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FIELD TEST INVESTIGATIONS INTO DISTRIBUTED FAULT MODELING IN WATER DISTRIBUTION SYSTEMS USING TRANSIENT TESTING

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ABSTRACT

Current condition assessment techniques are focused on leakage, however this forms only part of the story with regard to the efficiency and condition of pipelines. The neglected phenomena are distributed faults including pipe wall deterioration and blockages, where blockage refers to any build up ranging from increased pipe roughness to complete obstruction that may be caused by debris, sedimentation, tuberculation, biofilms or valves.

The objective of this research was to develop a non-invasive condition assessment technique for water distribution systems (WDS) that has the ability to detect distributed faults including blockages. Inverse Transient Analysis (ITA) has been identified as a potential method but requires developments in modeling techniques for distributed faults. Blockages can be caused by the build up of many different materials each with their own properties. Extended blockages also form complex flow routes, which cannot accurately be captured by the current approach unless extremely fine discretisation is incorporated, increasing computational effort very significantly. The current approach models extended blockages as reduced diameter sections of pipeline. While a blockage does reduce the diameter, the material properties of the blockage significantly differ from that of the pipeline. A viscoelastic element may be used to account for the change in pipe material and hence response due to the blockage material.

Field tests have been conducted on the Adelaide metropolitan water distribution system in streets that have been identified as having significant potential to form blockages. The transient tests indicated that the complex response of the pipe to transient excitation suggests that they are indeed suffering from substantial problems with blockages. The location and identification of zones of differing condition to the remainder of the pipeline, and hence having the potential for distributed faults, have been determined using inverse transient analysis.

1 INTRODUCTION

Pipeline rehabilitation and repair represents a significant capital investment in the water industry particularly as systems age and deteriorate. Condition assessment of pipelines plays an important role in a proactive approach to fault and deterioration detection. Current condition assessment techniques are focused on leakage, however leakage accounts for only part of the loss of efficiency and deterioration of pipelines. The neglected phenomena are distributed faults including pipe wall deterioration and blockages, where blockage refers to any build up ranging from increased pipe roughness to complete obstruction and be caused by debris, sedimentation, tuberculation, biofilms or partially closed or fully closed valves.

Operators require non-invasive techniques that limit customer disruption, that are low in cost and are not labour intensive. The technique is required to be applicable in all common pipe materials in a WDS (DICL, AC, PVC, Cast Iron) and to all typical network situations. Initially proposed by Liggett and Chen (1994) the use of hydraulic transients based on inverse analysis to diagnose faults represents one possible approach.

Theoretical development of a variety of transient techniques has been undertaken with a focus on leakage. These include, but are not limited to, Inverse Transient Analysis (Brunone 1999; Vítkovský 2001), resonance methods (Lee et al. 2002), and transient damping methods (Wang et al. 2002). However limited field application has been undertaken. Field application for leaks detection has been undertaken by Stoianov et al. (2003), Covas (2004) and Stephens et al. (2004), application to condition assessment has been undertaken by Arbon et al. (2006). Stephens et al. (2004) extended the field application to detection of simulated blockages and air pockets within a water distribution system through the use of Inverse Transient Analysis (ITA).

Although primarily applied to discrete faults, ITA has the potential for application to distributed faults. Stephens et al. (2005) has previously applied a trial and error approach to determining the location and extent of distributed blockages within a water distribution system. While reasonable agreement was found between the modeled approach and the actual location of blockage limitations were identified. The limitations centered on the ability to accurately model the distributed blockages particularly the damping effects.

Stephens et al. (2005) represented extended blockages in their Method of Characteristics (MOC) model by including sections of reduced diameter, necessitating the discretisation of the pipeline into sections of size no longer than the shortest length of extended blockage. Quasi-steady contraction and expansion losses at the ends of these sections were included through introducing additional pipe sections of equivalent friction losses. However this approach neglects the material properties of the blockages, which can affect the propagation of the transient.

1.1 Viscoelastic damping modeling

Blockages can be caused by the build-up of many different materials each with their own properties, which can differ significantly from that of the pipeline. A viscoelastic element has the potential to account for the change in material properties as the blockage material is proposed to act as a viscoelastic section of pipe. It is proposed that an extended blockage would result in a section of pipe with viscoelastic parameters that differ significantly from unaffected sections of pipe due to the difference in material properties of the blockage.

Stephens (2007) has incorporated viscoelastic elements in models for ITA to account for the theoretical uncertainties not directly modeled namely the effect of restraints, flexible joints, customer connections and soil/pipe interaction on the damping of the measured transient response of a pipeline. A one-element Kelvin-Voigt mechanical viscoelastic model was applied by Stephens (2007) to predetermined spatial zones along the pipeline and ITA undertaken to calibrate the viscoelastic parameters.

A single Kelvin-Voigt unit is illustrated in Figure 1, where E_0 is defined as the elastic modulus of the pipe wall, with the compliance of the elastic spring calculated by $J_0=1/E_0$. E_1 represents the modulus of elasticity of the creep deformation spring and the viscosity of the dashpot μ_1 represents the viscous creep behaviour.

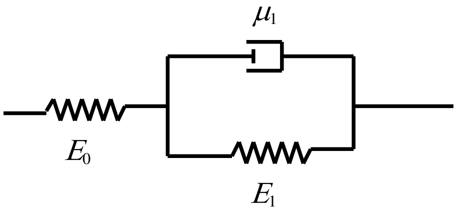

Figure 1. A one-element Kelvin-Voigt mechanical viscoelastic model

The compliance of the creep deformation spring, $J_1=1/E_1$, and the retardation time of the dashpot, $\tau_1 = \mu_1/E_1$, are the parameters needed for each Kelvin-Voigt spring and dashpot element to be included.

Stephens (2007) has shown that a spatial zoned approach is required to model the uncertainties within the pipeline and that through use of this approach it is possible to determine the size and position of artificially created discrete blockages and leaks.

A zone viscoelastic ITA procedure has the potential to account for the material property change of extended blockages leading to the detection of distributed faults in pipelines. In this paper an approach is presented whereby an extended blockage is modeled not through a reduction in diameter and equivalent losses as per Stephens et al. (2005), but as a viscoelastic section of pipeline. ITA is used to calibrate the viscoelastic parameters of each zone within the pipeline to determine which section differs more significantly from the expected parameters of the pipeline and thus has the greater potential for distributed faults.

2 FIELD TESTING ON WATER DISTRIBUTION SYSTEM

2.1 Location

Field tests have been conducted on the Adelaide Metropolitan Water Distribution System. Discussions with the operator of the system, United Water International, identified the potential for unlined Cast Iron pipes of 80 mm nominal diameter to become affected by extended blockages. Previous investigations using transient response techniques of an 80 mm diameter Cast Iron Cement Lined (CICL) pipeline in the suburb of Parkside have been undertaken by Stephens et al. (2005), leading to the replacement of a section of pipeline due to the presence of extended blockages. A street parallel to that testing location, of appropriate material and diameter, was selected for the tests described in this paper. The testing location selected was a

478m long section of Leicester St, Parkside between George St and Castle St as shown in Figure 2. The unlined Cast Iron pipeline of 80 mm nominal diameter was constructed in 1932. The boundary of the section consists of junctions with pipelines of similar diameter and the section of pipe can be isolated from the remainder of the system through the use of existing valves. There exist seven fireplugs along the street.

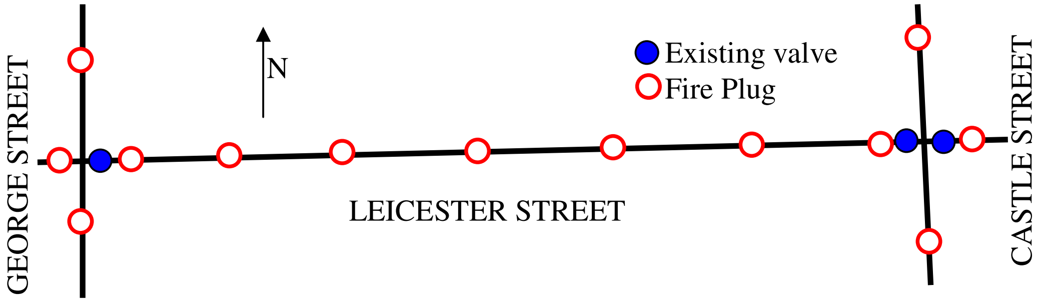

Figure 2. Plan of testing location

2.2 Transient Generation and Measurement

The pipeline in Leicester Street was isolated from the system through the closure of the existing valve at the Castle St end of the section. Synchronized pressure measurement at several locations (M1, M2, GEN) was possible through the use of the data acquisition system consisting of a 16 bit A/D converter sampling at 2000 Hz, a 1000 Hz low pass filter and GPS (Global Positioning System) time synchronization at each pressure transducer measurement station. Druck 810 pressure transducers (15 bar) were connected to the system through the use of existing fireplugs, the locations of which are shown in Figure 3.

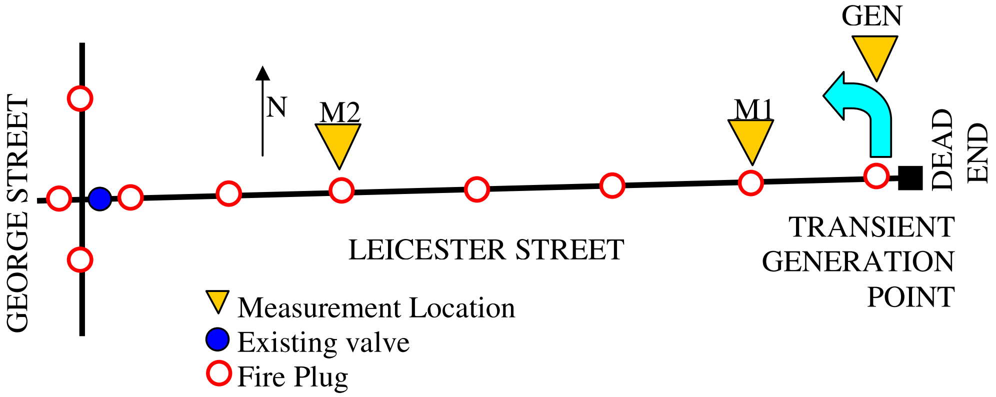

Figure 3. Testing Configuration

Controlled hydraulic transients were generated by the fast closure or opening of a 50 mm valve mounted on a 55 mm diameter 1.8 m high standpipe as shown in Figure 4. A custom-built quick release torsional spring device was used to close the valve with a closing time of 5 ms. In order to avoid large transients a 6 mm nozzle with smooth taper was connected to the ball valve.

Figure 4. Torsional Spring Transient Generator

Several repeats of the tests were conducted to ensure consistency of the results and that customer induced transients from within the street and the remainder of the system did not interfere with the measured response.

2.3 Measured Transient Response

The measured transient response was complicated in nature and differed significantly from the expected response for all measured responses as shown in Figure 5 to Figure 7. The expected response was based on a numerical transient model based on a Method of Characteristics (MOC) model with the boundary consisting of the remainder of the system represented by a reservoir. The reservoir water level determined such that the steady state pressure head of station M2 was as measured. Due to this representation modeling is limited to the time taken for the transient to travel from the transient generation point to the boundary at George St and back to the measurement location. If more than one measurement is used at once the shortest time is used.

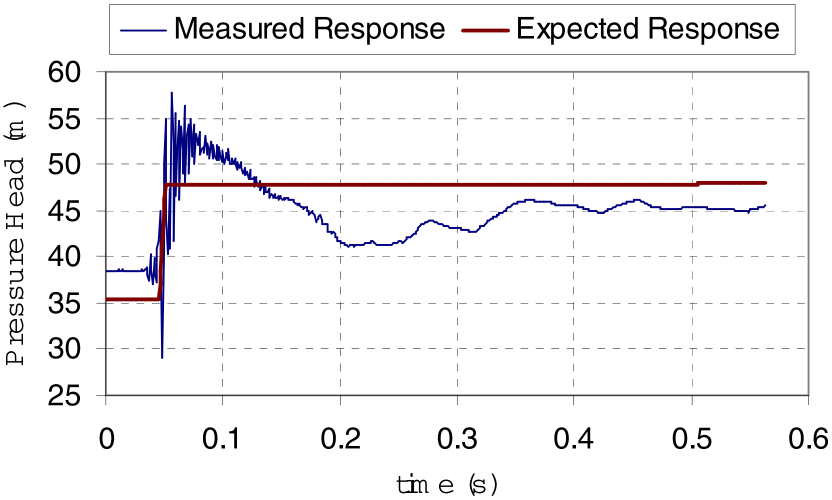

Figure 5. Measured and expected transient response (MOC) at generation station

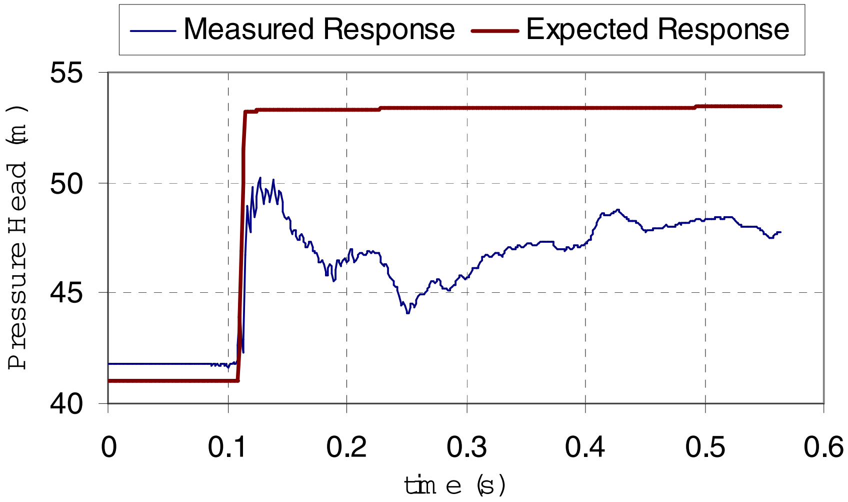

Figure 6. Measured and expected transient response at station M1

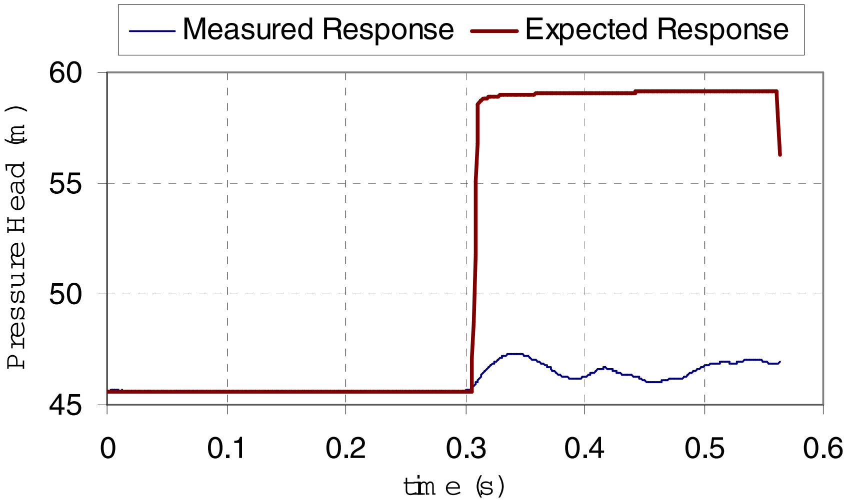

Figure 7. Measured and expected transient response at station M2

The initial high frequency oscillation in the generation station measured response (Figure 5) is due to oscillation in the generator standpipe and the location of the transducer, which was part way up the standpipe.

Significant head loss along the pipe is apparent due to the attenuation of the pressure rise from the transient generation point to station M2 and the difference between the measured and expected steady state pressures. This head loss is suspected to be due to a distributed blockage as was found by Stephens et al. (2005) in the parallel street of Foster Street. Faults within the pipeline are also apparent due to the difference in shape of the generation station and M1 responses. If no faults are present these responses should follow the same basic shape until reflections occur off the open boundary.

3 APPLICATION OF ITA WITH VISCOELASTIC ZONES

3.1 Inverse Solver

Inverse Transient Analysis was undertaken through the of use of the NLFIT Bayesian non-linear regression program developed by Kuczera (1994). The search algorithm implemented from the options within the program was the Shuffled Complex Evolution – University of Arizona (SCE-UA) global algorithm.

The number of calibration parameters is dependent on the number of spatial zones, with each zone requiring a Kelvin-Voigt element and hence the creep deformation spring compliance (J) and dashpot retardation time (τ) parameter of that element.

Viscoelastic elements have the potential to match the pattern of the transient response of the pipeline but are unable to account for the steady state losses along the pipe. A steady state pressure match is required for accurate inverse analysis, and thus a method must be employed to replicate the steady state pressures. There are several means by which this could be achieved, one of which is the incorporation of higher frictional losses along the pipe. However the distribution of the blockages and hence the distribution of the high frictional losses is unknown, thus another means was required. Since the focus was on the shape of the transient response rather than the pressure loss, the steady state pressure match was achieved through the initial calibration of the elevation of the measurement stations. Improvements to the methodology to incorporate the steady state pressure match are currently under investigation.

3.2 Single Zone Calibration

Naturally occurring deterioration of the pipeline was under investigation in this research and thus it was not possible to obtain a fault free data set during the field-testing. Hence it was not possible to calibrate the viscoelastic parameters required to account for physical uncertainties as undertaken by Stephens (2007) and thus the viscoelastic parameters calibrated in the following sections take into account both the deterioration of the pipeline and the physical uncertainties.

The pipeline was laid during a single construction period, is of one material and joint type and has a relatively consistent numbers of consumers along its length. Hence it is assumed that any large variation in viscoelastic parameters along the pipeline is mainly due to deterioration of the pipeline and not physical uncertainties.

To ensure that consistent viscoelastic parameters could not account for all of the variation of the measured response from the expected response, calibration assuming the entire pipeline was within a single zone was initially undertaken. ITA was performed on the transient generation point and station M1 measured transient responses.

The resultant parameters from the ITA were a creep deformation spring compliance, $J = 1.086 \times 10^{-10}$, and dashpot retardation time, $\tau = 0.210$ s, which represents a modulus of elasticity of the creep deformation spring, $E_1 = 9.21$ GPa and viscosity of the dashpot $\mu_1 = 1.93$ GPa·s. Comparisons of the modeled and measured responses at the generation station and first closest measurement station (M1) are shown in Figure 8 and Figure 9 respectively.

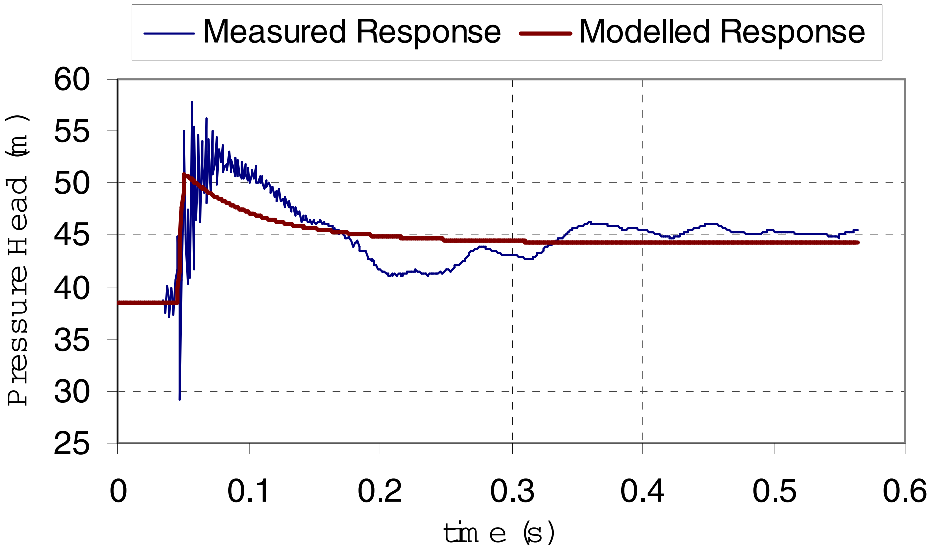

Figure 8. Single Zone Calibration comparison generation station

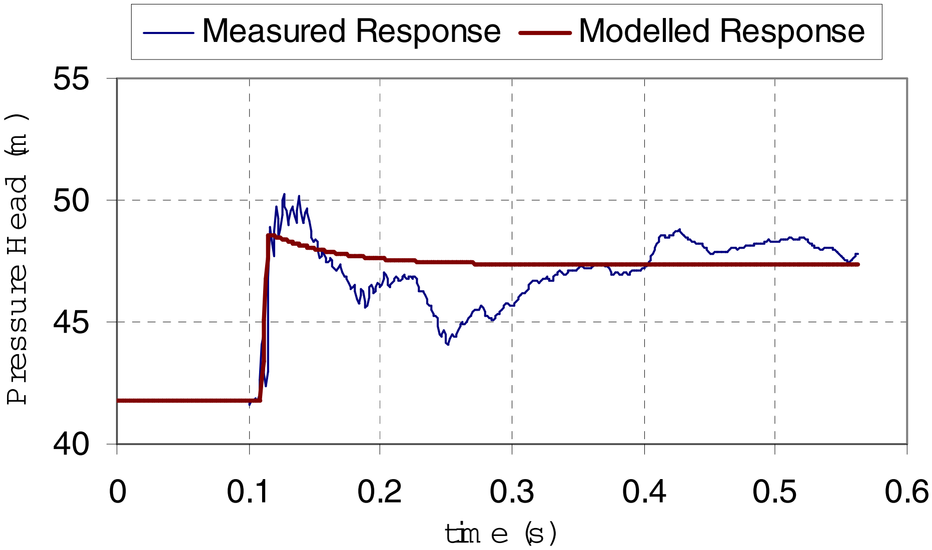

Figure 9. Single Zone Calibration comparison station M1

Based on the plots, a single viscoelastic parameter for the entire pipeline is clearly incapable of representing the variation of the measured responses. A zoned approach is used in the following sections.

3.3 Six Zone Calibration (6ZC)

For the first zone calibration the section under investigation was split into six zones defined by the location of the fireplugs as shown in Figure 10. Each zone was assumed to be governed by a single Kelvin-Voigt element.

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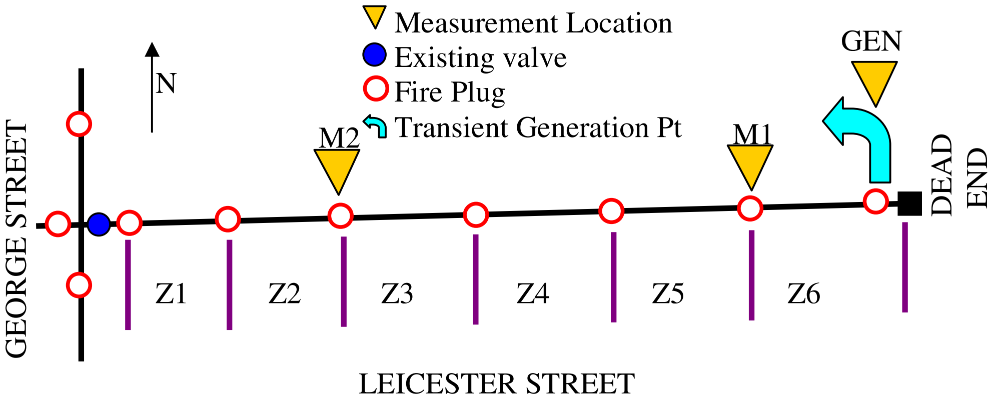

Figure 10. Six Zone Calibration layout

ITA was undertaken on each zone individually to identify the pair of *J* and τ parameters that resulted in the lowest objective function, in other words the best fit to the measured data. The measured responses at the generation point and station M1 were used and the objective function and associated viscoelastic parameter for each zone are shown in Table 1. A comparison of the measured data and the six zone model with the viscoelastic element in zone six with the calibrated data is shown in Figure 11 and Figure 12 for the generation station and M1 respectively.

Table 1. Parameters by Zone for 6ZC

Zone	Objective Function	*J* (Pa^{-1})	τ (s)
1	4.29	2.47E-10	0.54
2	3.82	6.95E-10	0.05
3	3.00	1.49E-10	0.05
4	1.86	1.26E-10	0.05
5	0.14	2.77E-10	0.05
6	0.09	5.95E-10	0.65

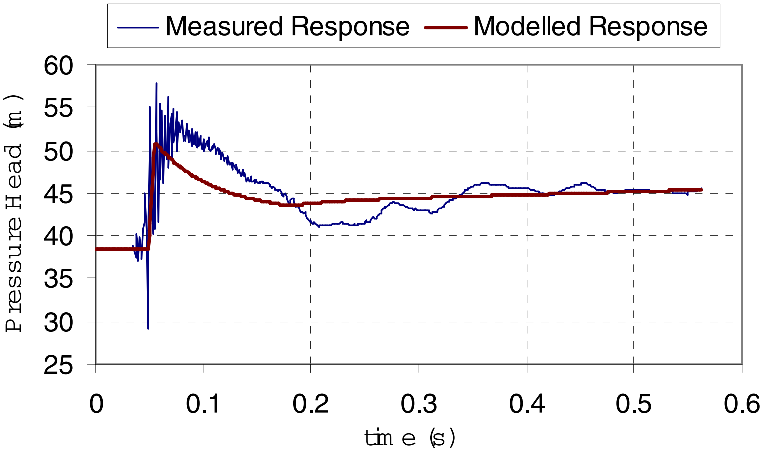

Figure 11. 6ZC comparison at generation station for Zone 6 parameters

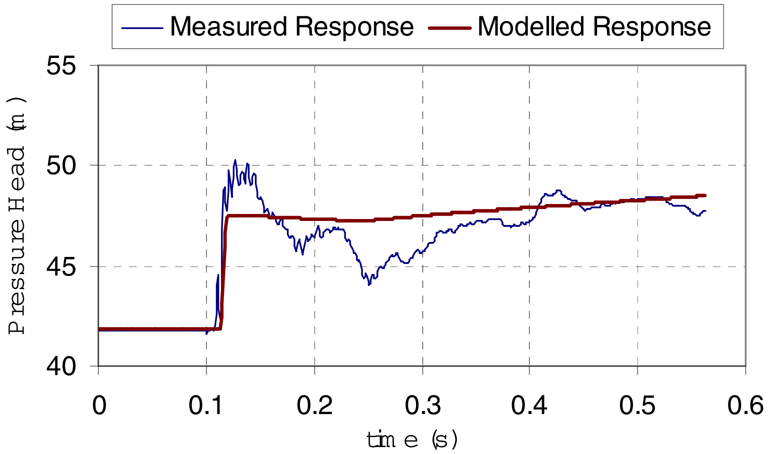

Figure 12. 6ZC comparison at station M1 for Zone 6 parameters

While this model was an improvement on the initially expected results and the single zone calibration, the calibrated parameters did not account for all of the exhibited transient behavior. The zone-by-zone procedure was repeated with the parameters of zone 6 set to determine which other zone had a significant influence on the transient behavior. The calibrated parameters and associated objective function are shown in Table 2. The comparison of modeled and measured data for these cases for the generation station and station M1 are shown in Figure 13 and Figure 14 respectively.

Table 2. Parameters by zone for 6ZC with zone 6 parameters set

Zone	Objective Function	J (Pa^{-1})	τ (s)
1	0.529	2.02E-09	0.32
2	0.527	1.76E-10	0.65
3	0.529	1.60E-11	0.65
4	0.528	6.12E-12	0.05
5	0.481	3.29E-11	0.05

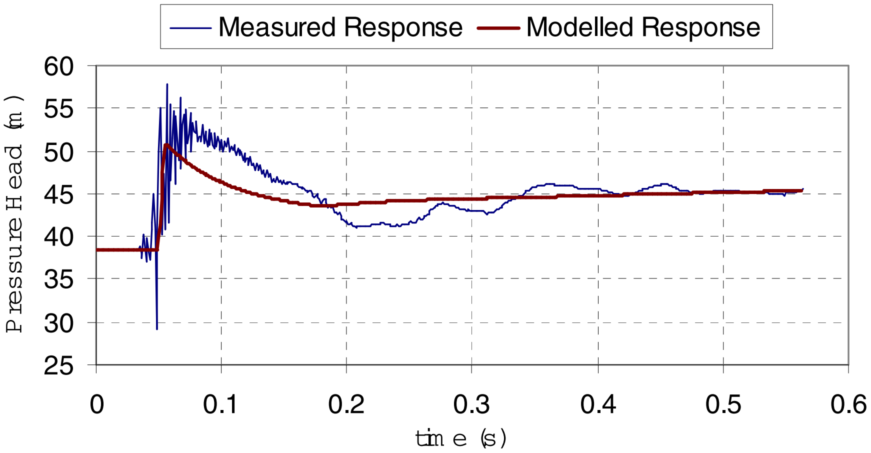

Figure 13. 6ZC comparison at generation station for Zone 6 and 5 parameters

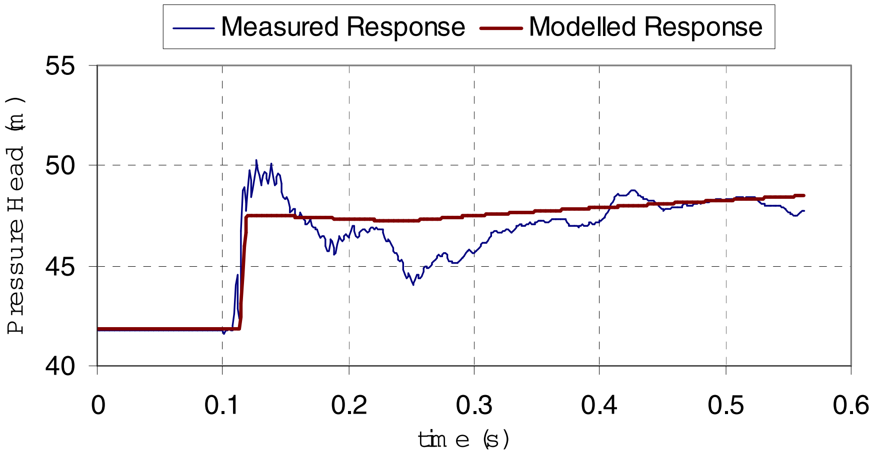

Figure 14. 6ZC comparison at station M1 for Zone 6 and 5 parameters

Further ITA for subsequent zones did not result in a significant improvement in the objective function, thus it is concluded that zones 5 and 6 had the largest influence on the transient behaviour, which was partially expected due to the proximity of the measurement stations to these zones. These zones became the focus of the subsequent analysis.

3.4 Nine Zone Calibration (9ZC)

Focusing on the previous zones 5 and 6 the pipeline was divided into nine zones as shown in Figure 15. The time over which ITA was applied was reduced, to the time taken for the hydraulic transient to travel to the generator to the western boundary of zone 2 and back to station M1, in order to focus on the area under investigation.

The aim was to determine if there exists variation within this area that may be due to the presence of extended blockages or other pipeline deterioration.

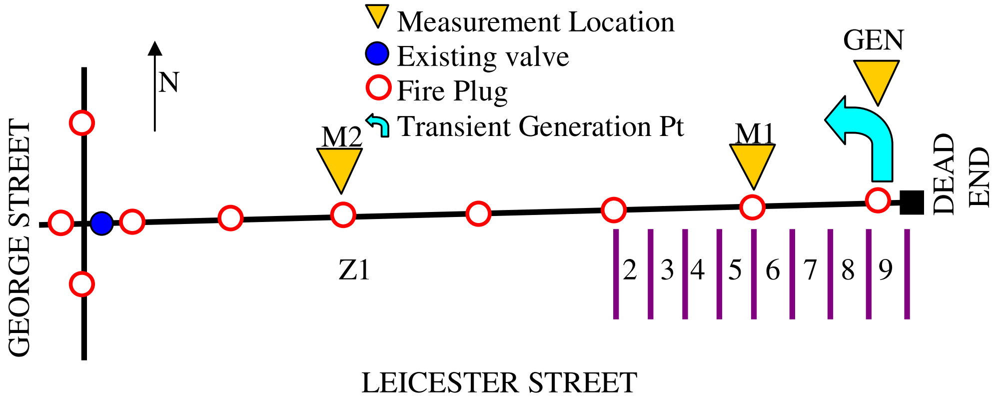

Figure 15. Nine Zone Calibration layout

A zone-by-zone approach was again applied based on the objective function and calibrated parameter values for iterations 1 to 3 are shown in Table 3 to Table 5. Zone 6 corresponding to the zone directly after the M1 measurement station was found to give the lowest objective function. After setting the parameters for that zone, further improvement was found through the influence of zone 7, which was likewise followed by zone 4. After this analysis the objective function did not differ significantly from the previous iteration. A comparison of the modeled results based on these parameters and the measured data is shown in Figure 16 and Figure 17 for the generation station and M1 respectively.

Table 3. Parameters by Zone for 9ZC

Zone	Objective Function	J (Pa^{-1})	τ (s)
1	2.04	2.92E-09	0.10
2	1.75	5.00E-09	0.17
3	1.44	1.24E-09	0.05
4	0.85	5.30E-10	0.05
5	0.46	2.29E-09	0.65
6	0.30	1.67E-09	0.65
7	0.41	1.31E-09	0.65
8	0.55	1.17E-09	0.65
9	0.68	1.24E-09	0.65

Table 4. Parameters by Zone for 9ZC with Zone 6 set

Zone	Objective Function	J (Pa^{-1})	τ (s)
1	0.296	1.79E-09	0.06
2	0.289	1.39E-10	0.05
3	0.258	3.07E-10	0.05
4	0.259	9.95E-10	0.65
5	0.288	2.79E-10	0.65
6	-	-	-
7	0.245	4.25E-11	0.05
8	0.246	1.08E-10	0.26
9	0.256	1.85E-01	0.65

Table 5. Parameters by Zone for 9ZC with Zone 6 and 7 set

Zone	Objective Function	J (Pa^{-1})	τ (s)
1	0.244	1.79E-09	0.06
2	0.237	1.76E-09	0.65
3	0.221	2.49E-10	0.05
4	0.202	1.00E-09	0.46
5	0.231	4.22E-10	0.65
6	-	-	-
7	-	-	-
8	0.236	1.23E-11	0.05
9	0.239	1.16E-11	0.08

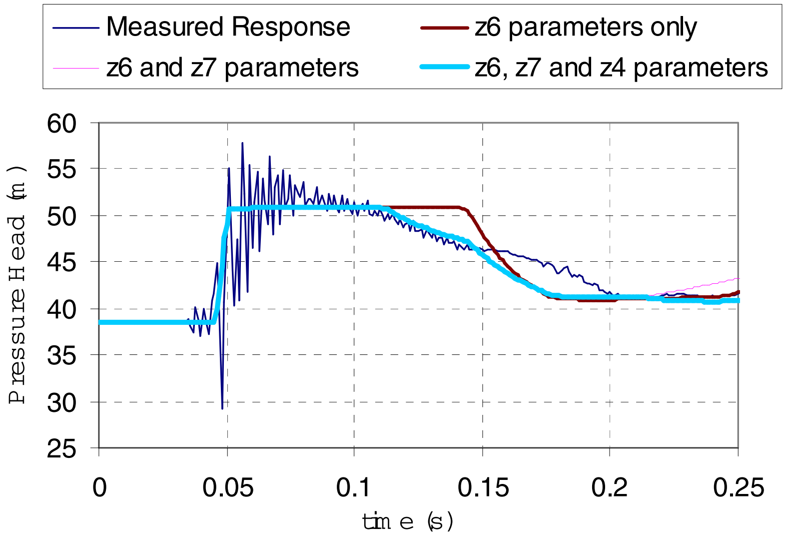

Figure 16. 9ZC comparison at the generation station for calibrated parameters

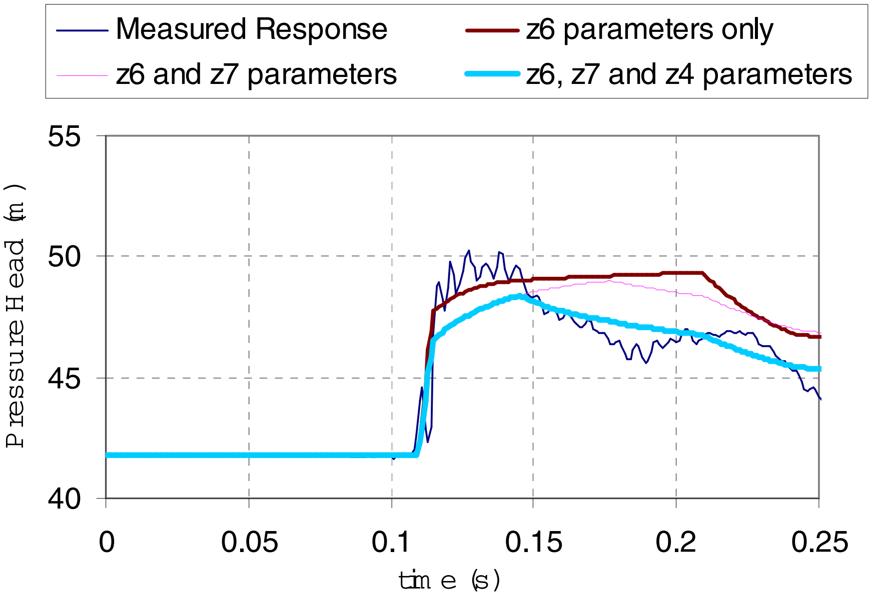

Figure 17. 9ZC comparison at station M1 for calibrated parameters

The Nine Zone Calibration focused at the eastern/generator end of the pipeline represents an improvement in the fit between the measured data and the model. The calibration parameters and the associated modulus of elasticity of the creep deformation spring, E_1, and viscosity of the dashpot, μ_1 are shown in Table 6.

Table 6. Best fit parameters for 9ZC

Zone	J (Pa^{-1})	τ (s)	E_1 (GPa)	μ_1 (GPa·s)
6	1.67E-09	0.65	0.60	0.39
7	4.25E-11	0.05	23.52	1.18
4	1.00E-09	0.46	1.00	0.46

These results indicate that the sections of pipeline designated as zones 6, 7 and 4 are responsible for the deviation of the measured responses from the initial expected results and that viscoelastic elements are capable of capturing the dynamics exhibited.

3.5 Two Phase Nine Zone Calibration (2P9ZC)

A two-phase process was also applied whereby zones 6 to 9 were calibrated solely based on the generator station response for the time taken for the transient to travel from the generator to station M1 and back. The second phase involved the calibration of zones 1 to 5 based on the generator station response and the response from station M1. The parameters for Phase 1, calibration of zones 6 to 9 is shown in Table 7. The continuation of this phase to further zones did not result in a significant reduction in the objective function.

Table 7. Parameters by Zone for Phase 1 of 2P9ZC

Zone	Objective Function	*J* (Pa^{-1})	τ (s)
6	0.19	1.15E-10	0.05
7	0.14	5.87E-10	0.65
8	0.18	3.41E-10	0.65
9	0.22	2.46E-10	0.65

Phase 2 involved the calibration of zones 1 to 5 with the parameters of zone 7 set from phase 1. Zone 5 was found to have the greatest influence on the objective function as shown in Table 8. Further zones did not result in a significant reduction in the objective function. The comparisons of the 2P9ZC calibrated model at each stage and the measured response at the generation station and M1 are shown in Figure 18 and Figure 19.

Table 8. Parameters by Zone for Phase 2 of 2P9ZC

Zone	Objective Function	*J* (Pa^{-1})	τ (s)
1	0.67	2.92E-09	0.10
2	0.61	3.39E-10	0.05
3	0.55	2.99E-10	0.05
4	0.29	3.51E-10	0.05
5	0.18	1.62E-09	0.65

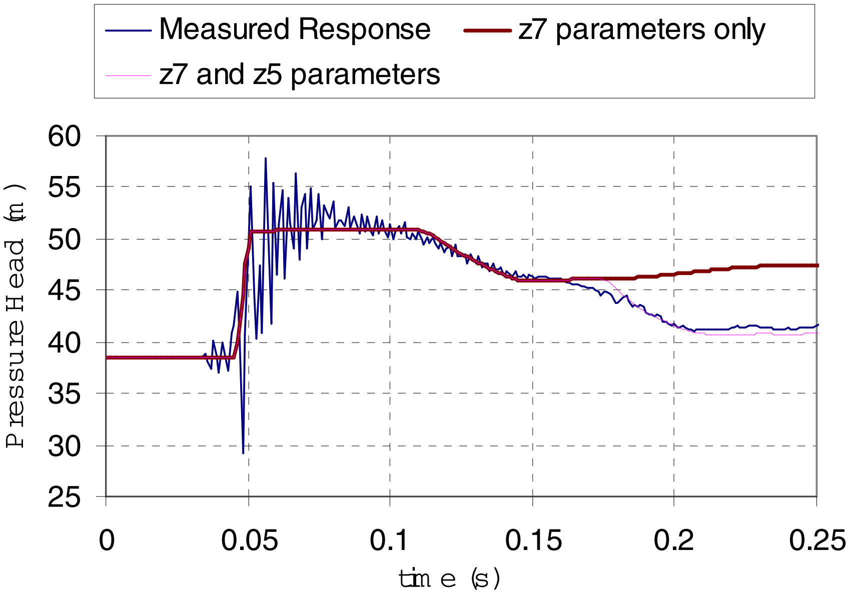

Figure 18. 2P9ZC comparison at generation station for calibrated parameters

Figure 19. 2P9Z Comparison at generation station for calibrated parameters

The Two Phase Nine Zone Calibration represents an improvement over the single phase Nine Zone Calibration. The calibration parameters and the associated modulus of elasticity of the creep deformation spring, E_1, and viscosity of the dashpot, μ_1 are shown in Table 9. As with the single phase Nine Zone Calibration zone 7 has again been identified as a zone that influences the transient behavior. However, the two-phase approach found zone 5 as the other greatest influence as opposed to the previous result of zones 4 and 6.

Table 9. Best fit parameters for 2P9ZC

Zone	J (Pa^{-1})	τ (s)	E_1 (GPa)	μ_1 (GPa·s)
7	5.87E-10	0.65	1.70	1.11
5	1.62E-09	0.65	0.62	0.40

The generation station is more closely matched to the measured data by the two phase calibrated parameters as shown in Figure 18. However the measurement at station M1 still differs significantly, this may be due to the discretisation of the zones. In the nine zone calibrations zones 2 to 9 are approximately 20m in length, a finer discretisation may be required to capture the behaviour of the transient recorded at this station.

4 CONCLUSION

Field tests in the Adelaide Metropolitan Water Distribution System of an 80 mm Cast Iron pipeline yielded a complicated transient response. The pipeline exhibited significant headloss along its length and changes to the shape of the response between measurement stations indicated the presence of faults. Due to previous experience with pipelines in the area of similar material, age and diameter it was assumed that the pipeline contained distributed faults, namely blockages.

Viscoelastic parameters were identified as an alternate means by which extended blockages could be incorporated into an ITA model to allow their identification. A single, consistent set of viscoelastic parameters for the entire pipeline was found not to be sufficient to model the transient behavior and a zone approach was applied.

Approximately equally distributed zones along the entire length of the pipeline were also found to be insufficient, due to the condition of the pipeline and hence the deterioration of the transient response. However the zones surrounding the measurement stations used for ITA were identified by the six-zone approach as those who matched more closely the recorded data when viscoelastic elements were applied to those zones.

Further investigation of this section through discretisation of each of these zones into four sub sections allowed a closer match to be obtained. An improvement to the nine-zone calibration through using only the generation station as the basis for zone 6 to 9 produced a further improvement. With the match for the generation station improving, although the M1 response still differed. A further discretisation of the zones may improve this match.

ITA has identified zones that required viscoelastic parameters in order to match the measured responses, and hence it can be assumed that these zones contain a fault or are of deteriorated condition. This assumption is based on the fact that the need for these parameters indicates that those sections differed significantly from the remainder of the pipeline. Further investigation of the parameters and their significance is required including the viscoelastic properties of blockage materials. CCTV or visual inspection of the interior of the pipeline to confirm that the zones identified are of deteriorated condition or blocked is also required.

For a pipeline of deteriorated condition such as the one investigated here it is recommended to generate transients at all possible locations along the pipeline to record the necessary data to determine the condition of the entire length of pipeline. More data and further discretisation of the pipeline into additional zones will give a clearer understanding of the variation of pipeline condition along the entire length and the potential presence of distributed faults such as blockages.

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