# Effects of leakage points on intrusion volume in a simulated water distribution system

Yu Shao, Shipeng Chu, Chenkai Dang and Tingchao Yu


## ABSTRACT

Contamination can intrude into urban water distribution systems through pipe leakage orifices or other deficiencies, which can create public health risks. Intrusion volume is a significant indicator of health risks when a pollution incident occurs. A pilot-scale platform was constructed to simulate the contamination intrusion through leakage holes caused by low or negative pressure events. The intrusion device was improved from the author's previous study by substituting the replaceable pipes in the main pipe for the side connecting pipe. Comparison between the two intrusion devices demonstrated that the intrusion device with the side connecting pipe may underestimate the intrusion volume. The orifice diameter range is extended to be 3–19.0 mm to analyze the effects of leakage sizes on the intrusion volume. The results show that the intrusion volume first increased and then decreased with increase of the orifice diameter. The calculated intrusion volume by the orifice discharge equation using the measured discharge coefficient is slightly different from the measured intrusion volume.


**Key words** | intrusion volume, negative pressure, orifice, water distribution system


**Yu Shao**
**Shipeng Chu**
**Chenkai Dang**
**Tingchao Yu** (corresponding author)
College of Civil Engineering and Architecture,
Zhejiang University,
Hangzhou,
China
E-mail: *yutingchao@zju.edu.cn*

**Yu Shao**
**Tingchao Yu**
Key Laboratory of Drinking Water Safety and Distribution Technology of Zhejiang Province,
Hangzhou 310058,
China


## INTRODUCTION

The intrusion of polluted water into water distribution systems during low or negative pressure events was studied by Karim *et al.* (2003) and Gullick *et al.* (2005). Pressure drop in pipes, buried below groundwater level, and poor structural integrity of pipes are the three necessary components of polluted water intrusion into water distribution systems (Hooper *et al.* 2006). Changes in water velocity, uncontrolled pump startup and shutdown, water main break, sudden valve closure or opening, and sudden changes in demand are the common transient events that produce low or negative pressure in pipes (Kirmeyer *et al.* 2001; Boyd *et al.* 2004a). Once internal pressure in pipes is lower than external pressure outside pipes, the contaminated water may intrude into pipes through pipe defects.

Health risks in water distribution systems associated with low or negative pressure events are a significant concern (Hunter *et al.* 2005). Besner *et al.* (2011) provided a conceptual model to assess the public health risk of microbial intrusion events in distribution systems. The accurate calculation of intrusion volume is important for risk assessment and decision-making. Boyd *et al.* (2004a, 2004b) measured the intrusion volume associated with valve shutdown events by using chemical tracer and volumetric methods and provided evidence of intrusion caused by transient negative pressure events. LeChevallier *et al.* (2004) and Fleming & LeChevallier (2008) used an orifice equation to estimate intrusion volumes through leakage points under various scenarios. Mora-Rodríguez *et al.* (2011) conducted experimental research to measure intrusion volume and used computational fluid dynamics to simulate pressure variation in pipelines during pressure transient events. Ebacher *et al.* (2011, 2012) analyzed the effects of leakage flow rate and the head of the leakage orifice on intrusion volume. Collins & Boxall (2013) presented a new analytical expression that considered the influences of ground conditions to compute intrusion flow rates. Yang *et al.* (2014)

doi: 10.2166/ws.2019.156

investigated the effects of porous media on intrusion flow rate and suggested a new expression to predict intrusion flow rates. Yu *et al.* (2016) used a pilot-scale experiment to propose a correction factor to improve the orifice equation for the intrusion volume calculation.

Liu & Simpson (2018) pointed out that the connection stub parameters and valve closure time have an influence on the transient measurement accuracy of a pressure transducer. Thus the intrusion device of Yu *et al.* (2016) was improved in this study by substituting the replaceable pipes in the main pipe for the side connecting pipe, because the side connecting pipe will regulate the transient pressure, and result in the underestimation of intrusion volume. The orifice diameter range was extended from 3.0–7.5 mm to 3–19.0 mm to evaluate the effect of leakage point size on the intrusion volume. Intrusion volumes were measured through a volumetric method and calculated by the orifice discharge equation using the measured steady discharge coefficient.

## MATERIALS AND METHODS

### Experimental devices

The main pipe layout is shown in Figure 1. The test rig includes an upstream constant-pressure tank, a downstream overflow tank, galvanized steel pipes, valves, electromagnetic flow meters, an intrusion-volume-measuring device, and pressure data loggers. The total length of the main pipe is 50.3 m. Its inner diameter is 50 mm and thickness is 4.0 mm. An electric ball valve lies between the water supply tank and the intrusion device, 43.9 m away from the downstream overflow tank. It is used to cause different negative pressure events by suddenly closing. The closing time of the valve ranges from 0.04 to 400 s and has an accuracy of ±0.02 s. Two electromagnetic flowmeters (KROHNE) are fixed 1.0 m away from the upstream and downstream of the pipeline respectively. They both have a full scale of 1.5–15 $m^3$/h and an accuracy of 0.5%. The pressure sensors (GE PTX5032) are 0.3 m away from the intrusion device at both sides, having a full scale of 0–1 MPa, an accuracy of 0.04%, and an acquisition frequency of 1,000 Hz.

The experimental intrusion device used here was improved from that utilized by Yu *et al.* (2016) and is shown in Figure 2(a). A leakage happens at the pipe wall of the stainless steel replaceable pipe, which is surrounded by the water in the sealed intrusion device. The replaceable pipe (50 mm inner diameter and 2.8 mm thickness) connects the main pipe directly, and has leakage holes of different shapes and sizes (Figure 2(d)) at the pipe wall. Two rectangular defects have the same area as the circular defect of 3 mm diameter. The circular defects have sizes of diameters from 3 mm to 19 mm. The intrusion device utilized by Yu *et al.* (2016), called 'old device' later in this article, was connected to the main

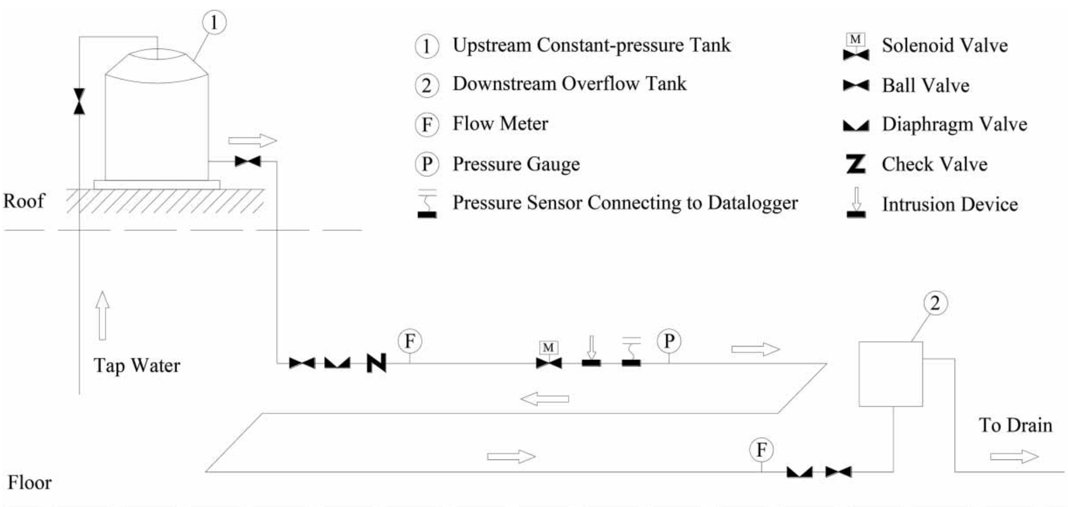


**Figure 1** | Schematic of the experimental installation (adapted from Yu *et al.* (2016)).

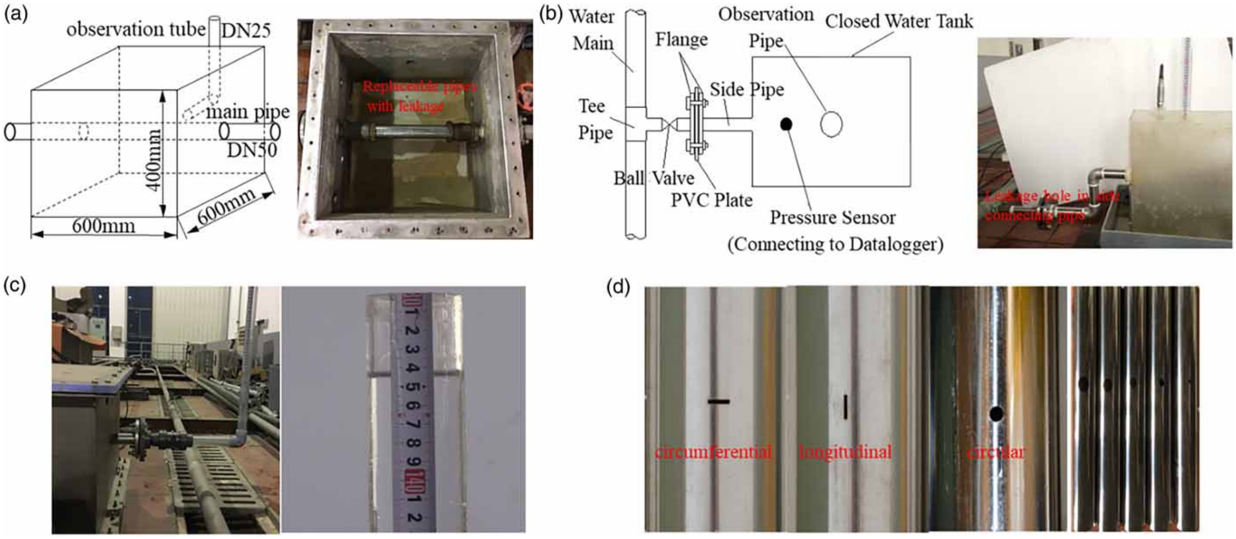


**Figure 2** | The intrusion device: (a) the opened new intrusion device with replaceable leakage pipe inside; (b) the sealed new intrusion device and its observation tube; (c) the intrusion device used in Yu *et al.* (2016); (d) leakage holes of different shapes in replaceable pipes.

pipe through a steel side tube. The side tube was fitted with a plate predrilled with a small hole in the center to simulate leakage (Figure 2(b)). The connected side pipe weakens the transient pressure. The sealed new intrusion device and the observation tube are shown in Figure 2(c). The observation tube, made of a transparent tube, is set at one side center of the device. Intrusion volume can be clearly read by observing the fluctuation of the water level through the ruler. And as an experimental parameter, the external pressure can be adjusted by changing the height of the observation tube.

### Measurement of the intrusion volume

The intrusion volume measured by video recording has the three steps. (1) *Initialization settings*: adjust the upstream and downstream valves to make the pressure and flow rate reach the design conditions. (2) *Recording transient event*: close the speed regulating valve to produce transient events; record videos of the water level fluctuation and data of the pressure sensor and flow meter. (3) *Data analysis and processing*: transform the videos into pictures, and read out the intrusion volume on the pictures. The water level in the observation tube may fall and rise in a transient event repeatedly. A digital video camera (SONY HDR-XR350) is positioned about 0.5 m away from the observation tube. The video file has 25 frames per second. Every frame image is extracted to capture such a water level fluctuation every other 0.04 s. The total intrusion volume is the sum of all the intrusion volumes for every pressure fluctuation during the whole transient event.

A typical pressure fluctuation process near the leakage and the dropping history of the water level in the observation tube during a complete valve shutdown event are shown in Figure 3. The pressure fluctuation with a leakage hole is close to, at the early stage, but decays faster than that without intrusion later (Figure 3(a)). The leakage hole does weaken the water hammer induced by a valve shutdown event, because the leakage hole connects the water in the main pipe to the surrounding water in the intrusion device, whose function is like that of a pressure regulator. Figure 3(b) shows the dropping history of the water level in the observation tube. The water level fluctuates for four to five cycles and then gradually stops.

### Calculation of the intrusion volume

Torricelli's formula (TOR) is most commonly used to calculate intrusion flow rate (Funk *et al.* 1999; Besner *et al.* 2011; Mora-Rodríguez *et al.* 2012). However, TOR may fail unless the variation of the leak area with the head is considered. Considering the steel pipe material and the thickness used,

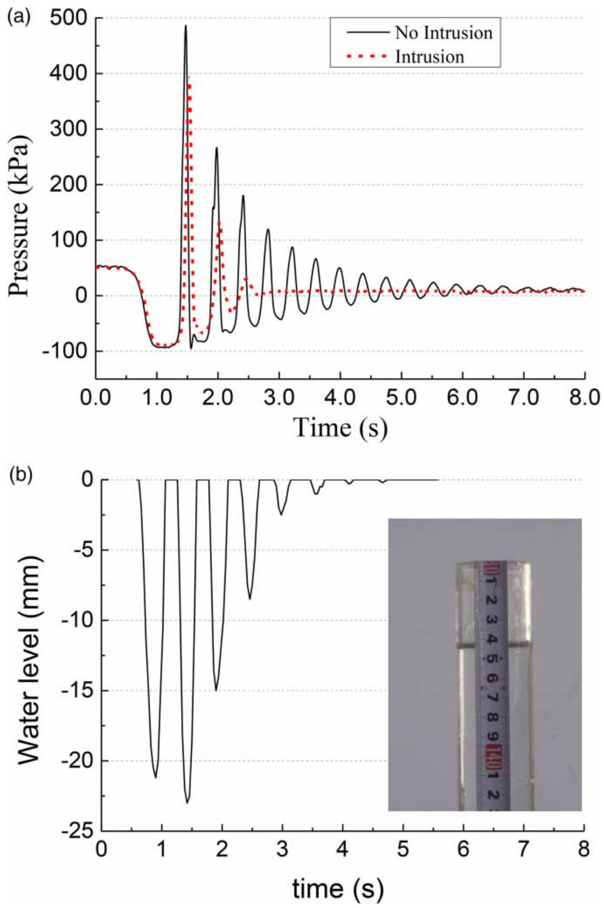


**Figure 3** | Typical history of the pressure and discharge during a transient event: (a) of the pressure change in the main pipe during a negative pressure event; (b) the dropping of the water level.

as Ferrante (2012) shows, TOR without considering area variation can be used at least in the examined range of pressure in this study. The discharge coefficient $\mu$ under steady-state experimental conditions was measured with different internal pressures. Then the intrusion volume can be calculated as Equation (1):

$$V = \sum_{i=1}^{n} \Delta V = \sum_{i=1}^{n} (A\mu_i \sqrt{2g(H_e - H_i)}\Delta t) \quad (1)$$

where $H_e$ is the external pressure; $H_i$ is the internal pressure; $\Delta t$ is the minimum calculation time (i.e., 0.001 s, according to the frequency of the pressure sensors); $\mu_i$ is the discharge coefficient, which can be obtained from experimental testing; and $\Delta V$ is the intrusion volume in the time interval ($\Delta t$). The total intrusion volume ($V$) can be accumulated from all the time that $H_e$ is larger than $H_i$ during a whole transient event.

### Experimental parameter setting

The intrusion process was affected by many factors, such as the size of leakage points, initial flow velocities ($v_0$), valve shutdown time ($T_z$), and external pressure and internal pressure. Sizes and shapes of leakage points were adjusted by changing the replaceable pipes. External pressures at leakage points were induced by overflowed observation tubes and adjusted by changing the length of the observation tubes. Initial flow velocities were changed by adjusting the diaphragm valves of the upstream and downstream. Quick valve closing causes transient pressure in pipes, and the characteristic of negative pressure can be adjusted by the valve closing time when other conditions remain unchanged. Ferreira *et al.* (2018) point out that the valve effective closure time varies between 4% and 10% of the total time of the maneuver. Because of shortage of data to estimate the valve effective closure time, the valve closing time is used to investigate its effect on the negative pressure. Valve shutdown time was set by the controller of the electric ball valve. More detailed experimental parameter settings are shown in Table 1. The orifice diameters ($d$) studied in Yu *et al.* (2016) are 3.0–7.5 mm, which are extended to 3.0–19.0 mm in this study.

## RESULTS AND DISCUSSION

### Steady discharge coefficient of the orifice

The discharge coefficient of the orifice may be influenced by the orifice shape and the pipe flow velocity (Shao *et al.* 2019). The steady-state experimental conditions for measuring the discharge coefficient are listed in Table 1. The measured discharge coefficient of the circular orifice is shown in Figure 4. Since the measurement accuracy of pressure can reach 0.04%, and the volumetric method (to use the volume of outflow in 5 minutes divided by time to get the average flow rate) is used to measure the flow rate, the accuracy of the measured discharge coefficient can be guaranteed. The discharge coefficient of the circular orifice is obviously higher than that of the rectangular

**Table 1** | List of experimental parameter settings

| Influence factors | Measurement experiment of μ | Intrusion experiment |
|---|---|---|
| Internal pressure $p_0$(kPa) | 10,30,50,70,90 | 50 |
| Flow velocity $v_0$(m/s) | / | 0.6,0.7,0.8,0.9,1.0 |
| Valve closure time $T_z$(s) | / | 0.1,1.0,2.0,4.0,6.0 |
| Orifice diameters $d$ (mm) | 3,7.5,11,15,19 | 3,7.5,11,15,19 and rectangular defects |
| External pressure $p_e$(kPa) | 0 | 3.92,4.90,5.88,6.86,7.85 |

defects with the same section-area (Figure 4(a)), and the longitudinal and circumferential rectangular defects have a close discharge coefficient. The effect of the internal pressure on the discharge coefficient depends on the orifice diameter. Figure 4(b) shows the orifice discharge coefficient for 3 mm diameter decreases from 0.715 to 0.625 as the internal pressure increases from 10 kPa to 95 kPa. The discharge coefficients stay constant with pressure when the diameters are 11–19 mm.

The intrusion process studied in this paper is transient. The steady orifice equation may not always be appropriate for calculating the intrusion volume associated with low or negative pressure events. Studies on pipe leakage issues have indicated that the exponential index of the head is not 0.5 because of the change in leakage area during transient pressure events (van Zyl *et al.* 2007; Cassa *et al.* 2010; Cassa & van Zyl 2011; Ferrante *et al.* 2011, 2013; Ferrante 2012). On the other hand, Al-Khomairi (2005) calculated the real-time unsteady leak of normal-sized leakages using the steady-state discharge coefficient. Here, we also use the steady discharge coefficient for the intrusion volume calculation.

## Effect of orifice size on intrusion volume

We redid the experiment using the old device (the same as Yu *et al.* (2016)), by extending the orifice diameter from 3.0 mm to 17.0 mm, and the results are shown in Figure 5(a). The results using the new intrusion device are shown in Figure 5(b), which are obviously higher than the former. The old device, which connected a branch pipe to the main pipe with a flange (Figure 2(b)), weakens the intensity of the pressure wave. Boyd *et al.* (2004a, 2004b) used experimental devices with a branch pipe to explore the intrusion

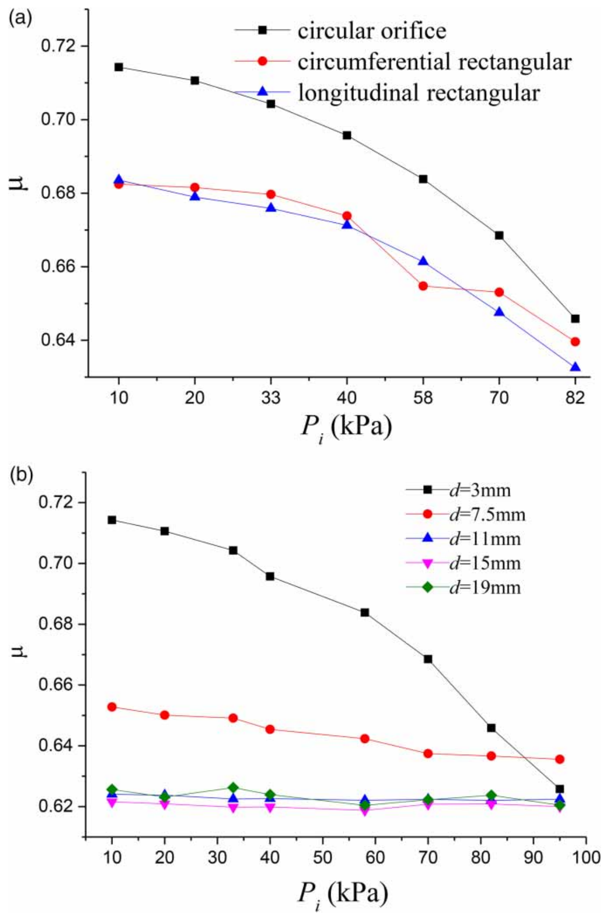


**Figure 4** | Measured discharge coefficient value of the defects: (a) circular hole of d = 3 mm and the rectangular defect of same area; (b) circular holes of d = 3−19 mm.

volume and got a measured intrusion volume of 119 ml, while the theoretical intrusion volume is 227 ml. It can be inferred that using devices with a branch pipe to measure intrusion volume may underestimate the intrusion volume.

Results of both intrusion devices show that the intrusion volume first increases and then decreases with increasing orifice diameter. The intrusion volume was affected by the maximal pressure drop $\Delta p$ (defined as the drop from the initial internal pressure to the minimal internal pressure), the duration time of negative pressure $T_n$ (defined as the accumulation of the duration of pressure below the atmospheric pressure), and the defect size and shapes, etc. The enlargement of the orifice diameter can increase the area of the intrusion orifice and then increase the intrusion discharge. But at the same time, $\Delta p$ and $T_n$ decrease with

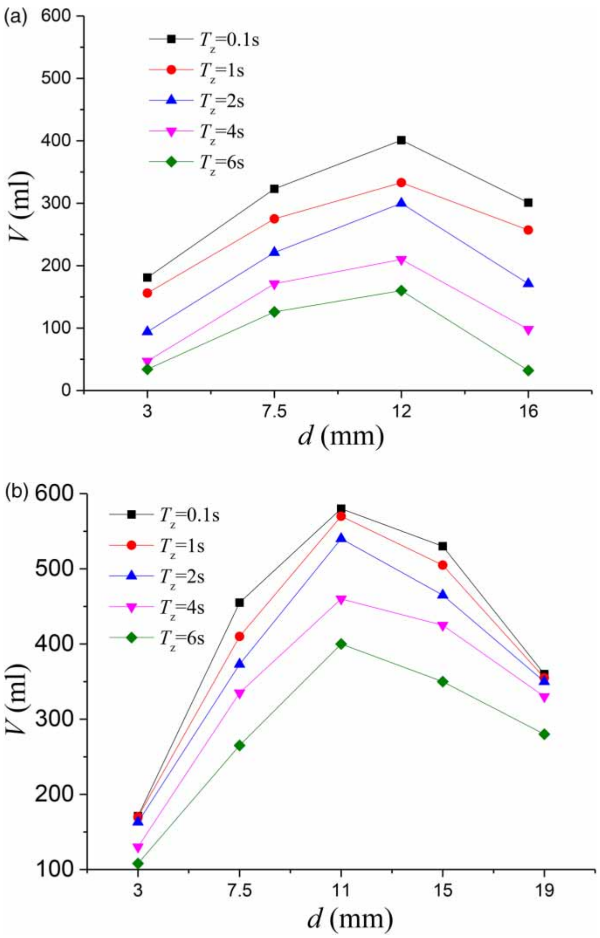


**Figure 5** | Intrusion volume comparison of the two devices ($v_0 = 0.6$ m/s, $p_e = 7.85$ kPa): (a) measured volume on the intrusion device of Yu *et al.* (2016); (b) measured volume on the new experimental device in this study.

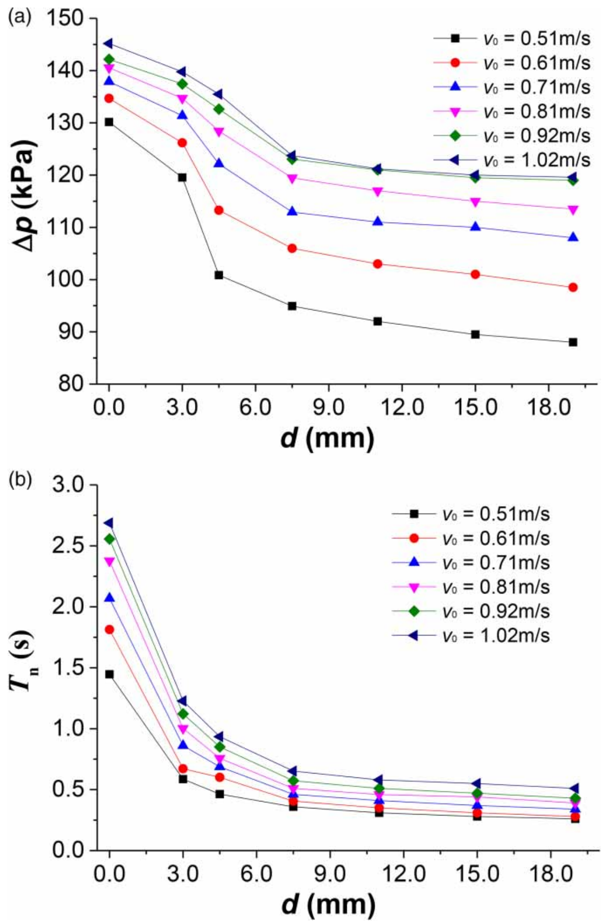


**Figure 6** | Effect of leakage point size on transient pressure, valve close time $T_z = 1.0$ s, external water pressure $p_e = 6.86$ kPa: (a) maximal pressure drop; (b) cumulative time of negative pressure.

increase of the orifice diameter, as shown in Figure 6 under the given experimental conditions (valve close time $T_z = 1.0$ s; external water pressure $p_e = 6.86$ kPa). Because the enlargement of the orifice diameter strengthens the pressure regulating ability of the intrusion device, this results in the decrease of the amplitude and duration time of pressure fluctuation. Considering the combined effect of these factors, the intrusion volume presents a trend of first increase and then decrease, as shown in Figure 5.

## Comparison between calculated and measured volume

The change of discharge coefficient is actually a reflection of energy loss of fluid through the orifice and can be influenced by various factors, like pipe materials, shapes of defects or smoothness of the defect edge. The experience value of 0.60 is usually used as the discharge coefficient in practical calculation. However, when the transient negative pressure event occurs, the flow velocity and pressure around the defects will change greatly in a short time. Then the calculation with the experience value may result in larger errors. Figure 7 shows comparison of calculated and measured volume under the experimental conditions ($p_e = 7.85$ kPa, $d = 3$ mm, $v_0 = 1.0$ m/s). The measured intrusion volumes by the observation tube are basically larger than the calculated intrusion volumes by the orifice discharge equation with $\mu = 0.6$. However, the difference between them is reduced if the calculated intrusion volume uses a measured discharge coefficient $\mu$, which varies with pressure.

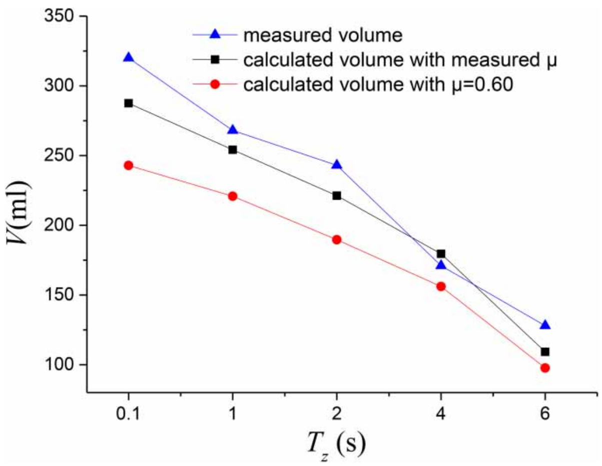


**Figure 7** | Comparison of calculated and measured volume ($p_e = 7.85$ kPa, $d = 3$ mm, $v_0 = 1.0$ m/s).

The following four points may explain the existence of the difference between the measured and calculated volumes. (1) Torricelli's formula is used to calculate the intrusion volume, which may lead to some errors because the variation of the leak area with pressure is not considered in this study. (2) Torricelli's formula is derived from the steady-state. Differently from the steady-state, for the transient events, water flows in and out of the orifice in rapid succession, thus the fluid inertia may have a significant effect on the calculation of the intrusion volume. (3) The external pressure fluctuates in the observation tube during a transient event, which is ignored in the calculation. (4) The used camera only has 25 frames per second to capture the change of water level in the observation tube, which may cause errors in capturing the maximum dropping water level. When using the model to estimate the intrusion volume for a water distribution system, we need to estimate the leakage distribution in the pipe network, external water pressure above the leakage, and the transient pressure in pipes. Because these estimates may have some errors, the error caused by using the orifice discharge equation is seen to be less significant than those errors.

## CONCLUSIONS

A pilot-scale platform and improved intrusion device were constructed to simulate the contamination intrusion through leakage holes caused by low or negative pressure events. Intrusion volumes were measured through a volumetric method and calculated by the orifice discharge equation. The difference between them can be reduced if the measured discharge coefficient $\mu$ is adopted in the orifice discharge equation. In comparison with the two intrusion devices, the new device can properly simulate the groundwater intrusion, while the old one with a side connecting pipe may underestimate the intrusion volume.

The intrusion volume is affected by various factors: sizes and shapes of defects, flow velocity, internal and external pressure, and closure time of valves. The size of leakage points exerted two opposite effects on intrusion volume: a positive contribution because of increasing flow area and a negative contribution because of the transient pressure regulation effect. The experimental results verified that intrusion volume first increased and then decreased with an increase in leakage point size. There is a critical orifice diameter of the maximum intrusion volume under the given intrusion conditions.

## ACKNOWLEDGEMENTS

The present research is funded by the National Key Research and Development Program of China (No. 2016YFC0400600), the National Science and Technology Major Projects for Water Pollution Control and Treatment (2017ZX07502003-05), the Science and Technology Program of Zhejiang Province (Nos. 2017C33174 and 2015C33007), the National Natural Science Foundation of China (No. 51761145022), and the Fundamental Research Funds for the Central Universities.

## REFERENCES

Al-Khomairi, A. M. 2005 Use of the steady-state orifice equation in the computation of transient flow through pipe leaks. *Arabian Journal for Science & Engineering* **30** (1B), 33–45.

Besner, M.-C., Prévost, M. & Regli, S. 2011 Assessing the public health risk of microbial intrusion events in distribution systems: conceptual model, available data, and challenges. *Water Research* **45** (3), 961–979.

Boyd, G. R., Wang, H., Britton, M. D., Howie, D. C., Wood, D. J., Funk, J. E. & Friedman, M. J. 2004a Intrusion within a simulated water distribution system due to hydraulic

transients. I: description of test rig and chemical tracer method. *Journal of Environmental Engineering* **130** (7), 774–777.
Boyd, G. R., Wang, H., Britton, M. D., Howie, D. C., Wood, D. J., Funk, J. E. & Friedman, M. J. 2004b Intrusion within a simulated water distribution system due to hydraulic transients. II: volumetric method and comparison of results. *Journal of Environmental Engineering* **130** (7), 778–783.
Cassa, A. M. & van Zyl, J. E. 2011 Predicting the head-area slopes and leakage exponents of cracks in pipes. In: *Urban Water Management: Challenges and Opportunities, CCWI 2011: Computing and Control for the Water Industry* (D. A. Savic, Z. Kapelan & D. Butler, eds), Centre for Water Systems, University of Exeter, Exeter, UK, pp. 485–490.
Cassa, A. M., van Zyl, J. E. & Laubscher, R. F. 2010 A numerical investigation into the effect of pressure on holes and cracks in water supply pipes. *Urban Water Journal* **7** (2), 109–120.
Collins, R. & Boxall, J. 2013 Influence of ground conditions on intrusion flows through apertures in distribution pipes. *Journal of Hydraulic Engineering* **139**, 1052–1061.
Ebacher, G., Besner, M.-C., Lavoie, J., Jung, B. S., Karney, B. W. & Prévost, M. 2011 Transient modeling of a full-scale distribution system: comparison with field data. *Journal of Water Resources Planning and Management* **137** (2), 173–182.
Ebacher, G., Besner, M. C., Clément, B. & Prévost, M. 2012 Sensitivity analysis of some critical factors affecting simulated intrusion volumes during a low pressure transient event in a full-scale water distribution system. *Water Research* **46**, 4017–4030.
Ferrante, M. 2012 Experimental investigation of the effects of pipe material on the leak head-discharge relationship. *Journal of Hydraulic Engineering* **138** (8), 736–743.
Ferrante, M., Massari, C., Brunone, B. & Meniconi, S. 2011 Experimental evidence of hysteresis in the head-discharge relationship for a leak in a polyethylene pipe. *Journal of Hydraulic Engineering* **137**, 775–780.
Ferrante, M., Massari, C., Brunone, B. & Meniconi, S. 2013 Leak behaviour in pressurized PVC pipes. *Water Science & Technology: Water Supply* **13** (4), 987–992.
Ferreira, J. P. B. C. C., Martins, N. M. C. & Covas, D. I. C. 2018 Ball valve behavior under steady and unsteady conditions. *Journal of Hydraulic Engineering* **144** (4), 04018005.
Fleming, K. K. & LeChevallier, M. W. 2008 Estimating risk of infection from low-level intrusion events. In: *Proceedings of AWWA Water Quality Technology Conference*, Cincinnati, OH, USA.
Funk, J. E., Wood, D. J., Van Vuuren, S. J., LeChevallier, M. & Friedman, M. 1999 Pathogen intrusion into water distribution systems due to transients. In: *Proceedings of the 3rd ASME–JSME Joint Fluids Engineering Conference FEDSM 99*, ASME, New York, USA.
Gullick, R. M. W., LeChevallier, M. W., Case, J., Wood, D. J., Funk, J. E. & Friedman, M. J. 2005 Application of pressure monitoring and modeling to detect and minimize low pressure events in distribution systems. *Journal of Water Supply: Research & Technology – AQUA* **54** (2), 65–81.
Hooper, S. M., Moe, C. L., Uber, J. G. & Nilsson, K. A. 2006 Assessment of microbiological water quality after low pressure events in a distribution system. In: *Water Distribution Systems Analysis Symposium 2006* (S. G. Buchberger, R. M. Clark, W. M. Grayman & J. G. Uber, eds), ASCE, Reston, VA, USA.
Hunter, P. R., Chalmers, R. M., Hughes, S. & Syed, Q. 2005 Self-reported diarrhea in a control group: a strong association with reporting of low-pressure events in tap water. *Clinical Infectious Diseases* **40** (4), e32–e34.
Karim, M. R., Abbaszadegan, M. & Lechevallier, M. 2003 Potential for pathogen intrusion during pressure transients. *Journal of American Water Works Association* **95** (5), 134–146.
Kirmeyer, G. J., Friedman, M., Martel, K., Howie, D., LeChevallier, M., Abbaszadegan, M., Karim, M., Funk, J. & Harbour, J. 2001 *Pathogen Intrusion into the Distribution System*. American Water Works Association Research Foundation and American Water Works Association, Denver, CO, USA.
LeChevallier, M. W., Karim, M., Aboytes, R., Gullick, R., Weihe, J., Earnhardt, B., Mohr, J., Starcevich, J., Case, J., Rosen, J. S., Sobrinho, J., Clancy, J. L., McCuin, R. M., Funk, J. E. & Wood, D. J. 2004 *Profiling Water Quality Parameters: From Source Water to the Household Tap*. American Water Works Association Research Foundation, Denver, CO, USA.
Liu, Z. & Simpson, A. R. 2018 Influence of connection stub parameters and valve closure time on transient measurement accuracy of a pressure transducer. *Water Science & Technology: Water Supply* **18** (6), 1984–1995.
Mora-Rodríguez, J., López-Jiménez, P. A. & Ramos, H. M. 2011 Intrusion problematic during water supply systems' operation. *International Journal of Energy and Environment* **2** (3), 391–400.
Mora-Rodríguez, J., López-Jiménez, P. A. & Ramos, H. M. 2012 Intrusion and leakage in drinking systems induced by pressure variation. *Journal of Water Supply: Research & Technology – AQUA* **61** (7), 387–402.
Shao, Y., Yao, T., Gong, J., Liu, J., Zhang, T. & Yu, T. 2019 Impact of main pipe flow velocity on leakage and intrusion flow: an experimental study. *Water* **11** (1), 118.
Yang, Y., Zhang, T. & Zhu, D. Z. 2014 Influence of porous media on intrusion rate into water distribution pipes. *Journal of Water Supply: Research & Technology – AQUA* **63** (1), 43–50.
Yu, T., Jin, H., Zhang, T., Shao, Y. & Wu, X. 2016 Experimental observation on factors affecting intrusion volumes during low or negative pressure events. *Journal of Water Supply: Research and Technology – AQUA* **65** (5), 396–406.
van Zyl, J. E. & Clayton, C. R. I. 2007 The effect of pressure on leakage in water distribution systems. *Water Management* **160**, 109–114.

First received 1 April 2019; accepted in revised form 14 October 2019. Available online 31 October 2019