Accepted version

Mark Stephens, Martin F. Lambert, Angus R. Simpson, John P. Vtkovsk and John B. Nixon

Using field measured transient responses in a water distribution system to assess valve status and network topology

Impacts of global climate change [electronic resource] : proceedings of the 2005 World Water and Environmental Resources Congress, May 15-19, 2005, Anchorage, Alaska / sponsored by Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers ; Raymond Walton (ed.): CDROM, pp.1-12

http://doi.org/10.1061/40792(173)54

Using field measured transient responses in a water distribution system to assess valve status and network topology

by

Stephens, M., Lambert, M.F., Simpson, A.R., Vítkovský, J.P. and Nixon, J.B.

7th Annual Symposium on Water Distribution Systems Analysis

Citation:
Stephens, M., Lambert, M.F., Simpson, A.R., Vítkovský, J.P. and Nixon, J.B. (2005). "Using field measured transient responses in a water distribution system to assess valve status and network topology", *7th Annual Symposium on Water Distribution Systems Analysis*, American Society of Civil Engineers, Anchorage, Alaska, USA, 15-19 May.

Using field measured transient responses in a water distribution system to assess valve status and network topology

Mark Stephens[1], Martin F. Lambert[1], Angus R. Simpson[1], John P. Vítkovský[1] and John B. Nixon[2]

[1] School of Civil and Environmental Engineering, University of Adelaide, South Australia 5005, Australia; PH +61 8 8303 5135; FAX +61 8 8303 4359;
email : mstephen@civeng.adelaide.edu.au
[2] Research and Development, United Water International Pty Ltd, Adelaide, GPO Box 1875, South Australia 5001, Australia; PH +61 8 8301 2834; FAX +61 8 8357 9728; email : john.nixon@uwi.com.au

1 ABSTRACT

Uncertainty about the status of valves in a water distribution system, or the existence of total blockages, is not uncommon. This paper presents an approach for determining topological changes using transient response analysis. Precise information is not available regarding all the physical elements contributing to the transient response of a water distribution system. Thus a parameterised model is developed and calibrated to represent "real" transient responses from a field water distribution system. The robustness of this model, and the methodology for diagnosing topological changes, are confirmed when used to successfully identify closed valves in the field.

2 INTRODUCTION

The use of the transient response of a water distribution system (WDS) to diagnose potential faults (sometimes referred to as "Inverse Transient Analysis (ITA)) was first proposed for leak detection by Liggett and Chen (1994). However, the potential for transient response analysis (or ITA) to be used to identify a particular fault in a water distribution system (WDS) is governed by the accuracy of the forward transient model.

This paper outlines the development of a forward transient model capable of including some aspects of the complexity that is faced in a "real" WDS. The forward transient model is parameterised, allowing calibration to measured responses, using a two parameter viscoelastic mechanism. Once an accurate parameterised model has been developed, it is used to determine which valves have been closed in a "real" WDS. It is shown that closed valves, or changes in the connectivity of pipelines (possibly due to complete blockage), represent an operational uncertainty that can be assessed using transient response analysis.

3 THE WILLUNGA NETWORK

The WDS used for the field testing is located in the township of Willunga, South Australia. The Willunga Network (WN) was selected because of its relatively small size, single gravity supply tank, uniformity of pipe material (asbestos cement (AC)) and the possibility of controlling the level of demand. The basic layout and details of the WN are shown in Figure 1 :

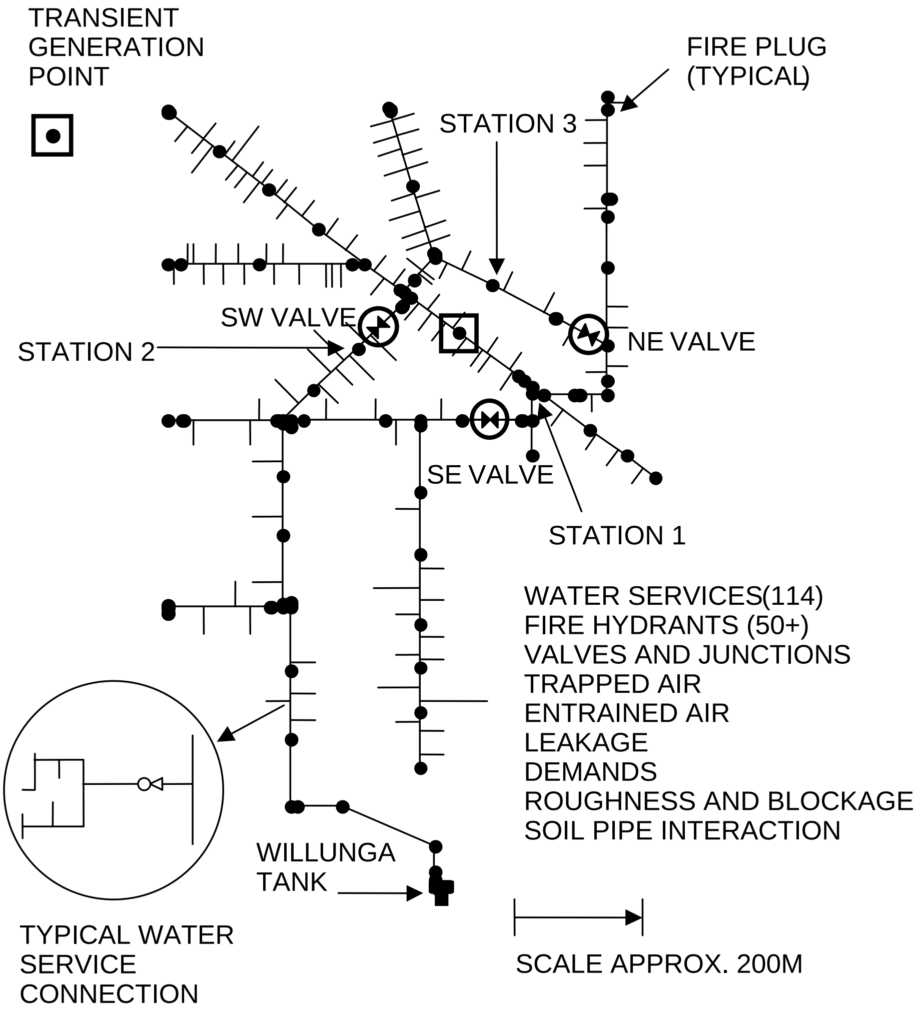

Figure 1 – Layout and details of the Willunga Network (WN)

3.1 Testing methodology

Controlled transients were generated at the “transient generation point” (as shown in Figure 1) by closing a small ball valve (15 mm) located on the end of a 1.8 m high “standpipe”, which in turn was mounted on an existing fire plug. Valve closures could be performed using a “torsional spring” device or manually. The speed of the valve closures was measured directly using a potentiometer. Further information on the method of generation can be obtained from Stephens et al. (2004).

The transient response of the WN was measured at Stations 1, 2 and 3 (as also shown in Figure 1). Rapid response pressure transducers were installed in existing fireplugs at these three locations and pressure response data was recorded at 500Hz.

3.2 Summary of controlled transient tests performed

This paper will examine 6 tests, performed on the 30th July 2003 between 12.00 midnight and 4.30 am), as detailed in Table 1 :

Table 1 – Summary of controlled transient tests

Test	Valve Closure Speed	Generation Method	WN Configuration	Time of Test	Test Purpose
1	4 ms	Torsion Spring	All Valves Open	12.45 am	Calibration
2	190 ms	Manual	All Valves Open	12.55 am	Calibration
3*	340 ms	Manual	All Valves Open	1.00 am	Calibration
4	4 ms	Torsion Spring	SE Valve Closed	1.15 am	Valve Status
5*	4 ms	Torsion Spring	NE Valve Closed	1.50 am	Valve Status
6*	4 ms	Torsion Spring	SW Valve Closed	3.00 am	Valve Status

* Plots of these results are not presented in this paper

4 PROBLEMS WITH TRANSIENT MODELLING IN FIELD SYSTEMS

4.1 Sources of transient model error

There have been very few field studies verifying the transient models used to analyse WDSs. McInnis and Karney (1995) tested a Canadian WDS (called the “Bearspaw System”) spanning approximately 10 kms. The authors focused, in particular, on the effects of model skeletonisation and demands on measured transient responses. They developed a physically simplified (skeletonised) model and used demand and steady-state friction factor calibration to achieve the best matches possible to measured responses.

The authors concluded that their calibrated model could match the initial surge following the transient event but that it thereafter lost accuracy. They pointed to a number of elements in WDSs, apart from demands and friction factors, that could account for the large amount of damping and dispersion apparent in the measured responses (see Section 4.4 for a summary of these elements).

4.2 Development of a network transient model for the Willunga Network

By focusing on the WN (a WDS approximately one tenth the size of the "Bearspaw System"), system skeletonisation has been avoided with respect to all of the main pipes (i.e., pipes over 100 mm in diameter). Three separate discretisations of 20, 40 and 80 m have been implemented in a traditional forward transient model without the loss of any significant accuracy in the representation of the true length of pipes or the position of junctions or other elements (including fireplugs). However, the non-inclusion of 114 water service connections (20 to 25 mm) represents a similar skeletonisation problem (although on a smaller scale) to that faced by McInnis and Karney (1995). It is not practical to include these water services and their influence upon the energy dissipation within the WN is unknown.

The traditional transient model used by McInnis and Karney (1995) only includes a quasi-steady friction approximation (i.e., no unsteady friction effects). It is based on the usual waterhammer equations as stated in Section 5.1 (without any viscoelastic component).

4.3 Elimination of sources of energy dissipation

Again, by focusing on the WN a number of sources of energy dissipation have been controlled, as detailed in the following sub-sections :

4.3.1 Trapped and entrained air

The presence of trapped or entrained air can cause an apparent slowing of the wave speed in a WDS. Furthermore, transient wavefronts disperse in the presence of entrained air. Fireplugs were known to be a common point at which trapped air could accumulate in the WN. Consequently, all fire hydrant plugs were flushed prior to the tests. The effect of even a small air pocket (less than 0.5 litres) is distinctive in a WDS the size of the WN. After testing, examination of the recorded transient responses did not suggest the presence of any significant pockets of trapped air.

Because the wavefronts for the 4 ms tests were very sharp an accurate estimate of the travel times to each of the 3 measurement stations could be made for a number of tests. The wave speed varied between 1040 and 1150 m/s with a mean of 1100 m/s. This mean is approximately equal to the theoretical wave speed of 1110 m/s for 4 inch (100 mm) diameter AC pipes (the predominant size of pipe in the WN). This, coupled with a lack of wavefront dispersion, suggested there was little entrained air.

4.3.2 Demands and leakage

To attempt to reduce the impact of demands the testing was conducted during the night (from approximately 12.00 midnight to 4.30 am) and in mid-winter. Furthermore, notices were issued to all water users served by the WN asking them to refrain (if possible) from using water between the abovementioned hours.

A number of “listening” tests were performed throughout the test period to gauge the general transient activity in the WN. These showed no activity except on one occasion when two discrete demands could be identified in time. It was suspected that these were either toilet flushes or tap openings. Both were of short duration (taking less than 5 s to dissipate) and were of an order of magnitude less than the controlled transients used to test the WN.

The WN is supplied from a single tank that has water level telemetry recorded at 0.5 hr intervals. By combining knowledge of the volumes that were used during the tests with the telemetry data the background demand / leakage was estimated to be approximately 0.8 L/s. This quantity was included in the modelling.

4.4 Discrepancies between the traditional model and measurements

Figures 2 and 3 show typical discrepancies between the results from a traditional transient model of the WN and the measured responses. There is insufficient energy dissipation and the phase is incorrectly modelled over longer time periods (as shown in Figure 3). Only the initial surges are modelled correctly. This result is consistent with the observations of McInnis and Karney (1995) for the “Bearspaw System” as modelled prior to any calibration.

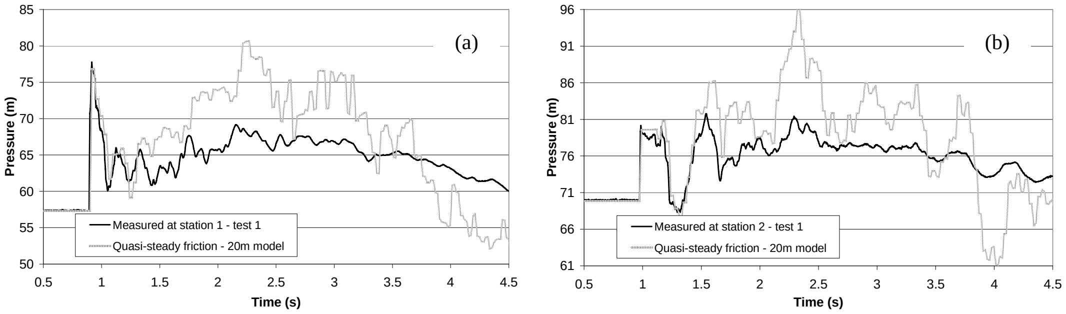

Figure 2 (a) and (b) – Comparisons of traditional transient model with measured responses (stations 1 and 2) over a 4 s time base for test 1 (4 ms event)

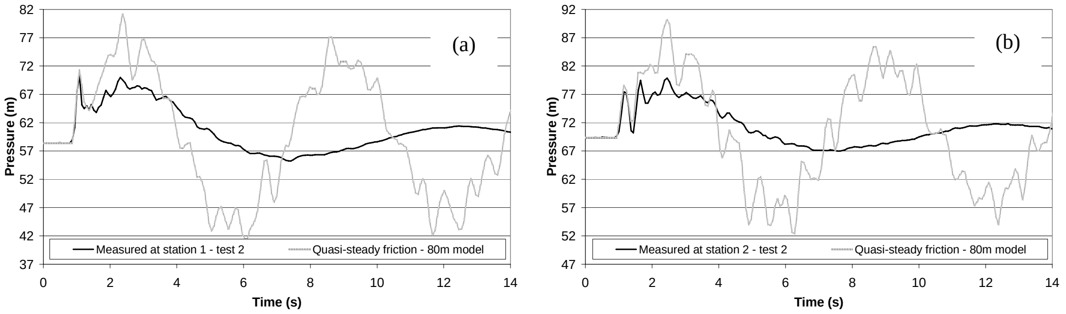

Figure 3 (a) and (b) – Comparisons of traditional transient model with measured responses (stations 1 and 2) over a 14 s time base for test 2 (340 ms event)

While some sources of energy dissipation may have been reduced, other uncertainties remain. Many of these uncertainties include effects from :

- pre-existing partial blockages
- junction losses
- flexible pipeline “rubber ring joints” at regular spacings
- hysteresis effects in the elastic behaviour of pipe walls and confining soils
- inadequacies in the data skeletonisation process

5 A PARAMETERISED TRANSIENT MODEL

5.1 A viscoelastic damping and dispersion mechanism

5.1.1 Justification for transient model parameterisation

A parameterised model, capable of replicating measured responses, is required to account for the uncertainties inherent in WDSs. McInnis and Karney (1995) used demand and friction factor calibration, as a form of parameterised model, to allow for unrelated energy dissipation mechanisms. In the case of the WN, the use of demand and friction factor calibration was unable to represent the energy dissipation in the measured responses without the use of highly unrealistic parameter values. Even then, the match to the phase of the transient was poor.

Unsteady friction and viscoelastic models have damping and dispersion mechanisms capable of forming the foundation of an appropriately parameterised model. Such mechanisms can facilitate a match between a measured transient response and that predicted by the parameterised model (even when the true sources of the damping and dispersion are unknown). Investigation into model parameterisations revealed that the inclusion of a viscoelastic mechanism, combined with non-parameterised unsteady friction, gave the best match between predicted and measured transient responses.

5.1.2 Implementation of a viscoelastic mechanism

A viscoelastic mechanism (normally exclusively associated with polyethylene pipes) can be introduced through the fundamental continuity equation :

$$\frac{dH}{dt} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} + \frac{2a^2}{g}\frac{d\varepsilon_r}{dt} = 0 \qquad (1)$$

The third term in Equation (1) includes a retarded strain effect in the pipe wall. The differential equations of continuity (including a viscoelastic effect) and momentum can be simplified in the usual manner using the Method of Characteristics (MOC) :

$$\frac{dH}{dt} \pm \frac{a}{gA}\frac{dQ}{dt} \pm ah_f + \frac{2a^2}{g}\left(\frac{\partial \varepsilon_r}{\partial t}\right) = 0 \tag{2}$$

Equation (2) can then be solved numerically using :

$$\begin{aligned}&[H(x,t) - H(x \mp \Delta x, t - \Delta t)] \pm \frac{a}{gA}[Q(x,t) - Q(x \mp \Delta x, t - \Delta t)] \pm \\ &a\Delta t h_f + \frac{2a^2 \Delta t}{g}\left(\frac{\partial \varepsilon_r}{\partial t}\right) = 0\end{aligned} \tag{3}$$

The only differences between this numerical scheme and the one used for traditional transient analysis are the inclusion of unsteady friction and a viscoelastic mechanism through the third and fourth terms in Equation (3) respectively.

The calculation of the rate of change of retarded strain in the fourth term of Equation (3) requires a mechanical model representing the creep behaviour of a viscoelastic material. A Kelvin-Voigt model is typically applied as shown in Figure 4 :

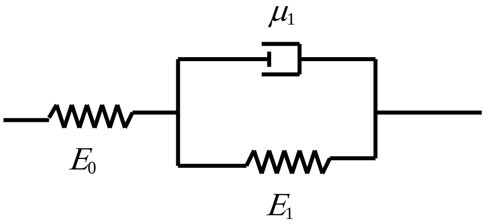

Figure 4 – A one-element Kelvin-Voigt mechanical viscoelastic model

where E_0 is the elastic modulus of the pipe wall (with $J_0=1/E_0$) and E_1 the modulus of elasticity of the spring (creep deformation) element. The viscosity of the dashpot element μ_1 represents the viscous creep behaviour. Further parameters J_1 and τ_1 are defined as $J_1=1/E_1$ (the creep compliance of the spring element) and $\tau_1= \mu_1/E_1$ (the retardation time of the dashpot element). These later two elements appear in an expression describing the creep function for the pipe wall :

$$J(t) = J_0 + J_1(1 - e^{-t/\tau_1}) \tag{4}$$

As shown in Figure 4, a one element Kelvin-Voigt model is used comprising a single spring and dashpot element. The evaluation of the rate of change of strain in a pipe wall, as required for the calculation of the fourth term in Equation (3), can now be performed using equations presented by Covas et al. (2005) :

$$\varepsilon_r(x,t) = \frac{\alpha D}{2e}\gamma\int_0^t \left[H(x,t-t') - H_0(x)\right]\frac{J_1}{\tau_1}e^{\frac{-t'}{\tau_1}}dt' \quad (5)$$

$$\frac{\partial \varepsilon_r(x,t)}{\partial t} = \frac{\alpha D}{2e}\frac{J_1}{\tau_1}\gamma\left[H(x,t) - H_0(x)\right] - \frac{\varepsilon_r(x,t)}{\tau_1} \quad (6)$$

The above equations have been implemented, together with an efficient 1-D weighting function unsteady friction model (developed by Vitkovsky et al. (2004)), in a general transient network solver called NETTRANS.

5.2 Using inverse analysis to fit parameters for the parameterised model

As described in Section 5.1, a one element Kelvin-Voigt spring and dashpot mechanism (i.e., only two parameters) is used to allow for additional dissipation and dispersion in the parameterised model. The inclusion of this mechanism does not equate to an argument that AC pipes behave viscoelastically (they do not). The purpose is to replicate the effect of uncertainties that may affect a transient response in a similar way to viscoelastic pipe wall effects (e.g., hysteresis effects in the elastic behaviour of the pipe walls and confining soils).

In order to replicate the behaviour of the WN, including its uncertainties, suitable values for the spring (J_1) and dashpot (τ_1) parameters must be calibrated using measured responses and inverse analysis. This calibration has been performed using a Shuffled Complex Evolution global search algorithm (included in the NLFIT suite of programs (developed by Kuczera (1994)). The results of the inverse fitting for 20, 40 and 80 m discretisations in the parameterised model are presented in Table 2 :

Table 2 – Results of inverse calibration to the "open" WN for tests 1, 2 and 3

Test	Event Speed	Model (dx)	Mean Value from Fitting		Std Deviation		Obj. Func.
			J_1 (x e-10)	τ_1	J_1 (x e-12)	τ_1 (x e-01)	
1	4 ms	20 m	0.290	1.528	0.253	0.185	1.932
1	4 ms	40 m	0.301	1.577	0.370	0.268	4.587
1	4 ms	80 m	0.306	1.648	0.540	0.399	3.326
2	190 ms	20 m	0.276	1.486	0.236	0.178	1.471
2	190 ms	40 m	0.289	1.528	0.346	0.258	1.792
2	190 ms	80 m	0.289	1.576	0.491	0.374	1.550
3	340 ms	20 m	0.278	1.508	0.241	0.183	0.820
3	340 ms	40 m	0.280	1.498	0.330	0.251	1.313
3	340 ms	80 m	0.284	1.568	0.482	0.374	1.213
	Overall average		0.288	1.546			

Consistent values for the spring (J_1) and dashpot (τ_1) parameters are obtained when the parameterised model is fitted to the measured responses from the "open" WN (for calibration tests 1, 2 and 3 and at all stations). It is important to note that the values obtained for the spring and dashpot parameters give rise to an equivalent creep function that is an order of magnitude smaller than that which would be obtained for a polyethylene pipe (i.e., the asbestos cement pipes are not being treated as truly viscoelastic).

The improvement obtained using the parameterised model, when the average values for the spring (J_1) and dashpot (τ_1) parameters from Table 2 are implemented, is illustrated in Figures 5 and 6, for 20 and 80 m model discretisations of the WN respectively. Similar improvements are obtained for all three measurement stations and tests 1, 2 and 3.

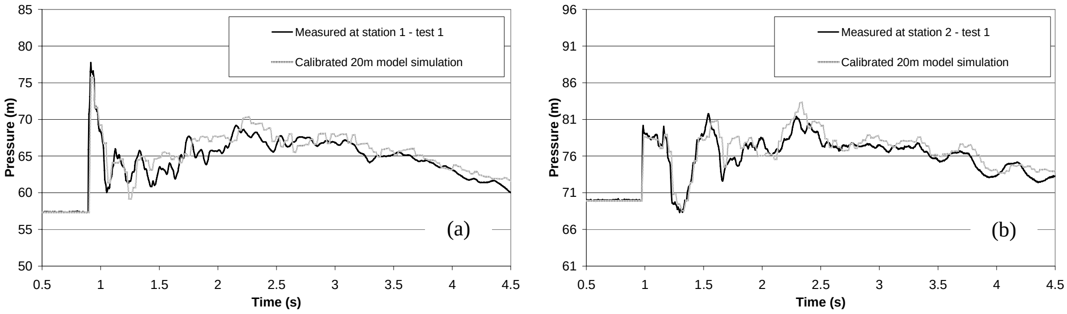

Figure 5 (a) and (b) – Measured response and parameterised model (20 m) predictions for stations 1 and 2 for test 1

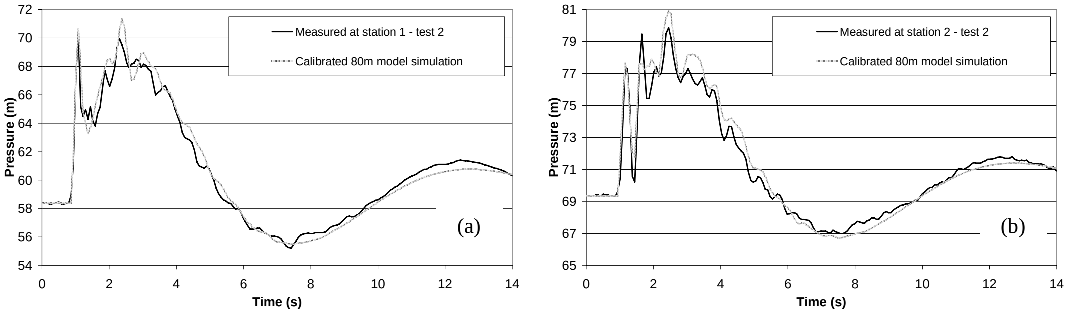

Figure 6 (a) and (b) – Measured response and parameterised model (80 m) predictions for stations 1 and 2 for test 2

6 APPLICATION TO TOPOLOGICAL CHANGE DETECTION

6.1 Closed valve or topological change detection using the parameterised model

The robustness of the parameterised model can be assessed by its ability to correctly predict the behaviour of the WN when a gross change to the topology is introduced (e.g., the closure of a valve). At the same time, it is the ability of the model to correctly predict the transient response of the WN, when a valve has been closed, that is relied upon when seeking to use transient response analysis to detect closed valves or topological changes. Either way, it is fundamentally important that the two parameters determined by reference to the measured responses of the “open” WN remain applicable to the system when topological changes occur.

6.2 Confirmation of model robustness and ability to detect closed valves

Consider the case where measurements of the transient response of the WN have been obtained when the SE valve is closed (i.e., test 4). Now consider what occurs if the incorrect valves are closed in the parameterised model. Figures 7 and 8 illustrate that if the SW or NE valves are closed in the model (i.e., the incorrect valves) then poor comparisons between the predicted and measured responses are obtained.

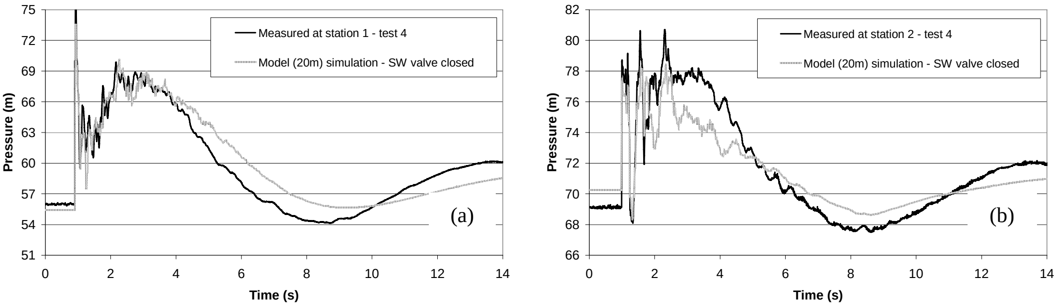

Figure 7 (a) and (b) – Comparison of measured response for SE valve closed and parameterised model prediction for SW valve closed at stations 1 and 2

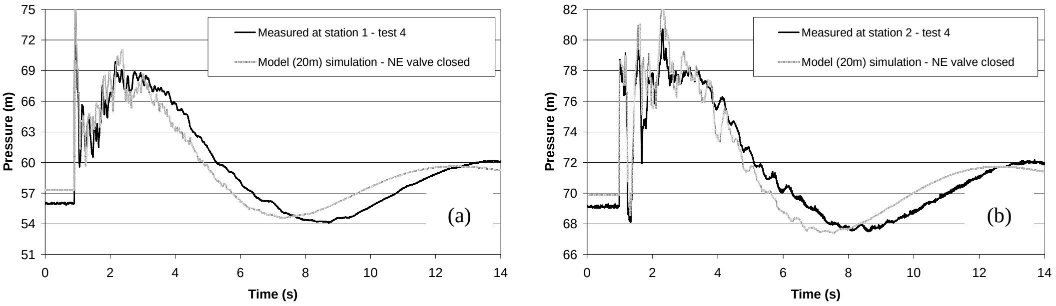

Figure 8 (a) and (b) – Comparison of measured response for SE valve closed and parameterised model prediction for NE valve closed at stations 1 and 2

However, Figure 9 illustrates that if the SE valve is closed in the parameterised model (i.e., the valve that was closed when the measurement was taken) then the predicted and measured responses are in good agreement.

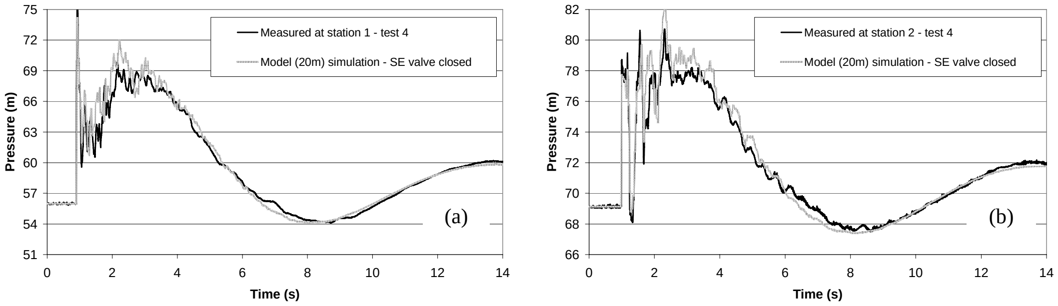

Figure 9 (a) and (b) – Comparison of measured response for SE valve closed and parameterised model prediction for SE valve closed at stations 1 and 2

The measured responses of the WN have been obtained when the SE, NE and SW valves (refer to Figure 1) have been closed (tests 4, 5 and 6). The parameterised model accurately predicted the response of the WN for each of these topological configurations, without the need for any parameter adjustment, confirming the robustness of the parameterised model and that closed valve detection can be accomplished using transient response analysis.

7 CONCLUSIONS

The objective, in this paper, has been to develop a model parameterisation for the WN and confirm the robustness of the parameter estimates. This work has opened the way for successful application of transient response analysis to the problem of closed valve detection. The results should facilitate further development of transient response analysis based techniques for the non-invasive assessment of other problems in WDSs.

8 ACKNOWLEDGEMENTS

The writers would like to gratefully acknowledge the financial and operational support received from United Water International Pty Ltd in carrying out this research. In particular, the writers thank operations staff that attended during the field tests.

9 REFERENCES

(1) Covas, D., Stoianov, I., Mano, J.F., Ramos, H., Graham, N. and Maksimovic, C. (2005) “The Dynamic Effect of Pipe-wall Viscoelasticity in Hydraulic Transients. Part II – Model Development, Calibration and Verification” *Journal of Hydraulic Research*, 43(1), 56-70

(2) Kuczera, G.A. (1994) "*NLFIT - A Bayesian Nonlinear Regression Program Suite - V 1.00g*", Department of Civil Engineering and Surveying, University of Newcastle, New South Wales, Australia

(3) McInnis, D. and Karney, B. (1995) “Transients in Distribution Networks : Field Tests and Demand Models” *Journal of Hydraulic Engineering*, ASCE, 121(3), 218-231

(4) Liggett, J.A. and Chen, L.C. (1994) “Inverse Transient Analysis in Pipe Networks” *Journal of Hydraulic Engineering*, ASCE, 120(8), 934-955

(5) Stephens, M., Lambert, M., Simpson, A., Vitkovsky, J. and Nixon, J. (2004) “Field Tests for Leakage, Air Pocket and Discrete Blockage Detection Using Inverse Transient Analysis in Water Distribution Pipes” *6th Annual Symposium on Water Distribution Systems Analysis*, EWRI Congress, Salt Lake City, USA

(6) Stephens, M., Vitkovsky, J., Lambert, M., Simpson, A., Karney, B. and Nixon, J. (2004) “Transient Analysis to Assess Valve Status and Topology in Pipe Networks” *9th International Conference on Pressure Surges*, BHR Group, Chester, UK

(7) Vitkovsky, J., Stephens, M., Bergant, A., Lambert, M. and Simpson, A. (2004) “Efficient and Accurate Calculation of Zielke and Vardy-Brown Unsteady Friction in Pipe Transients” *9th International Conference on Pressure Surges*, BHR Group, Chester, UK

10 NOTATION

a = wave speed
A = pipe cross-section area
D = pipe diameter
E_0 = Elastic modulus of pipe wall
E_1 = Elastic modulus of spring
g = gravitational acceleration
h_f = friction head loss
H = head
H_0 = steady state head
J_0 = elastic creep compliance
J_1 = creep compliance
Q = flow rate
t, t' = time
x = distance
α = pipe wall constraint factor
ε_r = retarded strain
γ = bulk unit weight water
μ_1 = viscosity of dashpot
τ_1 = retardation time of dashpot