Abstract:

Numerous leak detection methods have been developed for pipeline systems because of the shortage of water resources, increased water demand, and leak accidents. These methods have their advantages and disadvantages in terms of cost, labor, and accuracy; therefore, it is important to narrow down the location of a leak as easily, rapidly, and accurately as possible. This study applies the technologies based on the execution of a transient event (transient test-based technologies (TTBTs)), and a model is presented for representing the relation between the leak location and the damping of the pressure transient due to the leakage. The model is verified with laboratory experiments in which the leak location can be narrowed down to be less than 10% to 30% of the total pipe length. The model is found to be more effective if the leak location is nearer to the upstream end. In addition, the leak location found by the damping model varies with an approximate absolute error of 2% to 5% of the pipe length. It is suggested that the damping model is suitable for narrowing down and not for finding the leak location, and should be used in combination with other leak detection methods.

KEYWORDS detection of water leakage; pipeline; water hammer; damping of pressure transient; narrowing down of leak location; stock management of infrastructure

INTRODUCTION

Water leakage in pipelines occurs in all water distribution systems due to age, corrosion, or a third party (Zhang et al., 2015), and causes considerable economic loss, such as that related to shortages of drinking and irrigation water. The amount of water leakage in water distribution systems varies widely between different countries, regions, and systems (Puust et al., 2010). Especially in Asia, home of 53% of the world’s urban population, the estimated annual volume of leakage in urban water utilities is approximately 29 billion cubic meters; hence, water utilities are losing nearly 9 billion US dollars per year (Asian Development Bank, 2010). Leakage is not just an economic issue, it also has environmental, health, and safety implications (Puust et al., 2010). For example, leakage in pipelines causes ground subsidence, contamination, and sinkholes, which results in damage to the infrastructure (Ali and Choi, 2019). Moreover, leakage possibly influences water quality by introducing contamination into water distribution networks through leaks in low-pressure conditions (Colombo and Karney, 2002). Hence, detecting the existence and exact locations of leaks as quickly and accurately as possible is of utmost importance.

Although various leak detection methods have been developed (such as ground-penetrating radar, acoustic leak-detection, and infrared spectroscopy), no single method has been able to satisfactorily meet the operational needs from the perspectives of cost and labor. Hence, a simple, cheap, and reliable method for leak detection would be of great economic value (Pudar and Liggett, 1992). Leak detection by measurement of the pressure in a pipe can be employed in the daily maintenance of pipelines, because manometers are less expensive than flowmeters and can be easily installed at air valves on pipelines. However, a pressure change caused by leakage is too small to be detected, even in a steady flow. Additionally, in cases of low water pressure, it is difficult to detect leaks by capturing the force caused by the pressure change (Chatzigeorgiou et al., 2015).

As a recent solution to the aforementioned problems, transient test-based technologies (TTBTs), in which a transient hydraulic event (such as that caused by a water hammer) is used for leak detection, are attracting interest. TTBTs are expected to offer leak detection methods at a lower cost and with less labor compared to other methods (Meniconi et al., 2011). In a transient hydraulic event, a pressure wave sufficiently strong to be detected can be generated, and only a pressure measurement taking a few minutes (or even less) is required for detecting leaks. After a transient hydraulic event occurs in a pipe, a pressure wave travels repeatedly between both ends of the pipe stretch. The movement of this pressure wave is observed as cyclical pressure transients at an arbitrary point in the pipe stretch. Leakage in a pipeline system will result in an increased damping rate and the creation of new leak-reflected signals within the pressure transients. Most TTBTs have been developed and applied to water pipeline systems using information contained within these two effects (Duan et al., 2010). Brunone (1999) and Brunone and Ferrante (2001) investigated the effect of leak-reflected signals in the press-

Correspondence to: Masaomi Kimura, Graduate School of Agricultural and Life Sciences, The University of Tokyo, Japan

© The Author(s) 2020. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
sure transients, and demonstrated how leaks can be detected by leak-reflected signals in both laboratory and field experimental pipes. While the method adopted was simple and easy, it could not be applied in the case of a slight leakage and if noise due to the pipe structure is present (Asada et al., 2019). Inverse transient analysis is a more powerful TTBT method, using both leak-induced damping and leak-reflected signals (Covas and Ramos, 2010; Shamloo and Haghighi, 2010; Vitkovský et al., 2007), and it is theoretically applicable to pipes of any structure or characteristic. However, the computational complexity is generally enormous, and it is important to reduce it, for example, by narrowing down leak location with other methods in advance. Leak-induced damping is thought to be minimally affected by the noise compared to leak-reflected signals, thus it is effective for the leak detection in pipeline systems with a complicated structure (Asada et al., 2019). In addition, it was revealed that the damping rate of the pressure transients is faster because of an increased energy dissipation from the leak, because the leak location is nearer to the downstream end in the case of rapid and complete closing of the valve (Asada et al., 2019). In this study, the leak-induced damping is theoretically modelled for leak location by considering energy dissipation from the leak and friction in a pipeline. The effectiveness of the damping model for narrowing down leak location is demonstrated based on the experimental results.

**METHODS**

**Damping model**

The damping of pressure transients in the pipeline with leakage is represented by means of an exponential law, according to the results obtained by Ramos et al., (2004), assuming the damping by friction loss and leakage are mutually independent (Wang et al., 2002), as follows.

\[
\Delta H = \Delta H_d \exp\left\{- (R + R_l)\right\} \tag{1}
\]

where \(\Delta H\) is the change in the piezometric head generated by the water hammer (\(m\)), \(\Delta H_d\) is the initial change in the piezometric head (\(m\)), \(t\) is the time (\(s\)), \(R\) is the time nondimensionalized by the wave propagation period \(T\) (\(R = t/T\)), \(R_l\) is the friction-induced damping coefficient, and \(R_l\) is the leak-induced damping coefficient. To calculate the value of \(R\), a numerical simulation needs to be used because the damping by the unsteady state friction has to be considered in the complicated model proposed by two conceptually different approaches. In the first approach, the so-called weighting function-based, the unsteady state friction is given by a weighted integral of past fluid accelerations (Trikha, 1975; Vardy and Brown, 1995; Zielke, 1968.) In the second approach, the so-called instantaneous acceleration-based, it is assumed as a function of the instantaneous local and convective accelerations (Brunone et al., 1991; 1995; 2004). In this study, the value of \(R\) is measured by the experimental pressure transient in case of no leakage without resorting to a numerical simulation. Additionally, Meniconi et al. (2014) reported that there is a biunique correspondence between the damping of the pressure transient at any pipe section and the energy dissipation of the entire pipeline system. Therefore, the value of \(R_l\) related to leak location is derived from the energy dissipated from the leak.

In a single pipeline with total length \(L\) (\(m\)) and pipe cross-sectional area \(A\) (\(m^2\)), water is supposed to flow at a flow rate \(Q\) (\(m^3/s\)) from an upstream reservoir to a downstream end valve, in which the continuity equation is established as follows:

\[
Q_{up} = Q_{down} + Q_{leak} \tag{2}
\]

where \(Q_{up}\) is the flow rate upstream from the leak, \(Q_{down}\) is the flow rate downstream from the leak, and \(Q_{leak}\) is the rate of leakage volume in a steady flow. A leak is assumed to exist at a point \(x_L^*L\) from the upstream reservoir (0 ≤ \(x_L^*\) ≤ 1), where \(x_L^*\) is the distance to the leak nondimensionalized by the total length \(L\). A wave with the value of \(\Delta H\) generated by rapidly closing the valve propagates through the pipeline at wave speed \(c\) (\(m/s\)), which decreases because of the leakage during the transient event. The period is the time taken to propagate for two round trips through the pipe with the case of a reservoir–pipeline–valve system \((T = 4L/c)\).

The interpretation of transient conditions is simplified in almost the same manner as the models of spring oscillations by measuring displacements with respect to the spring’s equilibrium position (Karney, 1990). Thus, the energy dissipation under transient conditions can be considered using the change \(\Delta H\) with respect to the basis of the steady-flow condition. For the case in which \(\Delta H\) is zero at the leak, the energy in the pipeline is preserved because the change in kinetic and elastic energies is balanced, as in the case of no leakage. Therefore, the change in the energy from the leak in the pipeline is derived from the case in which the change in the piezometric head at the leak is \(\Delta H\), as shown in Figure S1.

\[
\Delta E = - \rho g \Delta H (Q_{leak} + \Delta Q_{leak}) \tag{3}
\]

where \(\Delta E\) is the change in energy per unit time (\(N m s^{-1}\)), \(\rho\) is the fluid density (\(kg m^{-3}\)); \(g\) is the gravitational acceleration (\(m/s^2\)); and \(\Delta Q_{leak}\) is the change in \(Q_{leak}\) when the wave with the value of \(\Delta H\) exists at the leak. The rate of the leakage volume is a function of the pressure head at the leak and the size of the leak, and \(Q_{leak} + \Delta Q_{leak}\) is expressed by the orifice equation as follows:

\[
Q_{leak} + \Delta Q_{leak} = a [2g(H_L + \Delta H - z_L)]^{1/2} \tag{4}
\]

where \(a\) is the product of the discharge coefficient and the cross-sectional area of the leak hole (\(m^2\)), \(H_L\) is the steady state piezometric head at the leak (\(m\)) and \(z_L\) is the elevation at the leak (\(m\)).

Substituting Equation (4) to Equation (3),

\[
\Delta E = - \rho g \alpha \Delta H (2gh) \left[1 + \frac{\Delta H}{h_L}\right] =
\]

\[
- \rho g \alpha \Delta H (2gh) \left[1 + \frac{\Delta H}{2h_L} - \frac{1}{8} \left(\frac{\Delta H}{h_L}\right) + \frac{1}{16} \left(\frac{\Delta H}{h_L}\right)^3 - \ldots\right] \tag{5}
\]

Assuming \(1/16(\Delta H/h_L)^3\) << 1 in Equation (5), it can be simplified as follows:
\[ \Delta E = -\rho g a (2gh_0)^{1/2} \Delta H - \rho g a \left( \frac{g}{2h_0} \right)^{1/2} \Delta H^2 \]
\[ -\rho g a \frac{1}{4h_0} \left( \frac{g}{2h_0} \right)^{1/2} \Delta H^3 \]

(6)

where \( h_0 \) is the steady state pressure head at the leak (m).

The value of \( \Delta H \) at the leak is influenced by the line packing via the influence of friction, by which \( \Delta H \) continues to rise to the maximum head after the wave passes until it is reflected back (Duan et al., 2012; Liou, 2016), while \( \Delta H \) reaches the full Joukowsky head immediately in case of no friction. The full Joukowsky head is the change in the piezometric head converted from the flow rate by closing the valve, and can be expressed as follows (Joukowsky, 1904):

\[ \Delta H_j = \frac{Q}{gA} \]

(7)

where \( \Delta H_j \) is the full Joukowsky head (m).

Liou (2016) presented an analytical formula for \( \Delta H \) in a downstream valve during a half period \((0 \leq t^* \leq 0.5)\). However, this underestimates an actual result for \( \Delta H \) because it neglects the line packing by the unsteady state friction, which cannot be derived analytically.

Thus, considering the line packing by the steady and unsteady state friction and smooth variation of \( \Delta H \), a formula is presented here for \( \Delta H \) at the downstream valve, by simply assuming power variations, as follows:

\[ \Delta H = (2t^*)^\alpha \beta \Delta H_j \quad \text{for} \quad 0 \leq t^* \leq 0.5 \]

(8)

where \( \alpha \) is the rate at which the initial head change increases to the maximum in the downstream valve \((0 \leq \alpha \leq 1)\), and \( \beta \) is the ratio of the maximum head change in the downstream end to the \( \Delta H_j \) value \((\beta \geq 1)\). The variation in \( \Delta H \) at the leak during a period \((0 \leq t^* \leq 1)\) is formulated based on Equation (8). In a transient event, the wave with \( \Delta H \) reflects in antiphase at the upstream reservoir, and it reflects in phase at the downstream valve. For the case of \( x^*_L \geq 0.5 \), the reflective wave from the downstream valve reaches the leak when \( \Delta H \) at the leak is varying to zero; whereas, for the case of \( x^*_L < 0.5 \) it reaches the leak after \( \Delta H \) at the leak has varied to zero as shown in Figure S2. Thus, \( \Delta H \) \((0 \leq t^* \leq 1)\) can be classified into two types, according to whether \( x^*_L \geq 0.5 \) or \( x^*_L < 0.5 \).

For \( x^*_L < 0.5 \), \( \Delta H \) is formulated for the duration of a half period \((0 \leq t^* \leq 0.5)\) as follows:

\[ \Delta H = (2t^*)^\alpha \beta \Delta H_j \quad \text{for} \quad 0 \leq t^* < x^*_L/2 \]

\[ \Delta H = [(x^*_L)^\alpha - (2t^* - x^*_L)^\alpha] \beta \Delta H_j \quad \text{for} \quad x^*_L/2 \leq t^* < x^*_L \]

\( \Delta H = 0 \) \quad \text{for} \quad x^*_L/2 \leq t^* \leq 0.5 \]

For \( x^*_L \geq 0.5 \), \( \Delta H \) is formulated for the duration of a half period \((0 \leq t^* \leq 0.5)\) as follows:

\[ \Delta H = [(2t^*)^\alpha + (2t^* - x^*_L)^\alpha - (x^*_L)^\alpha] \beta \Delta H_j \quad \text{for} \quad 0 \leq t^* < x^*_L - 0.5 \]

\[ \Delta H = (2t^*)^\alpha \beta \Delta H_j \quad \text{for} \quad x^*_L - 0.5 \leq t^* < x^*_L/2 \]

\[ \Delta H = [(x^*_L)^\alpha - (2t^* - x^*_L)^\alpha] \beta \Delta H_j \quad \text{for} \quad x^*_L/2 \leq t^* \leq 0.5 \]

(9)

The value of \( \Delta H (0.5 \leq t^* \leq 1) \) is equal in absolute value and opposite in sign to the value \((0 \leq t^* \leq 0.5)\). Figure 1 shows the variation in \( \Delta H \) at the leak during a period, calculated using Equations (9) and (10), for the case of \( \Delta H_j = 5 \text{ m}, \alpha = 0.1, \beta = 1.2, \) and using \( x^*_L = 0.2 \) for \( x^*_L < 0.5 \) and \( x^*_L = 0.8 \) for \( x^*_L \geq 0.5 \).

The total energy \( E \) in a pipe, on the left side of Equation (6), is expressed as the elastic energy form (Karney, 1990; Meniconi et al., 2014) and can be derived from the work of water and pipe by \( \Delta H \) as shown in the shaded area in Figure 2.

\[ E = \frac{1}{2} b E_p \varepsilon_p^2 + \frac{1}{2} E_w \varepsilon_w^2 \]

\[ \Delta H_j \]

\[ = \frac{1}{2} \rho g \Delta H_j^2 AL \]

\[ = \frac{1}{2} \rho g \Delta H_j^2 AL \quad \text{for} \quad 0 \leq t^* \leq 0.5 \]

\[ = \frac{1}{2} \rho g \Delta H_j^2 AL \quad \text{for} \quad 0 \leq t^* \leq 0.5 \]

\[ \rho g \Delta H_j = \frac{bh_p}{D} \varepsilon_p \]

\[ \rho g \Delta H_j = \frac{bh_p}{D} \varepsilon_p \]

Figure 1. Time variation of the change in the piezometric head at the leak during a period calculated from Equations (9) and (10) for the cases of \( x^*_L = 0.2 \) and \( x^*_L = 0.8 \)
As can be seen clearly from Figure 1, the first and third terms in Equation (12) become zero and the second term only needs to be integrated for \( t^* \) ranging from 0 to 0.5 and then doubled.

\[
d\left(\frac{1}{2} \frac{\rho g'(\Delta H)^2 A L}{c} \right)dt^* = -8\rho g\left(\frac{g}{2h_1}\right)^{1/2} \left[ \int_0^1 \left( \frac{\Delta H}{2} \right)^2 dt^* \right] (13)
\]

By solving Equation (13) for \( \Delta H \), using Equations (9) and (10), the formula for the damping of \( \Delta H \) due to the leakage is expressed as follows:

\[
\Delta H = \Delta H \exp\left(-\frac{R_L}{t^*}\right)
\]

\[
\frac{R_L}{c} = \frac{1}{2g h_1} \left[ \frac{2}{\alpha + 1} + 1 \right] \left( x^*\Delta H \right)^{2\alpha + 1}
\]

for \( x^* < 0.5 \)

\[
\frac{R_L}{c} = \frac{1}{2g h_1} \left[ \frac{2}{\alpha + 1} + 1 \right] \left( x^*\Delta H \right)^{2\alpha + 1} - \frac{\alpha + 1}{2\alpha + 1} (2x^* - 1)^{2\alpha + 1}
\]

for \( x^* \geq 0.5 \) (14)

**Collection of experimental data**

An experimental test was conducted in a pipeline to collect pressure transient datasets with simulated leakage to evaluate the effectiveness of the damping model at the Institute for Rural Engineering, Tsukuba, Japan. The pipeline has a spiral structure with bends at 25 m intervals, is composed of stainless steel, and has a 24.2 mm inner diameter, a thickness of 1.5 mm, and a length of 900 m (Figure 3). The pipeline includes a pump and a pressurized tank (maximum pressure 3.0 kg cm\(^{-2}\)) at the upstream end, and manual and ball valves at the downstream end. The manual valve is used to control the velocity of flow downstream from the leak, and the ball valve is used to generate a transient event via rapid and complete valve closure. A manometer (with a gauge pressure range of 0 MPa to 0.1 MPa and an accuracy of 0.5% of full range) is set just upstream from the ball valve to collect the pressure transient data. The experimental test cases are shown in the left side of Table I. The pressure transient data measured in each case is represented as the time variation of \( \Delta H \) in Figure S3. The wave speed in the pipeline was calculated by the time for a period of the measured pressure transient. Simulated leaks were established at three points: 150 m (upstream leakage (UL)), 450 m (middle leakage (ML)), and 750 m (downstream leakage (DL)) from the upstream end, corresponding to \( x^* \) values of 0.167, 0.500, and 0.833, respectively. The study assumes that the leak detection method uses the knowledge of the relative leak size to the pipe cross-sectional area \( a/A \) in advance using a water leakage test. Thus, the relative leak size was derived from the rate of leakage volume measured under two different hydrostatic conditions using the following equations, which are based on the orifice equation:

\[
z = \frac{2}{a} Q_{\text{leak}}^2 \left( 1 - \frac{Q_{\text{leak}}}{Q_{\text{tot}}} \right)^2 H_2
\]

\[
a_\alpha = \frac{Q_{\text{leak}}}{A \left( 2g \left( H_1 - z_l \right) \right)^2}
\]

where \( H_1 \) and \( H_2 \) are a pair of static piezometric heads, and

\[
x_{\text{leak}} = \left( \frac{Q_{\text{leak}}}{Q_{\text{tot}}} \right) \left( \frac{2g \left( H_1 - z_l \right)}{c} \right)
\]

and \( c \) is set as zero in this study.

**Experimental conditions and results for narrowing down leak location**

| Case | \( x^* \) | \( c \) (m/s) | \( a/A \) | \( h_1 + z_{l,b} \) (m) | \( R \) | \( R_c \) | \( x_{\text{leak}}^{\max} \) (m) | \( x_{\text{leak}}^{\min} \) (m) | Narrowing down rate (%) | Optimized result | \( x_{\text{leak}}^* \) (%) |
|------|----------|--------------|--------|-----------------|-----|--------|-------------------|------------------|-------------------|-----------------|-----------------|
| 1    | 0.833    | 1,355        | 0.00000707 | 27.1            | 0.34982 | 0.15382 | 0.999 | 0.675 | 32.4 | 0.849 | 1.6 |
| 2    | 0.500    | 1,355        | 0.0000627 | 27.0            | 0.35017 | 0.07659 | 0.588 | 0.379 | 20.9 | 0.476 | –2.4 |
| 3    | 0.167    | 1,355        | 0.0000694 | 26.7            | 0.34927 | 0.01899 | 0.173 | 0.079 | 9.4  | 0.126 | –4.1 |
| 4    | 0.833    | 1,355        | 0.0000321 | 26.5            | 0.34825 | 0.06832 | 1.000 | 0.640 | 36.0 | 0.808 | –2.5 |
| 5    | 0.500    | 1,355        | 0.0000323 | 27.5            | 0.34719 | 0.03940 | 0.597 | 0.371 | 22.6 | 0.434 | –1.6 |
| 6    | 0.167    | 1,355        | 0.0000280 | 27.6            | 0.34692 | 0.00725 | 0.174 | 0.080 | 9.4  | 0.118 | –4.9 |

\( z_{l,b} \) is set as zero in this study. \( x_{\text{leak}} = \left( x_{\text{leak}}^* - x_{\text{leak}}^* \right) \times 100 \)
\( Q_{\text{vol}1} \) and \( Q_{\text{vol}2} \) are the rates of leakage volume measured for the cases of static piezometric heads \( H_i \) and \( H_r \), respectively.

**Method of narrowing down leak location by damping model**

The procedure for calculating \( R_L \) in the experimental cases is as follows:

1. The change in the piezometric head \( \Delta H \) at the downstream end of the pipe is measured with and without the leakage for cases 1 to 6;
2. The total damping coefficient \( R + R_L \) and the friction-induced damping coefficient \( R \) for cases 1 to 6 are derived from the exponential variation in the two values, which are calculated by averaging each of the absolute values of \( \Delta H \) for \( t^* \) ranging from 0 to 1 and for \( t^* \) ranging from 1 to 2, with and without the leakage;
3. The values of the leak-induced damping coefficient \( R_L \) for cases 1 to 6 can be found by subtracting \( R \) from \( R + R_L \).

The value of \( R_L \) in Equation (14) is calculated by changing \( \alpha \) ranging from 0 to 1 by increments of 0.01, \( \beta \) ranging from 1 to 2 by increments of 0.01, and \( x_L^* \) ranging from 0 to 1 by increments of 0.001. The absolute error of \( R_L \) from Equation (14) and the experimental pressure transient is calculated for cases 1 to 6, and the leak locations are searched in order that the absolute error of \( R_L \) is almost negligible. The objective of the present study is to narrow down leak location using the damping model. However, the leak location cannot be completely narrowed down by using only the information of the leak-induced coefficient \( R_L \) as shown in Figure S4. Such a behavior was highlighted by Meniconi et al., (2014) in different pressure transients by numerical experiments. In fact, a given damping of pressure transients is not exclusive of a unique pressure transient, and provides multiple couples of solutions (i.e. the values of \( \alpha \) and \( \beta \)) if no other information is available.

Therefore, the time variation in \( \Delta H \) is used to further narrow leak location. The value of \( \Delta H \) (0 \( \leq t^* \leq 0.5 \)) in Equation (8) is calculated by changing \( \alpha \) within a range of 0 to 1 by increments of 0.01, and \( \beta \) within a range of 1 to 2 by increments of 0.01. The root mean squared error (RMSE) of \( \Delta H \) (0 \( \leq t^* \leq 0.5 \)) from Equation (8) and the experimental pressure transient is calculated for cases 1 to 6. Therefore, leak location searches return almost negligible absolute error of \( R_L \) and RMSE of \( \Delta H \).

**RESULTS AND DISCUSSION**

First, the value of \( \Delta H \) in Equation (8) is fitted to the measurement value of \( \Delta H \) (0 \( \leq t^* \leq 0.5 \)) for cases 1 to 6 to investigate the accuracy and the efficiency of this equation. In all cases, Equation (8) reproduces \( \Delta H \) (0 \( \leq t^* \leq 0.5 \)) with the minimum RMSE of approximately 0.2 m (Figure S5). The reason that the RMSE is considered is that the measurement value of \( \Delta H \) includes high frequency noise due to the spiral structure of the pipeline, and the model in Equation (8) neglects the variation of \( \Delta H \) during the relative short time until the complete closure of the valve \( (t^* = 0) \). In this study, the RMSE of \( \Delta H \) is set as \( \varepsilon_h < \max \varepsilon_h = 0.5 \) m to narrow down the leak location for cases 1 to 6, where \( \varepsilon_h \) is the RMSE of \( \Delta H \) (m) and \( \max \varepsilon_h \) is the maximum value of \( \varepsilon_h \). The leak-induced coefficient \( R_L \) largely influences \( \Delta H \) after a period from the initial state. The absolute error of \( R_L \) is set as \( \varepsilon_d < \max \varepsilon_d = 5.0 \times 10^{-4} \) so that the error of the \( \Delta H \) is negligible using Equation (14), where \( \varepsilon_d \) is the absolute error of \( R_L \) and \( \max \varepsilon_d \) is the maximum value of \( \varepsilon_d \).

The right side of Table 1 presents the results of the narrowing down of leak location for cases 1 to 6. Figure 4 presents error plots for the dimensionless leak location \( x_L^* \) under the conditions and shows they are dense around the true leak location \( x_L^* \) for cases 1 to 6. The vertical axis is the dimensionless hybrid error \( \varepsilon^* \) (0 \( \leq \varepsilon^* \leq 1 \)) of the RMSE of \( \Delta H \) and the absolute error of \( R_L \). The dimensionless error \( \varepsilon^* \) is represented so that the value of \( \varepsilon_h \) and \( \varepsilon_d \) can be evalu-

![Figure 4](image-url)
ing the leak location using only the damping model results (Asada et al., 2019; Wang et al., 2002). Therefore, optimizing the leak location using only the damping model results in an inaccurate estimation.

In addition, the leak location \( x_{L,\epsilon}^* \) is optimized when the parameters \( \alpha, \beta \) are varied, as shown in Figure 5.

In addition, the leak location \( x_{L,\epsilon}^* \) is optimized when the dimensionless error \( \epsilon^\ast \) is minimum for cases 1 to 6. The optimized results in Table I show that the error \( \epsilon_L \) of the leak location for the total pipe length varies largely from approximately –5% to 2% for cases 1 to 6. The accuracy of the damping model is the same (or lower) compared to that of the previous leak detection methods using damping (Asada et al., 2019; Wang et al., 2002). Therefore, optimizing the leak location using only the damping model results in an inaccurate estimation.

It is important to narrow down the leak location by the damping model with suitable conditions, and find the leak location using a combination of other methods, such as inverse analysis. Compared with DL and ML cases, in the UL case, the true leak location \( x_L^* \) is farther from the optimized leak location \( x_{L,\epsilon}^* \) of the minimum dimensionless error \( \epsilon^\ast \) in Table I and Figure 4. These differences result from neglecting the variation of \( AH \) during the valve closure, which gives the larger errors of \( \alpha \) and \( \beta \) to small energy dissipation from the leak in case of UL. Therefore, by improving the damping model considering the variation of \( AH \) by closing the valve, it is possible to narrow down the leak location further under severe conditions.

Additionally, the pressure transient is more affected and inhibited by viscosity diffusion in the pipe as the pipe length \( L \) is larger and the wave speed \( c \) and the pipe diameter \( D \) are smaller (Duan et al., 2012; Wahba, 2008); thus, the damping model cannot be used in this case. In further studies, the validation of the damping model needs to be investigated for different types of pipes and multiple leaks, so that the damping model can be widely applied to field pipes.

CONCLUSION

This paper presented a method for narrowing down leak location using the damping model of pressure transients in a pressurized pipe. The leak location was narrowed down from approximately 30% to less than 10%, and it was revealed that the effectiveness of the damping model increases as the leak location is closer to the upstream end. In this method, we assumed that \( 1/16(\Delta H/h_L)^3 \ll 1 \), which can be realized by restricting the valve in advance and suppressing the flow rate in field pipes. Under this condition, the application of the proposed method to field pipes can have considerable benefits, because the operation of rapidly closing the valve will be relatively easy given that the valve opening and the load on the pipe due to the pressure change are small. Therefore, the proposed damping model has a possibility of narrowing down the leak location simply and rapidly in field pipes by investigating the effectiveness of the model in different types of pipes in a detail.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant Number JP19J10410.

SUPPLEMENTS

Figure S1. Head and flow rate profiles for the case in which the change in the piezometric head at the leak is \( \Delta H \)

Figure S2. Diagram of the wave propagation through the pipeline and the pressure transient at the leak for the cases of (a) \( x_L^* \geq 0.5 \) and (b) \( x_L^* < 0.5 \)

Figure S3. Time variation of the change in piezometric head in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6

Figure S4. Narrowing down results of the leak location using only the information of \( R_L \) in the condition: \( \epsilon_d < 5.0 \)
× 10⁻³, where $\varepsilon_R$ is the absolute error of $R_t$ between the calculated and measured value in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6

Figure S5. The fitting curve of $\Delta H$ calculated by Equation (8) in (a) case 1, (b) case 2, (c) case 3, (d) case 4, (e) case 5, and (f) case 6

REFERENCES

Ali H, Choi J. 2019. A review of underground pipeline leakage and sinkhole monitoring methods based on wireless sensor networking. *Sustainability* **11**: 4007. DOI: 10.3390/su11154007.

Asada Y, Kimura M, Azechi I, Iida T, Kubo N. 2019. Leak detection by monitoring pressure to preserve integrity of agricultural pipe. *Paddy and Water Environment* **17**: 351–358. DOI: 10.1007/s10333-019-00730-5.

Brunone B, Golia UM, Greco M. 1991. Some remarks on the momentum equation for fast transients. *Proceeding of International Meeting on Hydraulic Transients with Water Column Separation (9th Round Table of the IAHR Group), Universidad Politecnica de Valencia, Spain*. 140–148.

Brunone B, Golia UM, Greco M. 1995. Effects of two-dimensionality on pipe transients modeling. *Journal of Hydraulic Engineering* **121**: 906–912. DOI: 10.1061/(ASCE)0733-9429(1995)121:12(906).

Brunone B. 1999. Transient test-based technique for leak detection in outfall pipes. *Journal of Water Resources Planning and Management* **125**: 302–306. DOI: 10.1061/(ASCE)0733-9496(1999)125:5(302).

Brunone B, Ferrante M. 2001. Detecting leaks in pressurised pipes by means of transients. *Journal of Hydraulic Research* **39**: 539–547. DOI: 10.1080/00221686.2001.9628278.

Brunone B, Ferrante M, Cacciamani M. 2004. Decay of pressure and energy dissipation in laminar transient flow. *Journal of Fluids Engineering* **126**: 928–934. DOI: 10.1115/1.1839926.

Chatzigeorgiou D, Youcef-Toumi K, Ben-Mansour R. 2015. Design of a novel in-pipe reliable leak detector. *IEEE/ASME Transactions on Mechatronics* **20**: 824–833. DOI: 10.1109/TMECH.2014.2308145.

Colombo AF, Karney BW. 2002. Energy and costs of leaky pipes: Toward comprehensive picture. *Journal of Water Resources Planning and Management* **128**: 441–450. DOI: 10.1061/(ASCE)0733-9496(2002)128:6(441).

Covas D, Ramos H. 2010. Case studies of leak detection and location in water pipe systems by inverse transient analysis. *Journal of Water Resources Planning and Management* **136**: 248–257. DOI: 10.1061/(ASCE)0733-9496(2010)136:2(248).

Duan HF, Lee PJ, Ghidaoui MS, Tung YK. 2010. Essential system response information for transient-based leak detection methods. *Journal of Hydraulic Research* **48**: 650–657. DOI: 10.1080/00221686.2010.507014.

Duan HF, Ghidaoui MS, Lee PJ, Tung YK. 2012. Relevance of unsteady friction to pipe size and length in pipe fluid transients. *Journal of Hydraulic Engineering* **138**: 154–166. DOI: 10.1061/(ASCE)HY.1943-7900.0000497.

Joukovsky N. 1904. On the hydraulic hammer in water supply pipes. *Proceedings of the American Water Works Association* **24**: 341–424.

Karney BW. 1990. Energy relations in transient closed-conduit flow. *Journal of Hydraulic Engineering* **116**: 1180–1196. DOI: 10.1061/(asce)0733-9429(1990)116:10(1180).

Liou JCP. 2016. Understanding line packing in frictional water hammer. *Journal of Fluids Engineering* **138**: 081303. DOI: 10.1115/1.4033368.

Marler RT, Arora JS. 2004. Survey of multi-objective optimization methods for engineering. *Structural and Multidisciplinary Optimization* **26**: 369–395. DOI: 10.1007/s00158-003-0368-6.

Meniconi S, Brunone B, Ferrante M, Massari C. 2011. Transient tests for locating and sizing illegal branches in pipe systems. *Journal of Hydroinformatics* **13**: 334–345. DOI: 10.2166/hydro.2011.012.

Meniconi S, Brunone B, Ferrante M, Massari C. 2014. Energy dissipation and pressure decay during transients in viscoelastic pipes with an in-line valve. *Journal of Fluids and Structures* **45**: 235–249. DOI: 10.1016/j.jfluidstructs.2013.12.013.

Pudar RS, Liggett JA. 1992. Leaks in pipe networks. *Journal of Hydraulic Engineering* **118**: 1014–1031. DOI: 10.1061/(ASCE)0733-9429(1992)118:7(1031).

Puust R, Kapelan Z, Savic DA, Koppel T. 2010. A review of methods for leakage management in pipe networks. *Urban Water Journal* **7**: 25–45. DOI: 10.1080/15730621003610878.

Ramos H, Covas D, Borga A, Loureiro D. 2004. Surge damping analysis in pipe systems: modelling and experiments. *Journal of Hydraulic Research* **42**: 413–425. DOI: 10.1080/00221686.2004.9728407.

Shamloo H, Haghhighi A. 2010. Optimum leak detection and calibration of pipe networks by inverse transient analysis. *Journal of Hydraulic Research* **48**: 371–376. DOI: 10.1080/00221681003726304.

Trikha AK. 1975. An efficient method for simulating frequency-dependent friction in transient liquid flow. *Journal of Fluids Engineering* **97**: 97–105. DOI: 10.1115/1.3447224.

Vardy AE, Brown JMB. 1995. Transient, turbulent, smooth pipe friction. *Journal of Hydraulic Research* **33**: 435–456. DOI: 10.1080/00221689509498654.

Vitkovsky JP, Lambert MF, Simpson AR, Liggett JA. 2007. Experimental observation and analysis of inverse transients for pipeline leak detection. *Journal of Water Resources Planning and Management* **133**: 519–530. DOI: 10.1061/(ASCE)0733-9496(2007)133:6(519).

Waheb EM. 2008. Modelling the attenuation of laminar fluid transients in piping systems. *Applied Mathematical Modelling* **32**: 2863–2871. DOI: 10.1016/j.apm.2007.10.004.

Wang XI, Lambert MF, Simpson AR, Liggett JA, Vitkovsky JP. 2002. Leak detection in pipelines using the damping of fluid transients. *Journal of Hydraulic Engineering* **128**: 697–711. DOI: 10.1061/(asce)0733-9429(2002)128:7(697).

Zhang T, Tan Y, Zhang X, Zhao J. 2015. A novel hybrid technique for leak detection and location in straight pipelines. *Journal of Loss Prevention in the Process Industries* **35**: 157–168. DOI: 10.1016/j.jlp.2015.04.012.

Zielke W. 1968. Frequency-dependent friction in transient pipe flow. *Journal of Basic Engineering* **90**: 109–115. DOI: 10.1115/1.3605049.