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Detection of localized deterioration distributed along single pipelines by reconstructive MOC analysis

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Abstract

The detection of localized deterioration that is distributed along pipelines, including wall thickness reduction caused by large scale corrosion, is essential for targeted pipeline maintenance and the prevention of pipe failure. This paper proposes a novel technique for the detection of distributed deterioration along a pipeline by estimating the distribution of pipeline properties using a measured pressure transient trace. The proposed technique is referred as *reconstructive MOC analysis* and it is an inverse process of the traditional forward MOC calculation. The reconstructive MOC analysis reconstructs the MOC grid and estimates the pipe parameters, such as impedance and wave speed, reach by reach from downstream to upstream. Numerical simulations are performed on a pipeline with three pipe sections of impedance changes. These deteriorated sections are accurately detected and located by using the new technique. Experimental verification is also

performed by successfully detecting a section of pipe with a thinner wall thickness in a single pipeline.

Keywords: distributed deterioration; fluid transient; localized deterioration; method of characteristics; pipeline condition assessment; water distribution systems; water hammer.

Introduction

Deterioration in pipelines can be divided into two categories: discrete deterioration and distributed deterioration. Discrete deterioration describes faults that occur at points, such as leaks or partially closed valves. Distributed deterioration refers to localized deterioration that typically extends meters or tens of meters along the pipeline and can reoccur multiple times. Examples of distributed deterioration include internal or external widespread corrosion or the spalling of cement mortar lining, which are common in aging water distribution pipelines and can be large in number (Stephens et al. 2008). Distributed deterioration may not impose imminent threats to the operation of a pipeline system, however it usually reduces water transmission efficiency (Tran et al. 2010), creates water quality problems (Vreeburg and Boxall 2007), and may also develop into more serious blockages or bursts over time (Zamanzadeh et al. 2007). Detection of localized deterioration that is distributed along pipelines in its early stages helps authorities to cost-effectively maintain, replace and rehabilitate their pipeline assets, and prevents potential pipe failure.

At present, transient pressure waves are recognized as a potential tool for non-invasive detection of both discrete and distributed deterioration in pressurized pipelines. Jönsson and Larson (1992) proposed a spectral analysis technique of a measured pressure trace for leak detection. Pudar and Liggett (1992) suggested that leak detection in water distribution networks could be accomplished by solving an inverse problem using measurements of steady-state pressure (and/or flow). Liggett and Chen (1994) recommended that inverse calculation under transient events would be more suitable for leak detection because some system parameters (e.g. friction factor) could be calibrated through the inverse analysis rather than approximately estimated. The transient-based inverse approach has been further developed in the last two decades (Vítkovský et al. 2000; Covas and Ramos 2010) and is now known as the inverse transient analysis (ITA). Several other transient-based leak detection techniques have also been proposed, either in the time domain (Brunone 1999; Lee et al. 2007a) or in the frequency domain (Ferrante and Brunone 2003; Covas et al. 2005; Lee et al. 2005; Gong et al. 2012). The transient analysis has also been used in detection of discrete blockages in pipelines (Wang et al. 2005; Lee et al. 2008a; Sattar et al. 2008).

Investigating distributed deterioration detection in water transmission pipelines, Stephens et al. (2008; 2013) attempted the detection of changes in pipe wall thickness for pipelines in the field. The field study used fluid transients and the inverse transient analysis (ITA). It indicated that the loss of cement mortar lining could lead to wall corrosion and significant changes in wave speed. However, the structural complexity and parametric uncertainties of real pipes proved to be a serious obstacle to an efficient and accurate ITA.

Duan et al. (2012) proposed a technique for the detection of extended blockages by analyzing the frequency response of the pipeline system. Their analysis indicated that extended blockages can cause the resonant frequencies of the pipeline system to shift, and the locations and sizes of the blockages can be determined through an inverse calibration approach with optimization algorithms. However, a number of system resonant frequencies need to be accurately determined to provide sufficient information for the inverse calibration. This is difficult in practice due to the limitations in achieving an acceptably large signal bandwidth and the effects of noise (Lee et al. 2008b).

Hachem and Schleiss (2012) advanced a transient-based technique for the determination of the location and stiffness of a structurally weak section in a single pipeline. The mean wave speed in the tested pipe and that in the intact pipe (without the weak section) were estimated from the pressure traces measured at the two ends. The location and length of the weak section were determined using the two mean wave speed values and the travel time of the reflections from the weak section. Thereafter, the wave speed in the weak section was estimated from the estimated length of this section and the two mean wave speed values. The stiffness was then estimated from the wave speed of the weak section. The major challenge for this technique is that the wave speed values in weak sections are difficult to estimate accurately, especially when multiple deteriorated sections exist in the same pipeline.

Gong et al. (2013) proposed a technique for detecting a single deteriorated section in a pipeline by analyzing the deterioration-induced reflections induced by a step transient wave. Wall thickness changes alter the impedance of the pipe section where the change exists. Using the measured pressure trace, Gong et al. (2013) demonstrated that the size of the deterioration-induced transient wave reflection is related to the impedance of the deteriorated section, while the travel time of the perturbation is indicative of its location. The technique was verified using experimental data, and the location and impedance of a pipe section with a thinner wall thickness were estimated successfully. However, this technique is hard to extend to pipelines with multiple deteriorated sections, especially where the deterioration-induced perturbations are complex. This occurs due to the effects of multiple reflections within and between the deteriorated sections.

This paper proposes a novel and efficient transient-based distributed deterioration detection method for single water transmission pipelines. The method is based on the reconstruction of the impedance distribution along the pipe using backwards method of characteristics (MOC) calculation. The MOC is a conventional method for modeling transient events in pipeline systems where their properties (such as length, diameter, roughness height and wave speed) are known (Chaudhry 1987). The reconstructive MOC analysis proposed in this research is an inverse process, by which the distribution of the impedance and the wave speed can be estimated from the measured transient data. Plotting the distribution of the impedance or the wave speed allows the deteriorated sections to be identified and located. Numerical simulations show that this technique can deal with complex multiple reflections in the measured pressure traces, allowing multiple deteriorated sections to be accurately detected and located.

Experimental data from a single pipeline containing a section with a thinner wall thickness is used to verify the proposed technique. A side-discharge valve was used to generate the incident transient wave in the experimental system. Because the transient generator valve is limited in its maneuverability, closing the valve to generate the incident wave is fast, but not instantaneous. The result is a wave front with a rise time of approximately 4 ms. This can be overcome by a signal preprocessing technique for estimating the step response function (SRF) of the pipeline from the measured pressure trace. The impedance, wave speed, location and length of the deteriorated section (a pipe section with a thinner wall thickness) in the experimental pipeline are estimated successfully.

Transient analysis in single pipelines

This section firstly gives the compatibility equations of the method of characteristics (MOC). The properties of a pipe are assumed to be distinct from reach to reach in the following derivation. Then the proposed reconstructive MOC analysis, which is an inverse process of the conventional MOC modeling, is described in detail.

Method of characteristics (MOC)

An example of the MOC grid in the $x-t$ plane for a single pipeline is shown in Fig. 1. Assume that properties of the pipe can be distinct from reach to reach, the MOC compatibility equations valid along the characteristic lines in the MOC grid [Fig. 1(b)] are

$$C^{+}: \quad H_P - H_M + B_{MP}(Q_P - Q_M) + R_{MP} Q_P |Q_M| = 0 \qquad (1)$$

$$C^{-}: \quad H_P - H_N - B_{PN}(Q_P - Q_N) - R_{PN}Q_P|Q_N| = 0 \tag{2}$$

where H_P, H_M and H_N are head values, and Q_P, Q_M and Q_N are discharges at points P, M and N, respectively, as shown in Fig. 1; B and R denote the characteristic impedance of a reach of pipe and the pipe reach resistance, with the subscripts 'MP' and 'PN' representing the pipe reach MP and PN shown in Fig. 1 respectively. Expressions for the impedance B and the reach resistance R for the ith pipe reach are given in Eq. (3) and Eq. (4), respectively.

$$B_i = a_i / (gA_i) \tag{3}$$

$$R_i = f_i \Delta x_i / (2gD_i A_i^2) \tag{4}$$

where a = wave speed; g = gravitational acceleration; A = pipe cross-sectional area; f = Darcy-Weisbach friction factor; D = internal diameter of the pipeline; and Δx represents the reach length, which is given by the x-t plane grid relationship

$$\Delta x_i = a_i \Delta t \tag{5}$$

where Δt is the time step in the MOC grid, as shown in Fig. 1.

In conventional MOC analysis, the structure of the MOC grid is predetermined and the properties of each reach (B_i, a_i, R_i and Δx_i) are known. The conventional MOC analysis is used to simulate the time-history of the transient pressure and flow at specific nodes.

Reconstructive MOC analysis

The reconstructive MOC analysis proposed in this research is the inverse process of the conventional MOC analysis described above. The MOC grid and the properties for pipe reaches are yet to be estimated from a measured time-history of transient pressure. In the following sections, previous research on performing MOC analysis backwards in time is reviewed; the problem to be solved in the proposed reconstructive MOC analysis is defined; the necessary assumptions are made; and then the detailed procedure of the reconstructive MOC analysis is presented.

Previous research on performing MOC analysis backwards in time

MOC analysis backwards in time has been used previously in valve stroking, a synthesis procedure that specifies the operation of control devices in order to prescribe the behavior of a transient to stay within a maximum head constraint (Wylie and Streeter 1993). The compatibility equations, Eqs (1) and (2), proved remarkably robust in calculating backwards in time, regenerating a transient effectively (Wylie and Streeter 1993).

Brunone and Morelli (1999) determined the characteristic curve of a valve (curve of the coefficient of discharge) by using the pressure traces measured at the upstream and downstream of the valve during an unsteady-state test. By solving the MOC capability equations and assuming as given downstream boundary condition the recorded time-history of pressure, the instantaneous discharge at the valve can be calculated. The flow-rate curve is then obtained from the orifice equation.

Shamloo and Haghighi (2009) used a backwards transient approach for leak detection in a reservoir-pipeline valve (RPV) system, where the head perturbations at the reservoir were estimated from the transient trace measured at the valve end of the pipe. They then defined an objective function using the theoretical constant head at the reservoir and the estimated head perturbations through a least-squares criterion. Thereafter, an inverse calibration process was performed to estimate the location and number of leaks. This is a complex problem involving the optimization of a significant number of parameters. An improvement was made by Haghighi et al (2012) on the backwards transient analysis-based leak detection technique, where a direct solution was used to replace the iterative optimization process. Leaks with unknown sizes are initially assumed at a number of characteristic nodes between the two ends of the pipeline. Equations for the estimated head at the upstream end were parametrically developed as a function of leak area using one period of the measured head data at the downstream end. Then a non-linear system of equations was achieved from the fact that the estimated head values (functions of leak area) should be equal to the measured (or theoretical) head values at the upstream end. As a result, the unknown leak sizes were solved directly from the non-linear system of equations by numerical methods.

All these uses of backwards MOC, however, assume that the MOC grid is explicit and the properties, including impedance, wave speed, diameter and friction factor, are known for every discretized reach. The innovation of the reconstructive MOC analysis proposed in this research is that this is the first time the MOC grid is reconstructed and the properties of each pipe reach are estimated using the first half period of the measured transient data. This one pass approach is quick and does not involve iteration or the calibration of a large number of parameters.

Problem definition

An example reservoir-pipeline-valve (RPV) system is shown in Fig 2 (a). The MOC grid shown in Fig. 2(b) is a plausible reconstruction of the MOC grid and presented here for illustration purposes only. The MOC grid is unknown at the beginning and it is constructed by the proposed method. Properties of each reach of pipe, including impedance B_i, wave speed a_i, reach resistance R_i and the length Δx_i, are unknown. The aim of the proposed reconstructive MOC analysis is to estimate these properties of each reach by reconstructing the MOC grid.

In order to conduct the reconstructive MOC analysis, a steady-state flow with a discharge of Q_0 is established first in the system. Then a step transient wave is generated at time $t = 0$ by abruptly shutting off the valve at the downstream end of the pipeline. Head perturbations are measured at the upstream face of the valve (at location x_0). The reconstructive MOC analysis utilizes the measured pressure transient trace to reconstruct the MOC grid. Perturbations shown in the plots of the estimated impedance and wave speed are indicative of the location and severity of deterioration throughout the pipe.

Assumptions

For simplicity, the inner diameter of the pipeline is assumed to be constant, uniform and known as D_0. This assumption is reasonable for pipelines where the wall thickness change attributable to deterioration is usually negligible when compared with the original diameter. As a result, the wave speed a_i in each reach can be estimated using Eq. (3) once the impedance value B_i has been determined, and the length of each pipe reach (or values of x_1 to x_3) can be estimated using Eq. (5).

Another assumption to be made is that the Darcy-Weisbach friction factor f is constant and uniform along the pipeline, and the effects of unsteady friction are negligible in the reconstructive MOC analysis. The value of the friction factor can be determined from steady-state conditions by

$$f = (H_r - H_{V0}) \frac{2gD_0 A_0^{\ 2}}{LQ_0^2} \tag{6}$$

where H_r = reservoir head and H_{V0} = steady-state head at the valve. The steady-state discharge Q_0 has to be known to enable the calculation for f, and Q_0 is also used in the reconstructive MOC analysis, as presented later in this paper. Note that Eq. (6) is an alternative to determining f from the pipe roughness height and Reynolds number, which are difficult to accurately estimate in field situations.

When f is constant, the steady-steady hydraulic grade line (HGL) is linear and known along the pipeline. As a result, R_i in Eq. (4) is only a function of Δx_i. It is suggested that the steady-state discharge Q_0 is kept small, so that the effects of friction are minimized.

The third assumption is that the incident wave is introduced by an abrupt closure of a valve at the end of the tested pipeline. The abrupt valve closure makes the wave front of the incident transient sharp and the rise time negligible. The sharp input signal can generate sharp reflections that are used by the reconstructive MOC analysis to build a picture of the pipe condition. In practice, however, due to limitations in the maneuverability of the transient generator valve, the incident wave usually has an inclined wave front. If the rise time of the wave front is greater than the sampling interval

Δt of the measurement, error will be involved into the proposed reconstructive MOC analysis. This practical problem can be solved by converting the measured pressure trace to the step response function (SRF) of the system through signal processing, which is described in the *experimental verification* section later on in this paper.

The last assumption is that, in the pressure transient trace resulted from the closure of the valve, a measured pressure value remains until the next one is registered. In fact, the measured pressure data are always discrete sequences with a specific sampling interval. This assumption implies that the pipe properties are uniform within a pipe reach and the discontinuity occurs only at the interface between reaches. This assumption is applicable when the sampling rate of the pressure measurement is high enough to satisfy the required spatial resolution.

Analysis for the first reach

The reconstructive MOC analysis is performed reach by reach from the downstream valve to the upstream reservoir, and the analysis for the first reach between N_1 and S_1 in Fig. 2(b) is presented here. Corresponding to the pipeline system and the MOC grid shown in Fig. 2, a hypothetical pressure trace resulting from the rapid valve closure at x_0 at time $t = t_0$ and measured at the upstream face of the closed valve is assumed to be the trace given in Fig. 3. Note that, in the hypothetical pressure trace, a measured pressure value remains until the next one is measured. As a result, all pipe properties are assumed to be constant within a reach.

For the first reach x_0x_1 as shown in Fig. 2(a), the impedance B_1 can be determined from the steady-state head (H_{V0}) and flow (Q_0) at the valve, and the head value H_{V1}, which is measured at point x_0 and time t_0 (just after the valve closure). A positive characteristic line can be used to facilitate the analysis, as given in Fig. 4.

In Fig. 4, δ is a positive value of time but tends to zero. As a result, the length of the positive characteristic line (C^+ in Fig. 4) is extremely short, the node N_1^- is very close to node N_1 and the effects of friction are negligible. The head and flow values for the two end points of this short positive characteristic line are shown in Fig. 4. At node N_1^- (time $t_0 - \delta$), the pipeline is still at the steady-state condition so the head and flow are H_{V0} and Q_0, while at node N_1 (time t_0) the head rises to H_{V1} and the flow becomes zero. Applying the positive compatibility equation [Eq.(1)] to this positive characteristic line, and neglecting the part associated with friction, the impedance B_1 for the first reach can be estimated as

$$B_1 = (H_{V1} - H_{V0}) / Q_0 \tag{7}$$

which actually is the same as the result from the Joukowsky head rise formula.

Once the impedance is determined, the wave speed in the first reach a_1 is estimated using Eq. (3), and the length of the reach, or the location of x_1, is estimated using Eq. (5). Then, the resistance factor R_1 for the first reach x_0x_1 can be estimated using Eq. (4), so that the steady-state head H_{S1} at the upstream end of the first pipe reach [x_1 in the pipeline in Fig. 2(a), which corresponds to node S_1 in the MOC grid in Fig. 2(b)] can be estimated by

$$H_{S1} = H_{V0} + R_1 Q_0^2 \tag{8}$$

Now, all the properties in the first pipe reach are known, including B_1, a_1, x_1, R_1 and H_{S1}. These parameters will be used in the analysis for the next pipe reach.

Analysis for the second reach

For the second reach $x_1 x_2$, to determine the value of B_2, the head H_{P1} and discharge Q_{P1} at node P_1 [Fig. 2(a)] are required. The characteristic lines between the three nodes N_1, N_2 and P_1 are given in Fig. 5 to facilitate the analysis. The arrows indicate the direction from known values to unknown values.

The information at node P_1 can be obtained from the information at nodes N_1 and N_2 by applying Eqs (1) and (2) to the characteristic lines N_2P_1 and N_1P_1, respectively. The impedance in the first reach B_1 is substituted into Eqs (1) and (2). The discharge values at nodes N_1 and N_2 are zero as the valve is fully closed. Finally, the equations for the characteristic lines N_2P_1 and N_1P_1 are:

$$H_{P1} - H_{V2} + B_1 Q_{P1} = 0 \tag{9}$$

$$H_{P1} - H_{V1} - B_1 Q_{P1} = 0 \tag{10}$$

Once H_{P1} and Q_{P1} at node P_1 are determined, the impedance B_2 of the second pipe reach $x_1 x_2$ can be estimated using MOC analysis at point x_1 around $t = \Delta t / 2$. In the MOC grid shown in Fig. 5, the change in the head and discharge at point x_1 occurs at

$t = \Delta t / 2$ instantaneously. When $t < \Delta t / 2$, along the dashed line from node S_1 to node P_1, the head and discharge at point x_1 remain at the steady state, which are H_{S1} and Q_0 respectively. Similar to the analysis for time t_0 shown in Fig. 4, the instantaneous change in the head and discharge at $t = \Delta t / 2$ can be described by a positive characteristic line with an extremely small time span, as given in Fig. 6.

In the MOC grid shown in Fig. 6, the area to the left of the characteristic line $N_1 P_1$ has steady-state conditions when $t < \Delta t / 2$. Consider a node S_1^- in the vicinity of node P_1 and along the line $S_2 P_1$ as shown in Fig. 6, it represents the steady state information at point $x_1^- = x_1 - a_2 \delta$ at time $t = \Delta t / 2 - \delta$. Since δ is positive but tends to zero, point x_1^- is located at the upstream of and in close proximity to point x_1, and the friction in the extremely short pipe reach between these two points can be neglected. As a result, the head and discharge at node S_1^- are the same as those at node S_1. Applying the positive compatibility equation [Eq.(1)] to the characteristic line $S_1^- P_1$ and neglecting the friction term R, the value of B_2 can be estimated as

$$B_2 = -(H_{P1} - H_{S1}) / (Q_{P1} - Q_0) \tag{11}$$

Other properties in this reach can be estimated using the same process as for the first reach, including a_2, x_2, R_2 and H_{S2}. The process of determining the properties of pipe reach $x_1 x_2$ from the information at nodes N_1 and N_2 is the key component of the *reconstructive MOC analysis*, which means the MOC analysis is performed backwards in time and the properties of the pipeline are estimated from the measured head data.

Analysis for the subsequent pipeline reaches

The ways in which the properties of the other reaches of pipe are determined are similar to the methods used for the second reach, and the reaches are analyzed sequentially from downstream to upstream. For the analysis of the ith reach, the estimated properties of the (i-1) downstream pipe reaches are used, as well as the first i head data measured at the end of the pipeline. By conducting the MOC analysis backwards in time and towards the reservoir from the valve end, the head and discharge for the nodes on the characteristic line N_1P_i can be determined.

A similar process as illustrated in Fig. 6 is then used to estimate the impedance B_i from the estimated information at node P_{i-1}, and the steady-state head and discharge at S_{i-1}, which are $H_{S(i-1)}$ and Q_0 respectively. Thereafter, Eqs (3) to (5) are used to determine other properties in this reach. The reconstructive MOC analysis continues until the properties of the final reach of pipe, that is adjacent to the reservoir, are estimated. At this point, plots of the impedance and wave speed distribution along the pipeline can be obtained, from which the number, location and severity of the deterioration can be estimated.

If only the condition of a specific section of the pipeline needs to be assessed, the reconstructive MOC analysis just needs to cover the length from the valve to the upstream boundary of the targeted section. If the whole pipeline is covered, the total number of pipe reaches used in the reconstructive MOC analysis equals the number of pressure data in the first plateau of the measured pressure trace (from the initial pressure jump to the first reflection from the reservoir). Within this range, the effects of friction are usually negligible, especially for a small steady-state discharge.

The major advantage of the proposed reconstructive MOC analysis is that complex reflections caused by natural pipeline parameter variations and/or multiple deteriorated sections can be interpreted appropriately. Because both the wave reflections and transmissions are considered in the restoration of the information (head and flow) for each node in the MOC grid, multiple reflections are intrinsically included in the analysis. As a result, theoretically the complexities in the measured pressure trace resulting from pipeline parameter variations and multiple deteriorated sections can be resolved, revealing the correct impedance distribution along the pipeline. This advantage is demonstrated in the numerical simulations for the detection of multiple deteriorated sections in a single pipeline as presented in the following section.

Numerical simulations

Numerical simulations performed on a single pipeline with three deteriorated sections are used to verify the proposed reconstructive MOC analysis for detecting widespread corrosion or other extended damage in pipelines. Firstly, conventional MOC modeling (in which all the properties of the system are explicitly specified) is conducted to obtain the head response induced by a step transient wave. Then, the reconstructive MOC analysis is applied to the pressure trace to derive the impedance and the wave speed along the pipeline.

The layout used for the numerical simulations is given in Fig. 7. The deterioration is represented by three pipe sections with changes in wave speed (a_1 to a_3 and B_1 to B_3 as shown in Fig. 7). The total length of the pipeline is L = 1500 m; the diameter is D_0 = 600 mm and uniform along the pipe; the wave speed in normal sections is a_0= 1000 m/s (impedance B_0= 360.5 s/m^2); the steady-state flow rate is Q_0 = 0.05 m^3/s (velocity = 0.177 m/s); the Darcy-Weisbach friction factor used for the forward MOC modeling is f = 0.02.

The time step for the MOC modeling was Δt = 1 ms, and the length of each reach in the grid was determined by $\Delta x_i = a_i \Delta t$. A step transient pressure wave is generated by shutting off the in-line valve at the end of the pipeline abruptly at time t_0= 0.1 s. The duration of the closure is assumed to be zero, so that the wave front is steep and satisfies the third assumption made previously. The pressure trace is measured at the upstream face of the valve, and the first plateau (with time duration of 3.065 s) is presented in Fig. 8.

It can be seen from Fig. 8 that the pressure trace is complex after about 1.7 seconds because of the multiple reflections within and between the three deteriorated sections. The perturbations in the oval, in particular, are just multiple reflections. It is difficult to estimate the number and various locations of the deteriorated sections using the single deterioration detection technique developed in Gong et al. (2013). The reconstructive

MOC analysis described in the previous section is therefore applied to interpret the pressure trace shown in Fig. 8. The distributions of impedance and the wave speed along the pipeline are estimated and presented in Fig. 9.

The three deteriorated sections can be identified and located accurately from the plots of the estimated distribution of the impedance and wave speed in Fig. 9. The values of the estimated location, impedance and wave speed are consistent with the theoretical values in the pipeline model in Fig. 3 (with discrepancy less than 0.05% between two numerical values). The successful numerical verification validates the proposed method of detecting widespread deterioration in a pipeline using the reconstructive MOC analysis. The method is able to deal with multiple reflections in the measured pressure trace. To further verify the proposed technique, data generated by an experimental pipeline in the laboratory is used, with details given in the following section.

Experimental verification

Experiments conducted on the single pipeline system in the Robin Hydraulics Laboratory at the University of Adelaide have produced data to verify the proposed technique for detecting widespread deterioration using the reconstructive MOC analysis. The experimental data has also been used in Gong et al. (2013) to verify a technique for detecting single distributed deterioration in pressurized pipelines.

The layout of the experimental pipeline system and the measured pressure traces are presented below. Because the proposed reconstructive MOC analysis requires a steep front in the incident wave, a preprocessing technique is adapted to transfer the measured pressure trace to a step response function (SRF), in which the rising front slope of the experimental incident wave is corrected to a sharp step. The reconstructive MOC analysis is then performed on the SRF to estimate the impedance and wave speed distribution in the experimental pipeline.

Experimental pipeline configuration

The layout of the experimental pipeline system is given in Fig. 10. The test pipeline is a 37.46 m in length of straight copper pipe with an internal diameter D_0 = 22.14 mm, and a wall thickness e_0 = 1.63 mm. One end of the pipeline is connected to an electronically controlled pressurized tank and the other to a closed in-line valve. A pipe section 1.649 m long with a thinner pipe wall thickness e_1 = 1.22 mm (the internal diameter D_1 = 22.96 mm) is placed 17.805 m upstream from the in-line valve. The material and external diameter of this section are the same as those of the original pipeline. This section represents a pipe section with a lower pressure rating, or could be interpreted as a section with uniform wall thickness reduction due to internal corrosion, disregarding the effects of spatial variability which would be present in realistic corroded sections. A side-discharge solenoid valve is located 144 mm upstream from the closed in-line valve for the generation of transient waves.

The wave speed in the intact pipeline is a_0 = 1328 m/s as determined by experiments (Lee et al. 2007b), which is very close to the theoretical wave speed 1329 m/s calculated from the theoretical wave speed formula for thick-walled pipes (Wylie and Streeter 1993). Using Eq. (3), the impedance of the original pipeline B_0 = 3.516×10^5 s/m^2. The theoretical wave speed in the thinner-walled section is estimated as a_1 = 1282 m/s using the theoretical wave speed formula, while $B_1 = 3.151\times10^5$ s/m^2 using Eq. (3).

Experimental pressure trace

The transient wave is generated by closing the side-discharge solenoid valve rapidly but not instantaneously. Pressure responses are monitored at the side-discharge valve with a sampling frequency of 2 kHz. The closure time is approximately 4 ms, which is much greater than the sampling interval, so that a rising front slope is obtained rather than a steep step as used in the numerical simulations. The steady-state flow rate is not measured and yet to be estimated. The tests are repeated for a number of times and the measured pressure traces are consistent (Gong et al. 2013). One of the measured pressure traces is presented in Fig. 11 (only the first plateau) [which is the pressure trace of *Test* 1 in Gong et al. (2013)]. The dip shown in the middle of the plot represents the reflections from the section with a thinner wall thickness.

The steady-state head at the valve is estimated to be H_{V0} = 25.55 m by averaging the head values within a short time interval before the wave front (6.92 s to 6.94 s). Similarly, the head value of the step incident wave can be estimated as H_i = 39.06 m (by averaging the head from 6.945 s to 6.947 s).

Preprocessing of the measured data

The experimental pressure trace shown in Fig. 11 has a rising front slope of approximately 4 ms. The shape of the initial wave front affects the shape of reflections from the pipeline, and a detailed discussion is given in Gong et al. (2013). In this experiment, the reflections from the thinner-walled section were not sharp because the original valve closure was not instantaneous. An improved estimation of the boundary between the normal pipe section and the thinner-walled section can be achieved if the measured pressure trace is pre-processed to build the steepness of the reflections before the reconstructive MOC analysis. In addition, the transient flow during this rising period is non-zero and unknown, so that the reconstructive MOC analysis described in the previous section cannot be performed directly on the measured trace.

A preprocessing procedure is proposed for deriving the step response function (SRF) of the pipeline from the measured pressure trace. The SRF is the response resulting from a theoretical step input transient wave, where the discharge is zero after the initial step head rise. The estimated SRF is then used in the proposed reconstructive MOC analysis to determine the distribution of impedance and wave speed along the pipeline.

To obtain the SRF of a linear system, both the input and the output signals are required. For the experimental pipeline system, the measured pressure trace (Fig. 11) can be used as the output. The *induced flow perturbation* at the side-discharge valve that is defined in Lee et al. (2006) can be used as the input. It is assumed that the flow perturbation is linearly related to the head perturbation during the generation of the transient (from 6.941 s to 6.945 s) by the Joukowsky formula, so that the input flow perturbation signal can be obtained by

$$\Delta Q = -\Delta H / B_0 \tag{12}$$

where ΔQ and ΔH are the discharge and head perturbation from the mean state at the generation point. Strictly speaking, B_1 should be used in Eq. (12) instead of B_0. However, since B_1 is unknown, an assumption that $B_1 = B_0$ has been made.

The unit SRF (which is the SRF of a system when the input is a step signal with magnitude of unity) is then obtained from the estimated input flow perturbation and the measured pressure trace. The determination of the unit SRF is based on correlation analysis of the input and output signals, and details can be found in Ljung (1999). In this research, the system identification toolbox in Matlab was used to facilitate the signal processing. The plot of the estimated unit SRF is given in Fig. 12.

Reconstructive MOC analysis for the step response function

The proposed reconstructive MOC analysis is performed on the estimated step response function (SRF) from t = 0 up to t = 0.0565 s. The plots of the estimated impedance and wave speed are given in Fig. 13.

The dip in the middle of each plot in Fig. 13 indicates that a pipe section with lower impedance and wave speed values is located in the experimental pipeline. The impedance and the wave speed of this pipe section are estimated as approximately $B_1 = 3.235 \times 10^5$ s/m^2 and a_1 = 1233 m/s respectively by averaging the values at the bottom of the dip in the plots. The first derivative of the estimated distribution of wave speed is calculated to yield the gradient (changing rate) in wave speed along the pipeline, where the two points with local maximum gradient values indicate the boundaries of the thinner-walled section. The length of this section is then estimated as 1.85 m starting from 17.8 m upstream from the closed valve. These estimates are close to the theoretical values of the thinner-walled pipe section in the experimental pipeline system, as shown in Table 1.

Analysis of pressure traces obtained in repeated tests yields consistent and similar results. Compared with the results $B_1 = 3.217\times10^5$ s/m^2 and $a_1 = 1292$ m/s obtained from the single distributed deterioration detection technique in Gong et al. (2013), the estimated impedance value for the thinner-walled pipe section are very close, while the wave speed estimated by the reconstructive MOC analysis is less accurate. The lower accuracy for the wave speed is because, in the reconstructive MOC analysis, it is derived from the estimated impedance using Eq. (3) under the assumption that the diameter of the pipeline is constant. In contrast, in the experimental pipeline, the deteriorated section has a thinner wall thickness and a larger internal diameter. This violates the assumption of 'constant internal diameter'. Considering the experimental pipeline is small in diameter (D_0 = 22.14 mm), this introduces an error into the estimated wave speed which is unlikely to occur in larger diameter pipes. If the wall thickness of the deteriorated section is known and the theoretical wave speed formula is applicable, the wave speed can be estimated more accurately. However, this information is usually unknown or inapplicable; therefore, the assumption that the internal diameter is constant is more practical for pipelines in the field where the diameter is much larger. Nevertheless, the proposed reconstructive MOC approach has a wider applicable range, since the technique proposed in Gong et al. (2013) is not able to interpret multiple reflections.

Small perturbations in the estimated distribution of impedance and wave speed are also observed in Fig. 13. They are related to the joints, pipeline parameter variations, and uncertainties in the experiments, such as fluid-structure interactions and pressure fluctuations in the tank. The magnitude of these perturbations is much smaller than the perturbation resulting from the pipe section with a thinner wall.

Decreasing patterns are observed in both the estimated wave speed and impedance at the end of the plots (greater than approximately 34 m). They are related to the curved head drop shown at the end of the measured pressure trace (Fig. 11, after about 6.995 s) and the estimated SRF (Fig. 12, after about 0.05 s). The curved head drop results from the curved wave front and signal dispersion and dissipation during wave propagation. As a result, the estimated impedance and wave speed values for the pipe section close to the tank (located from approximately 34 m upstream from the in-line valve to the tank) are inaccurate. However, the curved head drop at the end of the plateau in the pressure trace has no effect on the estimates for the pipeline reaches downstream (from 0 m to 34 m), because the reconstructive MOC analysis is performed from downstream to upstream reach by reach.

In summary, the experimental verification indicates that the proposed reconstructive MOC analysis works in controlled laboratory conditions. A pipe section with a thinner wall thickness can be detected successfully and its impedance, wave speed, location and length estimated with reasonable accuracy. An error in a later section in the measured pressure trace has no effect on the estimates obtained from the former pressure data.

Conclusions

A novel distributed deterioration detection technique is proposed in this paper. A reservoir-pipeline-valve system is analyzed, and the pressure response resulting from the step transient wave generated by shutting off the valve abruptly is used. A reconstructive MOC analysis technique is proposed in this research, which is an inverse process of conventional MOC analysis. The novel inverse process calculates the transient head and flow backwards in time and estimates the pipe parameters, such as impedance and wave speed, from the downstream valve to the upstream reservoir reach by reach.

Numerical simulations support the observation that the proposed technique can deal with complex multiple reflections caused by natural pipeline parameter variations and multiple deteriorated sections. The impedance, wave speed, location and length of three deteriorated sections in a single pipeline are estimated accurately in a numerical study.

Experimental verification indicates that the reconstructive MOC technique provides a new and useful way to analyze data from pipelines suspected of experiencing widespread deterioration. A signal preprocessing technique is adapted, which transfers the measured pressure trace to the step response function (SRF), removing the effects of the rising front slope in the experimental incident wave. The impedance, wave speed, location and length of a pipe section with a thinner wall thickness in a laboratory experimental pipeline apparatus are estimated successfully.

The reconstructive MOC analysis is a step forward in assessing the condition of expensive and critical pipeline infrastructure non-invasively and cost-effectively. This technique is a promising alternative to existing pipeline condition assessment techniques, such as the inverse transient analysis, and is efficient in implementation.

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Notation

The following symbols are used in this paper:

A	=	pipe cross sectional area;
a	=	wave speed;
B	=	impedance of a pipe section;
C^{+}, C^{-}	=	positive and negative MOC characteristic lines;
D	=	internal pipe diameter;
e	=	wall thickness of a pipe;
f	=	Darcy-Weisbach friction factor;
g	=	gravitational acceleration;
H_{V0}	=	steady-state head at the valve;
H_i	=	head value of an incident pressure wave;
H_r	=	reservoir head;
L	=	length of pipe;

M, N, P, S = node labels on the MOC grid;

Q_0 = steady-state discharge;

R = resistance coefficient for a pipe reach;

t = time;

x = distance along a pipe;

Greek symbols:

δ = a positive real value that tends to zero;

ΔH = head perturbation from the mean state;

ΔQ = discharge perturbation from the mean state;

Δt = time step on the MOC grid;

Δx = length of a pipe reach on the MOC grid;

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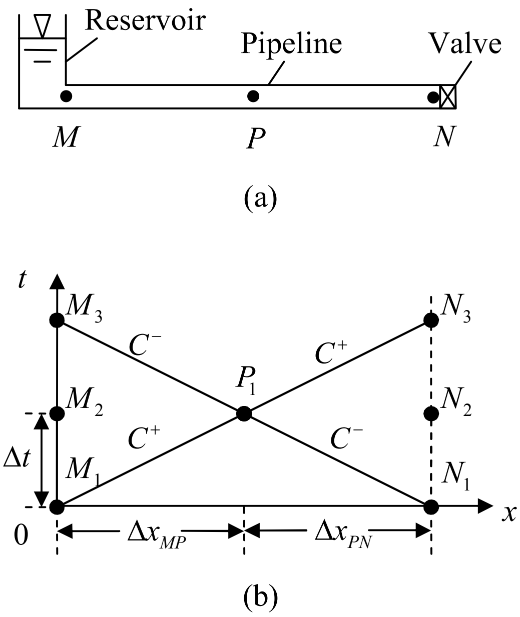

Fig. 1. (a) An example pipeline system; and (b) its MOC grid for conventional MOC analysis.

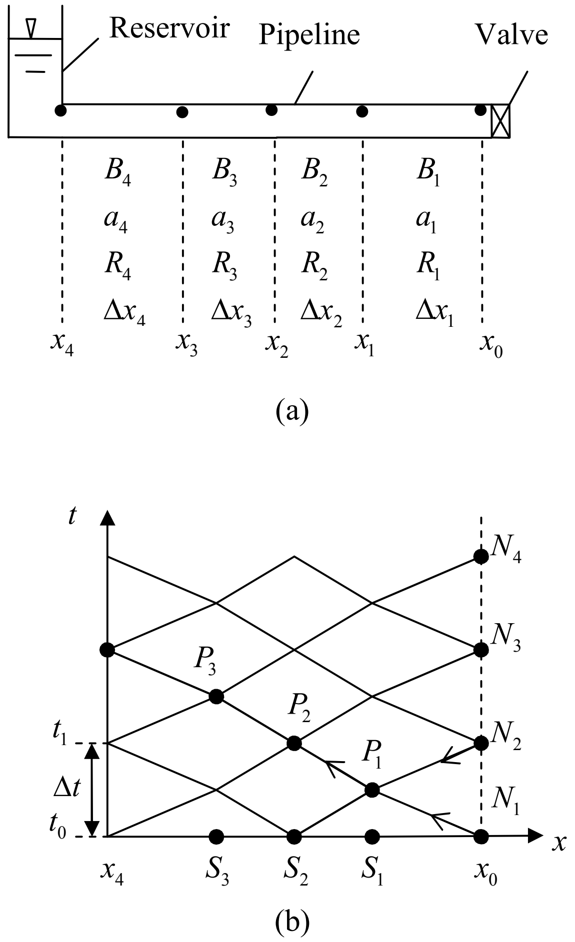

Fig. 2. (a) An example pipeline system; and (b) a possible MOC grid reconstructed by the reconstructive MOC analysis (note that the pipeline properties can be different between reaches).

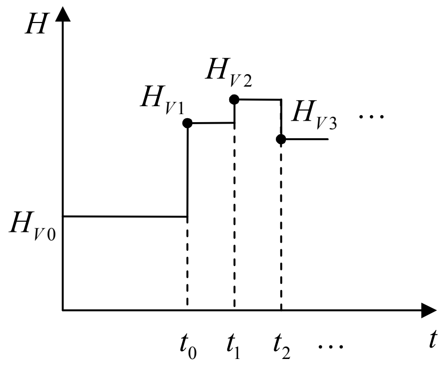

Fig. 3 An example pressure trace resulting from a rapid valve closure and measured at the upstream face of the closed valve.

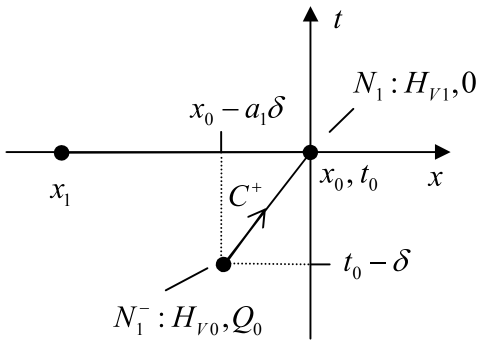

Fig. 4 MOC analysis at point x_0 for determining B_1.

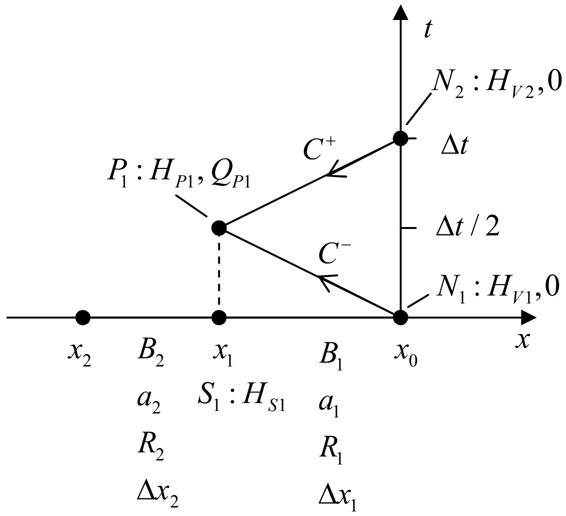

Fig. 5 Reconstructive MOC analysis for the second pipe section.

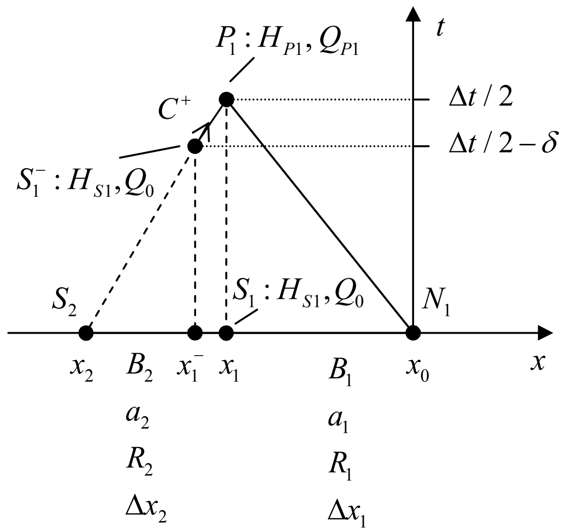

Fig. 6 MOC analysis for point x_1 at $t = \Delta t/2$.

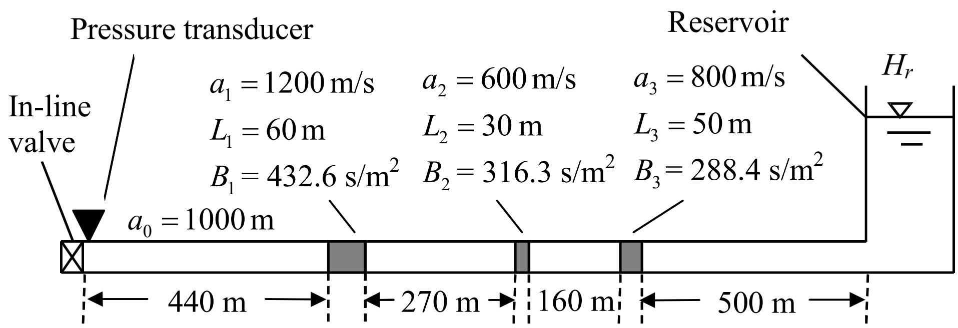

Fig. 7. The pipeline configuration for the numerical simulation.

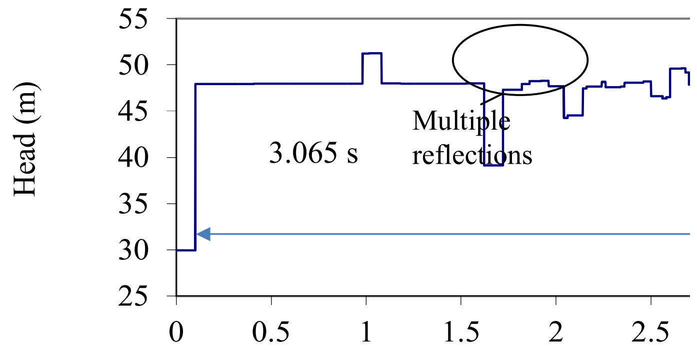

Fig. 8. The pressure trace obtained in the forward MOC modeling (the first plateau, i.e. from the initial wave jump to the first reflection from the reservoir).

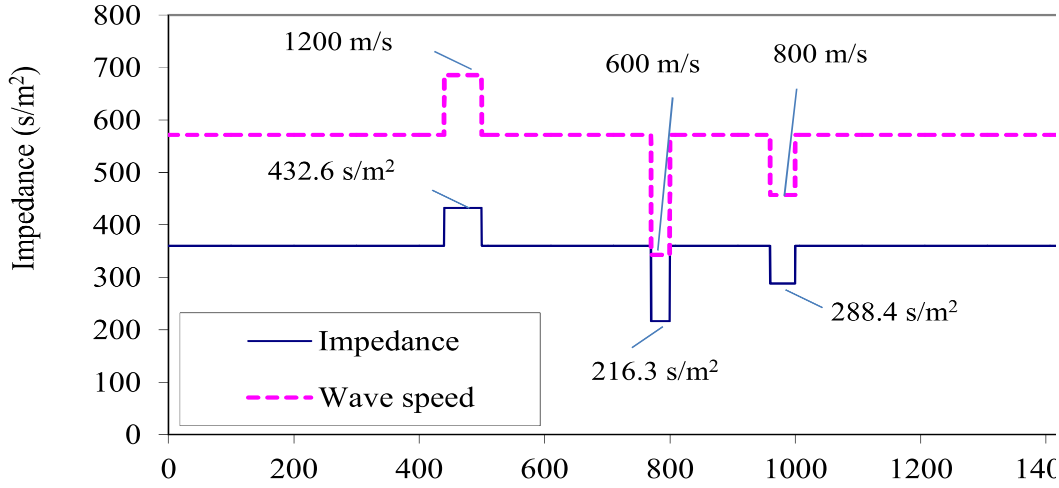

Fig. 9. The impedance (B , on the left axis) and wave speed (a , on the right axis) estimated from the reconstructive MOC analysis for the numerical simulations.

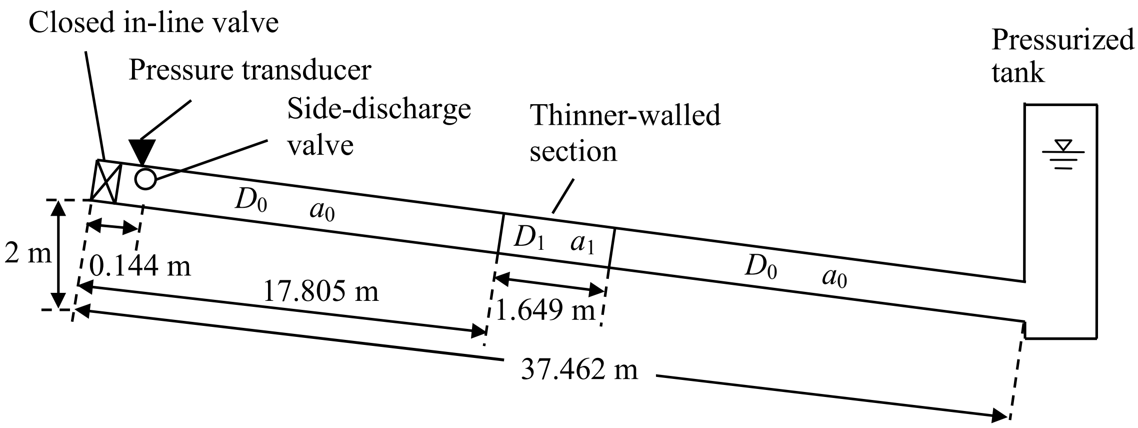

Fig. 10. The system layout of the experimental pipeline.

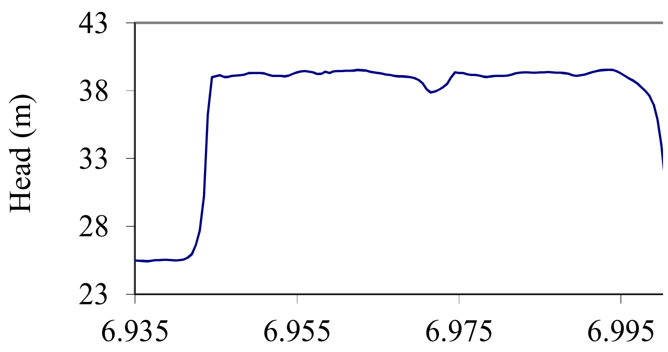

Fig. 11. The first plateau of the experimental pressure trace.

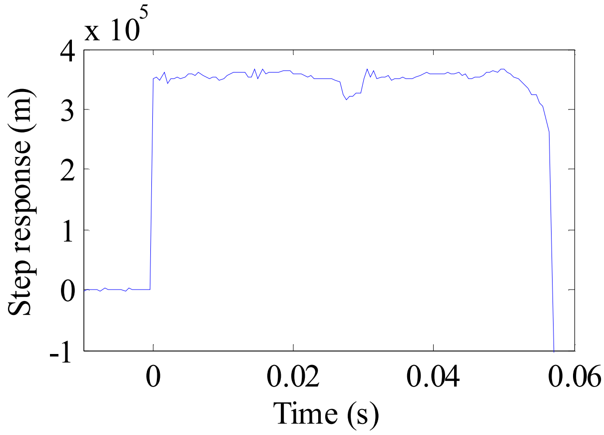

Fig. 12. The plot of the unit step response function (SRF) estimated from the measured pressure trace (SRF for Q_0 = 1 m^3/s).

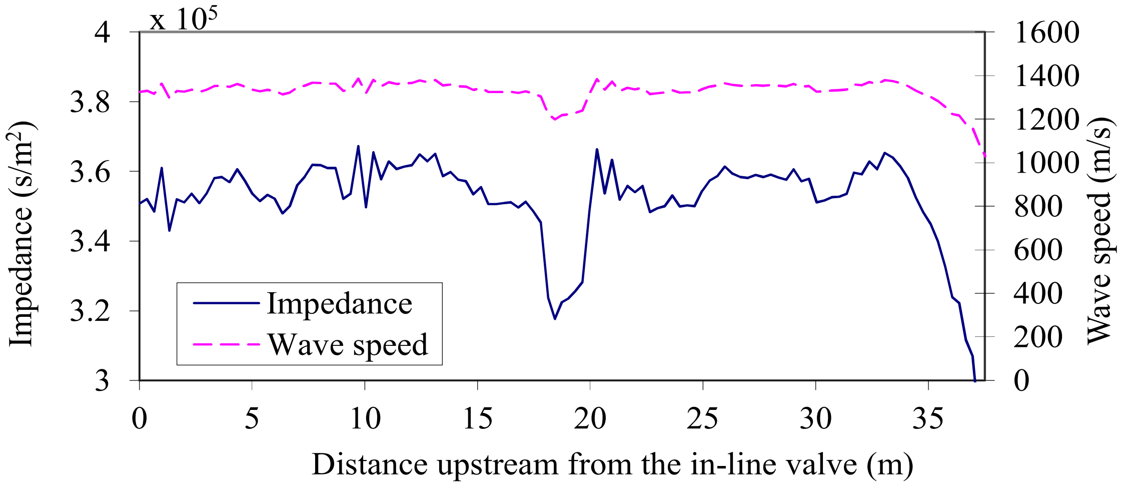

Fig. 13. The impedance (B , on the left axis) and wave speed (a , on the right axis) estimated from the reconstructive MOC analysis for the experimental pipeline.

Table 1. Estimated properties of the deteriorated section and corresponding error.

	Impedance (m/s^2)	Wave speed (m/s)	Length (m)	Starting location (m)
Theoretical values	3.151×10^5	1282	1.649	17.805
Estimated values	3.235×10^5	1233	1.85	17.8
Relative error*	2.7%	3.8%	12.2%	N/A

* Relative error = |(estimated value – theoretical value)/ theoretical value| × 100%