Distortions From a Simplified Approach to Fatigue Analysis in PVC Pipes

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This work examines the extent to which simplifications suggested for fatigue analysis of polyvinyl chloride (PVC) pipes can cause distortion in system evaluation. To this end, fatigue analysis is performed on a hypothetical pipe system using two independent approaches: first, using a recommended method that calculates the fatigue parameters through thorough transient modeling and, second, through a highly simplified but widely used approach arising from direct application of the Joukowsky equation (through Plastics Pipe Institute’s program Pipeline Analysis & Calculation Environment).

The results show that the simplified approach significantly overestimates the transient loading and tends to devalue the expected fatigue resistance of PVC pipe. This devaluation arises from the fact that the Joukowsky approach, along with several other assumptions, is too conservative and simplified for fatigue analysis. This study concludes that for the PVC pipe systems exposed to significant pressure cycles, fatigue analysis is a required design check, but only a thorough and thoughtful consideration of transient loading can provide accurate and meaningful results.

Keywords: fatigue analysis, numerical modeling, PVC pipes, transient flow

Although the phenomenon of hydraulic transients and cyclic events in polyvinyl chloride (PVC) pipe systems has been extensively researched, this article contends that the results and ramifications of this research have often been at least partially misinterpreted by many system designers. Most designers are aware of the ability of PVC pipes to bear both internal working pressures and external loads, as well as its ease of installation, relatively low capital and installation costs, and low production energy (Ambrose & Burn 2005). However, the fact that a PVC pipe possesses a low acoustic velocity and can readily tolerate large vacuum pressures is less well known. This capacity to withstand negative pressure may help to significantly reduce surge protection costs in both pumping and gravity pipe systems. Moreover, because of its high flexibility and viscoelastic character, PVC pipe is sometimes capable of absorbing an important portion of the mechanical energy associated with a transient flow. Thus, PVC pipes can at times be regarded as contributing to a distributed surge protection system.

The large amount of energy absorbed by the pipe wall during the course of transient flows, however, has a potential downside—it can cause plastic pipes to be more vulnerable to fatigue issues than more rigid types of pipe material. Although in practice, few fatigue-based failures have been reported for PVC pipes, laboratory tests confirm that the fatigue mode of failure remains a possibility that might compromise the life cycle of PVC pipe systems if cyclic loading is not given adequate consideration. Nonetheless, lab test results may misrepresent real loading because, to generate a quick fatigue failure in the lab, several years of cyclic loads may be imposed in just a few days. This may increase the effective frequency of the cyclic loads whereby the likelihood of a fatigue failure may be unreasonably magnified. Nevertheless, this conservatism means that the experimental data are a suitably conservative benchmark for exploring whether a fatigue mode of failure of PVC pipes is likely in practice.

On the basis of the laboratory data (Jeffrey et al. 2004), the AWWA standard, C900 (AWWA
such systems, the recurrent pressure surge amplitude and number of cycles can be significantly reduced by controlling the motor rundown speed through the careful selection of the number of pump units and the size of the suction well or through other surge protection measures.

Generally speaking, fatigue analysis is sensitive to the recurrent pressure surge amplitude and the number of cycles, so poor or overly conservative estimates of these variables may compromise the fatigue analysis. This article examines the challenges associated with the fatigue analysis in PVC pipes and seeks to understand to what extent a simplified approach like the one used in PACE might distort such analysis. To this end, fatigue analysis is explored in the context of a hypothetical PVC force main for which the recurrent pressure surge amplitude and the number of pressure cycles associated with different operational protocols are determined through a thoughtful transient analysis. The results of this approach are then used as a benchmark for evaluating the results obtained from the simplified approach used by PACE. It should be noted that the use of the simplified approach used in the PACE model is in fact commonly accepted in the water and wastewater conveyance industry; however, the distortion associated with overestimating the magnitude and frequency of transient pressures associated with the simplified approach is shown to be capable of requiring inappropriate and costly transient control systems.

**MODELING**

Transient flow in closed conduits is governed by two well-known partial differential equations, representing the momentum and continuity equations, respectively (Wylie & Streeter 1993, Chaudhry 1987):

\[
\frac{\partial V}{\partial t} + \frac{\partial H}{\partial x} + \frac{f}{2D} V |V| = 0
\]  
\[
\frac{\partial H}{\partial t} + \frac{a^2 \partial V}{\partial x} = 0
\]

where \(V\) is the velocity, \(H\) is the piezometric head, \(D\) is the pipe diameter, \(a\) is the elastic wave velocity, \(g\) is the gravitational acceleration, \(f\) is the friction factor in Darcy–Weisbach equation, and \(x\) and \(t\) are the independent variables of distance and time, respectively.

These equations are assumed to be valid as long as system pressures exceed the local vapor pressure. However, if local pressures drop to vapor pressure, as they can so easily do in practice, cavitating flow and column separation necessitates a modified approach. Cavitating flow naturally gives rise to vapor cavities and may separate the water column into effectively independent segments. These events frequently occur when a rarefaction wave causes the hydraulic grade line to fall below the pipe profile by one atmospheric pressure. It can also occur when two negative waves meet (are superimposed) at specific points. As cavitating flow
maintains the pressures constant at vapor pressure, the hydraulic grade lines on either side of the cavitating points often adopt different slopes. This behavior has the potential to produce large local mass imbalances at cavitating points whereby substantial cavities with high void fractions can form. The collapse of such cavities can produce significant and destructive transient pressures.

Past research and long-time use show that one of the most efficient and reliable approaches for handling column separation is the discrete gas cavity model (DCGM) (Simpson & Bergant 1994). In this approach, very small gas bubbles are assumed at the computational nodes, allowing the replication of cavity formation and collapse in the system. As long as the pressure in the system is above atmospheric, the cavities are too small to slow down the wave motions, and the water-hammer pressure is propagated in the system with the true speed of the acoustic velocity in the pipe. However, when the pressure drops to the liquid vapor pressure, the expansion of gas bubbles at the computational node accounts for a dramatic reduction of the acoustic velocity in the area of the cavitating flow. In addition, the expansion and contraction of gas bubbles replicates the formation and collapse of the cavities that may form in the system. To implement the DCGM, Eqs 1 and 2, along with the equations governing the evolution of the gas bubbles, should be solved numerically. Several numerical approaches have been proposed to solve these equations, among which the well-known method of characteristics provides more accurate results (Wylie & Streeter 1993, Chaudhry 1987); thus, it is used in this study.

It should be noted that, by using such a model for column separation, the authors are not in any way suggesting that significant concerns do not often arise from the occurrence of negative system pressures nor that other protection measures should not be considered if negative pressures are predicted or do occur. The point of this analysis is that, even in the extreme case that some negative pressures are expected and tolerated, fatigue analysis is perhaps particularly appropriate but must still be carried out in a reasonable manner.

Fatigue analysis instruction. On the basis of significant experimental data embedded in Figure 1 (Jeffrey et al. 2004), AWWA C900 (AWWA 2016) has a simple approach for calculating the number of pressure cycles leading to fatigue failure in PVC pipes. The key information required for extrapolating the graph are the hoop stresses associated with both the expected recurrent water-hammer pressure surges’ amplitude during the normal operation of the system and the mean pressure around which the transient pressures oscillate. Figure 2 illustrates this key information.

When the number of allowable cycles is extracted from the graph, the years to failure can be easily calculated from the following formula:

\[
\text{Years to failure} = \frac{\text{Number of allowable cycles}}{(SF \times \text{Number of cycles expected in a year})}
\]

where SF is a safety factor that must be 2, according to AWWA C900 (AWWA 2016).

**CHOICE OF THE PIPE SYSTEM**

As mentioned earlier in this article, the performance of the PACE program is evaluated in the context of a hypothetical pipe system for which a thorough transient analysis provides actual occasional pressure surge amplitudes and the number of pressure cycles. However, only a few pipe systems require any analysis at all because there are many types of water and wastewater systems for which the velocities and the rate of change of velocity are too slow to produce significant recurrent transient pressure cycles. Typical examples are water distribution networks supplied by service reservoirs, gravity water, and wastewater conveyance lines and variable-speed pumping systems in which the flow is smoothly changed. The systems of interest are therefore most applicable to force mains or systems with a flow control achieved through frequently turning pumps on and off.

Pipe system configuration. Figure 3 illustrates a hypothetical PVC force main with the maximum capacity, length, internal diameter, and static head of 0.7 m³/s, 5 km, 700 mm, and 100 m, respectively. The pump station consists of four parallel pumps, each providing the head of 118 m at the maximum flow condition. Pumps are equipped with 300 mm control valves at their discharge lines, allowing different operational protocols to be implemented.

To determine the pipe’s dimension ratio (DR), it is assumed that the internal pressure is the key controlling factor, and the external load does not play an important
role. According to manuals from Uni-Bell and AWWA (Uni-Bell 2012, AWWA 2002), the pipe’s DR has to be selected such that the following criteria are satisfied:

\[
WP + P_{rs} \leq 1.6 \times PC \times F_T \quad (3)
\]

\[
WP + P_{os} \leq PC \times F_T \quad (4)
\]

where WP is the working pressure, \( P_{rs} \) is the maximum recurrent surge pressure, \( P_{os} \) is the maximum occasional surge pressure, \( F_T \) is the thermal re-rating factor, and \( PC \) is the pipe pressure class, with the magnitude summarized in Table 1.

At temperature 23°C, \( F_T = 1 \), and for higher temperatures, this factor decreases as the operational temperature increases. Assuming that the operational temperature is 23°C, the thermal rerating factor is considered to be 1 in this study.

As shown in Figure 3, in the steady-state condition, the pipeline experiences the maximum pressure head = 118 m at the pump station. Although the maximum
pressure head varies along the pipeline and reduces as the pipe installation elevation increases, for the sake of uniformity, the whole length of the pipeline is designed for the same maximum pressure. Thus, WP is simply calculated as 1,158 kPa.

To determine whether the criteria expressed by Eqs 3 and 4 are met, both $P_{rs}$ and $P_{os}$ must first be calculated. However, because the magnitude of these parameters depends on the method used for calculating the transient flow, the two approaches used in this article may yield different results. This concludes that the pipe’s DR has to be independently determined for each approach.

The maximum occasional pressure surge is a result of when power failure causes all the pumps to be simultaneously shut down. To accurately calculate the resulting maximum pressure, many factors have to be considered, including the shape of the pipeline profile; pipe acoustic velocity; the moment of inertia of the pumps; size, type, and location of active air valves in the system; and type and specifications of surge protection device (if any). However, PACE excludes many of these parameters and, as mentioned, makes several simplifying and highly conservative assumptions: (1) there is no surge protection device, and the pipe tolerates both negative and positive transient pressures on its own; (2) the maximum occasional pressure surge amplitude is simply obtained from the Joukowsky equation with the assumption that the flow velocity is suddenly changed from the maximum (1.82 m/s in the current system) to zero.

As pipe acoustic velocity is a function of pipe’s DR, an occasional pressure surge has to be calculated through a trial and error procedure. DR = 21 is a good first guess because, as shown in Table 1, it can handle the pipe working pressure. From Table 1, the associated acoustic velocity is 361 m/s, and the occasional pressure surge is simply calculated as

\[
P_{os} = \rho a \Delta V = 657 \text{ kPa}
\]

Applying Eq 1 verifies that DR = 21 satisfies the criterion associated with the occasional surge.

To determine whether DR = 21 meets the requirement associated with Eq 4, the recurrent pressure surge amplitude also has to be calculated. PACE gives the users the option to input the maximum velocity change on the basis of calculated recurrent pressure surge amplitude. Nevertheless, for the sake of evaluation of PACE, the recurrent pressure surge amplitude is calculated on the basis of the minimum velocity assumed in this program, 1.22 m/s. This results in a pressure amplitude of 477 kPa. It is seen that Eq 4 is not satisfied, so the pipe DR has to be upgraded to 18. For this DR, the recurrent pressure surge amplitude is recalculated as 481 kPa according to the acoustic velocity of 394 m/s. Again, the criterion is not met, and the DR has to be upgraded to 14. In this case, the recurrent and occasional pressure surge amplitudes are 548 and 817 kPa, which satisfies the criteria presented in Eqs 3 and 4.

To independently determine the pipe’s DR for the proposed approach, a thorough transient analysis is performed to calculate the maximum occasional pressure surge occurring when all pumps are simultaneously shut down following a power failure. As the acoustic velocity depends on the pipe’s DR, three independent transient analyses are performed for DRs 21, 18, and 14 with the associated acoustic velocities of 361, 394, and 449 m/s, respectively.

Figure 4 depicts the envelope of the maximum and minimum pressures along the system during the course of the transient. The figure shows that the maximum transient pressures occur near the pump station.

![Figure 4](image-url)

**Figure 4** The envelope of maximum and minimum pressures induced following power failure

| DR | PC | Acoustic Velocity |
|----|----|------------------|
| 14 | 2,110 (305) | 449 |
| 18 | 1,620 (235) | 394 |
| 21 | 1,380 (200) | 361 |
| 25 | 1,140 (165) | 331 |
| 26 | 1,100 (160) | 325 |
| 32.5 | 860 (125) | 289 |
| 41 | 690 (100) | 259 |
| 51 | 550 (80) | 243 |

DR—dimension ratio, PC—pressure class

Adapted from Uni-Bell 2012
Figure 5 also represents the pressure time history at the pump station. It is seen that the maximum induced pressures for DRs 21, 18, and 14 are 1,783, 1,928, and 2,050 kPa, respectively. It is easy to justify that DR 21’s short rating pressure (1.6 \times PC = 2,208 kPa) is higher than the maximum occasional surge pressures of these three cases, so the criterion associated with Eq 3 is not a controlling factor here.

Figure 4 implies that the system experiences full vacuum conditions over a good portion of its length and, moreover, experiences column separation at the high points of the pipeline profile. Presenting this graph is not to imply that such pressures are recommended or indeed routinely permitted. However, pump power failure is usually an infrequent event and PACE assumes that no dedicated surge protection is present when calculating the parameters required for fatigue analysis. Thus, for a fair, apples-to-apples comparison, it is assumed here that the system receives no surge protection and that the pipe can bear both positive and negative pressures induced by the transient. Indeed, PVC pipes have a considerable capacity to resist negative pressures, being found capable of safely bearing essentially full vacuum pressure (Uni-Bell 2012). The full vacuum pressure may compromise the integrity of the joints, but in practice, specifying specialty gaskets or butt-fused joints resolves this problem as well. However, although the accuracy of DGCM in capturing positive pressures following cavity collapse has been widely proved in the lab (Bergant et al. 2006), further investigation is certainly required to confirm if similar accuracy can be achieved while applied on real and complex pipe systems being used in practice. Nevertheless, it is assumed that the overpressure captured by DGCM is accurate enough to be used for the sake of designing a pipe grade in this study.

Recurrent surge amplitude depends on the way the system is operated. It is assumed that the worst-case condition is associated with an operational protocol through which, every 10 min, two pumps are simultaneously shut down, and then the pumps are put into operation by simultaneous starting up of two pumps in the same time period.

In practice, it is common to start up the pumps against their closed pump control valves, and when the pumps achieve their operating speed, the valves open in the prescribed time to minimize hydraulic transient conditions. Similarly, when shutting down the pumps, the discharge valves are usually closed under control before the pumps turn off. The valve operational time has to be sufficiently long to allow the pumps to become stabilized at their working point. An efficient time period is the one allowing the pumps to have adequate communication with the downstream system while converging toward their steady-state condition. Perhaps a time = 4 L/a = 56 s satisfies this condition, but for the sake of producing more intensive transient conditions and a more conservative design, opening and closing time is considered to be 30 s in this study.

The operational protocol discussed is implemented on the numerical model, and the consequent transient flows in the system are calculated. The transient pressure time histories induced at the pump stations at DRs 21, 18, and 14 are summarized in Figure 6. As can be seen, the maximum pressures induced in the system are 1,311, 1,345, and 1,406 kPa for the DRs 21, 18, and 14, respectively. It is also seen that, for DR = 21, the maximum pressure surge is less than its pressure class, 1,380, so pipe DR = 21 satisfies both design criteria expressed in Eqs 3 and 4. The simplified approach used by PACE has come up with a pressure class two grades...
higher as a result of overestimating the recurrent pressure surge amplitude.

**FATIGUE ANALYSIS**

Although the simplified approach used by PACE is independent of the system operation, in reality, a proper fatigue analysis shows significant sensitivity to the pace of operation. To show how this affects the fatigue analysis results, different operational protocols are examined in this article; the scenarios are designed to produce different intensities of transients that may be expected in the real-time operation of pumping systems. The three (rather extreme) scenarios considered in this study are as follows:

1. Every 10 min, two pumps are simultaneously turned off and then turned on in the same order.
2. One pump stays on, while the other three pumps simultaneously turn off and on every 10 min.
3. All pumps are first sequentially turned off every 10 min and then turned on in the same order in 10 min intervals.

The rate of flow change in the operational protocols defined by scenarios 1 and 2 are too high to represent the operation of many force mains being used in practice. Nevertheless, these scenarios are proposed to represent either the pumping systems rarely responding to highly variable flow or those with poor design. In addition, these scenarios are considered to clearly show that, even in such rapid flow change as that used by PACE, the resistance of PVC pipes to the fatigue mode of failure is far higher than that implied by PACE’s results.

To perform fatigue analysis, the recurrent pressure surge amplitude, mean pressure, and the number of pressure cycles per day have to be first calculated for both the simplified and proposed approaches presented in this article. As explained earlier, the simplified approach does not distinguish among the scenarios, and for all aforementioned scenarios, the same maximum recurrent pressure amplitude and mean pressure of 548 and 1,158 kPa, respectively, are considered. The number of cycles obtained from the thorough transient analysis will be applied in both simplified and detailed approaches unless the number of cycles is less than the minimum number of the cycles allowed in PACE, 55. In such cases, the number of cycles considered in the simplified approach is assumed to be 55.

For the proposed method, transient analysis needs to be carried out to calculate the key parameters for each operational scenario. However, as the pipe’s DRs in the proposed and simplified approach are different, transient analysis has to be carried out for different DRs to make an apples-to-apples comparison possible.

Figures 6–8 depict the pressure time histories at the pump station where the maximum pressure occurs. It is observed that, for the operational scenarios 1 and 3, as long as the flow does not reach zero, no significant transient pressure cycles occur, and the induced pressure pulses are too weak and short lived to even be called cyclic pressures. However, when the last pump(s) is(are) shut down, significant transient pressure oscillation occurs, with the amplitude decreasing with time.

In no evaluated scenario did the pipe system experience a full vacuum condition. In the evaluated systems, the most severe negative pressures are produced at the end of the evaluated pipeline (the last 200 m) with a magnitude of about −5 m of water pressure or ½ a full vacuum. Such residual negative pressures can easily be tolerated by the pipe system itself.

From the fatigue analysis perspective, the train of pressure cycles is shown to be equivalent to 1.55 cycle of a pressure rise having the maximum amplitude of the wave train (Uni-Bell 2012, Jeffrey et al. 2004). As shown in Figures 6 and 8, the pressure cycles in
scenarios 1 and 3 occur every 40 and 80 min, respectively, so the number of cycles per day in these scenarios is 56 and 24, respectively. For scenario 2, one pressure cycle occurs every 20 min, so 72 cycles per day are expected for this scenario. Table 2 summarizes the key parameters considered in fatigue analysis in both approaches.

On the basis of the information in Table 2, the number of cycles leading to pipe failure is retrieved from Figure 1, and the years to failure for each scenario and pipe DRs are calculated by considering the number of pressure cycles and the safety factor of 2; the results are shown in Table 3.

As can be seen, the proposed approach’s results show significant sensitivity to the mode of operation, while the simplified approach provides almost the same results for different scenarios. For the worst-case scenario and for DR 14, the years to failure calculated by the detailed approach is more than two times longer than that estimated by the simplified approach. For the other two scenarios, the results obtained from the simplified approach are even more different from the detailed approach values. As an example, for scenario 3, the real years to failure of the pipe is 1,584, while the simplified approach underestimates it at 77 years. That is why the simplified approach used by the PACE clearly produces distorted and highly conservative results.

**DISCUSSION**

To explain the reasons for the difference between the results from the detailed and the simplified approach, it is helpful to look closer at the transient responses of the system to the different operational scenarios. To this end, Figures 9–11 represent the time histories of the velocity and pressure associated with scenarios 1–3, respectively.

As can be seen, the velocity drops of 1.11, 1.33, and 0.6 m/s in scenarios 1–3 increase the pressures from 522, 689, and 727 kPa to 1,406, 1,142, and 1,224 kPa, respectively. However, according to the simplified approach, these velocity changes should have given rise to the maximum pressures of 1,656, 1,755, and 1,427 kPa, respectively calculated by adding the maximum working pressure of the system, 1,158 kPa, to the waterhammer pressure rise associated with the velocity change, which is calculated using the Joukowsky equation. The simplified approach significantly overestimates the maximum pressure in all scenarios for the following reasons.

- The Joukowsky equation cannot provide accurate results in complex systems used in practice, as the transient responses of the system depend on many other factors other than velocity change, the most

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**TABLE 2**  
Maximum, minimum, and mean transient pressures calculated for proposed and simplified approach

| Scenarios | DR   | Maximum Pressure | Minimum Pressure | Mean Pressure | Number of Cycles |
|-----------|------|------------------|------------------|--------------|-----------------|
| Proposed  |      |                  |                  |              |                 |
| 1         | 14   | 1,406            | 522              | 964          | 56              |
|           | 18   | 1,354            | 581              | 963          |                 |
|           | 21   | 1,311            | 617              | 964          |                 |
| 2         | 14   | 1,237            | 681              | 959          | 72              |
|           | 18   | 1,233            | 719              | 976          |                 |
|           | 21   | 1,230            | 740              | 985          |                 |
| 3         | 14   | 1,224            | 727              | 976          | 24              |
|           | 18   | 1,208            | 755              | 982          |                 |
|           | 21   | 1,195            | 774              | 985          |                 |
| PACE      |      |                  |                  |              |                 |
| 1         | 14, 18, and 21 | 1,706            | 610              | 1,158        | 56              |
| 2         |      |                  |                  |              | 72              |
| 3         |      |                  |                  |              | 55              |

DR—dimension ratio, PACE—Pipeline Analysis & Calculation Environment

Dashes indicate that the value is the same as that in the previous row.

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**TABLE 3**  
Years to failure for different scenarios

| Scenarios | Proposed | PACE |
|-----------|----------|------|
|           | DR = 21  | DR = 18 | DR = 14 | DR = 14 |
| 1         | 71       | 99     | 168     | 75      |
| 2         | 164      | 237    | 438     | 59      |
| 3         | 711      | 996    | 1,584   | 77      |

DR—dimension ratio, PACE—Pipeline Analysis & Calculation Environment
important of which is the performance of the pumps and valves during the course of transient. For example, in scenario 2, when three pumps are simultaneously shut down, the significant flow change of 1.33 m/s produces the maximum pressure of just 1,142 kPa, which is far lower than that calculated using the Joukowsky equation, 1,755 kPa. This is attributed to the performance of the pump that remains on during the course of transient. The running pump controls the pressure in the system and theoretically does not allow the pressure to go beyond the shut-off pressure of the pump.

- To calculate the maximum transient pressure, the simplified approach adds the water-hammer pressure rise to the maximum working pressure of the system. However, as shown in Figures 1–3, the pressure rises are not built on the maximum working pressure of the system but rather built on markedly lower average pressures of 964, 959, and 976 kPa, respectively.

As Figure 1 implies, overestimating both mean pressure and recurrent pressure surge amplitude can significantly distort fatigue analysis results. In addition, the restriction that PACE puts on the minimum number of pressure cycles and velocity change further distorts the resultant fatigue analysis. This restriction prevents the user from applying a lower number of cycles and velocity change than 55 and 1.22 m/s (4 fps), respectively. The authors do not understand the rationale behind considering such a high velocity for calculating recurrent surge pressure amplitude. AWWA C900 (AWWA 2016) does not restrict the minimum velocity or the number of pressure cycles, and they are both left to the designer to be selected based on the configuration and mode of operation of the system being analyzed. It is interesting to note that, in the design example presented in AWWA’s standard (C900; AWWA 2016) for PVC, the pressure surge amplitude considered (207 kPa) is associated with a velocity change that is significantly lower than 1.22 m/s. Considering the pipe DR (18) in this example, the velocity change can be calculated as follows:

$$\Delta V = \frac{\Delta P}{\rho a} = \frac{207,000}{1,000 \times 394} = 0.53 \text{ m/s}$$

As can be seen, this velocity is less than half of the minimum velocity considered by PACE. The limitations enforced by PACE violate the standard itself.

**SUMMARY AND CONCLUSIONS**

This research considers the challenges associated with the fatigue analysis of PVC pipes and seeks to understand to what extent one of the simplified approaches

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**FIGURE 9** Pressure and velocity history for scenario 1 and DR 14

| Time | Pressure (kPa) | Velocity (m/s) |
|------|----------------|----------------|
| 500  | 1,000          | 0.5            |
| 700  | 1,100          | 0.75           |
| 900  | 1,200          | 0.9            |
| 1,100| 1,300          | 1.05           |
| 1,300| 1,400          | 1.2            |

**FIGURE 10** Pressure and velocity history for scenario 2 and DR 14

| Time | Pressure (kPa) | Velocity (m/s) |
|------|----------------|----------------|
| 0    | 600            | 0.1            |
| 100  | 700            | 0.25           |
| 200  | 800            | 0.4            |
| 300  | 900            | 0.55           |
| 400  | 1,000          | 0.7            |
| 500  | 1,100          | 0.85           |

**FIGURE 11** Pressure and velocity history for scenario 3 and DR 14

| Time | Pressure (kPa) | Velocity (m/s) |
|------|----------------|----------------|
| 700  | 1,100          | 0.2            |
| 1,400| 1,300          | 0.45           |
| 2,100| 1,400          | 0.6            |
| 2,800| 1,500          | 0.75           |
| 3,500| 1,600          | 0.85           |
| 4,200| 1,700          | 0.95           |
suggested for this analysis can distort system evaluation. To this end, fatigue analysis is performed on a hypothetical pipe system using two independent approaches: (1) a proposed method calculating the parameters required for fatigue analysis by performing a thorough transient modeling and analysis and (2) a simplified approach used by PACE designed mainly on the basis of the Joukowsky equation and several other simplifying assumptions.

Of the many types of pipe systems, force mains with on–off flow control systems are much more exposed to fatigue failure risk; thus, this type is selected for the hypothetical pipe. Fatigue analysis is then performed for different operational scenarios using both the proposed approach and the simplified approach used by PACE to examine the sensitivity of the results to the mode of operation in each method and to explore the accuracy of the PACE results.

The proposed approach shows that fatigue analysis results are significantly sensitive to the mode of operation such that, for the scenarios studied, the years to failure range from 71 to 1,584, while the PACE results ignore the mode of operation.

The results also show that PACE significantly distorts the results toward devaluing PVC pipe resistance against the fatigue mode of failure. This is shown to be attributed to the simplicity of the Joukowsky equation in the context of fatigue analysis. This simplicity, along with the minimum velocity considered in PACE for calculating recurrent pressure surge amplitude, enforces extensive and frequent water-hammer pressure rises, which in turn overestimates the fatigue loading. Moreover, limiting the value used for both minimum velocity and number of pressure cycles (to 1.22 m/s and 55, respectively) does not comply with AWWA C900 (AWWA 2016), which clearly states that the pressure surge amplitude and the number of cycles have to be selected by the designer on the basis of the system being analyzed.

It is emphasized that the current research is limited to exploring the system without additional surge protection. Further research is required to explore how a simplified approach can distort the fatigue analysis in the system under a surge-protection device. Intuitively, as the rate of transient pressure is reduced through additional surge protection, the simplified approach may even more dramatically distort the fatigue analysis results in these cases. Nevertheless, this contention also needs a thorough and systematic consideration.

Certainly, any condition that stresses pipe systems, whether single extreme events or more moderate but repetitive events, can be crucial to system performance and to the avoidance of system failure. Any PVC pipe system that is expected to be exposed to a significant number of intensity of pressure cycles must definitely undergo a thoughtful fatigue analysis as a mandatory design check. This article has described one approach to undertaking such a task, one that is still conservative but not unreasonably so.

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