnerability of the dominant joint design.

Perhaps the most obvious conclusion to be drawn from this exercise is that there is an opportunity for change in the way water utilities manage the use of PVC that would mean a savings in maintenance and reduced upward pressure on water rates. Corresponding recommendations follow.

- Delete from design standards undefined or unenforceable language (e.g., “gentle curvature,” “recommended joint deflection limit”). If a design standard cannot be met, a written, attributable explanation subject to the utility’s approval (also attributable) must be entered into the record.
- If a plan proposes to curve PVC pipe by bending, require that the consultant submit a sealed calculation of the bending force and a written description of the procedure for review by the construction unit.
<table>
<thead>
<tr>
<th>Present Status</th>
<th>Comparison Status</th>
<th>Station</th>
<th>Fitting Removed</th>
<th>R'</th>
<th>( \Delta )</th>
<th>( \lambda )</th>
<th>( \beta )</th>
<th>( \theta )</th>
<th>( \frac{b}{2} )</th>
<th>L/( \lambda )</th>
<th>Bend Mult</th>
<th>V</th>
<th># FCAs (4°)</th>
<th># Cplngs (8°)</th>
<th>Cost/ Bend $</th>
<th>Cost/ FCA $</th>
<th>Total for Bends $</th>
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</thead>
<tbody>
<tr>
<td>Bend fittings removed</td>
<td>Bend fittings redeployed</td>
<td>1-11.25</td>
<td>185.00</td>
<td>33.75</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>278.77</td>
<td>NA</td>
<td>500.89</td>
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<tr>
<td>Bend fittings removed</td>
<td>Bend fittings redeployed</td>
<td>1-22.5</td>
<td>177.00</td>
<td>45.00</td>
<td>NA</td>
<td>NA</td>
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<td>NA</td>
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<td>NA</td>
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<td>NA</td>
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<td>33.75</td>
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<td>432.00</td>
<td>4905.00</td>
<td></td>
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</tbody>
</table>

Dashes—absence of data, FCA—flange coupling adapter, NA—not applicable

R' = R + \( \frac{b}{2} \) (Figure 4)
\( \Delta \) = total change of alignment—degrees
\( \lambda \) = lay length of a single stick of pipe, typically 20 ft
\( \beta \) = nominal bend angle of fitting—degrees
\( \theta \) = actual bend angle (Figure 4)
\( \frac{b}{2} \) = radial separation between circumscribed and inscribed radii—feet (Figure 4)
L/\( \lambda \) = number of sticks of pipe between bends
Bend Mult = number of full bends plus a fractional component that may need one or two flange coupling adapters
V = number of vertices for a uniform structure deviating no more than \( \frac{b}{2} \) from an arc of radius R'
# FCAs = number of restrained flange coupling adapters, 4° max deflection
# Cplngs = number of restrained couplings, 8° max deflection (4° per side)
In addition, require a calculation of the stress concentration factor around a 1 in. hole in the pipe located on the outside surface of the curved pipe away from the center of curvature at the highest stress location, with the pipe operating at an internal pressure of 200 psi. The bend radius shall not be treated as constant in this calculation but is to be that radius corresponding to the maximum curvature of a pipe subject to central point loading of a simply supported beam, allowing for the pipe’s material properties as a function of temperature. The calculation must demonstrate a safety factor of 2.0 with respect to allowable bending stress per equation 4-13 in AWWA Manual M23 at the maximum anticipated water temperature (in Tucson’s case, 90°F).

- Stipulate a particular method, or methods, by which joint deflection limits are to be verified by the manufacturer. Require certification to ISO 13845 (ISO 2000) along with a copy of the test procedure and results. Certification to ASTM D3139 with procedure and results should be acceptable only if the results show a minimum deflection of 2° without leakage.
- Specify a method of blocking joint deflection that takes soil-bearing pressure limitations into account.
or makes them irrelevant (similar to the relationship between thrust blocking and thrust restraint).

- Specify a method of measuring joint deflection and require qualifying that method by a gauge R&R (repeatability and reproducibility) procedure per ASTM E2782. Use a maximum measured deflection of 0.2° in order to retain most of the manufacturer’s allowable deflection for unplanned incidents such as ground movement, settling, pressure surges, and loss of soil-bearing capacity as a result of saturation or physical disturbance by maintenance activity. In the absence of a qualified method of measuring joint deflection, disallow the use of PVC pipe longitudinal bending in design.

- Prohibit use of gasketed PVC pipe when surface terrain is ungraded or rough-graded (requiring a profile for ungraded or rough-graded terrain for all pipe diameters should obviate this requirement because joint deflection would not need to be inferred from surface grading with assumed constant depth, as is currently the case) and when curved PVC fails its joint deflection check.

- Do not qualify any gasketed PVC pipe with bell-and-spigot joints and an allowable joint deflection of less than 2° per ASTM D3139 or ISO 13845.

ACKNOWLEDGMENT

The author is indebted to various departments and individuals at Tucson Water and to various individuals in the Tucson developer community for their valuable data, thoughts, and insights. In particular, Tom Victory and his System Planning and Evaluation unit at Tucson Water provided the raw pipe failure data in assimilable spreadsheet form. Gabriel Hernandez of Tucson Water’s construction unit provided cost data for components in Table 2 to enable estimation of the impact of costs. He also conducted the utility specification benchmarking review mentioned in this article.

ABOUT THE AUTHOR

Laurence B. Winn is a civil engineer at Tucson Water, 310 W. Alameda St., Tucson, AZ 85726 USA; laurence.winn@tucsonaz.gov. He holds a master of engineering degree with an emphasis in fluid mechanics from UCLA (1980). His professional registration (Arizona) is in mechanical engineering. He is a nine-year veteran of Tucson Water’s New Area Development Unit as a civil engineer engaged in plan review, project management, and standards development. Winn’s previous employment and continuing interests have been in the energy, aerospace, and heavy-duty automotive industries.

REFERENCES


