Transient Response Analysis for Fault Detection and Pipeline Wall Condition Assessment in Field Water Transmission and Distribution Pipelines and Networks

by

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Chapter 7

Transmission Pipeline Tests and Transient Modelling

Two transmission pipelines were tested during the research program. These pipelines are geographically distinct sections of a single pipeline system that transfers water from the Murray River to major regional centres throughout South Australia including Port Pirie, Port Augusta, Whyalla and Port Lincoln (over 400kms to the south and west). The two transmission pipelines are called the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP). This chapter describes the conduct and results of tests, and transient modelling, for these two transmission pipelines. It was assumed that the transmission pipelines would be straightforward candidates for transient modelling and subsequent transient response analysis or Inverse Transient Analysis (ITA). However, it is revealed that many complex physical phenomena affect the transient response of a transmission pipeline including discrete air pockets and entrained air, unsteady friction and fluid structure interaction.

7.1 Summary of transient tests on transmission pipelines

7.1.1 Details of the Hanson Transmission Pipeline

Figure 7-1 shows the general locality of the first section of the overall pipeline system referred to as the Hanson Transmission Pipeline (HTP). The HTP was tested on the 20th and 21st May 2004. The HTP is located near the township of Hanson, in regional South Australia, and is approximately 13.5km long with a 650mm nominal diameter. It was selected because it has gravity supply tanks, a uniform diameter and composition (it is mild steel cement mortar lined (MSCL)), and the main could be shut down for inspection because a second parallel main was available. The HTP was also selected because it was scheduled for CCTV camera investigation in the month of June 2004 and the South Australian Water Corporation were interested in any information that could be used to predetermine locations at which to conduct the CCTV investigation.

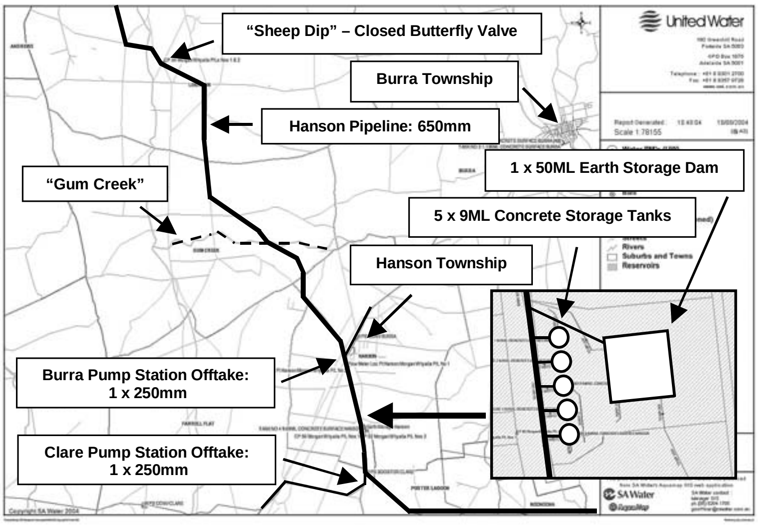


Figure 7-1 – Locality plan for the Hanson Transmission Pipeline (HTP)

Figures 7-2 and 7-3 show photographs of the upstream (summit storage tanks) and downstream (in-line butterfly valve) ends of the HTP, respectively. Five 9.1ML tanks connected in series, comprising part of the summit storage at Hanson, formed an upstream boundary while an in-line butterfly valve (newly installed) could be closed, at a location known as "Sheep Dip", in order to form the 13.5km section of transmission pipeline. A top view of the butterfly valve at "Sheep Dip" is shown in Figure 7-3. A 250mm diameter Asbestos Cement (AC) offtake pipe is located approximately 3.0km from the upstream tanks. This offtake is approximately 800m long and supplies a pump station that lifts water to the township of Burra located approximately 10km to the northeast. In addition, a single 100mm diameter service pipeline to the township of Hanson is supplied by the 250mm diameter AC offtake.

During the tests, isolation valves upstream of the five 9.1ML tanks, and between a 50ML earth storage dam and the HTP, were closed. While the 250mm diameter AC offtake to the Burra township pump station was not closed, the pump station was turned off. Furthermore, the 100mm diameter service pipeline to the township of

Hanson was isolated. Existing insertion flowmeters, as described in Appendix J, were used to monitor the flows in the HTP and Burra township pump station offtake throughout the tests.


Figures 7-2 and 7-3 – Hanson summit storage tanks and “Sheep Dip” in-line butterfly valve boundaries

Figure 7-4 shows the general configuration of the HTP during the transient tests conducted on the 20th and 21st May 2004. The HTP was surveyed using a Global Positioning Survey (GPS) unit and this information was verified using “as constructed” plans as described in Appendix K. A transient generator was installed at chainage 8498m from the junction immediately adjacent to the most downstream of the five 9.1ML tanks. The method for generating the transients involved the rapid closure of a side discharge valve as described in Chapter 6.

Two synchronised pressure measurement stations were installed at chainages 7620m and 8589m. As described in Chapter 6, these pressure measurement stations each included a Druck PDCR-810 pressure transducer mounted in a fitting attached to an existing fire plug/air valve (these manual valves could be operated to release accumulated air and also gave a pressure measurement access point). The pressure measurement stations recorded the transient response of the HTP at 500Hz and were synchronised using a radio tone of a known frequency that was transmitted simultaneously to both stations and recorded. An artificial 9L/s leak, as described in Chapter 6, was introduced to the HTP at chainage 9290m to conduct transient tests with leakage for comparison to those tests conducted without leakage.

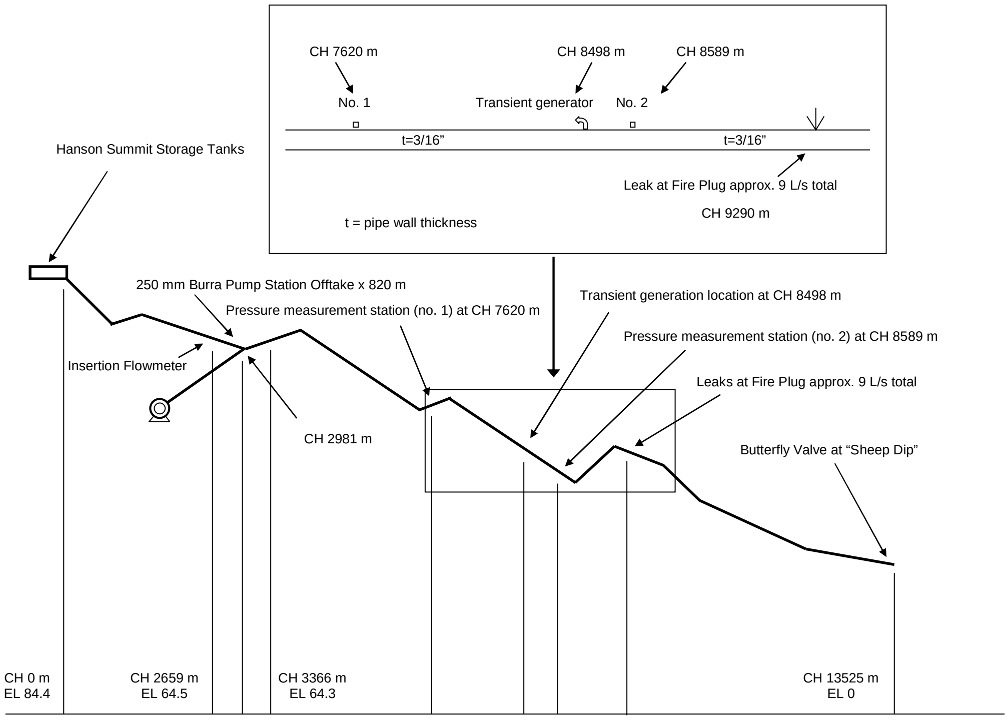


Figure 7-4 – Test configuration for the Hanson Transmission Pipeline (HTP)

7.1.2 Tests performed on the Hanson Transmission Pipeline

Four controlled transient tests were performed on the 21st May 2004 as listed in Table 7-1. The controlled transients induced during tests 1 and 2 resulted in an immediate pressure rise in the Hanson Transmission Pipeline (HTP) of approximately 7.5m and a maximum pressure rise of approximately 15m (tests 3 and 4 resulted in marginally smaller pressure rises). These pressures were within the operator defined allowable pressure range for the HTP.

A regional South Australian Water Corporation work crew, together with an asset manager, attended during the tests. The work crew was responsible for closing in-line gate valves, cross-connection valves and flushing fire plug/air valves (AVFPs) located at local high points along the HTP. The work to configure the pipeline and flush the air valves was undertaken over a period of approximately 2 hours while the author and two instrumentation technicians from the University of Adelaide established two radio synchronised measurement stations and connected the custom built transient generator used to induce the controlled transients. When finished, the work crew reported that no air was observed at any of the AVFPs that were flushed. This was surprising but may be explained by the fact that there was very little air in the HTP.

Table 7-1 – Summary of controlled transient tests for the HTP on the 21st May 2004

Test No.	Initial flow in main pipe	Initial velocity in main pipe	Burra pump station flow	Leak flow	Initial Reynolds No. for main pipe	Test description
1	43.0 L/s	0.140 m/s	0 L/s	0.0 L/s	76,725	No-leak test
2	43.0 L/s	0.140 m/s	0 L/s	0.0 L/s	76,725	No-leak test
3	52.0 L/s	0.169 m/s	0 L/s	9.0 L/s	92,783	Leak test
4	52.0 L/s	0.169 m/s	0 L/s	9.0 L/s	92,783	Leak test

7.1.3 Details of the Morgan Transmission Pipeline

Figure 7-5 shows the general locality of the second section of the overall pipeline system called the Morgan Transmission Pipeline (MTP). The MTP was tested on the 19th and 20th May 2004 and the 11th and 12th August 2004. The MTP is located near the township of Morgan, on the Murray River in regional South Australia, and is approximately 26.1km long with a 750mm nominal diameter. It was selected because the South Australian Water Corporation was particularly interested in its overall condition and had recently conducted CCTV camera investigation along two relatively short sections of the pipeline. The MTP was more complex than the HTP with its normal configuration being a pumped rising main from a water filtration/treatment plant near Morgan to a pair of 9.1ML storage tanks located 26.1km to the west. Furthermore, the thickness of the steel walls varied between 4.76mm (3/16 of an inch) and 7.94mm (5/16 of an inch) at various locations. As for the HTP, the MTP comprised MSCL pipe and could be shut down for inspection because a second parallel main was available.

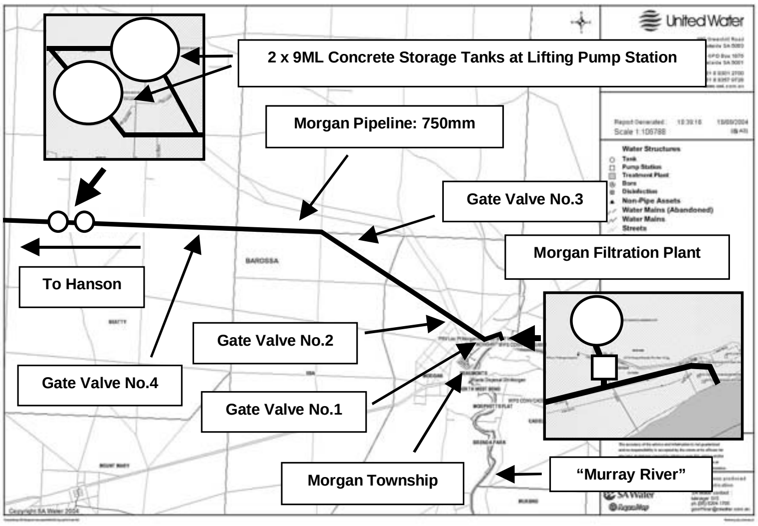


Figure 7-5 – Locality plan for the Morgan Transmission Pipeline (MTP)

Figure 7-6 shows the general configuration of the MTP during the transient tests conducted on the 19th and 20th May 2004. The MTP was surveyed using a Global Positioning Survey (GPS) unit and this information was verified using "as constructed" plans as described in Appendix K. The transient generator was installed at chainage 9275m from the discharge junction immediately adjacent to the filtration/treatment plant. As for the HTP, the method for generating the transients involved the rapid closure of a side discharge valve as described in Chapter 6. Two synchronised pressure measurement stations were established, either side of an existing in-line gate valve called the "No.3" valve, at chainages 6995m and 8117m. As for the HTP, these pressure measurement stations each included a Druck PDCR-810 pressure transducer mounted in a fitting attached to an existing air valve and were synchronised using a radio tone of a known frequency.

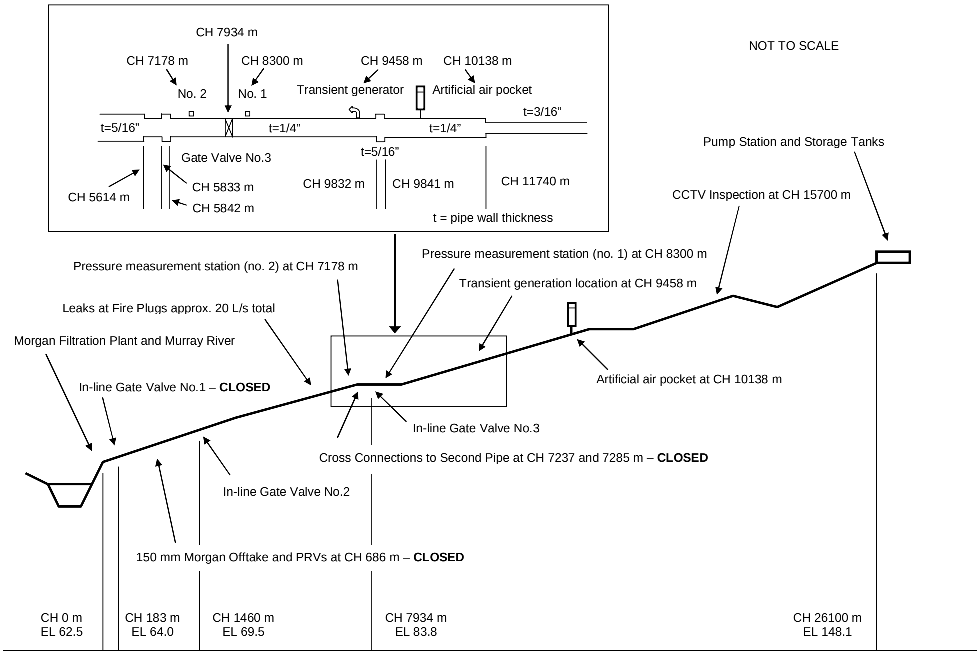


Figure 7-6 – Test configuration for the Morgan Transmission Pipeline (MTP) on the 19th and 20th May 2004

During the tests, the boundaries to the 26.1km long section of transmission pipeline were formed, after reconfiguring the pumped rising main in reverse as a gravity main, by the two 9.1ML tanks, which normally received pumped water and were located at the highest elevation along the main, and by the closure of an in-line gate valve near the filtration/treatment plant at Morgan (or other valves along the length of the MTP as specified for particular tests). A 150mm nominal diameter offtake to the Morgan township was closed. Furthermore, 700mm diameter cross-connections to a second parallel pipeline (offset from the MTP by approximately 10m) were closed.

The “No.3” in-line gate valve was used to introduce an artificial discrete blockage to the MTP at chainage 7751m and conduct comparative transient tests with and without blockage. Furthermore, an artificial air pocket was introduced to the MTP at chainage 11,153m to assess the impact of a relatively small air pocket on the response of the pipeline. The method of introducing this air pocket to the MTP and the results of those tests are described in Appendix T and Appendix L. A significant complication, relevant to the tests conducted in May and August, was the change in pipe wall thickness along the MTP. Figure 7-6 shows that, for the tests conducted in May 2004, there are four significant changes in the thickness of the MTP between chainages 5450m and 11,576m (either side of the location of the transient source).

Figure 7-7 shows the general configuration of the MTP during the transient tests conducted on the 11th and 12th August 2004. The configuration of the boundaries for the 26.1km long section of the MTP was the same as for the tests conducted in May 2004 except that the tests were conducted with the “No.1”, “No.2” and “No.3” valves closed to form different downstream boundaries in each case. The transient generator was installed at chainage 15,709m from the discharge junction immediately adjacent to the filtration/treatment plant. Two synchronised pressure measurement stations were established, either side of an existing in-line gate valve called the “No.4” valve, at chainages 13,758m and 15,627m. As for the HTP, these pressure measurement stations each included a Druck PDCR-810 pressure transducer mounted in a fitting attached to an existing fire plug/air valve and were synchronised using a radio tone of a known frequency.

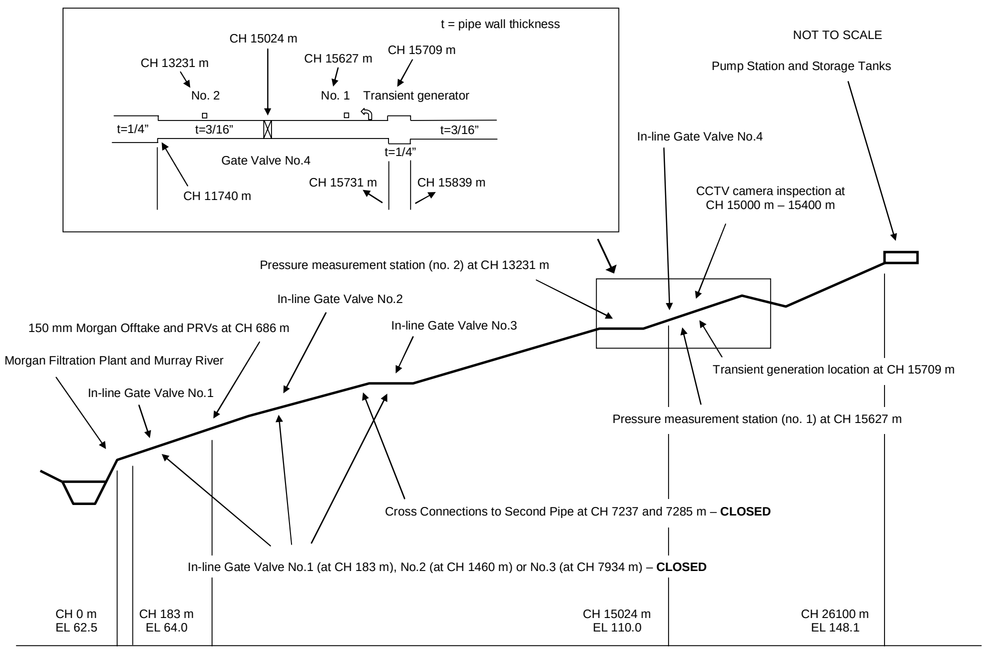


Figure 7-7 – Test configuration for the Morgan Transmission Pipeline (MTP) on the 11th and 12th August 2004

No specific artificial faults were introduced to the MTP for the tests conducted in August 2004. The purpose of the tests was to assess whether the measured responses contained any information that could be correlated to observations from the CCTV camera investigations carried out in close proximity to the "No.4" valve. As for the tests conducted in May 2004, changes in the pipe wall thickness were a significant complication. Figure 7-7 shows three significant changes in the thickness of the MTP between chainages 11,741m and 15,841m. These changes in thickness have a significant impact on the transient response of the MTP as investigated in Chapter 10.

7.1.4 Tests performed on the Morgan Transmission Pipeline

On the 20th May 2004, six controlled transient tests were performed as listed in Table 7-2. The Courant number is listed because the "as constructed" wall thickness (and therefore also wave speed) was known to vary over the length tested. The controlled transients induced during all tests resulted in an immediate pressure rise in the Morgan Transmission Pipeline (MTP) of approximately 5.0m and a maximum pressure rise of approximately 10m. As for the Hanson Transmission Pipeline (HTP), these pressures were within the operator defined allowable pressure range for the MTP. Although the same size nozzle, with the same discharge coefficient was used, with similar pressures at the location at which the transient was induced, the pressure rise in the MTP was less than in the HTP because of the increase in diameter from 625.5mm for the HTP to 724.3mm (average) for the MTP.

Table 7-2 – Summary of controlled transient tests for the MTP on the 20th May 2004

Test No.	Initial flow in main pipe	Initial velocity in main pipe	End flow	Initial Reynolds No. for main pipe	Test description	Courant Number
1	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Clear pipe	0.834
2	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Clear pipe	0.834
3	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Air pocket	0.834
4	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Air pocket	0.834
5	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Blockage	0.834
6	44.1 L/s	0.107 m/s	2.5 L/s	67,773	Blockage	0.834

On the 11th August 2004, three controlled transient tests were performed as listed in Table 7-3. The controlled transients induced during all tests resulted in an immediate pressure rise in the MTP of approximately 6.0m and a maximum pressure rise of approximately 12m (for test 9 when the return reflection from closed in-line gate valve “No.3” doubled the pressure in the MTP before relief from the tank reflection). These pressures were within the operator defined allowable pressure range for the MTP. They were larger than those generated for the tests conducted in May 2004, despite approximately 5m to 10m less pressure at the location at which the transient was induced, because the discharge coefficient for a modified nozzle was higher.

Table 7-3 – Summary of controlled transient tests for the MTP during August 2004

Test No.	Initial flow in main pipe	Initial velocity in main pipe	End flow	Initial Reynolds No. for main pipe	Test description	Courant Number
7	50.2 L/s	0.122 m/s	2.5 L/s	77,030	SV1 boundary	0.834
8	47.7 L/s	0.116 m/s	0.1 L/s	73,273	SV2 boundary	0.834
9	47.7 L/s	0.116 m/s	0.1 L/s	73,273	SV3 boundary	0.834

A South Australian Water Corporation work crew attended during the tests on the MTP. This work crew was responsible for closing the “No.1” in-line gate valve near the Morgan filtration and treatment plant for the May 2004 tests, alternately closing the “No.1”, “No.2” and “No.3” in-line gate valves for the August 2004 tests, closing four in-line cross-connection gate valves linking the MTP with a parallel transmission pipeline and, finally, closing the 150mm diameter offtake to the Morgan township. Once the MTP was configured for the testing conducted in May 2004, the work crew assisted by partially closing in-line gate valve “No.3” to form a partial blockage (as described in Chapter 6) for tests 5 and 6.

The author and a technician from the University of Adelaide personally undertook flushing of the 62 fire plug/air valves (AVFPs) located at, or near, local high points along the MTP before the tests conducted in May 2004. This exercise was time consuming and took over 2 hours. The author can report the release of occasional small bubbles of air but no significant quantity at any of the AVFPs.

7.2 Development of traditional transient models

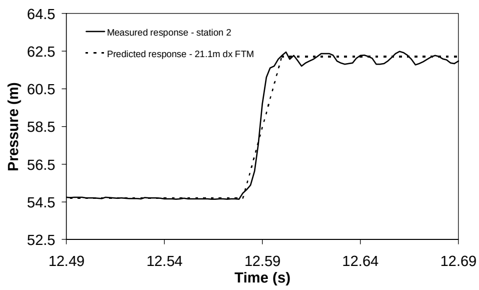
A traditional transient model, utilising an explicit Method of Characteristics (MOC) scheme, has been implemented in a traditional manner to determine the response of single and branched pipe systems. Traditional algorithms have been included in the program for the calculation of quasi-steady friction and minor losses and for the implementation of linear timeline interpolation where a non-constant wave speed is applicable. Other algorithms, used for the calculation of the effect of discrete air pockets, entrained air, unsteady friction, discrete air pockets and/or entrained air and fluid structure interaction, have been included in the program called BSOLVER. Where applicable, BSOLVER uses efficient implementations of these algorithms. A listing of the Fortran source code developed by the author is included in Appendix M.

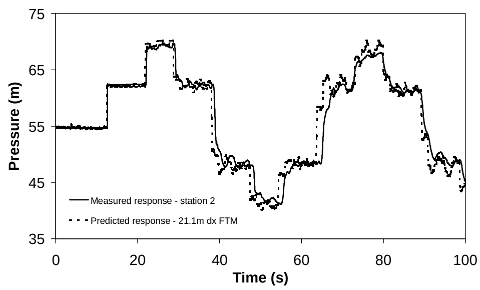
The program is applied to conduct the forward transient modelling of the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP) reported below. As mentioned in Chapter 4, the forward transient program is modified and linked to the NLFIT suite of Bayesian non-linear regression programs, developed by Kuczera (1994), in order to perform the inverse analysis described in Chapters 8 and 9, for the HTP, and later in Chapters 12, 13 and 14 for two small distribution pipelines. Again, the modified subroutines developed by the author for this analysis are presented in Appendix M.

7.2.1 Transient model for the Hanson Transmission Pipeline

The Hanson Transmission Pipeline (HTP) has a total length of 13,504m and is discretised into 640 sub-pipe segments (each 21.1m long). A uniform wave speed of 1055m/s is applied giving a time step in the calculations of 0.02s. A uniform wave speed was adopted based on the constant wall thickness of 3/16 of an inch along the HTP and the direct wave speed assessment described in Appendix N. An underlying discharge of 0.1L/s, through the “Sheep Dip” butterfly valve, has been included to allow for leakage under the valve seal. The Burra Pump Station offtake, comprising approximately 820m of 250mm nominal diameter Asbestos Cement (AC) pipe, has also been included in the model. Five 9.1ML tanks comprising part of the summit storage at Hanson and the downstream butterfly valve at "Sheep Dip" form the boundary conditions. The transient generator has been included in the model as a side discharge valve.

Figure 7-8 shows the comparison between the measured and predicted wavefronts, over the time scale of the initial wavefront, obtained using the traditional transient model for test 1 at station 2 (located 91m downstream of the transient generator). Overall, the approximation of the initial wavefront is considered satisfactory. Figure 7-9 shows that, over a longer time scale of 100s, the model discretisation is sufficient to represent the observed details in the measured response of the HTP. The discrepancy between the measured and predicted responses is not due to the discretisation being too coarse. Instead, the predicted response is too sharp and does not replicate observed dispersion and damping.





where FTM = forward transient model

Figures 7-8 and 7-9 – Comparison of measured and predicted waveforms using a traditional transient model over time scales of 0.2s and 100s, respectively

7.2.2 Transient model for the Morgan Transmission Pipeline

The length of the Morgan Transmission Pipeline (MTP) varied depending upon which in-line gate valve was closed to form a downstream boundary condition. Furthermore, each in-line gate valve sealed to a different degree when closed and residual discharges along the MTP were observed. Table 7-4 summarises the length of the MTP when each of the in-line gate valves was closed, the corresponding number of sub-pipe segments and the discretisation interval. In addition, the wave speed along the MTP varied with known changes in the pipe wall thickness (refer to Appendix N for the direct estimation of the wave speeds along sections of the MTP). Different wave speeds have been incorporated in the traditional transient model of the MTP, to account for the changes in wall thickness, and linear timeline interpolation is used. The same Courant number is obtained for each configuration because each length of the MTP contains sections of pipe with wall thicknesses ranging from 3/16 to 5/16 of an inch.

Table 7-4 – Summary of Morgan Transmission Pipeline (MTP) details for different downstream boundary conditions

Downstream boundary condition	Length of MTP (m)	Number of sub-pipe segments	Discretisation (m)	Background flowrate (L/s)	Courant number
SV1 closed	25920	1296	20.0	2.5	0.834
SV2 closed	24640	1232	20.0	0.1	0.834
SV3 closed	18160	908	20.0	0.1	0.834

Figure 7-10 shows the comparison between the measured and predicted wavefronts, over the time scale of the initial wavefront, obtained using the traditional transient model for test 7 at station 1 (located 82m downstream of the transient generator). Overall, the approximation of the initial wavefront is considered satisfactory. Given that the model is capable of representing the sharpest wavefronts (i.e., the wavefronts recorded close to the source of the induced transient at station 1), the discretisation of 20.0m is considered adequate. A transient model of the section of the MTP with internal pipe wall damage is developed in Chapter 10 using a discretisation of 10m.

The use of the 20.0m discretisation for the MTP requires 908, 1232 or 1296 computational sub-pipe segments when in-line gate valves "No.3", "No.2" and "No.1" are closed, respectively. This represents 1.42, 1.93 and 2.03 times the number of computational segments used for the Hanson Transmission Pipeline (HTP) and increases the forward calculation time such that inverse analysis cannot be practically performed on a typical desktop computer (available at the time this research was conducted). This problem can be overcome by performing selected computations on more powerful computers, by improving the efficiency of the algorithms or limiting the analysis to a section of the MTP only. Given limitations in the scope of the research, inverse analysis has only been undertaken for the results for the HTP.

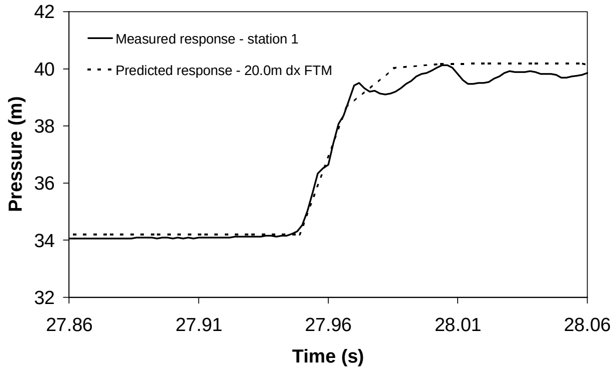


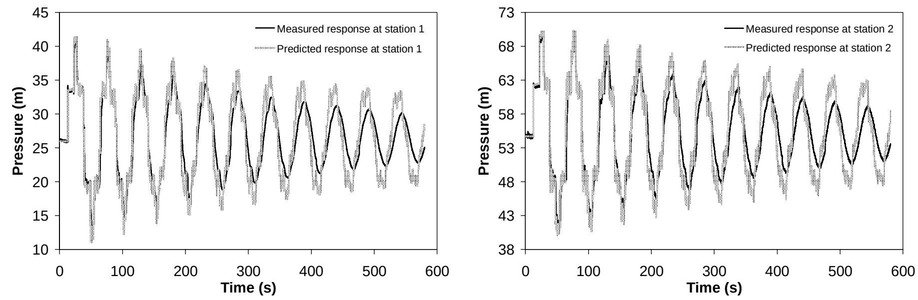
Figure 7-10 – Comparison of measured and predicted wavefronts using a traditional transient model over a time scale of 0.2s

7.3 Transient modelling with quasi-steady friction

Fluid friction is a potentially significant source of damping during a transient event that affects the potential use of transient response analysis and/or Inverse Transient Analysis (ITA) for the interpretation of faults or condition assessment. The effect of friction is traditionally incorporated in transient models using a quasi-steady approximation. The predicted responses from the two transmission pipelines tested in this research, obtained using a quasi-steady friction approximation, are presented below.

7.3.1 Hanson Transmission Pipeline with quasi-steady friction

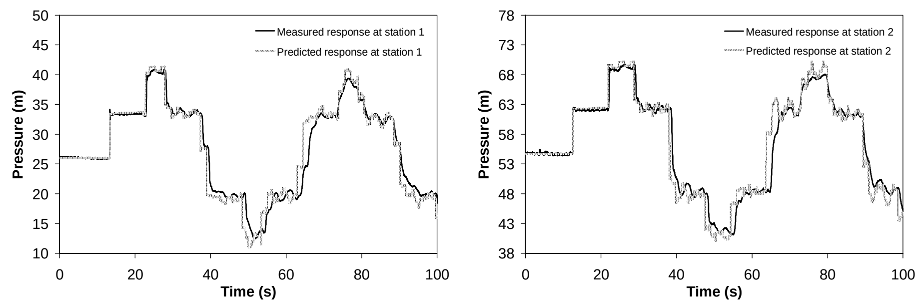
Quasi-steady friction transient modelling is undertaken below before implementing unsteady friction in a forward transient model of the Hanson Transmission Pipeline (HTP). Figures 7-11 and 7-12 show the comparison between measured and predicted responses, obtained using a forward transient model with quasi-steady friction over a time scale of 580s for test 1 on the HTP, at stations 1 and 2, respectively. The roughness of the HTP is assumed, at this stage, to be a constant 2mm.



Figures 7-11 and 7-12 – Measured versus predicted responses determined using quasi-steady friction model over 580s for test 1

The dispersion of high frequency information in the measured responses is not correctly predicted over the long term. Furthermore, the overall damping is underestimated. However, there is a relatively accurate match between the overall phase of the measured and predicted responses. The results demonstrate that a forward transient model with quasi-steady friction can only replicate the measured response of the HTP with limited accuracy.

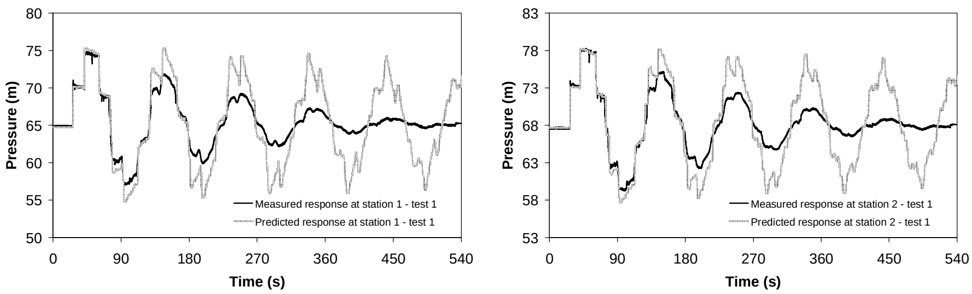
Figures 7-13 and 7-14 show the comparison between measured and predicted responses, obtained using a forward transient model with quasi-steady friction over a time scale of 100s. As for the results over a time scale of 580s, the dispersion of high frequency information in the measured responses is not correctly predicted. As time increases, and also the distance travelled by the wavefronts, so does the observed dispersion.



Figures 7-13 and 7-14 – Measured versus predicted responses determined using quasi-steady friction model over 100s for test 1

7.3.2 Morgan Transmission Pipeline with quasi-steady friction

Quasi-steady friction transient modelling, has been undertaken for the Morgan Transmission Pipeline (MTP). Figures 7-15 and 7-16 show the comparison between measured and predicted responses, obtained using a forward transient model with quasi-steady friction over a time scale of 540s for test 1 on the MTP, at stations 1 and 2, respectively. The roughness of the MTP is assumed, at this stage, to be a constant 3mm. An estimated discharge under in-line gate valve “No.1” of 2.5L/s is included in the model to theoretically account for imperfect sealing as observed by South Australian Water Corporation operators.

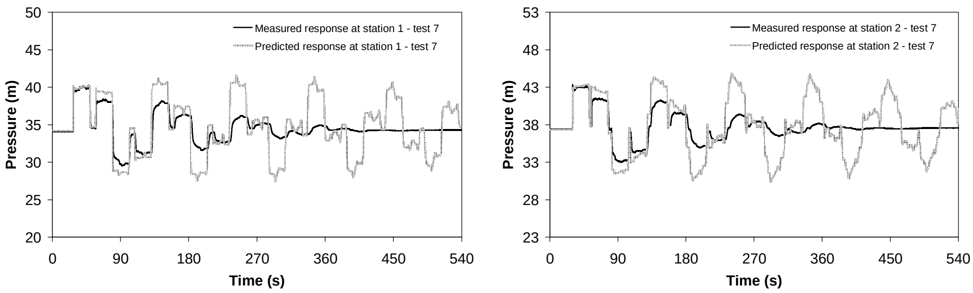


Figures 7-15 and 7-16 – Measured versus predicted responses determined using quasi-steady friction model over 540s for test 1

There is a more significant discrepancy between the measured and predicted damping (relatively greater than for the Hanson Transmission Pipeline (HTP)). The results demonstrate that a forward transient model with quasi-steady friction cannot replicate the measured damping but they do not give any further insight into the cause of the discrepancy. The inclusion of 2.5L/s of leakage under in-line gate valve “No.1” does not improve the comparison. However, the phases of the measured and modelled responses match satisfactorily suggesting that the wave speeds are correct.

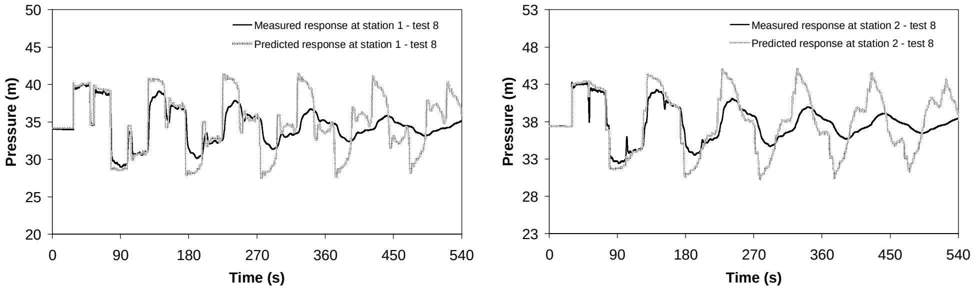
Quasi-steady friction modelling has also been undertaken for tests 7, 8 and 9 conducted in August 2004. These tests provide an important comparison to the May 2004 tests given the damping discrepancies noted above. The MTP was configured in the same way for test 7, conducted during August 2004, as it was for tests 1 and 2, conducted during May 2004. The only differences were the location of the transient generator and measurement stations and so relative damping in each of the tests can be compared.

Figures 7-17 and 7-18 show the comparison between measured and predicted responses, obtained using a forward transient model with quasi-steady friction over a time scale of 540s for test 7, at stations 1 and 2, respectively. While the relative positions of the transient generator and measurement stations are different from those for the tests in May 2004, the damping of the long-term response is similar. This suggests that the phenomena responsible for the damping have not changed significantly over the period between May and August 2004. As for the HTP, the quasi-steady friction model does not replicate the observed damping.



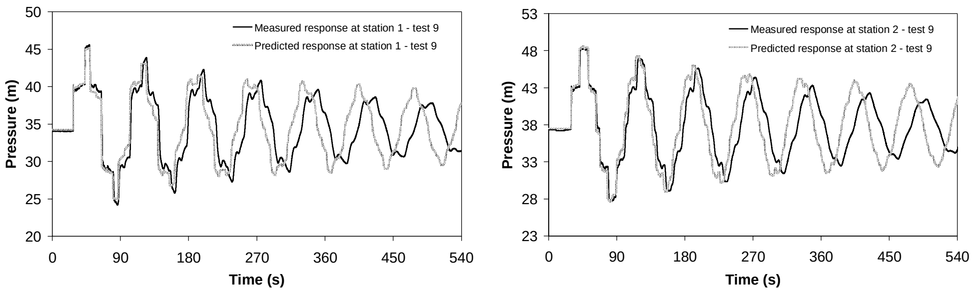
Figures 7-17 and 7-18 – Measured versus predicted responses determined using quasi-steady friction model over 540s for test 7 (in-line gate valve "No.1" closed)

The imperfect seal formed when in-line gate valve "No.1" was closed to create a downstream boundary condition does not explain the damping. Figures 7-19 and 7-20 show the measured response of the MTP continues to be significantly damped for test 8, conducted during August 2004, when in-line gate valve "No.2" was closed to form the downstream boundary condition for the MTP (and no significant leakage occurred under the valve). The observed damping is similar to that for the tests conducted during May 2004 but marginally less than that for test 7 conducted in August 2004.



Figures 7-19 and 7-20 – Measured versus predicted responses determined using quasi-steady friction model over 540s for test 8 (in-line gate valve “No.2” closed)

The MTP was reconfigured for test 9, conducted during August 2004, with in-line gate valve “No.3” closed to form the downstream boundary condition. Figures 7-21 and 7-22 show the measured response of the MTP is less significantly damped for test 9 than for any of the other tests conducted in May or August 2004. This suggests that reducing the length of the pipeline has isolated an important physical phenomena in the MTP. Possible explanations for this are explored below. The quasi-steady friction model is better able to approximate the measured response of the MTP for test 9. However, the phase of the predicted response precedes that of the measured response. This phase discrepancy is considered below in the context of unsteady friction and entrained air modelling.



Figures 7-21 and 7-22 – Measured versus predicted responses determined using quasi-steady friction model over 540s for test 9 (in-line gate valve “No.3” closed)

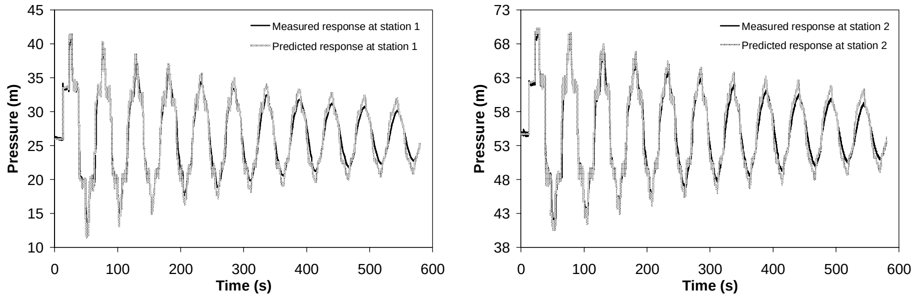
7.4 Transient modelling with unsteady friction

Researchers have developed complex algorithms to include the effects of unsteady friction on transient pipe flow (e.g., refer to Zielke (1968)). Some of these models have been verified experimentally using single pipelines under laboratory conditions (e.g., refer to Vitkovsky (2001)). Nevertheless, the significance of damping related to unsteady friction has not been demonstrated for transmission pipelines in the field.

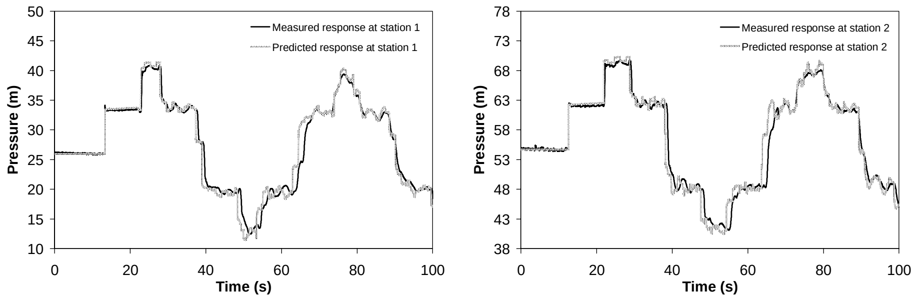
Unsteady friction was thought to be responsible for at least a proportion of the damping observed in the measured transient responses of the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP). The effect of unsteady friction varies with the initial flow conditions in, and roughness along, pipelines on a case-by-case basis. A forward transient model, modified to include unsteady friction for laminar and turbulent (smooth and rough pipe) flow conditions, using an efficient recursive approximation and 1-D weighting functions for laminar, smooth pipe turbulent and rough pipe turbulent flow, as detailed in Appendix E, is used in the following analysis.

7.4.1 Hanson Transmission Pipeline with unsteady friction

The inclusion of unsteady friction for turbulent flow in the Hanson Transmission Pipeline (HTP), using an estimated roughness of 2mm, significantly improves the performance of the forward transient model. Figures 7-23 and 7-24 show that, based on visual comparison, the measured and predicted responses have similar dispersion and damping. However, the rate of damping for the predicted responses remains less than that observed for the measured responses. Furthermore, high frequency structure persists in the predicted responses. Figures 7-25 and 7-26 show the comparison between measured and predicted responses, obtained using a forward transient model with unsteady friction over 100s, and illustrate some of the residual discrepancies between the measured and predicted responses.

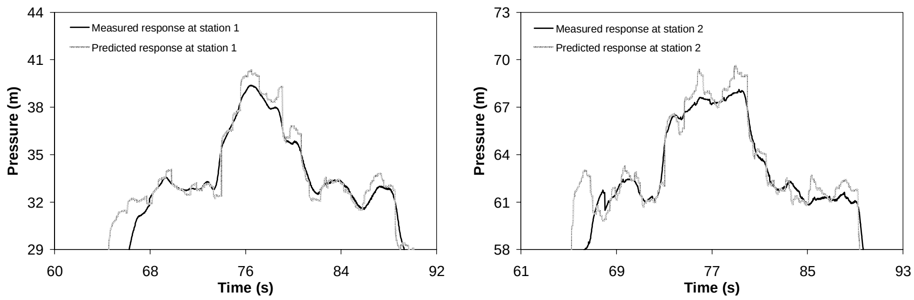


Figures 7-23 and 7-24 – Measured versus predicted responses determined using unsteady friction model over 580s for test 1



Figures 7-25 and 7-26 – Measured versus predicted responses determined using unsteady friction model over 100s for test 1

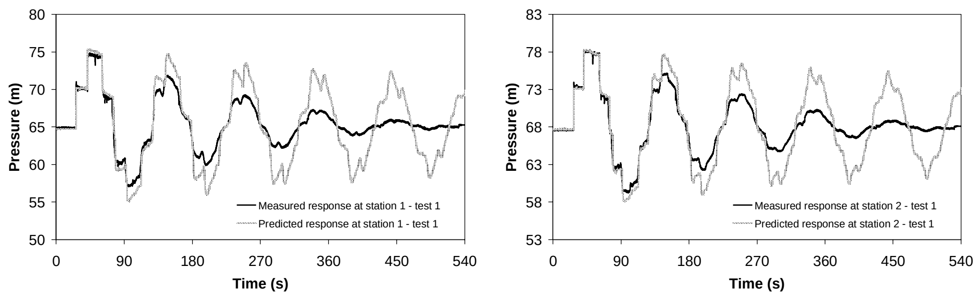
Figures 7-27 and 7-28 reveal, upon even closer inspection, dispersion in the measured responses, which is not predicted despite the inclusion of unsteady friction, over, in particular, the first 100s of the transient. This dispersion is significant and is investigated in further detail in Chapter 8. The structural discrepancies between the measured and predicted responses may point to additional phenomena influencing the transient response of the HTP.



Figures 7-27 and 7-28 – Measured versus predicted responses determined using unsteady friction model showing dispersion and structural discrepancies for test 1

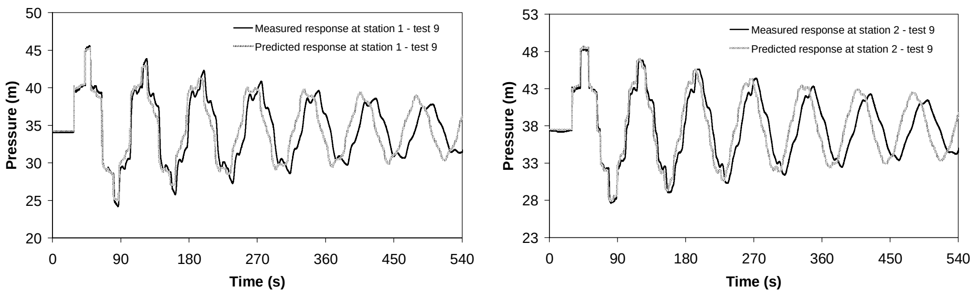
7.4.2 Morgan Transmission Pipeline with unsteady friction

The inclusion of unsteady friction for turbulent flow in the Morgan Transmission Pipeline (MTP), using an estimated roughness of 3mm, improves the performance of the forward transient model but does not account for the bulk of the observed damping. Figures 7-29 and 7-30 show that while the predicted damping has increased, relative to the results obtained using a quasi-steady friction model, there is an order of magnitude difference between the measured and predicted damping for test 1. Possible physical explanations for this are explored below and include imperfect sealing at in-line gate valve "No.1", at the Morgan township offtake or at the cross-connections to the parallel transmission main near in-line gate valve "No.3". An allowance for 2.5L/s flow under in-line gate valve "No.1" has already been made.



Figures 7-29 and 7-30 – Measured versus predicted responses determined using unsteady friction model over 540s for test 1

As identified above, the closure of in-line gate valve "No.3" appears to isolate important phenomena in the MTP that contribute to the observed damping. As a consequence, the quasi-steady friction model is better able to approximate the measured response of the MTP for test 9. Figures 7-31 and 7-32 show that the inclusion of unsteady friction further improves the predicted response such that the measured damping approximates the predicted damping. However, the phase of the predicted response still precedes that of the measured response. This phase discrepancy may be due to the presence of entrained air.



Figures 7-31 and 7-32 – Measured versus predicted responses determined using unsteady friction model over 540s for test 9

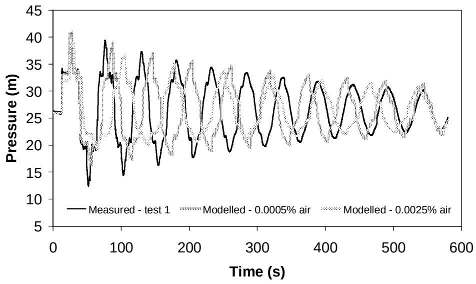
7.5 Modelling of entrained air and in-situ air pocket(s)

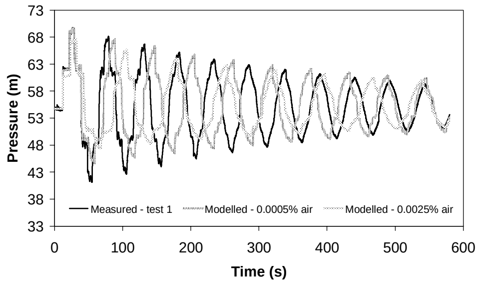
The assessment of the likely quantity of entrained air within the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP), presented in Appendix N, suggests that any entrained air in both pipelines should have migrated to local high points prior to the transient tests and that flushing of the air valves at these points should have effectively purged the system. However, the measured responses obtained for the MTP in May 2004 contain evidence of a small air pocket trapped in the vicinity of in-line gate valve "No.5". This confirms that internal roughness or features within the pipelines may act to capture entrained air.

The presence of a discrete air pocket or entrained air can be modelled using the Discrete Gas Cavity Model (DGCM) developed by Wylie (1984). This method was developed in response to the problem of the complexity and non-linearity of the equations required to directly implement a pressure dependent water-air mixture wave speed (which can be used to model the effect of entrained air). Air pockets can be placed at one or all of the computational nodes in a transient model with a Method of Characteristics (MOC) grid using the DGCM to represent a discrete air pocket or entrained air. Liquid water is assumed to occupy each computational sub-segment. The effect of each pocket of air is then incorporated by including it in the calculation of nodal continuity using the ideal gas equation to account for its compressibility. Details of the relevant equations and solution scheme are presented in Appendix O.

7.5.1 Hanson Transmission Pipeline with entrained air

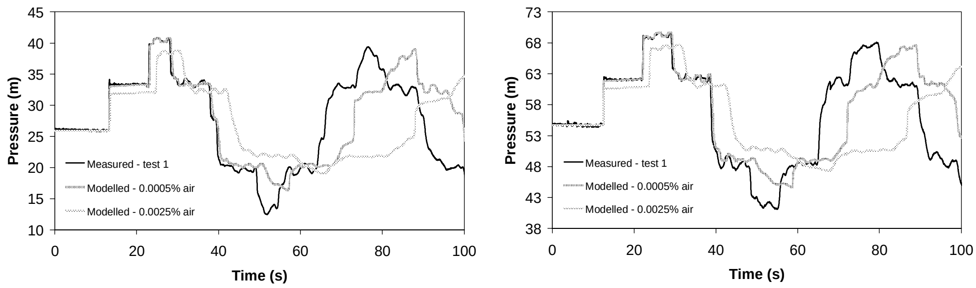
Despite the likelihood that there was little entrained air in the Hanson Transmission Pipeline (HTP), the effect of even a small quantity of entrained air along the HTP must be examined in order to assess whether it might be responsible for the dispersion in the measured responses. Figures 7-33 and 7-34 show the effect of entrained air in the HTP for test 1 at measurement stations 1 and 2, using an estimated pipe roughness of 2mm, for air contents of 0.0005% and 0.0025%, respectively. It is apparent that each percentage of entrained air causes excessive dispersion, without any significant damping, in the predicted responses over the duration of the transient.





Figures 7-33 and 7-34 – Measured versus predicted responses with unsteady friction and 0.0005% and 0.0025% of entrained air for test 1

Figures 7-35 and 7-36 show the discrepancies between measured and predicted responses over a shorter time scale of 100s for test 1 at measurement stations 1 and 2, respectively. That said, the match between the measured and predicted responses, for 0.0005% of entrained air, is satisfactory over the first 45s of the transient (i.e., the inclusion of this quantity of entrained air enables a match with the observed dispersion over this time period). However, as shown in Figures 7-33 and 7-34 above, this percentage of entrained air results in erroneous long-term dispersion of the predicted responses.

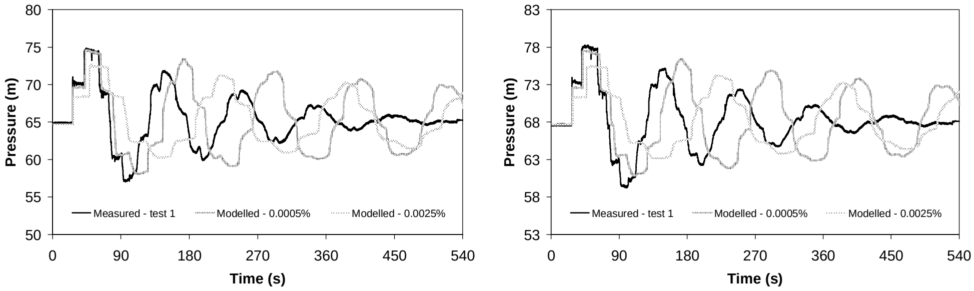


Figures 7-35 and 7-36 – Comparison of measured and predicted responses with various percentages of entrained air over 100s for test 1

The analysis of the effect of 0.0005% and 0.0025% of entrained air along the HTP indicates that significant quantities of entrained air are not likely to be present in the HTP. This conclusion is consistent with the knowledge that the air valves at high points along the HTP were flushed to clear accumulated air pockets. However, the above results do not eliminate the possibility of small quantities of entrained air. In recognition of this reality, a method of calibrating for small quantities of entrained air in pipelines is presented in Chapter 8 and applied to the HTP to determine whether a small quantity of entrained air can explain the dispersion in the measured responses.

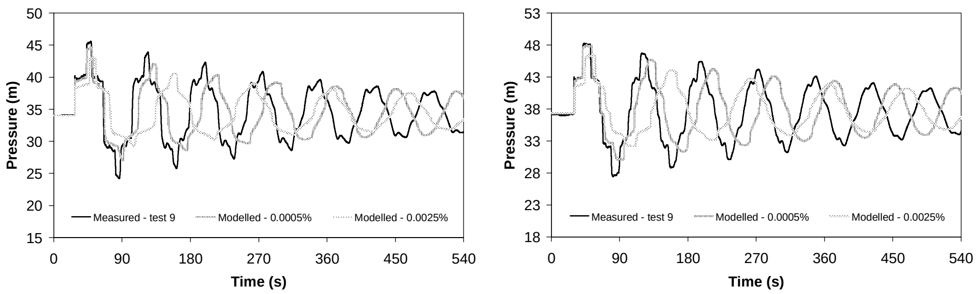
7.5.2 Morgan Transmission Pipeline with entrained air

Figures 7-37 and 7-38 show the effect of entrained air in the Morgan Transmission Pipeline (MTP) for test 1, conducted during May 2004, at measurement stations 1 and 2, using an estimated pipe roughness of 3mm, for air contents of 0.0005% and 0.0025%, respectively. It is apparent that each percentage of entrained air causes excessive dispersion, without any significant damping, in the predicted responses over the duration of the transient.



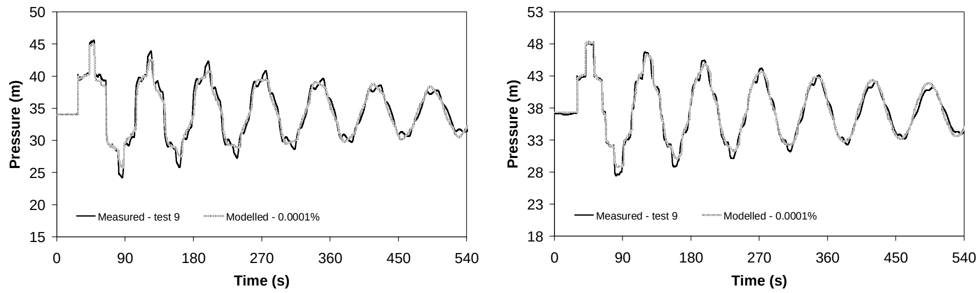
Figures 7-37 and 7-38 – Measured versus predicted responses with unsteady friction and 0.0005% and 0.0025% of entrained air for test 1

Figures 7-39 and 7-40 show the effect of entrained air in the MTP for test 9, conducted during August 2004, at measurement stations 1 and 2, using an estimated pipe roughness of 3mm, for air contents of 0.0005% and 0.0025%, respectively. As previously explained, the closure of in-line gate valve "No.3" appears to have isolated the phenomena contributing to the observed damping for tests 7 and 8 and, in turn, the predicted responses better approximate the measured responses. That said, each percentage of entrained air causes excessive dispersion in the predicted responses.



Figures 7-39 and 7-40 – Measured versus predicted responses with unsteady friction and 0.0005% and 0.0025% of entrained air for test 9

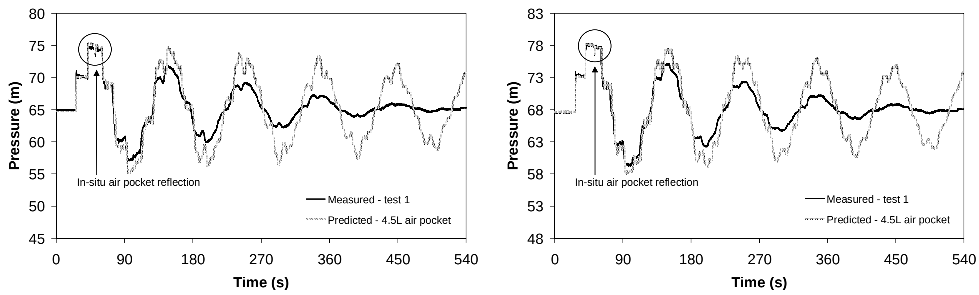
However, as shown in Figures 7-41 and 7-42, the predicted response for an air content of 0.0001%, when unsteady friction is also modelled, visually matches the measured response for test 9. The comparison between the measured and predicted responses with unsteady friction and 0.0001% entrained air for test 9 are encouraging and suggest that, provided the physical mechanisms contributing to the dispersion and damping of the transient response of the MTP can be identified and included, an accurate forward transient model can be developed.



Figures 7-41 and 7-42 – Measured versus predicted responses with 0.0001% of entrained air for test 9

7.5.3 Morgan Transmission Pipeline with in-situ air pocket

The results of the tests conducted on the during May 2004 suggest that a small in-situ air pocket was present in the vicinity of in-line valve “No.5” at approximate chainage 21550m. Figures 7-43 and 7-44 show the predicted responses obtained using a 4.5L air pocket, with a reference pressure of 40.0m, located at chainage 21620m, for test 1, at stations 1 and 2, respectively.



Figures 7-43 and 7-44 – Comparison of measured and predicted responses without and with a 4.5L air pocket near the location of in-line valve “No.5” for test 1

The inclusion of the air pocket gives rise to a local dip of a magnitude and location matching those in the measured response. As expected, the suspected in-situ air pocket does not give rise to any significant dispersion or damping in the long-term measured or predicted responses. Tests 3 and 4, conducted with an 18.8L artificial air pocket (as reported in Appendix L), confirm that air pockets of this approximate magnitude do not cause significant dispersion or damping.

7.6 Damping along the Morgan Transmission Pipeline

7.6.1 Eliminated factors

Significant long-term damping of the measured responses from the Morgan Transmission Pipeline (MTP), for the tests conducted in May and August 2004, has been identified above. In the case of the tests performed with in-line gate valves “No.1” and “No.2” closed to form downstream boundary conditions, neither quasi-steady friction nor unsteady friction models accounted for this damping. Furthermore, the quantity of entrained air required to match the measured damping gave rise to an order of magnitude more dispersion than was observed.

Information from South Australian Water Corporation operators confirmed that a small amount of flow occurred under in-line gate valve “No.1” because of a small amount of debris lodged in the seat of the valve. The operators estimated that a flow of approximately 2.5L/s was coming through at the offtake to the Morgan filtration/treatment plant adjacent to the pump discharge location. A flow of 2.5L/s under the downstream boundary valve has been incorporated when in-line gate valve “No.1” forms a downstream boundary. However, this only marginally increases the predicted damping. Furthermore, a similar magnitude of damping was observed when in-line gate valve “No.2”, which does not leak, was used to form a downstream boundary condition. Finally, it has been confirmed that this damping cannot be explained by the presence of a single air pocket (either in-situ or artificially introduced). As a consequence, it is necessary to investigate other possible physical phenomena that may be contributing to the excessive damping observed in the measured responses of the MTP with either valves “No.1” or “No.2” acting as boundary conditions.

7.6.2 Possible damping through cross-connections

A pair of 700mm diameter cross-connections to a parallel transmission pipeline were located at chainages 7237m and 7285m along the Morgan Transmission Pipeline (MTP). It was thought that, if they could not be completely sealed, cross-flow to the parallel main might damp the measured responses. A forward transient model has been developed including the cross-connections and a section of the parallel transmission pipeline with a nominal diameter of 1200mm. In-line valves in each cross-connection were opened to form 70mm equivalent diameter orifices. The boundary conditions for the second main were adjusted such that a flow of 4.3L/s was established through the cross-connections from the MTP to the parallel pipeline.

Figure 7-45 shows the predicted long-term response of the system including the partially open cross-connections to the parallel pipeline. Unfortunately, the predicted response, while including significantly more damping than the predicted response without the partially open cross-connections, shows an order of magnitude less damping than the measured response of the MTP for test 1 conducted in May 2004. Furthermore, the phase of the predicted response of the system including the partially open cross-connections to the parallel lags that of the measured response.

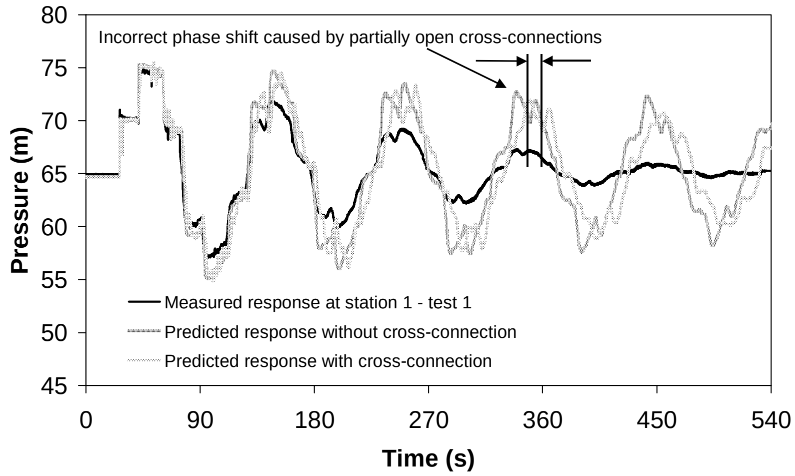
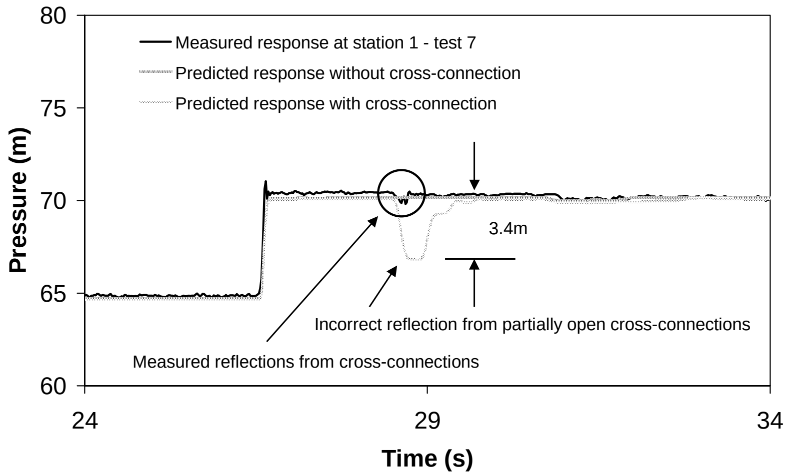


Figure 7-45 – Long-term period comparison between measured and predicted responses with closed and partially open cross-connections

Figure 7-46 shows the predicted response of the system over a time period of 10s. There is a much too pronounced dip in the reflection plateau of the predicted response. Interestingly, this dip is much larger than that for an equivalent side discharge leak of 4.3L/s. The reason is the coupling, through the partially open cross-connections, to the large 1.2m nominal diameter parallel pipeline. Based on the results of the modelling, and indications from South Australian Water Corporation operators, it appears that the cross-connections were fully closed.



Figures 7-46 – Comparison between measured and predicted responses with closed and partially open cross-connections to parallel transmission pipeline over 10s

7.7 Effects of mechanical motion and flexural waves

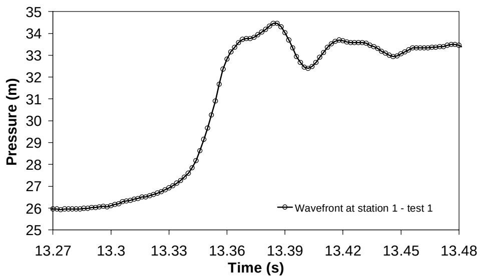
7.7.1 Expectations from previous research

Fluid Structure Interaction (FSI) and mechanical damping refer to the interaction between a pipe wall and the contained fluid, resulting in the formation of precursor waves (i.e., waves travelling in the pipe wall faster than the main wave in the fluid), lower frequency flexural waves and/or energy loss from the pipeline, via forms of mechanical motion, to external restraints. General mechanical dispersion and damping mechanisms include radial pipe hoop motion, wall bending and shear stress near steep wavefronts, longitudinal and lateral motion along pipes and at bends, and sliding and/or other inelastic behaviour at supports.

Skalak (1956) theoretically confirmed that the inertial effects of a pipeline, coupled with the ability to move or vibrate, could lead to the formation of precursor waves with associated wavefront dispersion. Williams (1977) confirmed that the interaction of precursor and main waterhammer waves with changes in pipeline profile could give rise to flexural waves and further wavefront dispersion. Budny et al. (1991) demonstrated in the laboratory that inelastic dispersion and damping are caused by the transfer of energy from motion and vibration to pipeline restraints. As a consequence, it is necessary to consider the likely impact of these FSI effects upon the transient response of the Hanson Transmission Pipeline and Morgan Transmission Pipeline.

7.7.2 Potential Skalak effects in the Hanson Transmission Pipeline

Figures 7-47 and 7-48 show the measured response of the Hanson Transmission Pipeline (HTP) for test 1, at stations 1 and 2, respectively, immediately after the arrival of the initial transient wavefront. An oscillating waveform is superimposed on the transient plateau following the initial step at both stations. This waveform is better defined, but smaller in amplitude, at station 2 (i.e., closer to the transient source). Furthermore, the initial wavefront has dispersed significantly by the time the wavefront has reached station 1 (only 878m from the transient source).



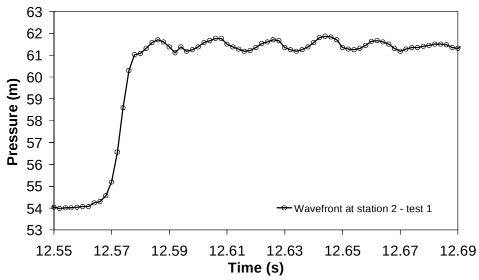
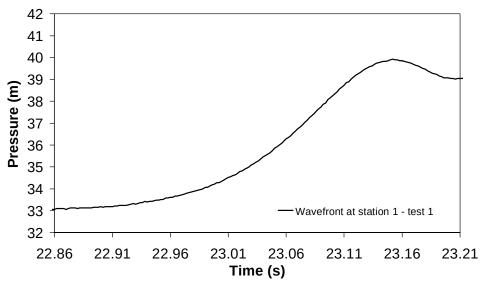
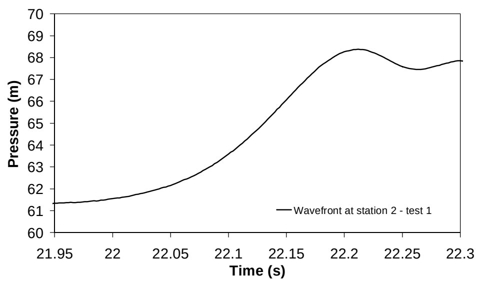


Figure 7-47 and 7-48 – Oscillation and dispersion of initial wavefront for no-leak test after travelling to stations 1 and 2, respectively

Figures 7-49 and 7-50 show the progressive dispersion of the transient wavefront after reflecting from the closed in-line valve at "Sheep-Dip". As mentioned previously, the extent of dispersion is significantly greater than that predicted using a forward transient model with either quasi-steady or unsteady friction. The unevenness in the plateau is related to an amalgamation of reflections from the Burra township pump station offtake.





Figures 7-49 and 7-50 – Dispersion of reflected wavefront from closed in-line valve for no-leak test after returning to stations 1 and 2, respectively

A preliminary investigation into the presence of entrained air has been outlined above with the conclusion that only a small quantity is likely to be present in the HTP. While entrained air can cause dispersion, the percentage of air required to match the dispersion observed over the initial stages of the measured responses from the HTP causes excessive dispersion in the long-term. The possibility that the measured responses obtained from the HTP include some or all of the effects described by Skalak (1956), Thorley (1969), Williams (1977) and Budny et al. (1991), relating to precursor and flexural waves and mechanical dispersion and damping, needs to be further investigated.

7.7.3 Predicted and observed oscillations following main wavefront

Skalak (1956) derived four equations relating the pressure, axial velocity, axial displacement and radial deflection in a coupled pipe-fluid system. The equations relating the pressure and axial velocity in a fluid to the axial displacement and radial deflection of the containing pipe wall involve indefinite integrals. However, Skalak (1956) realised that asymptotic solutions could be determined by approximating the integrals for sufficiently large values of |z| where z is the relative distance from the initial wavefront. These solutions confirmed that the wavefront should theoretically disperse with increasing time and that oscillations will occur for both precursor and main waterhammer waves. Tijsseling et al. (2006) presented a detailed review of the mathematics and derivations developed by Skalak (1956) and these have been reproduced, in part, in Appendix Q. The key asymptotic solution, necessary to reproduce previous numerical results presented by Skalak (1956) and, more importantly, to model the oscillations and dispersion in the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP), is also presented in Appendix Q. The oscillation in the main waterhammer wave can be theoretically predicted using the solution for the integral representing the dimensionless wave height and coefficients Cp_n and Cw_n using the equation:

$$p_n(\beta_n) = \frac{p_0}{2} - Cp_n Cw_n \int_0^{\pm\infty} \frac{\sin(\eta + \beta_n \eta^3)}{\eta} d\eta \qquad (7\text{-}1)$$

where p_0 is the pressure immediately after the passage of the main waterhammer wavefront and the other terms have been defined in Appendix Q

The physical and geometric details of the HT have been used to determine the range of parameters and coefficients, originally derived by Skalak (1956), which are required to determine the form of the theoretically predicted oscillation in the main waterhammer wave (n=1) and precursor wave (n=2). The calculated parameters and coefficients for the HTP are listed in Table 7-5:

Table 7-5 – Skalak (1956) parameters for the Hanson Transmission Pipeline

NOTE: This table is included on page 139 of the print copy of the thesis held in the University of Adelaide Library.

Using the parameters and coefficients above we can calculate:

$Cp_1Cw_{1(stn1)} = 19441.3$ and $Cp_2Cw_{2(stn1)} = 54.7$

$Cp_1Cw_{1(stn2)} = 19530.8$ and $Cp_2Cw_{2(stn2)} = 54.9$

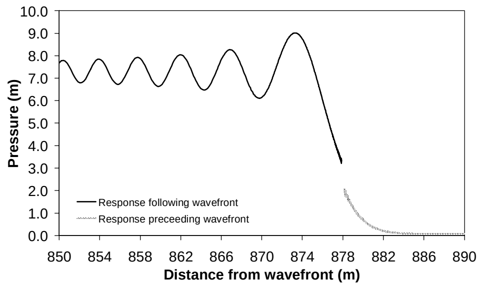
It is apparent that the magnitude of any precursor wave in the HTP will be approximately 0.28% of the magnitude of the main waterhammer wave (based on the ratios of the above coefficients). Given the pressure rise immediately after the passage of the main waterhammer wave was on average 7.40m, the maximum size of the precursor wave that is theoretically predicted is approximately 0.02m at both stations. This explains why precursor waves were not observed in the measured responses.

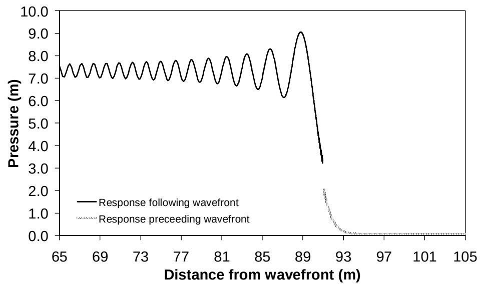
Coefficients Cp_1 , $Cw_{1(stn1)}$ and $Cw_{1(stn2)}$, and the solution for the integral representing the dimensionless wave height, can be combined to obtain the predicted response of the main waterhammer wave immediately following the passage of the wavefront. The integral solution is plotted against the dimensionless distance from the wavefront, z^*, divided by $\sqrt[3]{d_1 t}$ (which equates to $1/\sqrt[3]{\beta_n}$). This quantity can be converted to a distance from the wavefront, in both positive and negative directions, by multiplying through by $\sqrt[3]{d_1 t}$ and using the relationship:

$$z = z^* + c_1 t \qquad (7\text{-}2)$$

where both c_1 and d_1 for the Hanson Transmission Pipeline are listed in Table 7-5

Figure 7-51 shows the predicted response of the main waterhammer wave at station 1, as a function of distance from the wavefront, using a time = 0.835s after the generation of the transient (it takes approximately 0.835s for the wavefront to reach station 1 following the induction of the controlled transient). The distance the wavefront has travelled is approximately 878m (i.e., the distance from the position at which the transient is induced to the location of station 1). Hence, at distances less than 878m the wavefront has already passed and a pressure rise and oscillation is observed. Figure 7-52 shows the predicted response of the main waterhammer wave at station 2 using a time = 0.087s after the generation of the transient. In this case, it takes approximately 0.087s for the wavefront to reach station 2 following the induction of the controlled transient and the distance the wavefront has travelled is approximately 91m (i.e., the distance from the position at which the transient is induced to the location of station 2). Hence, at distances less than 91m the wavefront has already passed and a pressure rise and oscillation is observed.





Figures 7-51 and 7-52 – Response of the main waterhammer wave, predicted using Skalak's equations, at stations 1 and 2, respectively

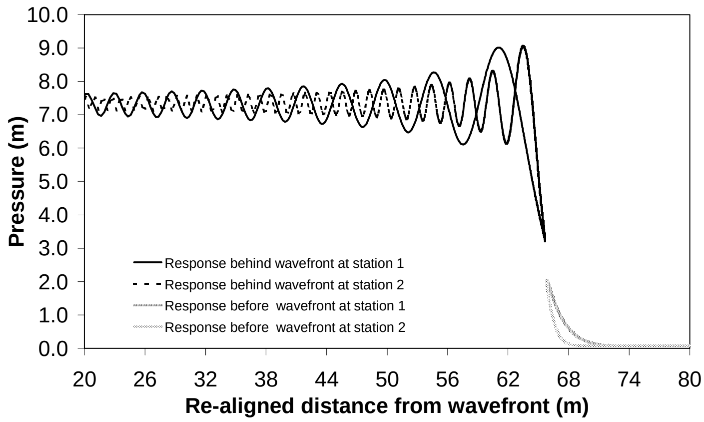
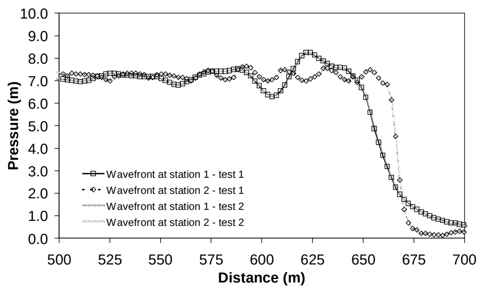
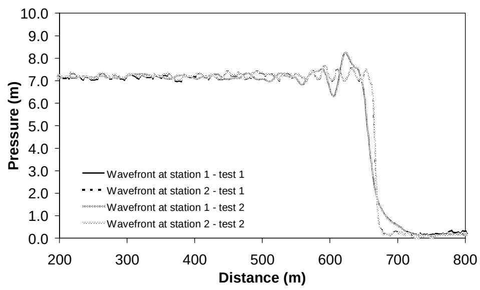


Figure 7-53 – Comparison of predicted response of main waterhammer wave, predicted using Skalak's equations, at stations 1 and 2

The distance axis can be adjusted to overlay the predicted responses at stations 1 and 2 and facilitate a direct comparison as shown in Figure 7-53 (above). The comparison between the two predicted responses, plotted over the same relative distance scale of 60m, illustrates the important result that the frequency of the oscillations is less at station 1 than station 2. Furthermore, the dispersion of the wavefront at station 1 is more than at station 2.

Figures 7-54 and 7-55 show the measured response of the HTP for the no-leak tests 1 and 2, at stations 1 and 2, with time converted to distance on the horizontal axis using c_1 = 1051.3m/s and the data order reversed to plot the pressure rise and oscillations as a function of the relative distance before and after the passage of the wavefront. Both figures show the measured response over a similar scale to that previously used to present the measured responses (previously with pressure as a function of time).





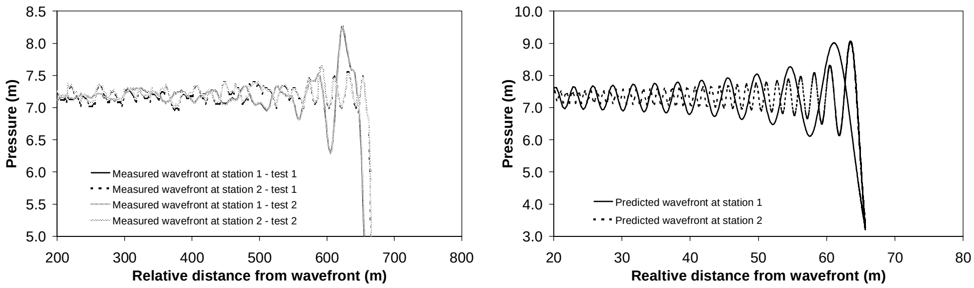
Figures 7-54 and 7-55 – Measured responses of the HTP for test 1 and 2, at stations 1 and 2, plotted against distance over scales of 200 and 600m, respectively

A comparison of Figures 7-56 and 7-57 reveals that, while the nature of the oscillations are similar for the measured and predicted responses, the frequency is in error by a factor of approximately 12. Figures 7-58 and 7-59 confirm the discrepancy by illustrating the measured and predicted responses over a distance scale of 80m. The discrepancy between the measured and predicted frequency of oscillations, at both stations, has been confirmed by applying Skalak's equations from Appendix Q to obtain the predicted frequency of oscillation at stations 1 and 2 (i.e., at times 0.835s and 0.087s, respectively):

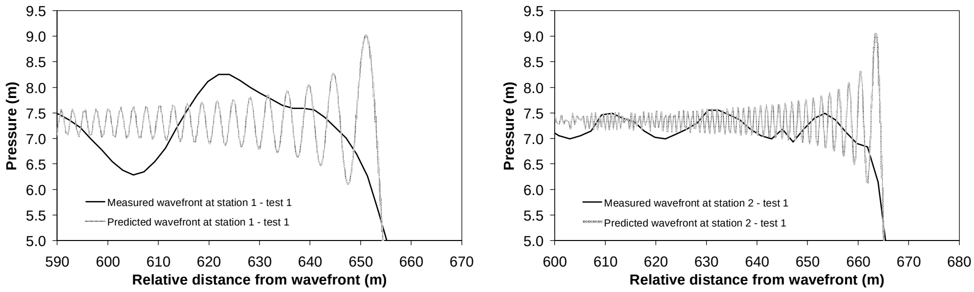
$$f_{1(stn1)} = 0.36 \frac{c_1}{\sqrt[3]{d_1 t_{(stn1)}}} = 270.5Hz$$

$$f_{1(stn2)} = 0.36 \frac{c_1}{\sqrt[3]{d_1 t_{(stn2)}}} = 575.9Hz$$

The measured frequencies of oscillation, based on the first 5 periods of the responses at stations 1 and 2, are 21.6Hz and 54.8Hz, respectively. This confirms that the frequency of the predicted oscillation is in error by an average factor of approximately 11.5.



Figures 7-56 and 7-57 – Measured and predicted responses for tests 1 and 2 at stations 1 and 2, respectively



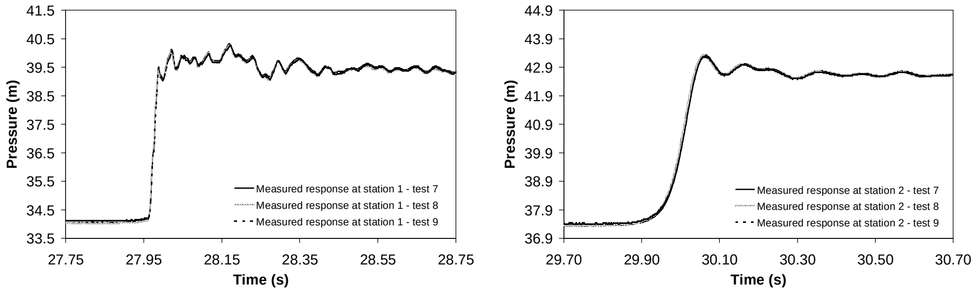
Figures 7-58 and 7-59 – Direct comparison of measured and predicted responses for test 1 at stations 1 and 2, respectively

There are many reasons that could account for the significant discrepancy between the measured and predicted frequency and magnitude of oscillations. These include assumptions made in the calculation of a composite elasticity and Poisson's ratio for the steel walled and cement lined HTP. Perhaps more significantly, the equations presented by Skalak (1956) are based on the assumption of thin walled shell behaviour and neglect vibration and the likely presence of flexural waves. Furthermore, the theory presented by Skalak (1956) does not take into account different forms and magnitudes of pipeline restraint and/or mechanical damping.

Finally, the solution of the integral governing the dimensionless wave height is based upon assumptions of relatively large distances and times (i.e., greater than approximately 1s). Station 2, in particular, is only 91m from the source of the transient and this may mean the accuracy of the Skalak formulation is reduced when applied to predict the measured response at this location. Nevertheless, the similarities between the measured and predicted responses are sufficient to suggest some form of phenomena which, if not immediately explicable using the theory developed by Skalak (1956), is suggestive of a Fluid Structure Interaction (FSI) effect. That said, there may be non-fluid structure interaction related explanations for the observed waveforms as investigated in Chapter 10.

7.7.4 Potential Skalak effects in the Morgan Transmission Pipeline

Figures 7-60 and 7-61 show the measured response of the Morgan Transmission Pipeline (MTP) for tests 7, 8 and 9, at stations 1 and 2, respectively, immediately after the arrival of the initial transient wavefront. An oscillating waveform is superimposed on the transient plateau following the initial step at both stations. The waveform has a lower frequency than that observed for the corresponding station on the Hanson Transmission (HTP) and the form of the oscillation is irregular. As for the HTP, it is apparent that the initial wavefront has dispersed significantly by the time the wavefront has reached the measurement station located further from the transient generator (in the case of the MTP, this is station 2 located 2478m from the transient source).



Figures 7-60 and 7-61 – Oscillations in the measured responses for tests 7, 8 and 9 at stations 1 and 2, respectively

As for the HTP, the theory and equations developed by Skalak (1956) can be applied to determine the predicted form of the oscillations for the MTP. The physical and geometric details of the MTP have been used to determine the range of parameters and coefficients required to determine the form of the oscillation in the main waterhammer wave (n=1). The calculated parameters and coefficients for the MTP are listed in Table 7-6:

Table 7-6 – Skalak (1956) parameters for the Morgan Transmission Pipeline

Skalak parameter	**Main wave**
C_1,c_2	c_1 = 962.3m/s
D_1,d_2	d_1 = 4.95
p_o (stn 1)	p_o (stn 1) = 5.53m
p_o (stn 2)	p_o (stn 2) = 5.34m
D_1, D_2	D_1 = 4.30e^{08}
$C_{p1,2}$	C_{p1} = -8.45e^{09}
$C_{w1,2}$ (stn 1)	C_{w1} (stn 1) = -1.66e^{-06}
$C_{w1,2}$ (stn 2)	C_{w1} (stn 2) = -1.60e^{-06}

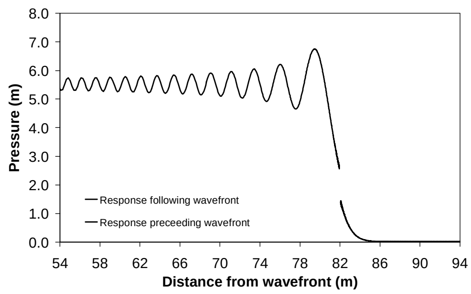
Using the parameters and coefficients above we can calculate:

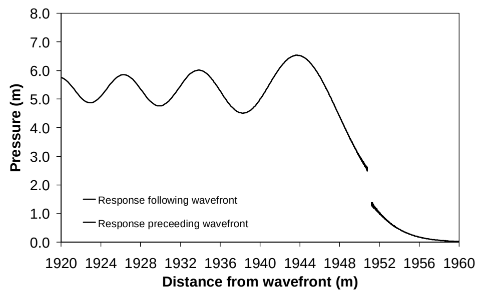
$$Cp_1Cw_{1(stn1)} = 14027.0$$

$$Cp_1Cw_{1(stn2)} = 13520.0$$

As for the HTP, these coefficients can be combined with the solution for the integral representing the dimensionless wave height to obtain the predicted response of the main waterhammer wave, immediately following the passage of the wavefront, for the MTP.

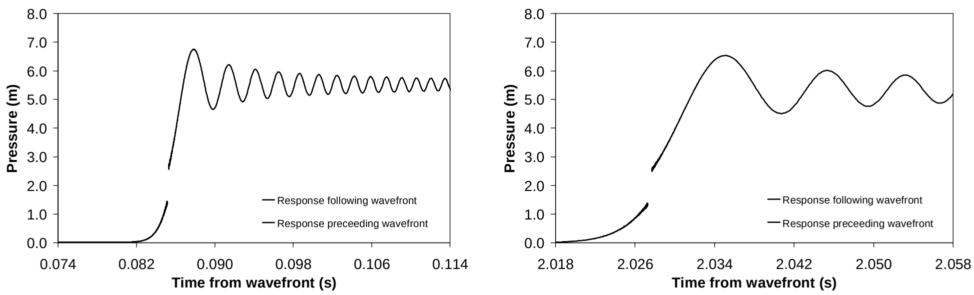
Figure 7-62 shows the predicted response of the main waterhammer wave at station 1, as a function of distance from the wavefront, using a time = 0.085s after the generation of the transient. It takes approximately 0.085s for the wavefront to reach station 1 following the induction of the controlled transient. The distance the wavefront has travelled is approximately 82m (i.e., the distance from the position at which the transient is induced to the location of station 1). Hence, at distances less than 82m the wavefront has already passed and a pressure rise and oscillation is observed. Figure 7-63 shows the predicted response of the main waterhammer wave at station 2 using a time = 2.575s after the generation of the transient. It takes approximately 2.575s for the wavefront to reach station 2 following the induction of the controlled transient and the distance the wavefront has travelled is approximately 2478m (i.e., the distance from the position at which the transient is induced to the location of station 2). Hence, at distances less than 2478m the wavefront has already passed and a pressure rise and oscillation is observed.



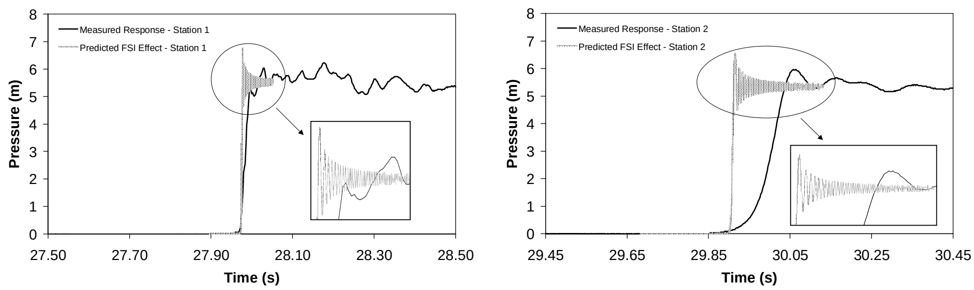


Figures 7-62 and 7-63 – Response of the main waterhammer wave, predicted using Skalak's equations, plotted against distance at stations 1 and 2, respectively

Figures 7-64 and 7-65 show the predicted response of the main waterhammer wave at stations 1 and 2, respectively, plotted against a horizontal axis converted from distance to time with both plots over a time scale of 0.04s. Arranging the predicted responses in this form enables a direct comparison with the measured responses from the MTP (as shown in Figures 7-66 and 7-67 over a time scale of 1.0s). The oscillations in the main waterhammer waves at stations 1 and 2, as predicted using the theory and equations developed by Skalak (1956), are of a much higher frequency than those that were measured.



Figures 7-64 and 7-65 – Response of the main waterhammer wave, predicted using Skalak's equations, plotted against time at stations 1 and 2, respectively



Figures 7-66 and 7-67 – Predicted versus measured responses for test 7 (similar results obtained for test 8 and 9) at stations 1 and 2, respectively

The predicted waveforms do not include the dispersive effect of entrained air (or dispersion and damping caused by mechanical motion and vibration). This is why, at station 2 in particular, there is a significant discrepancy between the predicted and observed wavefronts. Nevertheless, it is clear that the oscillations predicted by Skalak (1956) do not explain the observations.

7.7.5 Flexural waves and structural oscillations

There are discrepancies and similarities between the measured waveforms and those predicted using the theory and equations presented by Skalak (1956). In particular, the measured waveforms from the Hanson Transmission Pipeline (HTP) take a form similar to that predicted by Skalak (1956), but have a lower frequency, while those from the Morgan Transmission Pipeline (MTP) are irregular and of even lower frequency (less like the form predicted by Skalak (1956)). A possible explanation, or contributing factor, may be that the HTP and MTP vibrate and/or oscillate following the sudden closure of the side discharge valve used to generate the controlled transient. Figure 7-68 shows an idealised representation of a section of transmission pipeline at the location of the transient generator and possible structural oscillation that may have been induced.

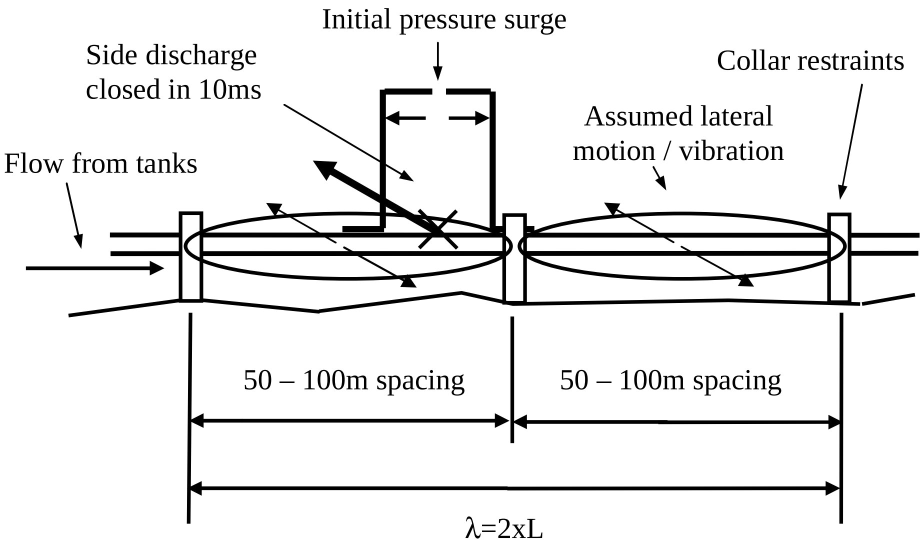


Figure 7-68 – Idealised mode of structural oscillation for aboveground pipeline

If the sections of the transmission pipeline between each collar restraint are treated as having open - open boundary conditions then the period of any structural oscillation may be calculated using $T = 2L/a$ where the period is equal to the inverse of the frequency of oscillation (i.e., $T = 1/f$ and $f = v/\lambda$ where v is the velocity of the waves in the structure or pipe wall and λ is the wavelength of the oscillation or two times the spacing between collar restraints for open - open boundary conditions). If the speed of propagation of the precursor waves in the pipe wall is, for example, approximately 4479.7m/s (see parameters for the HTP determined above) and the spacing of the collar restraints is, on average, 75m, then the frequency and period of the oscillations can be calculated as:

$$f = \frac{v}{\lambda} = 29.9Hz \text{ and } T = \frac{1}{f} = 0.0335s$$

As summarised previously, the measured frequencies of oscillation for the HTP, based on the first 5 periods of the responses at stations 1 and 2, are approximately 21.6Hz and 54.8Hz, respectively. The measured frequencies for the irregular patterns observed for the MTP, based on the first 5 periods of the responses at stations 1 and 2, are approximately 27.5Hz and 10.0Hz, respectively. These measured frequencies are, in contrast to the predicted frequencies determined using Skalak's formulation, of the same order as the calculated frequency based on an idealised structural oscillation.

Further work, outside the scope of this research, has since been undertaken by the author involving direct measurement of the motion and vibration of the pipelines using accelerometers. Figure 7-69 indicatively shows structural accelerations recorded after the passage of a main wavefront along the 1200mm diameter transmission pipeline parallel to the MTP. A Skalak-like oscillation is clearly apparent in the pressure response. The results confirm that the pipelines do move or vibrate in oscillating patterns immediately following the passage of the main wavefront. The results and additional analysis of the FSI problem as it relates to large diameter aboveground transmission pipelines will be published in due course.

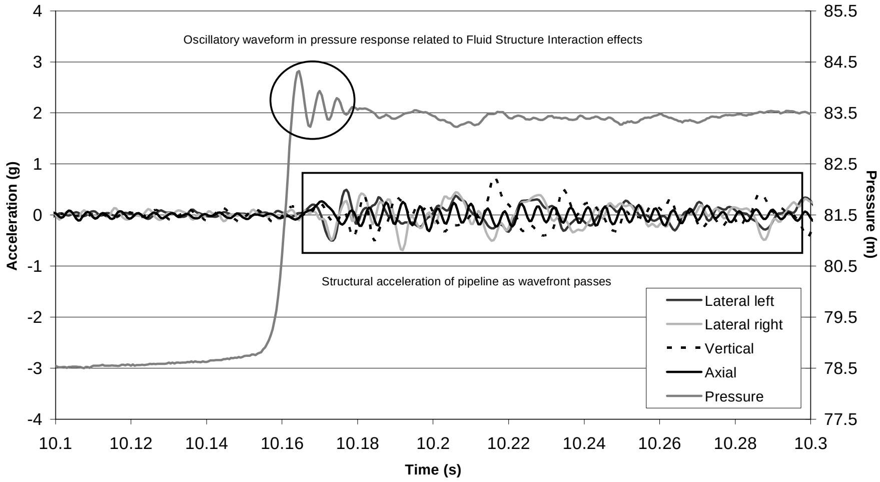


Figure 7-69 – Pressure response showing Skalak-like oscillations and structural accelerations for transmission pipeline parallel to MTP

7.8 Possible explanations for dispersion and damping

The observed wavefront dispersion for the Hanson Transmission Pipeline (HTP) is summarised below. Results from the Morgan Transmission Pipeline (MTP) confirm similar or greater levels of dispersion. Table 7-7 presents the measured (75% of total pressure rise across the respective wavefronts) and predicted dispersion for the main waterhammer wave, at times corresponding to the arrival of the wavefronts at stations 1 and 2, following the induction of the initial transient for test 1 on the HTP. Significantly, the rate of dispersion predicted, using the theory developed by Skalak (1956), is an order of magnitude less than that observed for the measured responses. This may be explained by the fact that the effect of flexural wave formation and mechanical dispersion and damping associated with restraints is neglected in Skalak's formulation. That is, the dispersion theoretically predicted by Skalak (1956) is a function of only the inertial mass of the pipeline, and contained fluid, and not the loss of energy to other forms of wave formation and the pipeline restraints.

Williams (1977) performed laboratory tests in which flexural wave formation, for pipes with the flexibility to move between restraints, was observed. Flexural waves are produced when precursor and waterhammer waves interact with changes in pipe profile in plan and elevation. In the case of the HTP, there are numerous such changes in the plan and elevation profile. As time increases after the induction of the transient, and the wavefronts for the precursor and main waterhammer waves propagate along the HTP, the number of superimposing incident and reflected waves increases exponentially. As explained by Williams (1977), this proliferation of waves will be accompanied by the growth of flexural waves between points of restraint along a pipeline.

Table 7-7 – Comparison of observed and theoretically predicted wavefront dispersion using equations derived by Skalak (1956) for the HTP

Wavefront Type	Time after transient induction (s)	75% rise time (ms)	Skalak (Main Wave) (ms)	Potential flexural wave dispersion (ms)
Initial Front – station 1	0.832	36	5.4	30.6
Initial Front – station 2	0.086	10	2.5	7.5
Valve Reflection – station 1	10.322	160	12.5	147.5
Valve Reflection – station 2	9.404	154	12.1	141.9

As Williams (1977) points out, it is extremely difficult to accurately predict, even in the laboratory, the mechanical dispersion and damping that is associated with the production of precursor and flexural waves. However, if the effect of pipe motion is significant, as it appears to be for the HTP and other large aboveground transmission pipelines, then the dissipation of energy from these waveforms into restraints must be taken into account. Furthermore, the energy loss to the restraints will, in some cases, although seemingly not for the HTP, exceed the energy lost to internal fluid friction. Williams (1977) suggests that a mechanism for elastic hysteresis could be used to mimic the loss of wave energy to pipeline restraints.

Finally, the laboratory work of Budny et al. (1991) clearly identifies additional dispersion and damping associated with the mechanical restraint of pipelines. As mentioned above, Budny et al. (1991) derived four coupled, linear, first order, hyperbolic, partial differential equations to include the effect of the pressure and axial velocity of the water contained in a pipeline with the axial stress and velocity of the pipeline itself. In addition, mechanical damping due to pipeline restraints was incorporated using an equivalent "viscous" damping mechanism in a similar fashion to that adopted in other fields of engineering with dynamic loads and damping. This mechanism forms the basis for the conceptual transient model previously proposed by the author in Chapter 5.

7.9 Summary

The details and results of the controlled transient tests conducted on the Hanson Transmission Pipeline (HTP) and Morgan Transmission Pipeline (MTP) are presented in this chapter. Traditional transient models are developed to obtain predicted transient responses for comparison with the measured responses. Friction is initially accounted for using a quasi-steady approximation. However, the measured damping over the long term response for both transmission pipelines significantly exceeded the friction damping predicted using the quasi-steady approximation. Unsteady friction algorithms are then included in the forward transient model to improve the representation of friction damping. This improved the comparison between the long term measured and predicted damping. However, a persistent discrepancy, in terms of both dispersion and damping, was observed for both transmission pipelines.

Different quantities of entrained air are included in the forward transient model, using the Discrete Gas Cavity Model (DGCM), in an attempt to account for dispersion observed in the measured responses. However, the inclusion of entrained air could not consistently explain the observed dispersion. It was found that the percentage of entrained air required to give a satisfactory match over the initial stages of the measured responses gave excessive dispersion over the long term. That said, the inclusion of small percentages of entrained air improved the comparison between measured and predicted responses for the MTP when in-line gate valve “No.3” was closed to form a boundary condition. The effect of an in-situ air pocket, identified during the tests conducted on the MTP during May 2004, is found to be insignificant. Furthermore, the possibility of significant damping through partially open cross-connections to a second transmission pipeline parallel to the MTP has been eliminated. Overall, the application of existing algorithms for quasi-steady friction, unsteady friction, entrained air, discrete air pockets and cross-connection damping are not generally able to account for the long term dispersion and damping observed in the measured responses from the HTP and MTP.

The effect of Fluid Structure Interaction (FSI) and, in particular, the oscillations predicted by Skalak (1956), is investigated. Skalak's (1956) algorithms predicting precursor and main waterhammer wave oscillations together with wavefront dispersion have been applied in this chapter to determine whether they can replicate observed oscillations in the measured waveforms, over the short term, and significant wavefront dispersion. While some similarities in the form of the measured oscillations with those predicted by Skalak (1956) are observed for, in particular, the HTP, there are significant discrepancies between the measured and predicted frequency of the oscillations. Furthermore, the oscillations in the measured responses from the MTP are irregular and do not agree well with those predicted by Skalak (1956). The possible formation of proliferating flexural waves, as predicted by Williams (1977), has been investigated but no definitive conclusion could be drawn that observed dispersion was caused by this effect.

The application of the existing algorithms in complex forward transient models, has not been able to explain observed dispersion nor damping in the measured transient responses from either transmission pipeline. In the context of the long term response of the pipelines, the damping discrepancies are problematic and of a magnitude that will prevent the successful application of transient response analysis and/or Inverse Transient Analysis (ITA) for fault detection. In this regard, parameters such as pipeline roughness may need to be calibrated. Furthermore, the effects of pipeline restraints and mechanical dispersion and damping need to be taken into account by calibrating a conceptual transient model, such as the one presented in Chapter 5, to measured responses. In the context of the short term response of the pipelines, the oscillations observed following the passage of the initial wavefronts may prevent the successful application of transient response analysis and/or ITA unless a physical explanation for the phenomena can be identified. Reflections from faults, unless very distinct, may be obscured by these oscillations.