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Field study on pipeline parameter identification using fluid transient waves with time-domain analysis

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ABSTRACT
This paper presents some results from a field study on the identification of pipeline properties (such as impedance, wave speed, wall thickness and length) using fluid transient waves with time-domain analysis. Branches or off-takes, changes in pipeline material and changes in pipeline diameter are identified in a field pipeline through transient testing. The corresponding pipeline parameters are determined through analysis of the measured transient pressure wave reflections. The results are generally consistent with the information shown in the GIS drawings and/or the design drawings, which verifies the usefulness of the time-domain approach for pipeline parameter identification using fluid transient waves. Challenges in field applications are also identified and discussed.

NOTATION

A	cross-sectional area of pipeline;
a	wave speed;
B	characteristic impedance of pipeline;
B_r	impedance ratio;
c	pipe restraint factor;
D	pipe internal diameter;
E	Young's modulus of the pipe wall material;
e	pipe wall thickness;
g	gravitational acceleration;
H_r^*	dimensionless head perturbation of the reflected wave;
ΔH_i	dimensional head perturbation induced by the incident pressure wave;
ΔH_r	dimensional reflected head perturbation;
K	bulk modulus of elasticity of fluid;
L	location of deterioration (relative to the generation and measurement point);
L_d	length of deteriorated section;
t	time;
Δt	time interval;

ρ density of fluid;

1 INTRODUCTION

Water distribution systems (WDS) are critical infrastructure for every city and town. However, the infrastructure has been suffering continuous deterioration since been installed in the field due to environmental and operational conditions as well as quality of manufacturing and installation [1]. The deterioration of WDS leads to many problems such as leakage and bursts, blockages and extended pipe wall deterioration, which induce water loss [2, 3], extra cost for operation and maintenance [4, 5], and water quality issues [6, 7].

Water utilities need a good understanding of the current condition of their WDS. The information is essential for targeted maintenance and rehabilitation, and preventing disruptive events such as pipe failure and water contamination. Although many techniques have been developed for leak management [8] and pipeline condition assessment [9], difficulties and challenges still exist in the field due to the sheer size of the network and the fact that most pipelines are buried underground.

Research in the past two decades has shown that fluid transient waves (pressure surges) can have many useful applications in the collection of information for the management of pipeline systems, such as leak detection [10-23], discrete blockage detection [24-28], extended blockage detection [29, 30], and more recently, pipe wall condition assessment [31-34] and general parameter identification [35-37]. Fluid transient-based techniques are promising because controlled small transient pressure waves are non-destructive and can collect pipeline information for a long distance (a couple of kilometres) in a single test [38]. However, field verification of transient-based techniques for pipeline fault detection and condition assessment is still limited.

This paper presents results of a transient field test on a water main in Victoria, Australia. The aim of this research is to assess the effectiveness of pipeline parameter identification and condition assessment using transient pressure waves with time-domain analysis. Branches or off-takes, changes in pipeline material and changes in pipeline diameter are identified in field pipelines through transient testing. The corresponding pipeline parameters, such as wave speed, pipeline diameter and length, are determined through time-domain analysis of the measured transient pressure traces. The results are generally consistent with the information shown in the GIS drawings or the design drawings provided by the Victorian water utility. A few practical issues have also been identified and discussed. The field case study verifies that time-domain analysis of fluid transient waves can facilitate pipeline parameter identification and condition assessment.

2 TIME-DOMAIN ANALYSIS OF TRANSIENT PRESSURE WAVES

Gong et al. [31, 39] have previously conducted numerical and laboratory research on the determination of pipe wall thickness using time-domain analysis of transient pressure wave reflections. The theory is briefly reviewed here and adapted to the analysis of the field data.

Under one dimensional water hammer theory [40, 41], the speed for a transient pressure wave travel in a pressurised elastic pipeline is given by

$$a = \sqrt{\frac{K/\rho}{1+(K/E)(D/e)c}}\,, \tag{1}$$

where a is wave speed, K is the bulk modulus of elasticity of fluid, ρ is the density of fluid, E is Young's modulus of the pipe wall material, D is the pipe internal diameter, e is the wall thickness and c is a factor depending on the restraint condition of the pipeline [40, 41].

The characteristic impedance of a pipeline, B, is defined as

$$B = \frac{a}{gA}\,, \tag{2}$$

where g is the gravitational acceleration and A is the cross-sectional area of a pipeline.

When an incident pressure wave encounters any physical changes in a pipeline, such as a deteriorated pipe section with a change in wall thickness, wave reflections are generated and propagate towards the source of the incident wave. In a measured pressure trace, as shown in Figure 1, the size of a pressure wave reflection induced by a deteriorated pipe section is related to the size of the incident wave and the degree of change in pipeline impedance [31, 39]. The wave reflection can be non-dimensionalised by dividing itself by the size of the incident wave, and written as

$$H_r^* = \frac{\Delta H_r}{\Delta H_i}\,, \tag{3}$$

where H_r^* is the dimensionless head perturbation of the reflected wave, ΔH_r is the dimensional reflected head perturbation and ΔH_i is the dimensional head perturbation induced by the incident pressure wave. Note that ΔH_r is negative if the head induced by reflection is lower than that of the incident wave, and ΔH_i is positive if it is generated by an abrupt closure of a side-discharge valve.

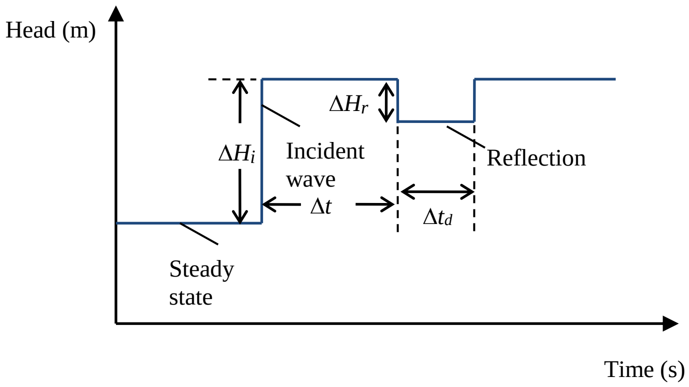

Figure 1. Example of a measured transient pressure trace.

Provided that the transient wave reflection is measured at the same location as where the incident wave is generated, the impedance ratio between a deteriorated section and the section where the incident wave is generated can be determined from the dimensionless head perturbation by [31]

$$B_r = \frac{1+H_r^*}{1-H_r^*}, \qquad (4)$$

where B_r is the ratio of impedance.

The location of the deterioration, relative to the location of the generation and measurement point, can be determined by the theory of time-domain reflectometry [15] using

$$L = \frac{a\Delta t}{2}, \qquad (5)$$

where L is the distance between the measurement point and the deterioration and Δt is the time interval between the wave front and the reflection as shown in Figure 1.

Similarly, the length of a deteriorated section can be determined using

$$L_d = \frac{a_d \Delta t_d}{2}, \qquad (6)$$

where L_d is the length of a deteriorated section, a_d is the wave speed in the deteriorated section and Δt_d is the duration of the reflection as shown in Figure 1.

3 FIELD CASE STUDY ON PIPELINE PARAMETER IDENTIFICATION

3.1 Background

Field testing was conducted by the authors in April 2014 on a regional water main in Victoria, Australia. As illustrated in Figure 2, a set of test typically involves a generation and measurement point (Gen) and one or more additional measurement points (M1 and M2). The transient generator is a customised side-discharge valve based on a ball valve. To generate an incident step pressure wave, the valve is open for several minutes and then closed abruptly (within 10 ms). Pressure transducers are installed at the generation point and other measurement points to record the pressure response from the pipeline at a sampling frequency of 2 kHz. The transient generator and pressure transducers are connected on existing assess points along a pipeline, such as air valves and fire hydrants. Details of the equipment and the procedure of data collection can be found in Stephens et al. [32]. In the following sections, a case study on parameter identification for pipeline material and diameter changes, and a branch or off-take is presented.

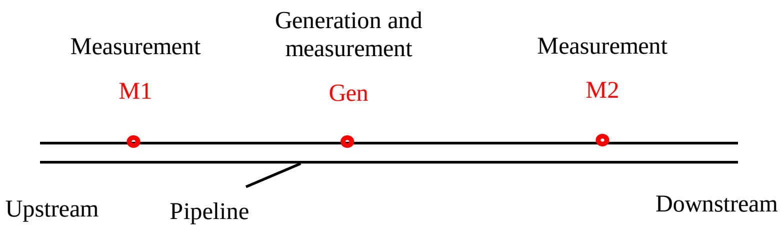

Figure 2. Typical configuration for field testing using transient pressure waves.

3.2 Case study

3.2.1 System layout

A case study is conducted on an underground water main with a branch and changes in pipe diameter and material. The upstream of the pipeline is connected to a T-junction and the downstream end was closed during the test. The layout of the section of pipeline under test is illustrated in Figure 3 (not to scale). The section of interest is between connection points J1 and J3, which consists of two 225 mm asbestos cement pipe (225 AC) sections, a 225 mm mild steel cement lined (225 MSCL) pipe section, a 300 mm ductile iron cement lined (300 DICL) pipe section, and a 100 mm AC branch (100 AC) connected at the junction between the 300 DICL and the 225 AC. The majority of the pipeline was constructed in 1980s, but the branch was constructed in 1964. The information shown in Figure 3 is from the GIS drawings and the design drawing provided by the water utility, complemented with the manual measurements conducted in the field. Two sets of tests were conducted in the field for the investigation of the section between J1 and J3. One test had the generator at J3 and pressure transducers at all the three locations, and the other test had the generator at J8 and transducers at J3 and J8.

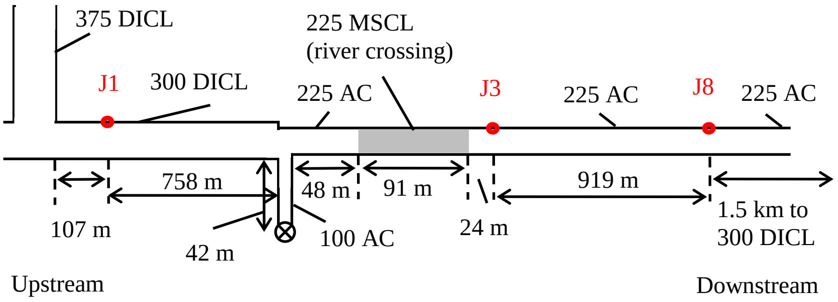

Figure 3. Layout of the section of pipeline in the case study.

The focus of the case study is on the parameter identification for the 225 MSCL river crossing section and the 100 AC branch. The 225 MSCL section represents a change in pipe material and/or diameter, which is frequently seen in field pipelines. It is also common that unregistered branches (including illegal connections) exist in some water distribution systems and they are difficult to find. In this case study, the known 100 AC branch is connected to a junction with pipe diameter and material changes, which is a more complicated situation than it is just connected to a uniform pipeline.

3.2.2 Measured pressure traces

For the test with the generator at J3, the non-dimensionalised and time-shifted pressure traces measured at the three connection points are given in Figure 4. The non-dimensionalisation is conducted using Eq. (3). The time shifting [42] is to highlight the wave reflections from the section between J1 and J3. The pressure trace measured at J1 (the dotted line) is shifted backward in time to double the time interval between its wave front and the wave front measured at J3 (Gen, the solid line). The pressure trace measured at J8 (the dashed line) is shifted forward in time to line up its wave front with the wave front measured at J3 (Gen, the solid line). The time-shifting enables wave reflections induced by anomalies located between J1 and J3, and as measured at location J3 and J8, line up in time. The time-shift wave front measured at J1 indicates the far boundary of the section of interest.

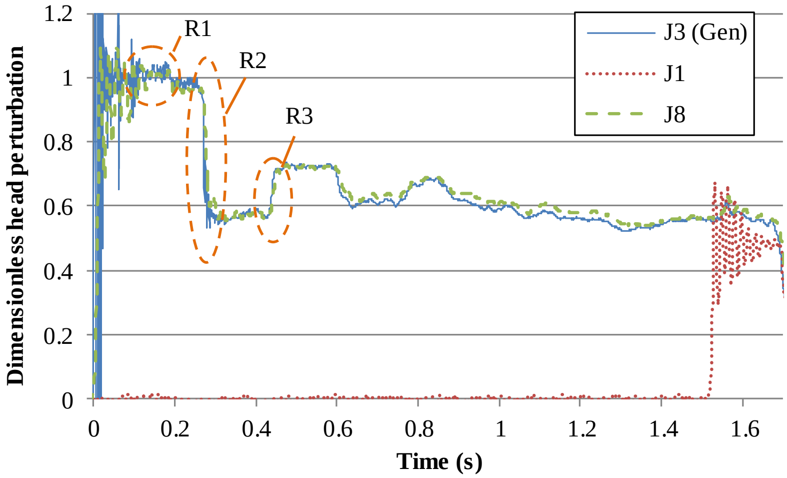

Figure 4. Non-dimensionalised pressure traces measured in the test with the transient generator at J3, time-shifted to highlight reflections from the section between J1 and J3. Three significant reflections (R1 to R3) are highlighted in circles.

It can be seen from Figure 4 that all the three pressure measurements show significant oscillations within the first 0.1 s following the wave front. The significant pressure oscillation is mainly due to multiple reflections within the stand pipe used to connect the generator to the main pipe [32], and partially contributed by the fact that the generation point is close (approximately 24 m) to a junction with pipe material change (225 AC to 225 MSCL). Beyond the part that is contaminated by the oscillation, the first three identifiable wave reflections as measured at J3 and J8 are highlighted in circles (R1 to R3) in Figure 4 and analysed in detail.

Reflection R1 includes a pressure jump followed by a drop. The pressure jump is induced by the material change from 225 AC to 225 MSCL (the downstream boundary of the 225 MSCL section), and the drop is induced by the material change from 225 MSCL back to 225 AC (the upstream boundary of the 225 MSCL section). Reflection R1, although identifiable in Figure 4, is contaminated by the pressure oscillations associated with the wave generation, so that detailed analysis of this reflection is difficult. Alternatively, the non-dimensionalised and time-shifted pressure traces measured in another test with the generator at J8, as given in Figure 5, is used to analyse this change in pipe material.

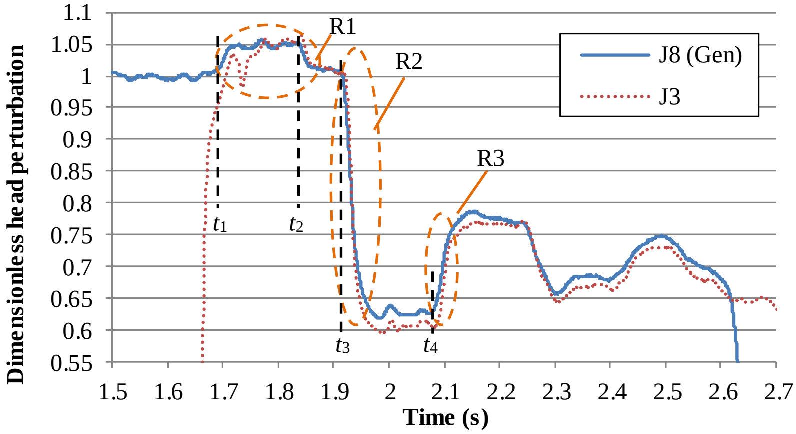

Figure 5. Non-dimensionalised pressure traces measured in the test with the transient generator at J8, time-shifted to highlight reflections from the section between J1 and J3. Three significant reflections (R1 to R3) are highlighted in circles.

3.2.3 Parameter identification for the MSCL section

As a preparation for the analysis of reflection R1 induced by the 225 MSCL section, the 225 AC is studied first. The wave speed in the 225 AC section is determined as a_{225AC} = 1123 m/s by dividing the distance between J3 and J8 by the time delay between the wave fronts measured at J3 and J8. The determined wave speed is in between the theoretical wave speeds of Class C and Class D 225 AC, which are calculated using Eq. (1) and the pipe information from Australian standard for AC pipes [43]. Considering the AC pipe may have wall deterioration and, therefore, a lower wave speed than the theoretical value, the 225 AC is most likely to be in Class D, which has an internal diameter of 209.3 mm and a wall thickness of 24.9 mm. It is known that the wall deterioration of AC pipes is typically due to lime leaching and does not change the physical thickness of wall [44]. As a result, the impedance of the 225 AC is calculated as B_{225AC} = 3327 s/m^2 by Eq. (2) using the wave speed a_{225AC} and the internal diameter of 209.3 mm.

Analysis is then conducted to identify the parameters of the MSCL section from the measured pressure wave reflection R1. In Figure 5, the reflection R1 induced by the 225 MSCL section is very clear in the pressure trace measured at J8 (Gen, the solid line), from time t_1 = 1.695 s to time t_2 = 1.837 s. A very similar reflection is also shown in the trace measured at J3 (the dotted line) at the same time. The reflection measured at J3 includes an additional dip (around time 1.73 s), which does not line up with any reflections measured at J8, therefore it is induced by an anomaly located downstream of J8 and out of the section of interest.

The dimensionless size of reflection R1 is approximately $H^*_{r\_R1}$ = 0.05. Using Eq. (4), the impedance ratio between the 225 MSCL and the 225 AC is determined as B_r =

1.105. The impedance of the MSCL section is then obtained as B_{MSCL} = 3676 s/m^2. The length of the MSCL section as read from the GIS map is 91 m, so that the wave speed can be determined by Eq. (5) using the duration of the reflection and the result is a_{MSCL} = 1268 m/s. Substituting B_{MSCL} and a_{MSCL} into Eq. (2) gives the internal diameter of the MSCL as D_{MSCL} = 212 mm. Substituting a_{MSCL} and D_{MSCL} together with the values of other parameters (K = 2.24 Gpa, ρ = 997.1 kg/m^3, E = 207 Gpa, c =0.91) into Eq. (1), the equivalent steel thickness (with the cement mortar lining converted to equivalent steel wall) is determined as 5.26 mm. Unfortunately, the physical details of the 225 MSCL pipe when it was intact are unknown in this case study, and Australian standard for steel water pipes does not include the nominal size of 225. As a result, further investigation into the degree of deterioration of this MSCL section is difficult. Nevertheless, these results verify that it is feasible to estimate the wave speed and wall thickness of a section of pipe with a material change using the size and duration of its wave reflection.

3.2.4 Parameter identification for the AC branch

Reflections R2 and R3 are analysed together for the parameter identification of the 100 AC branch. From Figure 4 or Figure 5, reflection R2 has a dimensionless size of approximately $H^*_{r\_R2} = -0.41$, and R3 has a size of $H^*_{r\_R3} = 0.15$. Apparently R2 is the first wave reflection from the three-way junction. Substituting the size of R2 and the impedance of the 225 AC pipe into Eq. (4), the impedance for the pipe upstream of the 225 AC pipe is determined as 1392 s/m^2. This impedance is the equivalent impedance for the 300 DICL and the 100 AC pipes in parallel. The equivalent impedance of two pipelines in parallel can be derived as [41]

$$B_{eq} = \frac{B_1 B_2}{B_1 + B_2}, \tag{7}$$

where B_1 and B_2 are the impedance of the two pipelines in parallel and B_{eq} is the equivalent impedance.

As a result, an equation linking the impedance of the 300 DICL and that of the 100 AC can be written as

$$\frac{B_{100AC} B_{300DICL}}{B_{100AC} + B_{300DICL}} = 1392\,. \tag{8}$$

Reflection R3 is the wave reflected from the closed end of the 100 AC branch. After the first reflection and transmission at the three-way junction (which generates R2), a pressure wave with a dimensionless size of 0.59 (i.e. $1 + H^*_{r\_R2}$) was propagating along the 100 AC pipe. This wave was reflected back at the closed end of the 100 AC with its size doubled, which means a pressure wave with a dimensionless size of 0.59 (note that the previous pressure of 0.59 has become the new datum) was propagating towards the three-way junction. When the reflected wave arrives at the three-way junction, wave reflection and transmission resulted in a pressure wave with a dimensionless size of 0.15

(i.e. R3) propagating towards three directions. Taking an interior point in the 100 AC branch as the observation point and using the concept of dimensionless wave reflection given in Eq. (3), the second reflection at the T-junction actually gave an reflection with dimensionless size of – 0.75 [i.e. (0.15−0.59)/0.59]. Substituting this dimensionless reflection into Eq. (4) gives an impedance ratio of 0.143. This is the ratio of the equivalent impedance of the 300 DICL and 225 AC in parallel to the impedance of the 100 AC branch, and it can be written as

$$\frac{B_{225AC}B_{300DICL}}{(B_{225AC}+B_{300DICL})B_{100AC}} = 0.143\,. \qquad (9)$$

Substituting the previously determined impedance of the 225 AC pipe (B_{225AC}) into Eq. (9) and then solving Eqs (8) and (9) together, the impedance of the 300 DICL and the 100 AC are obtained as $B_{300DICL}$ = 1692 s/m^2 and B_{100AC} = 7851 s/m^2.

The class information for the 300 DICL and the 100 AC pipes is unknown. However, from the Australian standard for DICL pipes [45], 300 DICL in Class K12 has an internal diameter of 313 mm, a thickness of ductile iron of 10 mm and a thickness of cement mortar lining of 6 mm. From the Australian standard for AC pipes [43], 100 AC Class B has an internal diameter of 100.5 mm and a thickness of 10.7 mm. As a result, the theoretical impedance of the 300 DICL K12 and the 100 AC Class B pipes are calculated as 1715 s/m^2 and 13800 s/m^2.

The determined impedance $B_{300DICL}$ is close to the theoretical value for 300 DICL K12 pipe, so that it can be concluded that the 300 DICL is likely to be in Class K12 and in generally good condition. However, the determined impedance for the 100 AC pipe is much smaller than the theoretical value for intact 100 AC Class B, which indicates that the 100 AC branch may have significant wall deterioration. Substituting B_{100AC} into Eq. (2), the wave speed in the 100 AC branch is calculated as a_{100AC} = 605 m/s. The time interval between R2 and R3 is read from Figure 5 as $\Delta t = t_4 - t_3$ = 0.160 s. Using Eq. (5), the length of this 100 AC branch is estimated as 48 m, which is close to the length 42 m as read from the GIS drawings.

3.3 Discussions

The case study shows that it is feasible to extract pipeline information from time-domain analysis of transient pressure wave reflections. The pipeline parameter identification helps water utilities to better understand the configuration and condition of their pipeline system.

A few practical issues have been identified through the case study. First of all, prior information about the pipeline system is important and critical, such as the pipeline length, diameter and class information. However, the information is not always available from the record held by water utilities. Uncertainties in the length of a pipeline will introduce uncertainties in the determination of the impedance and wave speed. The pipeline condition is difficult to assess if the original physical details of the pipeline are unknown.

Second, it is very challenging to analyse the transient pressure wave reflections when the pipeline system is complex. Multiple reflections may occur and superimpose with each other, resulting in pressure responses too complicated to analyse.

Third, the generation of an incident wave through a stand pipe brings high frequency oscillations (see Figure 4). These oscillations make the initial part (0.1 s) of a measured pressure trace difficult to analyse. However, the high frequency signal may not transmit to a measurement station hundreds meters away from the generator (see the trace measured at J3 in Figure 5). As a result, it is suggested that multiple tests with the generator at different locations should be conducted for the investigation of a specific section of pipeline.

4 CONCLUSIONS

A field case study has been conducted on a regional water main in Victoria, Australia to study the feasibility of pipeline parameter identification using time-domain analysis of fluid transient waves. The case study involves a pipeline with varying material (AC, DICL, MSCL) and diameter and a short AC branch with an closed end. Time-domain analysis has been conducted on the pressure traces measured at multiple locations. The impedance, wave speed, length and wall thickness of an MSCL river crossing section have been determined. The impedance, wave speed and length of the AC branch have also been estimated. The determined lengths are generally consistent with the information provided by the water utility, which verifies that the procedure of the analysis is correct.

Challenges in field applications have been identified. In particular, prior information of the pipeline system (physical details of the pipeline when intact) is important but not always known. This brings difficulty in assessing the condition of the pipeline because lack of a standard condition to compare with. Other practical issues include the complexities induced by multiple reflections and the effects of the high frequency pressure oscillations induced by the transient generator.

Overall, this field study verifies that fluid transient waves can be used as a tool for pipeline parameter identification and condition assessment. Challenges, however, exist in the field and further development is required to improve the resolution and accuracy of the analysis.

5 ACKNOWLEDGEMENTS

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