Stephens, Mark Leslie; Lambert, Martin Francis; Simpson, Angus Ross
Determining the internal wall condition of a water pipeline in the field using an inverse transient
Journal of Hydraulic Engineering, 2013; 139(3):310-324

DETERMINING THE INTERNAL WALL CONDITION OF A WATER PIPELINE IN THE FIELD USING AN INVERSE TRANSIENT MODEL

M. L. Stephens[1], M. F. Lambert[2] and A. R. Simpson[3]

CE Database subject headings:

Pipelines, Deterioration, Corrosion, Diagnosis, Transients, Field Tests

Abstract

The application of Inverse Transient Analysis (ITA) to estimate the location and magnitude of lost lining and internal corrosion of metal pipelines is demonstrated for a field pipeline. The method uses a transient model and inverse search algorithm to analyse patterns of measured pressure reflections obtained after a transient pressure wave is induced in a pipeline. The method is applied in the field on a 6km long section of a 750mm nominal diameter steel pipeline with internal cement mortar lining. The equipment used for generating hydraulic transients and measuring pressure responses in the pipeline is described. Results of the field tests are analysed to estimate the location and extent of internal wall damage along the pipeline. Extensive ultrasonic thickness survey results are used to corroborate the approximate location and magnitude of predicted pipeline wall damage.

Introduction

The loss of protective linings from the inside of transmission pipelines and subsequent wall corrosion is an important problem for engineers planning rehabilitation and when estimating the remaining working life for expensive pipeline assets. Internal damage is historically more difficult to determine because is not immediately detectable by visual inspection (e.g., once a

[1] Principal Engineer, South Australian Water Corporation, mstephen@civeng.adelaide.edu.au
[2] Professor, School of Civil, Environmental and Mining Engineering, the University of Adelaide, South Australia
[3] Professor, School of Civil, Environmental and Mining Engineering, the University of Adelaide, South Australia

pipeline is excavated if buried). The investigation of transmission pipelines in South Australia has revealed that internal corrosion typically occurs along individual pipeline sections (up to approximately 15m long). This may be because of manufacturing defects or installation issues specific to each section of pipe comprising the overall pipeline. The damage to the pipeline walls is often intermittent with damaged and undamaged sections of pipeline interspersed with each other. Generally, there are more undamaged sections than damaged sections. The ability to detect and locate the damaged sections is therefore important. Existing technologies provide location specific information but can only be intermittently deployed along the length of a pipeline. This means that the information from such inspections may either coincide with a damaged section of pipeline or not. The statistical risk of biasing a condition assessment survey using existing technologies may be increased depending on whether selected investigation locations coincide with damaged or undamaged sections of pipeline. Furthermore, closed circuit television (CCTV) camera investigations may only be conducted over limited lengths of pipeline.

Hydraulic transients provide a method by which pipelines can be investigated over their entire length (i.e., statistical extrapolation from results at specific locations is not required). The response to a transient test is directly related to the remaining wall thickness along the pipeline and thereby provides an indication of the capacity of the pipeline to resist pressure changes at specific locations. This paper presents field evidence of the physical relationship between pipeline wall condition and transient response and presents the application of Inverse Transient Analysis (ITA), conducted using a Shuffled Complex Evolution University of Arizona (SCE-UA) search algorithm, to estimate the location of internal damage along a pipeline wall by attempting to minimise the difference between field measured and predicted transient responses. The tests results presented relate to a 6km long section of a pipeline called the Morgan Transmission Pipeline (MTP) in South Australia.

Problem Definition

There are two primary processes by which metal pipelines deteriorate. Externally, they may be subject to an aggressive environment which attacks external coatings and corrodes the outside of the pipeline wall. Internally, cement mortar lining (CML) may be lost and internal corrosion may then begin. Both processes apply to cast iron, ductile iron and mild steel pipelines (which may all be manufactured with CMLs).

External Corrosion

External corrosion can be detected by visual examination for aboveground pipelines. For below ground pipes other techniques are required. Point sampling techniques are relatively common and include excavation and coupon sampling or soil resistivity techniques. The major drawback with these techniques is that they only give information at a limited number of locations along a pipeline and require probabilistic algorithms to infer the condition between samples. For example, Linear Polarisation Resistance (LPR) is a soil resistivity technique that recommends sampling at a different spacing depending on the length of pipeline investigated. The condition of the pipeline between spot samples is then inferred using a probabilistic algorithm. Cathodic protection checks are another example and provide specific information along sections of protected metallic pipelines.

Internal Corrosion and Cement Mortar Lining Loss

Based on detailed ultrasonic thickness measurements, undertaken as part of this research as described below, internal wall thinning appears to occur over discrete 5-15 m long lengths of pipeline (i.e., the typical manufactured length of individual sections of pipeline). This may indicate that deterioration is a function of the initial manufactured quality of particular sections of pipe or of events during the installation of the length such as damage during lifting or re-instatement of the cement mortar lining (CML) after joints have been welded (if welded joints have been used). These conclusions are based on detailed examination of the information collected for the mild steel Morgan Transmission Pipeline (MTP). It is likely that cast or ductile iron mains would also exhibit different rates of corrosion over individual lengths due to manufacturing and installation variables (although elastomeric and not welded joints are typically used).

An important characteristic of deterioration due to loss of CML and internal wall corrosion is that, based on observations of the MTP, there is rarely any external manifestation of the internal process. This means that external inspection does not necessarily confirm whether internal damage has occurred. This is also important because external signs of deterioration are often used to guide the design of current condition assessment programs (which might deploy soil resistivity or CCTV camera techniques). Figure 1 shows a typical occurrence where the left hand photograph is an external view and the right hand photograph is an internal view (obtained after a section was cut out of the pipeline) of the same location along the MTP. There is no external sign of the significant internal deterioration that has occurred.

Figure 1 – External and internal views of a section of pipe with internal damage

Background Research

The theoretical potential of Inverse Transient Analysis (ITA) was first proposed and numerically explored for leak detection by Liggett and Chen (1994). The presence of a leak in a pipeline or network results in additional reflections and damping in the response of the system to a hydraulic transient. If a measured response of a system is obtained, and a transient model of the system is developed, then inverse analysis may be able to be performed to estimate the location and size of leaks in the system. Liggett and Chen (1994) demonstrated the technique using a theoretical model of a small water network, numerical data sets and a Levenberg-Marquardt gradient optimisation algorithm to conduct the inverse analysis. A least squares minimisation criterion was applied to minimise the difference between the numerical data and the predicted transient responses as the location and size of leaks in the system were varied by the optimisation algorithm.

A limited number of researchers have subsequently tried to use hydraulic transients for leak and air pocket detection on field pipelines. In particular, Covas et al. (2004) installed leaks at known locations and of known sizes on a 6km long by nominal 300mm diameter ductile iron field pipeline and then induced hydraulic transients by closing a side discharge valve to obtain measured transient responses including the effect of the leaks. Covas et al. (2004) were able to isolate and analyse the reflection information within the measured pressure responses that was related to the leaks and successfully confirm their location and size. Stephens et al. (2004) installed a 10mm diameter leak on a 378m long by nominal 94mm internal diameter ductile iron cement mortar lined field pipeline and then induced a hydraulic transient by either opening or closing a mechanical side discharge valve (4ms closing time) on the top of a standpipe connected to an existing fire hydrant. ITA was successfully applied to the measured response of the pipeline to relatively accurately determine the size and location of the leak. Stephens et al. (2004) also installed a 1.6L air pocket on the same pipeline, obtained a measured response to a hydraulic transient and successfully applied ITA to relatively accurately determine the size and location of the air pocket.

Significant research has been undertaken to develop signal analysis type methods (distinct from ITA) for analysing the measured response of pipelines containing features such as valves, junctions, blockages and leaks. Misiunas et al. (2005) described a method for determining the quality of a valve’s seal based on the reflection of a transient wave from the "closed" valve and a calculated valve resistance coefficient. Laboratory and field tests were undertaken to initiate hydraulic transients in pipelines, using the closure of side discharge valves, and determine the magnitude of transient wave reflections from "closed" valves. Brunone et al. (2008) reported the development of a new method for initiating controlled hydraulic transients in pipelines using a Portable Pressure Wave Maker (PPWM). The device utilises a 200 litre cylindrical pressure vessel and quick opening ball valve connection to a pipeline to enable the injection of higher pressure water from inside the pressure vessel and the creation of a controlled hydraulic transient. Methods for analysing reflections based on timing and magnitude information were applied to measurements from a 352m long by 93.3mm internal diameter high density polyethylene laboratory pipeline including a junction and a leak. The use of the PPWM to detect pipe faults and anomalies such as leaks, illegal branch connections, partial blockages and partially closed valves is further demonstrated, under laboratory conditions, by Meniconi et al. (2011).

Taghvaei et al. (2010) used a side discharge through a solenoid valve at the end of a length of pipe mounted on a fire hydrant to initiate hydraulic transients in a 90m long by 79mm internal diameter medium density polyethylene laboratory pipeline including a leak. Measured reflections were analysed using wavelet decomposition to filter the data and then subject to Cepstrum analysis. The wavelet decomposition, and then re-composition to build the filtered response, was undertaken using the Orthogonal Wavelet Transform (OWT) described by Taghvaei (2009). The filtered response was then subject to Cepstrum analysis (involves taking the Fourier transform of the logarithm of the Fourier transform of the measured response as described by Taghvaei et al. (2006) for leak detection in pipelines). Meniconi et al. (2011) used the combination of a wavelet transform and Lagrangian model to evaluate the causes of discontinuities, such as topological and valve status uncertainties, for a field pipeline. The method was used in preference to ITA, as all of the above reflection analysis techniques are, to avoid difficulties with the simulation of the transient response of the pipeline using complex numerical models.

The physical mechanisms that give rise to pressure reflections from valves, junctions, blockages and leaks, during a transient event, are different to those that give rise to pressure reflections from pipeline wall thickness variations. As mentioned by Hachem and Schleiss (2012), continuous variations in hydroacoustic parameters along a pipeline, such as wave speed due to pipeline wall thickness variations, have not been examined in the above investigations.

Pipeline Wall Thickness Determination Using Hydraulic Transients

To the author's knowledge, the assessment of pipeline wall thickness using hydraulic transients has only been proposed in two previous publications. The first publication is Stephens et al. (2008). To the author's knowledge, this is the first and only time Inverse Transient Analysis (ITA) has been proposed for the determination of continuous pipeline wall thickness variations. Stephens et al. (2008) presented the equations used to develop the transient models and identified key parameters, including pipeline wave speed, relating wall characteristics and thickness to the pressure reflections expected in the response of a pipeline subject to a hydraulic transient. Measured data showing the response of a nominal 750mm diameter steel field pipeline (the Morgan Transmission Pipeline (MTP)) was presented containing pressure reflections from sections of the pipeline with wall damage. It was shown that the representation of wall thickness variations by adjusting the wave speed in the transient model gave a reasonable match between the measured and modelled responses.

Stephens et al. (2008) also presented a method for determining changes in internal pipe wall condition and thickness based on the use of ITA. The method was tested using transient data generated numerically from a pre-determined distribution of known, inferred and arbitrary variations in pipeline wall thickness along a section of the field pipeline. A Genetic Algorithm was used to conduct the inverse analysis, using the numerical data and a least squares minimisation criterion, and the pre-determined distribution of pipeline wall thickness variations was successfully confirmed. The current research describes the extended use of ITA with a new search algorithm and field measured data.

The second publication is Hachem and Schleiss (2012) in which a reflection analysis technique was used to analyse measurements obtained from a 6.25m long by 150mm internal diameter steel laboratory pipeline, with and without an inserted single "weak" section of either aluminium or PVC pipe (typically 50cm long), after it was subject to hydraulic transients. The hydraulic transients were generated using a fast closing in-line valve forced closed by an air jack. Hachem and Schleiss (2012) presented three methods for estimating the wave speed of the hydraulic transient wavefront and then a method for determining the incident reflection travel time from the single "weak" section to the measurement locations. This method involved firstly taking the Fast Fourier Transform of the measurements and then wavelet transform decomposition to localise the "weak" reach. The severity of the local stiffness reduction in the "weak" reach was then estimated using the estimated length of the "weak" reach and wave speed equation inside the reach. The methodology did not use ITA.

Previous Observation of Transient Reflections from Pipeline Wall Damage

Reflections in pressure signals are generated when a transient wave passes along a section of pipe wall that is either thicker or thinner than the majority of the pipe wall. A thinner section of wall (e.g., due to corrosion) gives rise to a slower wave speed for the transient along that section of pipeline. That is, the transient wave slows down and travels more slowly when it enters the thinner walled damaged section and speeds up and returns to its original speed as it leaves it. The reverse occurs for a thicker section of wall which gives rise to a faster wave speed for a transient along that section of pipeline. This process gives rise to observed patterns of pressure reflections. This physical phenomenon was confirmed by Stephens (2008) using transient test results for the Morgan Transmission Pipeline (MTP) from 2004.

It is the correlation between the changes in the metal thickness (and cement mortar lining(CML)) with the speed of propagation of the transient that gives rise to the observed reflections which can, in turn, be used to classify the condition of the pipeline. This correlation can be theoretically predicted by applying Equation (1) as presented by Wylie and Streeter (1993):

$$a = \sqrt{\frac{K/\rho_W}{1 + \left(K/E_S\right)\left(D/e_{eq}\right)c_1}} \tag{1}$$

The contribution of the CML can be included as an equivalent thickness of steel using Equation (2):

$$t_{eqS} = t_C \times \frac{E_C}{E_S} \tag{2}$$

When the CML spalls off the inside of a section of pipeline, and the metal wall corrodes, changes in the impedance and wave speed of that section of pipeline occur. The loss of the CML reduces the stiffness of the pipeline wall by an amount proportional to the loss in thickness and modulus of elasticity of the cement. Once exposed, the pipe wall begins to corrode leading to a reduction in the thickness of metal.

The impedance and wave speed of a section of pipeline are sensitive to the combined effect of the loss of the CML and corrosion of the metal wall. As a consequence, the magnitude and frequency of reflections following a hydraulic transient will increase as a transient wavefront moves along a section of pipeline that is damaged. It is important to recognise that the wave speed will also be sensitive to a reduction of wall thickness caused by external corrosion (i.e., pipe wall thinning gives rise to pressure reflections regardless of whether it is due to external or internal corrosion).

Characterisation of Pipeline Wall Damage

Figure 2 shows the physical and geometric properties of the Morgan Transmission Pipeline (MTP). In addition to the properties illustrated, the elastic modulus of the metal (steel) pipe wall (E_S) is 210GPa, the elastic modulus of the cement mortar (E_C) is 25GPa, the bulk modulus of water (K) is 2.14GPa at 15°C, the density of water (ρ_W) is 999.1 kg/m3 at 15°C and the density of metal (ρ_S) is 7850kg/m3. The composite wall thickness e_{eq} equals 6.25 mm for the MTP when in "good" condition (where the original metal thickness is 4.76 mm). This assumes that the cement mortar lining (CML) is intact and fully bonded with the metal pipe wall. Given that the pipeline is axially and laterally restrained by saddles and integral collar restraints at regular intervals, the restraint factor c_1 should be calculated using Equation (3) in which Poisson's ratio for steel (v) is taken as 0.3:

$$c_1 = 1 - \nu^2 \tag{3}$$

The application of a pipeline restraint factor c_1 = 0.91 allows for Poisson coupling in the pipeline wall and redistribution of stress and strain given axial and lateral restraint. The theoretical wave speed for the MTP in "good" condition can now be calculated as 1015m/s. It is possible to replicate the effect of a damaged section of pipeline in a transient model by varying the pipeline's physical and geometric properties. By way of example, Figure 2 shows four discrete levels of damage for the MTP (when MSCL stands for Mild Steel Cement Lined pipe).

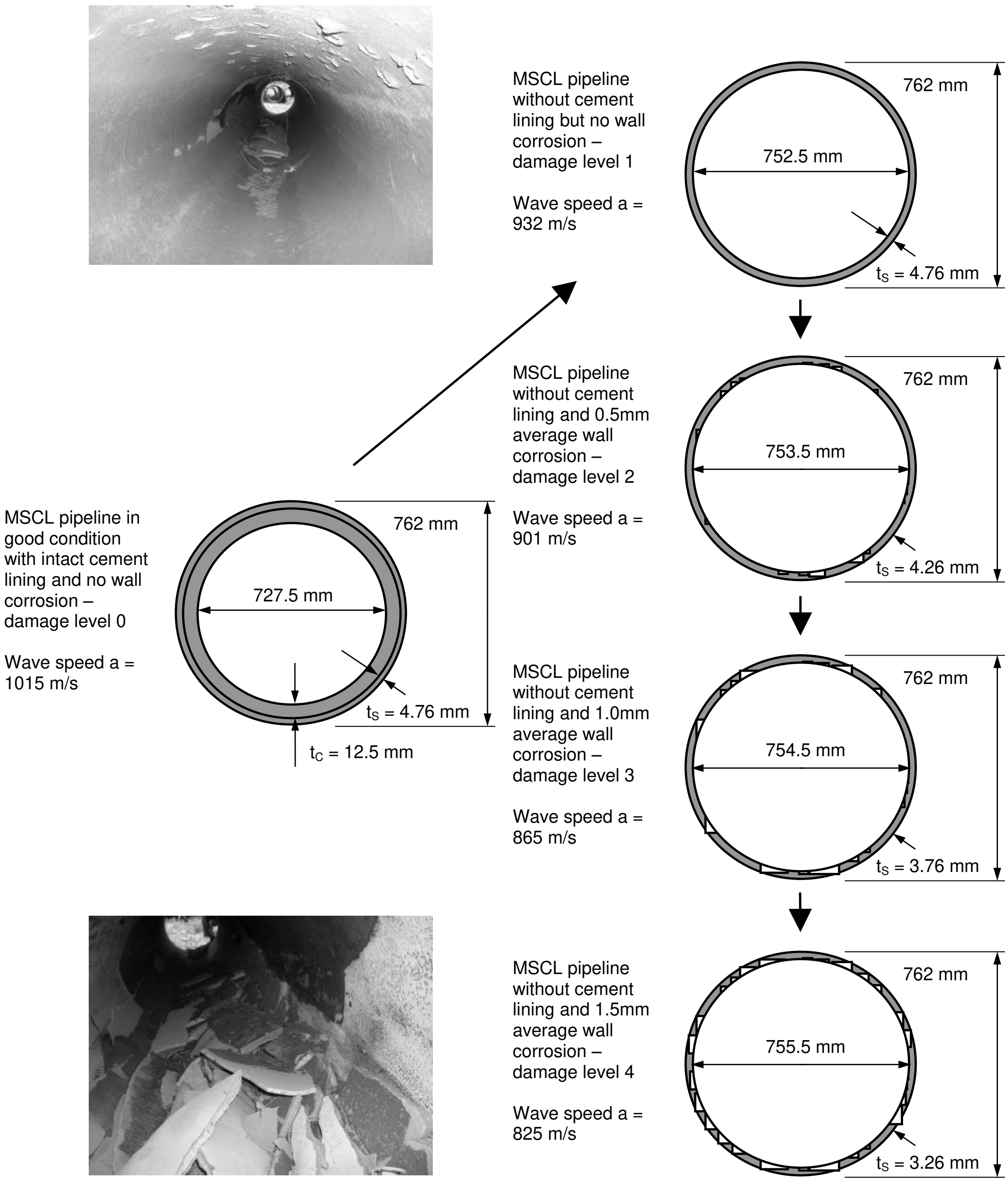

Figure 2 – Approximate representations of four discrete levels of pipeline damage for the Morgan Transmission Pipeline

Numerous combinations of partly lost CML and corroded metal wall can physically occur as can many more categories of damage. Indeed, there is a continuous spectrum of levels of damage that are possible along the MTP. For example, CML may be fully, partially or not be bonded with the pipe wall and this effect can occur over short or longer lengths of pipe.

Similarly, corrosion may have occurred over a significant length of pipe to a relatively uniform degree or may have occurred only in patches to variable degrees. While internal pitting depths cannot be represented, the loss of CML can be specified, as can average reductions in pipeline wall thickness for different degrees of corrosion, over a selected length of pipe. A continuous spectrum of possible wave speeds will be determined, to account for the potential continuous variation of pipe wall condition, in the analysis of the field results presented below.

Inverse Search Algorithm and Error Variance

Shuffled Complex Evolution University of Arizona (SCE-UA) Search Algorithm

The Shuffled Complex Evolution University of Arizona (SCE-UA) inverse search algorithm was developed by Duan et al. (1992) for use in parameter estimation for conceptual hydrological models. Duan et al. (1994) subsequently reported, amongst other things, the selection of optimal algorithmic parameters for the SCE-UA. More recently, Thyer and Kuczera (1999) have compared the performance of the Shuffled Complex Evolution Algorithm (SCE-UA) with the Simulated Annealing Algorithm (SA-SX) and concluded that the former algorithm was generally superior due to its use of multiple complexes. Previous work, has found that the SCE-UA is more robust and efficient than a traditional Genetic Algorithm (GA) which may account for the inability of the GA used in Stephens et al. (2008) to be adapted to the increased number of wave speed parameters fitted in the current research.

The general operation of the algorithm involves generating a random sample of points from possible parameter values (for multiple parameters if required) within the feasible search space (i.e., pre-determined limits to the values the points can take based on parameter feasibility) and evaluating a criterion value (i.e., the fitness of the prediction) for each point and corresponding parameter value. The sample points are ranked from smallest to largest criterion value and then partitioned into complexes (larger criterion values are preferred). Each complex is evolved using a Competitive Complex Evolution (CCE) algorithm and then shuffled (by recombining the sample points into a single population, re-ranking each sample point and re-partitioning the sample points into complexes). If the search has not converged to an optimum, then complexes with the lowest ranked points are removed (until the minimum number of complexes is reached) and the remaining complexes are subject to further evolution using the CCE algorithm. The operation of the CCE algorithm involves the creation of a sub-complex by randomly selecting a number of points from within each complex using a specified probability distribution. The point with the smallest criterion value within each sub-complex is identified and then reflected through the centroid of the sub-complex (determined by excluding this point) to generate a new point within the feasible workspace. If the new point has a criterion value greater that the previous point then it is retained. If not, then the point with the smallest criterion value is replaced with a randomly generated point within the feasible space.

The numerical transient model of the Morgan Transmission Pipeline (MTP) has been coupled with the Bayesian Non-Linear Regression Program Suite (NLFIT) developed by Kuczera (1994) to form an inverse transient model. NLFIT provides options for the application of a number of inverse search algorithms including the SCE-UA. Algorithmic parameters including the number of parameter complexes, the minimum number of complexes required for a random sample population within the search space, the number of sample points assigned to each complex, the number of sample points assigned to each subcomplex, the number of consecutive offspring generated by each subcomplex and the number of evolution steps taken by each complex are generally set to default values from NLFIT. The number of parameter complexes is initially set to the number of pipeline segment wave speeds to be fitted and the initial value of each of the wave speed parameters is set to 1015m/s (the wave speed of the pipeline in “good” condition). The feasible search space for each wave speed parameter is significantly restricted by limiting the range of non-penalised wave speeds to between 700m/s and 1100m/s. This limitation was justified by prior examination of the measured responses to confirm that the magnitude of all positive and negative reflections could be matched to wave speeds within the restricted feasible search space. The restriction of the search space based on the feasible range of wave speed parameters is important in reducing the scale of the inverse problem to a manageable level.

Use of Error Variance to Guide Inverse Transient Model

Inverse Transient Analysis (ITA) is used to vary the pattern and extent of wave speed variations in pipe sections along the Morgan Transmission Pipeline (MTP) until the fit between the predicted pattern of reflections from the inverse transient model and the measured pressure responses from the field is optimised (or at least improved). The fit between the predicted response of the MTP and the measured response obtained in the field is assessed, after iterative variations of the wave speeds for each pipe section along the MTP, using the residual error variance (s^2). The error variance is proportional to the sum of the square of the differences between the predicted and measured responses (i.e., proportional to the objective function) and represents the unbiased sample variance of the model error after each iteration using the transient model and SCE-UA inverse search algorithm. The objective is to determine the pattern and variation in the magnitude of wave speed along the MTP that gives the best match between the predicted and measured transient responses (i.e., minimises the error variance) using Equation (4) below:

$$s^2 = \frac{1}{M-N}\sum_{i=1}^{M}\left(H_i^m - H_i\right)^2 \qquad (4)$$

where M is the number of measured data points, N is the number of model parameters, H_i^m is the measured pressure response and H_i is the predicted pressure response

Field Tests on the Morgan to Whyalla Trunk Transmission Pipeline

Details of the Morgan to Whyalla Transmission Pipeline

Figure 3 shows the overall elevation of the Morgan Transmission Pipeline (MTP) between a pump station and staging tank over a length of 26.1km. The location of a 6km long section that is subject to hydraulic transient field tests, as described below, is shown in greater detail in the insert within Figure 3 together with the locations of a scour valve (SC24) and two manual air relief valves (AVFP43 and AVFP44). Scour valve SC24 is used as the location along the MTP at which to connect a custom built transient generator and pressure transducer (to enable the measurement of the response of the MTP to hydraulic transient tests). Manual air relief valves AVFP43 and AVFP44 are used as locations at which to connect a dummy plug and pressure transducer to enable the measurement of the response of the MTP at locations remote from the source of the hydraulic transients. It is noted that the tests reported here are different and additional to the tests previously reported in Stephens et al. (2008) and Stephens (2008) and were conducted as part of a pilot technology program with the South Australian Water Corporation.

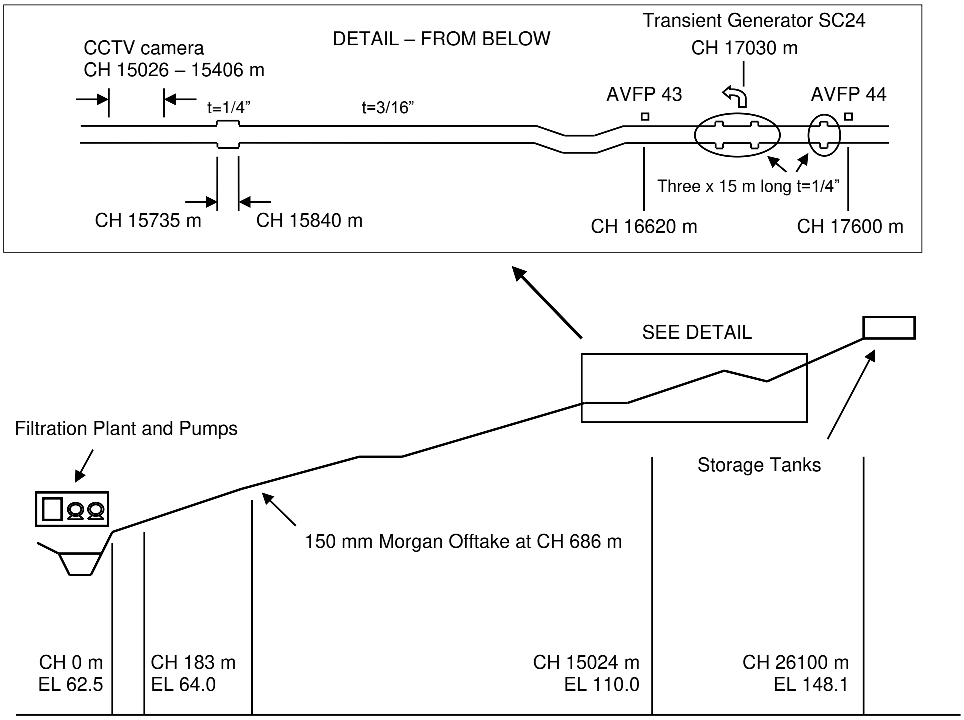

Figure 3 – Morgan to Whyalla Pipeline Elevation and Detail along Test Length

Extensive hydraulic transient testing has been undertaken on the MTP in 2004, 2007 and 2008 and detailed knowledge of the physical configuration of the pipeline has been gathered. The diameter of the MTP has been confirmed from "as-constructed" plans, by inspection and measurement of removed sections and by ultrasonic measurements. There are no lateral pipe offtakes apart from a single 150mm diameter branch at chainage 686m that has no affect on the measured responses reported below. The MTP is located entirely above ground except for three "gullet" sections (approximately 150m out of 26.1km). All aboveground sections of the MTP have been visually surveyed for leaks in August 2007 and none were identified. The only location at which a possible leak might have persisted, and affected the measured responses, was in a "gullet" section near chainage 16500m. However, based on discussions with the pipeline operators, a leak was considered unlikely at this location. Based on this prior knowledge, it has been concluded that unknown diameter changes, lateral pipelines and leaks are not potential sources of pressure reflections in the measured responses.

Forty six (46) separate hydraulic transient tests have been undertaken along the section of the MTP between chainages 11000m and 19000m between 2004 and 2008 under a variety of operational conditions (including different tank levels, boundary valves and pumps being on and off). Repeated patterns of transient reflections obtained for different groups of tests, within the overall total number of tests, have been distinct with an example presented in Stephens et al. (2008). In-situ and deliberately created air pockets were tested on the MTP as reported in Stephens (2008). The results indicated that the response of the MTP to relatively small in-situ and deliberately created air pockets is distinct and distinguishable to the pattern of consistently structured pressure reflections otherwise obtained in the tests. The authors believe that, based on extensive experience with the MTP, air pockets are not the dominant explanation for the pressure reflections in the measured responses. Nevertheless, air pockets can cause reflections similar to those observed, as can pipeline wall thickness changes, and separating the two root causes is, as a matter of practice more generally, a significant challenge.

Setup and Conduct of Hydraulic Transient Field Tests

Typically, 5000 litres of water needs to be discharged to establish a relatively stable flow along the Morgan Transmission Pipeline (MTP) to the discharge point before shutting the scour valve (SC24) abruptly to generate a positive pressure transient wavefront in the MTP (this is done using a custom built transient generator, including a ball valve, mounted on the downstream side of the scour valve). This quantity of water used is not expensive based on per kilolitre rates but given a climate of water scarcity it was considered reasonable to capture and re-use the discharge. Furthermore, it was important to develop a discharge capture system for future application of the technique in metropolitan areas where significant discharges to atmosphere are not generally practical.

The transient generator used when connecting to scour valves comprises a flange plate to suit the scour diameter, a ball valve and torsion spring device that powers its opening and closing operations and a regulating discharge nozzle (between 25-50mm in diameter depending on static system pressure). The pressure response at the location at which the hydraulic transient events are generated is measured (i.e., at SC24) by installing a pressure transducer in the flange plate used to connect the transient generator to the scour valve.

PN16 PVC discharge pipes are connected to the downstream side of the transient generator in order to divert flow to a water tanker. The PVC pipeline is equipped with three inverted foot valves to relieve negative pressures within the discharge line, by facilitating air entrainment, after the transient event has been triggered. Two paddle wheel flow meters are also installed to monitor the discharge along the PVC pipeline. Figure 4 shows the transient generator, the PN16 PVC discharge pipe and inverted foot valves and the paddle wheel flow meter locations.

Figure 4 – Transient Generator, PN16 PVC Discharge Pipe, Inverted Foot Valves and Paddle Wheel Flow Meter Locations

Measurement stations were required to record the response of the MTP to hydraulic transients. Measurements are taken at strategically selected fire pug/air valves. For the test results presented here, the measurements were taken at manual air valves AVFP43 and AVFP44 as shown in Figure 3 above. The practical requirements for connection have been streamlined such that all that is required is the installation of a dummy plug and connection of a pressure transducer. A small area is needed nearby to setup a laptop computer, data acquisition unit and battery. The laptop and data acquisition unit are GPS synchronised with other measurement stations (both at the transient generator and other fire plug/air valves). Each measurement station is configured to record the pressure response of the pipeline following initiation of a hydraulic transient for 4-6 minutes at 2000Hz.

Previous field tests conducted in 2004 and reported in Stephens et al. (2008) and Stephens (2008) did not involve the capture of the discharge from the MTP during the test. The need to capture the discharge from the test, and develop a system suitable for future application of the technique in metropolitan areas, complicated the measured response obtained at the custom built transient generator. Figure 5 shows the typical response measured at the pressure transducer installed in the transient generator backing flange (see Figure 6 for location). The measured response captures high and low pressure fluctuations in a chamber, formed between the existing 150mm diameter scour valve and the transient generator backing flange, in the period immediately following the initiation of the hydraulic transients.

Immediately following the transient generator closing operation, the pressure in the scour valve chamber rises from approximately 34m to 90m. This significant local pressure rise at the scour valve is within the pressure rating for the scour valve. Furthermore, the condition of the scour valve was assessed before the tests to confirm its suitability for the test. The pressure rise in the scour valve is over a very short duration of approximately 10ms and then quickly reduces to the level of the pressure rise created in the 750mm diameter main pipeline after the closing operation. The pressure rise created in the main pipeline is from a level of approximately 34m to 40m (i.e., 6m).

Figure 5 shows further positive and negative pressure oscillations between 90ms and 140ms after the closing operation. These oscillations are caused by the opening of the inverted foot valves to relieve negative pressures within the discharge PN16 PVC pipework downstream of the transient generator, by facilitating air entrainment, after the transient event has been triggered. Cavitation, and associated pressure fluctuations, occur in the PN16 PVC pipework and are transmitted past the closed ball valve in the transient generator through a loosened plastic seal as shown in Figure 6. The seal was loosened to reduce friction and enable the ball valve to close in 10ms.

The maximum and minimum measured pressures, recorded in the scour valve chamber, during the operation of the inverted foot valves are approximately 70m and 10m, respectively. The magnitude of the pressure oscillations is greatly reduced once they leave the scour valve and enter the 750mm diameter main pipeline (approximately 2-3m in the main pipeline). Furthermore, the oscillations only persist for approximately 50ms. While the measurements taken at SC24 do include the pressure spikes and oscillations caused by the transient generator set up, and location of the pressure transducer in the scour valve chamber, they are able to be used, with the measurements from AVFP43 and AVFP44 in the inverse transient analysis. Neither the 90m local pressure rise, following the transient generator closing operation, nor the pressure fluctuations transmitted from the discharge PN16 PVC pipework are detected in the measurements taken at AVFP43 or AVFP44.

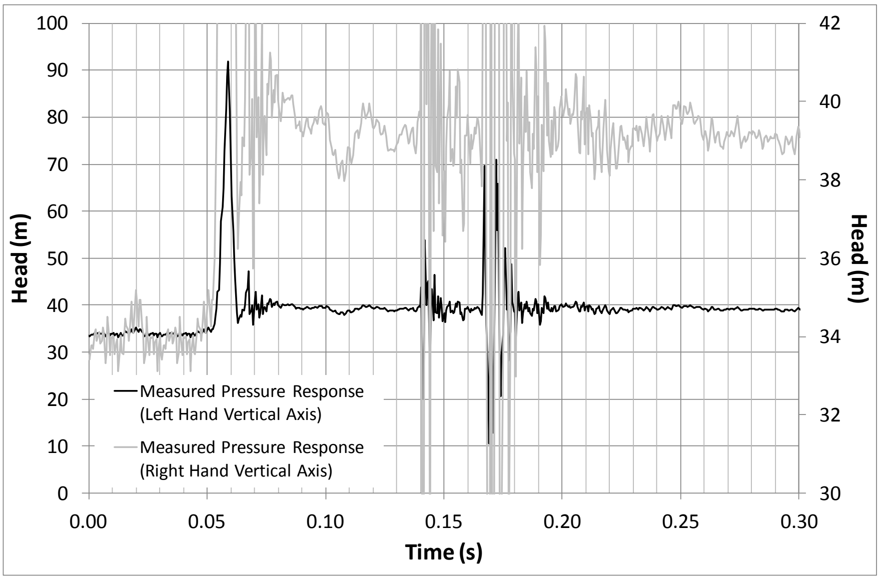

Figure 5 – Higher Frequency Positive and Negative Pressure Oscillations after Initiation of Transient Event

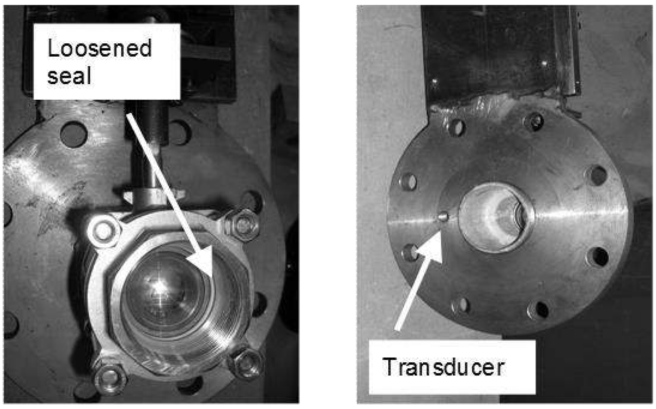

Figure 6 – Loosened Ball Valve Seal in Transient Generator (LHS) and Pressure Transducer Location in Backing Flange (RHS)

Test Results and Data Processing

Quiescent conditions (i.e., a steady state) could not be achieved before triggering each hydraulic transient test because the quantity of discharge had to be limited to ensure complete capture and not overfilling the tanker. In the absence of quiescent conditions, long period pressure oscillations related to the initial opening of the side discharge persisted at the time at which the transients were triggered. The opening operation was conducted typically 5 minutes before the closing operation and the initiation of the hydraulic transient test event. At this time, pressure oscillations with a magnitude of approximately 1m and a period of 10 minutes were still typically occurring in the Morgan Transmission Pipeline (MTP). Figure 7 shows a typical record of a pressure oscillation prior to the initiation of a hydraulic transient event as measured at AVFP43.

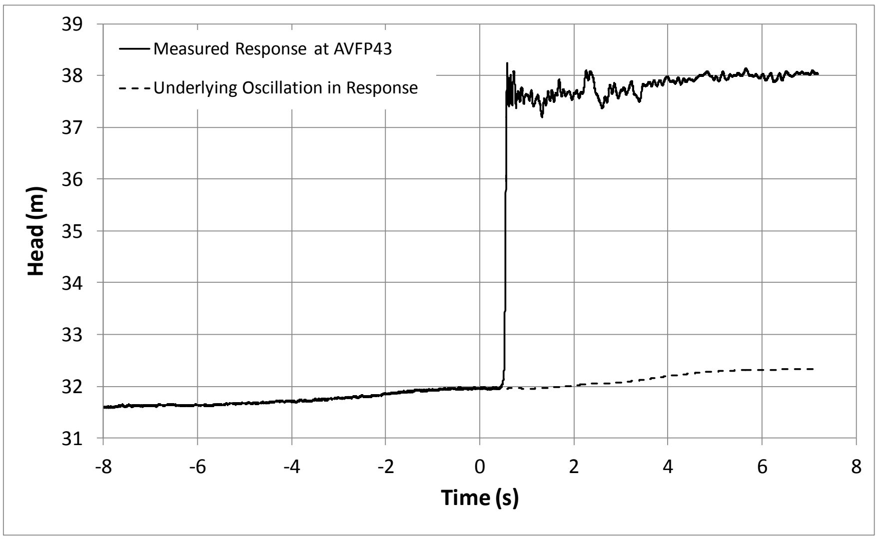

Figure 7 – Measured Pressure Response Before and After Transient Event Showing Prior Pressure Oscillation

Accurate inverse transient modelling can be implemented with such long period pressure oscillations in the measured responses. However, the required transient model would need to encompass the entire 26.1km of the Morgan Transmission Pipeline (MTP) and this was not practical for the finely discretised transient model (1.5m discretisation) used for Inverse Transient Analysis (ITA) as described below. Hence, de-trending of the measured pressure responses has been preferred. For pipelines with other topological configurations (in particular, that are shorter), a transient model could be adapted to take account of fluctuations caused by an opening operation 5 minutes prior to the closing operation and initiation of the transient event of interest. Ideally, the transient tests would not be conducted until quiescent conditions were confirmed. This approach was followed by Stephens (2008) when conducting tests with discharge to atmosphere. However, as explained above, this approach is not ultimately practical and a data processing technique is required to enable the removal of the long period pressure oscillations from the measured responses in cases where this is required.

A de-trending procedure has been developed that involves removing the pressure rise associated with the arrival of the transient wavefront after the closing operation, smoothing the result with a low pass band filter and then subtracting the smoothed response from the original to obtain the de-trended result. Figure 8 illustrates the process for de-trending the measured response at AVFP43 over a time scale of 5 minutes. The unmodified measured response is plotted showing the period immediately before the closing operation, the pressure rise after the initiation of the hydraulic transient event and a sequence of pressure reflections along the transient plateau. The transient pressure rise is removed from the measured response by subtracting the period of the response encompassing the pressure rise over approximately 150ms. This subtraction leaves a signal which contains the pressure reflections after the initiation of the transient event but not the pressure rise. A low pass band filter is then applied using the FiltFilt function in Matlab to obtain the low frequency trend or underlying pressure oscillation in the signal that was created before the initiation of the transient event. The difference between this low frequency trend and the response with the pressure reflections (but without the pressure rise) is then calculated and is plotted. Finally, the period of the response encompassing the pressure rise that was initially subtracted is added back to the difference between the low frequency trend and the pressure reflections to obtain a reconstructed measured response without the underlying long period pressure oscillation. The de-trended or reconstructed responses at AVFP43, SC24 and AVFP44 are used later as the measured responses in the inverse transient modeling.

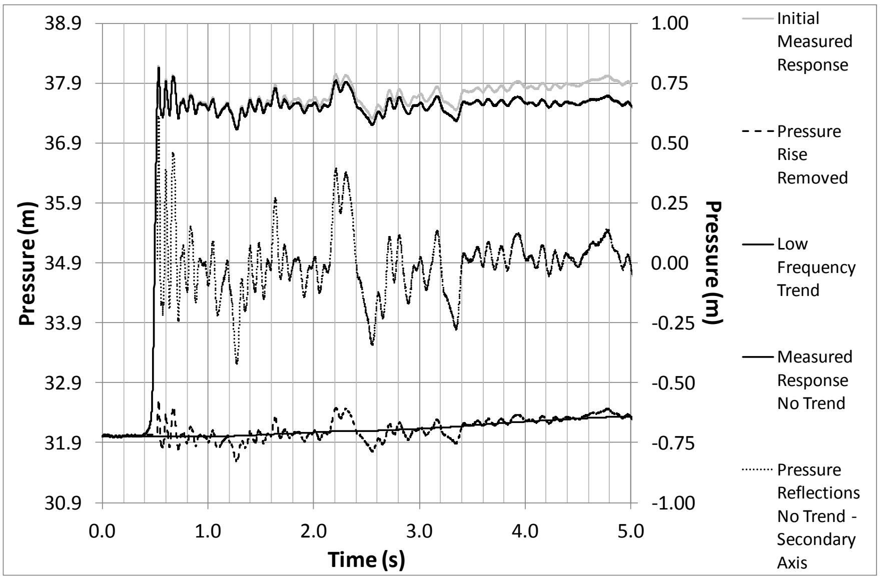

Figure 8 – Conversion of Initial Measured Response at AVFP43 to Measured Response without Underlying Long Period Oscillation

Numerical Transient Model of the Morgan Transmission Pipeline

The theoretical basis for the transient model used in the Inverse Transient Analysis (ITA) conducted in this study, including the "Method of Characteristics" C^+ and C^- compatibility equations rearranged to solve for pressure response, was previously presented in Stephens et al. (2008) and is not repeated here.

Use of Artificial Boundary Conditions to Simplify Numerical Transient Model

A transient model of the 6000m long section of the MTP between chainages 13900m and 19900m was established rather than a model of the entire 26.1km pipeline between the pumps and downstream tanks. The model was limited to reduce computational time and limit the scale of the inverse transient model. Artificial boundary conditions were required at the upstream and downstream ends of the 6000m long section of the MTP to provide equivalent steady state pressure conditions along the 6000m long section of the MTP as existed within the overall 26.1km long pipeline. Tank and closed valve boundary conditions were used at the higher (chainage 19900m) and lower (chainage 13900m) ends of the 6000m long section of the MTP, respectively. As shown in Figure 3 above, the three measurements locations were at chainages 16620m (AVFP43), 17030m (SC24 – generator) and 17600m (AVFP44).

The offset of the measurement location AVFP44 towards the chainage 19900m artificial tank boundary condition means that after a time of approximately 5 seconds this artificial condition starts feeding back into the predicted response at AVFP44. Feedback from the artificial boundary condition is not desirable and so the time over which analysis was undertaken was limited to less than 5 seconds. This time was sufficient for pressure reflections from damaged sections of pipeline between chainages 14900m and 18900m to be captured at all three measurement locations and between 13900-14900m and 18900-19900m to be captured at two measurement locations. It is assumed that the most accurate fitted wave speeds from the ITA will be between chainages 14900m and 18900m and this is why the independent ultrasonic wall thickness measurements described below were undertaken between these chainages.

Linear Timeline Interpolation for Numerical Transient Model

A linear timeline interpolation scheme is used in the transient model in the implementation of the "Method of Characteristics". The numerical attenuation caused by the interpolation scheme was considered before the inverse analysis was undertaken and it was confirmed that a discretisation of 1.5m or less for a numerical model of the 6000m long section of the Morgan Transmission Pipeline (MTP) would limit the error introduced by the interpolation. The appropriateness of the discretisation adopted is assessed below in the context of the results of the ITA.

Numerical Transient Model Simplifications – Steady and Unsteady Friction

Significant prior information about the Morgan Transmission Pipeline (MTP) identified above has enabled a simplification of the transient model. A restriction to the time over which analysis was required and undertaken has also been identified to achieve realistic calculation times for the transient model, given that a discretisation of 1.5m has been identified as necessary to reduce interpolation error, and for the Inverse Transient Analysis (ITA). Fixing the friction parameters for the transient model was also considered as a way of reducing the calculation times for the model and the ITA. The steady state friction factor was determined for a fixed internal pipeline roughness of 0.3mm. This roughness was determined on the basis of typical published values for cement mortar lined (CML) pipe and by inspection of four different sections of the MTP which had previously been removed for replacement. The sensitivity of the results of the ITA to different pipeline internal roughness values is assessed below in the context of the results of the ITA.

Unsteady friction calculations were initially performed (before ITA) using a transient model and were found to add substantially to the computational time and therefore, potentially, to the time required to undertake ITA. The efficient weighting function unsteady friction implementation for turbulent flow developed by Vitkovsky et al. (2004) was used (Re was approximately 75000). The effect of unsteady friction was shown to be relatively insignificant and so unsteady friction calculations were not performed in the transient model used in the ITA. The sensitivity of the results of the ITA to the omission of unsteady friction is assessed below in the context of the results of the ITA.

Setup for Inverse Transient Model and Analysis of Test Results

Setup for Inverse Transient Model

Finer spatial discretisation for the transient model improves accuracy by reducing the numerical error. However, a fine discretisation significantly increases the computational effort and the time required for the transient model to complete a simulation. This time was important because over 2.8 million evaluations with different parameter values (wave speed variations along the Morgan Transmission Pipeline (MTP)) were required to explore the parameter space for the problem, using the Shuffled Complex Evolution (SCE-UA) inverse search algorithm described above, and to determine the pattern and variation in the magnitude of wave speed along the MTP that gave the best match between the predicted and measured transient responses. A 1.5m transient model discretisation has been used because it significantly reduces the numerical error as demonstrated in the results reported below.

An important linkage between the transient model discretisation and the number of parameters that can be managed in the inverse analysis exists. The finer the model discretisation the more potential parameters can be introduced to the inverse analysis. However, the finer the discretisation, and the greater the number of parameters, the slower the transient model computations and the inverse analysis, respectively. The section of MTP subject to inverse analysis is 6kms long and fitting wave speeds at 1.5m intervals would require 4000 parameters to explore the accompanying search space. This size of inverse problem was unmanageable using a conventional computing resource (i.e., a PC) with the transient model and inverse search algorithm having an upper limit of approximately 400 parameters.

A practical compromise was developed to satisfy both computational restrictions and take into account the likely distribution of damaged sections of pipe along the MTP. The 1.5m discretisation for the transient model was retained, to minimise numerical error, but the length of pipeline over which the wave speed was varied and fitted was set to 15m (i.e., 10 times the discretisation used in the transient model). This resulted in 400 pipe lengths of 15m each for which distinct wave speed parameters were fitted during the inverse analysis (the transient model was executed for each inverse evaluation with a discretisation of 1.5m). Hence, the resolution with which damaged sections of the MTP could be resolved was 15m. This resolution was considered acceptable given the MTP was typically manufactured and installed in 7.5m lengths and more significant damage was typically observed over two or more adjacent pipe lengths (i.e., over lengths in the order of 15m).

Results of Inverse Analysis and Estimated Wave Speeds for Pipeline Segments

Figure 9 shows the convergence of the inverse analysis with the error variance measure decreasing as more evaluations, to determine the optimal pattern and variation in the magnitude of wave speed along the Morgan Transmission Pipeline (MTP), were completed. The error variance reduced from 0.254 to 0.026 over 2,835,531 evaluations when the inverse analysis was terminated.

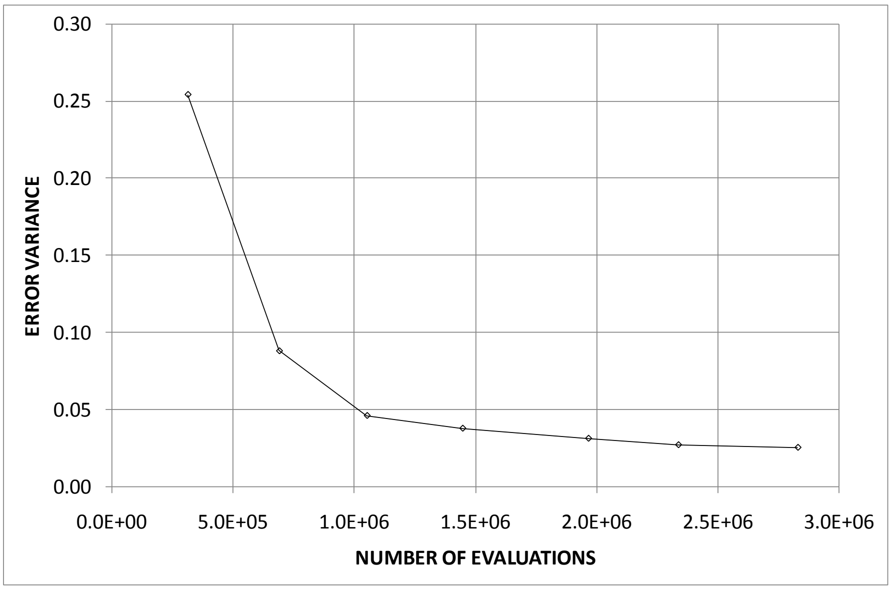

Figure 9 – Error Variance versus Number Evaluations During Inverse Analysis

The thickness of the MTP was known over approximately 150m of the 6kms because thicker walled new sections of pipeline had been originally installed. The longest length of new thicker walled pipeline was located between chainages 15735m and 15840m and was 105m long. The wave speed for this thicker walled pipe was calculated to be 1050m/s. Three other thicker walled sections of the MTP were identified along the 6kms of the MTP with each section being approximately 15m long. The locations of these thicker walled sections of pipe are shown in Figure 3 with two of the sections between 16980m and 16995m, and then 17130m and 17145m, both having a calculated wave speed of 1111m/s. The third 15m section of thicker walled pipe was located between chainages 17550m and 17565m and had a calculated wave speed of 1050m/s. The wave speed parameter values were fixed for ten locations or pipe sections (with each pipe section being 15m) where the MTP included thicker walled pipe. This reduced the overall number of parameters being fitted during the inverse analysis from 400 to 390.

The fitted values for wave speed of the 390 by 15m long sections of the MTP subject to inverse analysis vary from a minimum of 834.4m/s to 980.2m/s and are within the limiting range from 700m/s to 1100m/s that was determined by prior examination of the measured responses (and use of the Joukowsky equation). As mentioned previously, there is a continuous spectrum of possible wave speeds to account for the potential continuous variation of pipe wall condition.The wave speeds for each 15m length will not be tabulated but will be graphically compared with corroborating results in the section entitled "Comparison with Ultrasonic Measurements" below. Fitted wave speeds are plotted between chainage 14900m and 18900m to match the length of pipeline subject to ultrasonic survey.

The fitted wave speeds are generally depressed below the intact and undamaged wave speed for the MTP of 1015m/s indicating some deterioration along the length of the pipeline. Furthermore, there are 7 locations (each with a different length) over which a relatively more depressed wave speed of around approximately 850m/s is fitted. This can be interpreted as indicating specific pipe wall damage at these locations. The locations at which damage is predicted will be compared with corroborating ultrasonic wall thickness measurements below. Based on the discrete classifications described previously, a wave speed of 850m/s corresponds to the loss of cement mortar lining (CML) and marginally over 1.0mm of wall corrosion if distributed uniformly around the circumference of the pipeline. If the distribution of the damage is non-uniform along the length of the 15m pipe section or around the circumference of the pipe then it is likely that the damage will be more significant where it occurs to give an overall apparent wave speed of 850m/s along the relevant 15m pipe section.

Fits between Observed and Predicted Responses

The results of the inverse analysis can be assessed by comparing the locations at which damage is predicted with corroborating ultrasonic results (see corroboration section below). The results can also be assessed by examining the fit between the measured pressure responses to the hydraulic transient event and the predicted pressure responses obtained with the fitted values for wave speed of the 390 by 15m long sections of the Morgan Transmission Pipeline (MTP).

Figure 10 shows the period prior to the initiation of the hydraulic transient event, the pressure rise during the event and the patterns of measured and predicted pressure reflections for 5 seconds after the event for measurement station AVFP43. Figures 11 and 12 show the comparisons between measured and predicted responses over a similar period for stations SC24 and AVFP44, respectively. Each figure focuses on the patterns of measured and predicted pressure reflections after the main pressure rise and they show that a reasonably good comparison between the measured and predicted responses is achieved. The positive pressure reflection caused by the known increase in wall thickness of the MTP between chainages 15735m and 15840m is clear in all responses.

Figure 11 shows high frequency positive and negative pressure oscillations at SC24, between 0ms and approximately 150ms after the initiation of the hydraulic transient event, which are not apparent in the predicted response. As discussed above, these oscillations are caused by the opening of the inverted foot valves to relieve negative pressures within the discharge line after the transient event has been triggered. These oscillations are not capable of being replicated by the transient model.

A further predicted response is determined using the transient model, with the fitted values for wave speed of the 390 by 15m long sections of the MTP, but with a model discretisation of

1.0m instead of 1.5m. This additional predicted response has been included in Figures 10, 11 and 12 for measurement stations AVFP43, SC24 and AVFP44, respectively. The predicted responses obtained with the transient model, using the same wave speed distribution along the MTP, are very similar and confirm that the numerical error introduced by using a 1.5m, instead of 1.0m, discretisation is not significant.

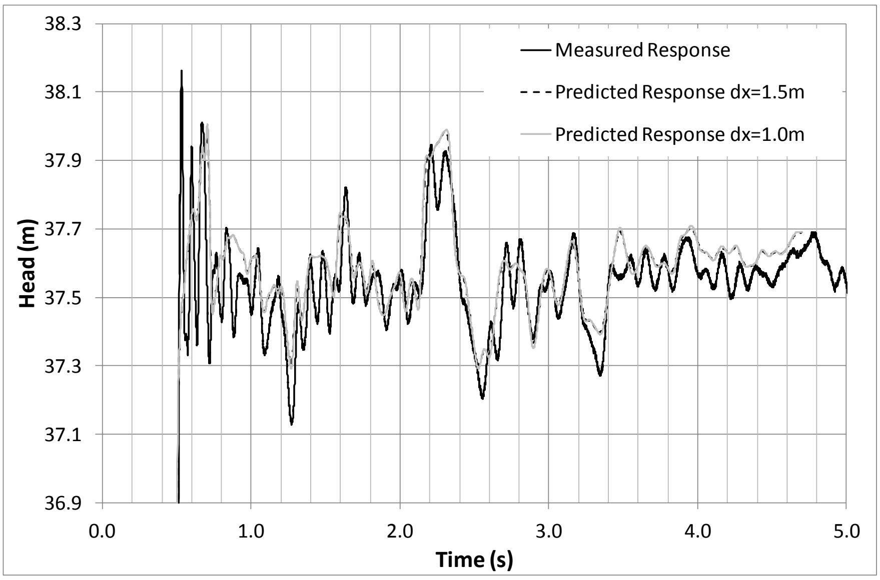

Figure 10 – Measured Response at AVFP43 versus Predicted Response Obtained with 1.5m and 1.0m Model Discretisations

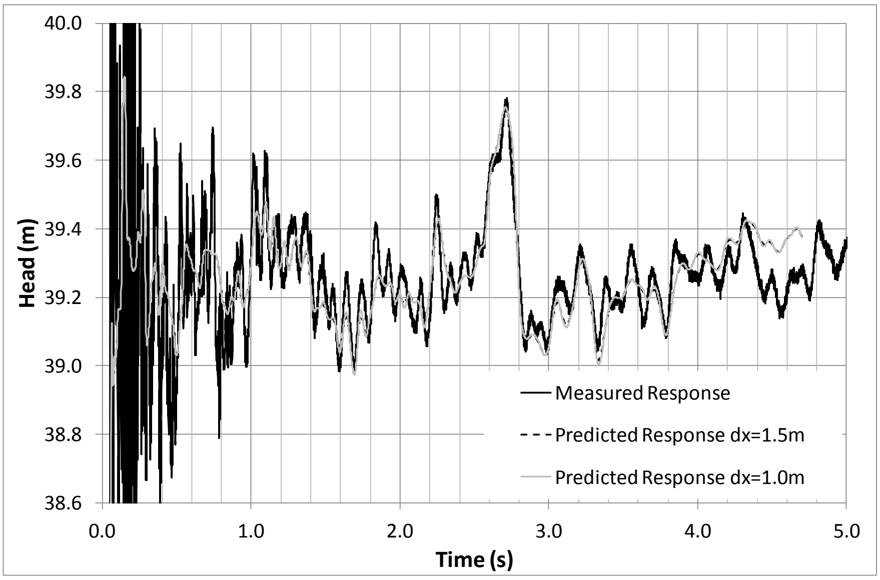

Figure 11 – Measured Response at SC24 versus Predicted Response Obtained with 1.5m and 1.0m Model Discretisations

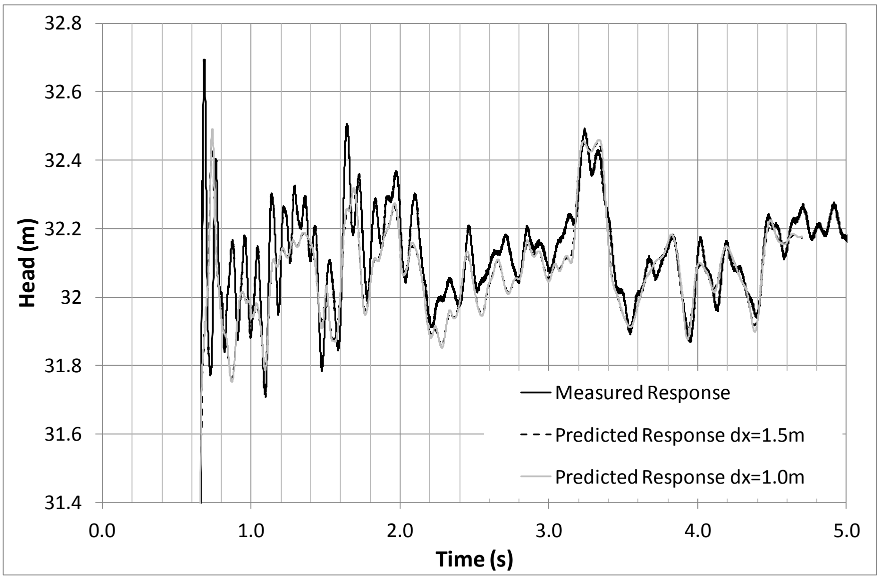

Figure 12 – Measured Response at AVFP44 versus Predicted Response Obtained with 1.5m and 1.0m Model Discretisations

Sensitivity to Prior Information and Other Physical Mechanisms

Assumptions and Effect of Known Modelling Simplifications

The prior information regarding the physical configuration of the Morgan Transmission Pipeline (MTP) is important in limiting some of the unknowns during the Inverse Transient Analysis (ITA). Unknown pipeline diameter, lateral connections, leaks and, to the degree possible, air pockets and/or entrained air are not significant sources of error for the MTP. Other prior information that has been used includes the fixed wall thickness for 150m of the 6000m long section of the MTP that was tested and the limitation of the range of wave speeds for the remaining 15m long sections to between 700m/s and 1100m/s.

Modelling errors and approximations that have been explicitly considered include interpolation errors in the transient model and the treatment of steady and unsteady friction losses. The use of a 1.5m discretisation has reduced the level of numerical attenuation caused by interpolation to a level where further reduction in the discretisation provides little further improvement. This is demonstrated in Figures 10, 11 and 12 above in which the results of the ITA performed using a 1.5m discretisation are compared with a check using the fitted wave speeds and a 1.0m discretisation with the transient model. Figure 13 below further illustrates the effect of varying the model discretisation from 1.0m, 1.5m, 3.0m to 5.0m. The numerical attenuation introduced reduces with increasing discretisation of the model. That said, numerical attenuation persists when 1.5m and 1.0m discretisations are used.

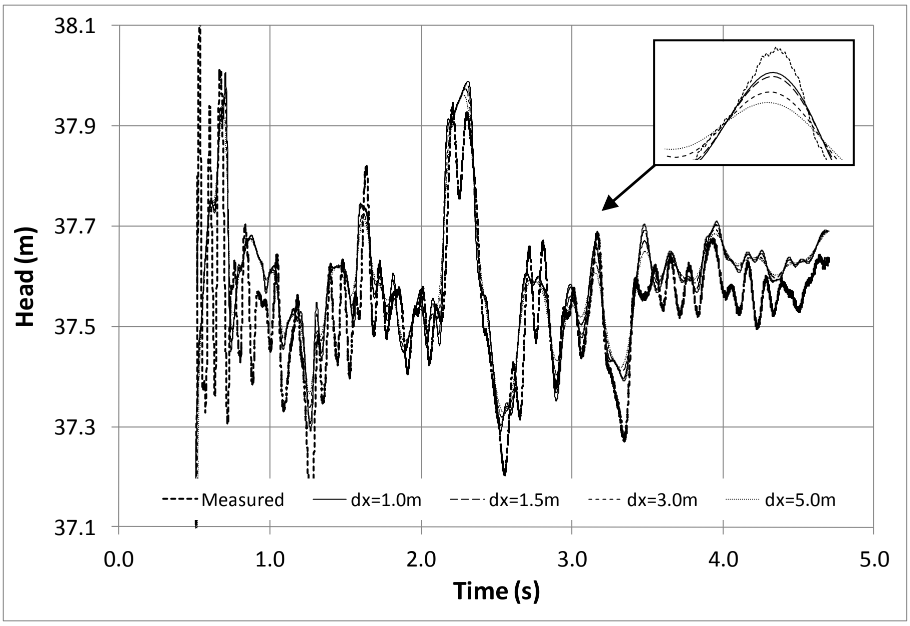

Figure 13 – Effect of using different discretisations in the transient model, with the fitted wave speeds, at AVFP43

The effect of varying the pipeline roughness (roughness of the internal Cement Mortar Lining (CML)) from relatively smooth to rough (increasing the steady state friction factor) is illustrated in Figure 14 below for the response of the MTP at AVFP43. Relatively minor changes in the predicted responses are introduced as the pipeline roughness is varied. The effect of neglecting unsteady friction is also illustrated in Figure 15 below. As for the case of pipeline roughness variation, the inclusion of unsteady friction results in a relatively minor change to the predicted response with more fluid friction damping but not enough to affect the reasonableness of the fit between the measured and predicted responses. The errors introduced by these modelling simplifications were knowingly accepted to reduce computational times and the number of model parameters to make the inverse problem manageable.

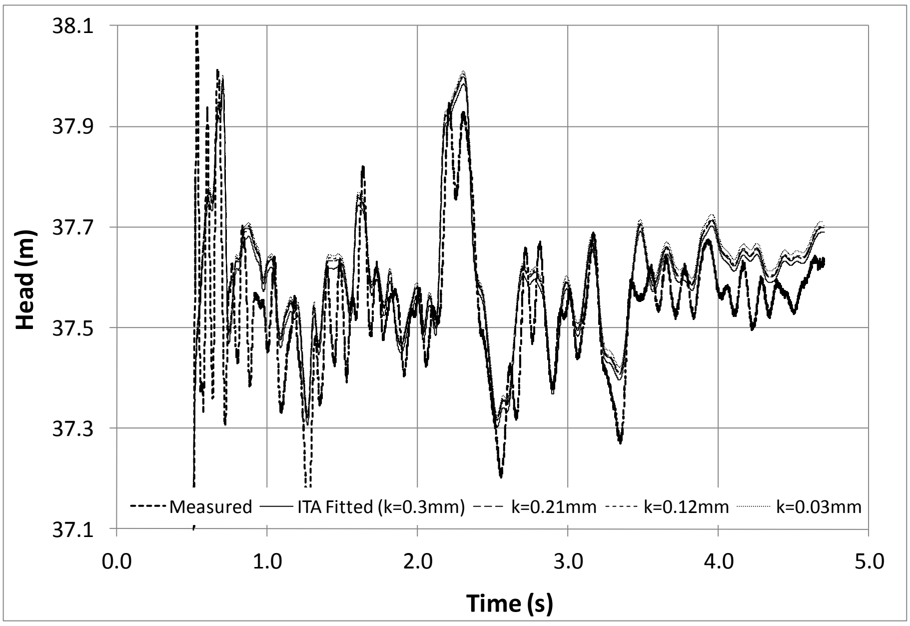

Figure 14 – Effect of varying pipeline roughness in the transient model, with the fitted wave speeds, at AVFP43

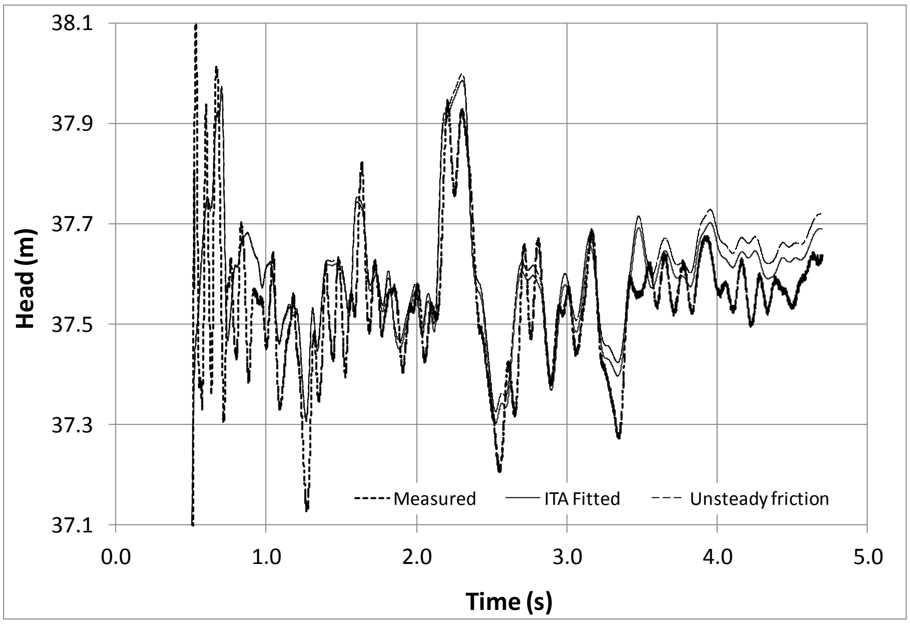

Figure 15 – Effect of inclusion of unsteady friction in the transient model, with the fitted wave speeds, at AVFP43

Discrepancies due to Other Limitations and Physical Mechanisms

The differences between the measured and predicted responses revealed in Figures 10, 11 and 12 indicate important phenomena that have not been able to be replicated by the transient model or inverse analysis process proposed in this research. All the measured responses include pressure reflections changing at a higher frequency than the model can predict. This is unlikely to be a result of the discretisation used in the transient model (1.5m) and is more likely to be a result of the limitation of the inverse problem by fitting only variations in wave speed over 15m long lengths of pipe. As discussed above, this limitation was necessary to make the inverse analysis manageable using a conventional computing resource. If the wave speed was able to be varied along 1.5m lengths instead of 15m lengths then this may have improved the fit between the measured and predicted response and given a better inferred estimate of damage along the MTP.

However, more fundamental physical mechanisms are likely to ultimately limit the potential improvement to the match between the measured and predicted responses. A gross example is the inability of the transient model to replicate the high frequency positive and negative pressure oscillations caused by the relief of negative pressure in the discharge line of the field equipment used. If a modification to the field equipment cannot be developed, then this particular discrepancy will persist and may require a signal analysis approach to rectify.

There are more subtle examples of problems with fundamental physical mechanisms that require model development or signal analysis approaches to rectify. Numerous field tests have been conducted by the authors that have provided insight into Fluid Structure Interaction effects that have occurred when the MTP has been subject to hydraulic transients. The ability to fit model parameters for these effects has not been included in the transient model described above. Distinct from this is the problem of the physical variability of the damage to the inside of the MTP (and other pipelines) in terms of degree and distribution of lining loss and corrosion. Even if a model was developed with wave speed able to be varied along 1.5m lengths this would not necessarily account for all physical combinations of lining loss and corrosion.

A balance between model refinement and increased sophistication and parameterisation, inverse analysis effort and strategy (for complicated physical problems where some mechanisms cannot be fully represented) and the required accuracy of the predicted wave speeds and, hence, inference of the location of damage is required. In the results presented above, the predicted responses do not capture all of the pressure reflections in the measured response. Nevertheless, the predicted responses do reasonably accurately trend through the main pressure reflections as for, by way of example, the known increase in wall thickness between chainages 15735m and 15840m. Locations at which more significant pressure drops are observed are reasonably well replicated in the predicted responses.

Corroboration of Predicted Pipe Wall Damage

The usefulness of the proposed methodology can be ultimately assessed by comparing the distribution along the Morgan Transmission Pipeline (MTP) of 15m lengths of pipe with depressed wave speeds (derived from the results of the inverse analysis) with independently corroborated locations at which the pipe wall is damaged. The independent estimation of locations at which the wall of the MTP is damaged was undertaken by extensive ultrasonic wall thickness measurements and the use of limited closed circuit television (CCTV) camera imaging of the inside of the pipeline. It is important to note that the ultrasonic wall thickness measurements are not an absolute measure by which to decide whether the Inverse Transient Analysis (ITA) has been successful.

Comparison with Ultrasonic Measurements

Extensive ultrasonic wall thickness measurements were manually undertaken using an ultrasonic thickness measurement instrument at 5m intervals along the Morgan Transmission

Pipeline (MTP) between chainages 14900m and 18900m. Measurements were taken at 8 points around the circumference of the pipe at each location as shown in Figure 16. The accuracy of the ultrasonic thickness measurement instrument was regularly checked during the measurements using a calibration bar.

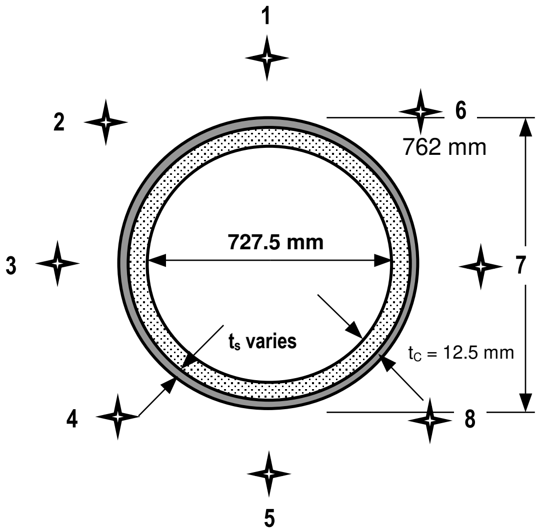

Figure 16 – Circumferential Locations of Ultrasonic Measurement Points

It is difficult to graphically represent the approximately 6400 individual pipe wall thickness measurements that were undertaken using the ultrasonic thickness measurement instrument. Figure 17 attempts to show each individual measurement and, despite the number of points, patterns in the wall thickness variation are apparent. There are a number of lengths of pipe along which a relatively higher wall thickness is encountered. These sections are where either thicker walled pipe was used in the original construction or thicker walled pipe replacement sections have been installed. A greater number of thicker walled pipe sections were recorded during the ultrasonic survey than are described above because numerous short (less than 5m long) thicker walled pipe sections have been progressively installed since the original pipeline construction (to undertake specific repairs). These shorter thicker walled pipe sections have not been included in the modelling described above because their effect on the overall response of the MTP is limited because of their relatively short length.

Sections along the MTP at which groups of relatively lower wall thicknesses are observed were indicative of locations at which internal damage to the MTP had occurred. There were no external indications of the internal damage to the MTP that was identified during the ultrasonic survey at all except 2 locations within the length of MTP that was surveyed.

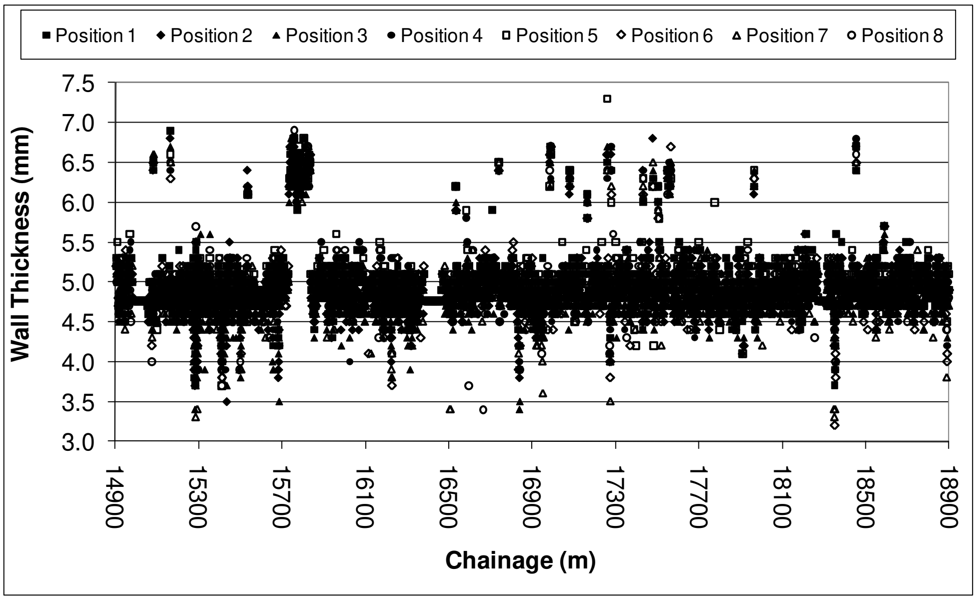

Figure 17 – All Ultrasonics Measurements of Wall Thickness Taken Between Chainage 14900m and 18900m

To improve the clarity of the ultrasonic wall thickness measurement data, and focus on the measurements which identify the most significant internal wall corrosion, only wall thickness measurements below 4.3mm are shown in Figure 18 (original typical thickness is 4.76mm). Figure 18 clearly shows the locations at which the most significant reductions in wall thickness have occurred along the MTP and therefore, by inference, the locations at which the ultrasonic survey indicates damage is most likely.

The results of the inverse analysis, and the locations at which the fitted wave speeds were depressed below the intact and undamaged wave speed for the MTP, are compared with the locations identified by the ultrasonic survey with pipe wall thickness less than 4.3mm in Figure 18.

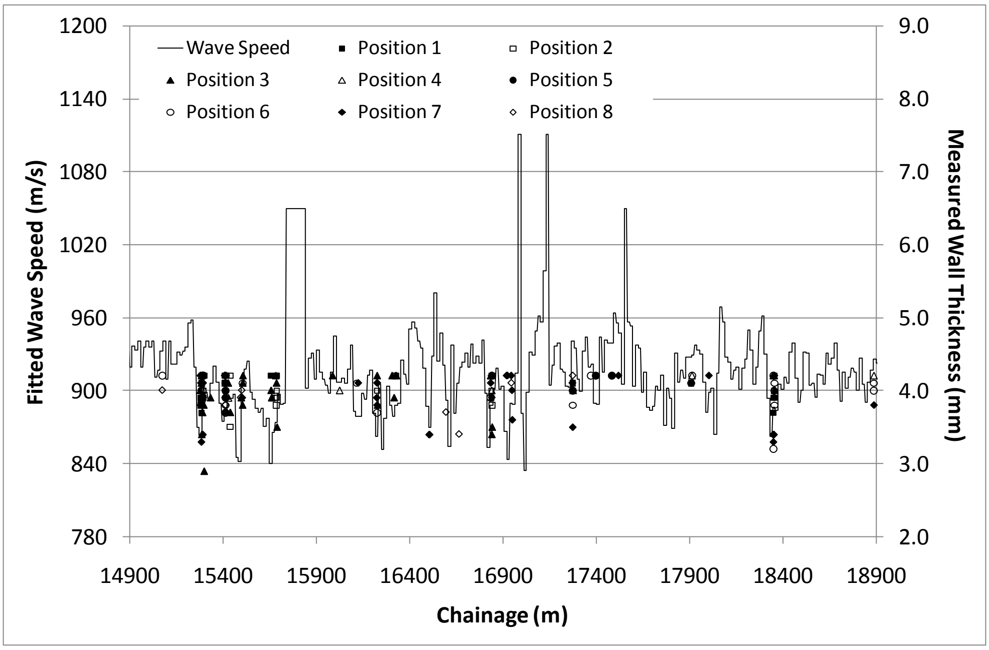

Figure 18 – Comparison of Fitted Wave Speeds with the Locations Identified by the Ultrasonic Survey with Pipe Wall Thickness less than 4.3mm

The relatively strong correlation between the location of damaged sections of the MTP identified by the inverse analysis and the ultrasonic survey indicates that hydraulic transient tests and subsequent inverse transient modelling can be used to approximately locate damaged sections of pipe wall. The results also confirm that the approximate magnitude of the damage (i.e., the approximate degree of pipe wall thickness reduction) can be determined using an inverse transient model. The fitted wave speeds at the damaged sections of pipe are in the order of 850-900 m/s and these correspond with approximately 0.5mm to just over 1mm of average wall thickness loss over 15m pipe segments. The ultrasonic survey confirms that the remaining wall thicknesses at the damaged locations are between 2.9mm and 4.3mm and these correspond to the loss of 1.86mm to 0.46mm of wall thickness, respectively (based on an original wall thickness of 4.76mm). Furthermore, the 2.9mm was an extreme ultrasonic thickness measurement with the more typical maximum reduction in wall thickness being approximately 3.5mm (corresponding to a wall thickness reduction of 1.26mm).

CCTV Camera Images

The only closed circuit television (CCTV) camera information that overlaps the 4kms of the Morgan Transmission Pipeline (MTP) subject to ultrasonic survey was obtained between chainages 15026m and 15406m. Figure 19 shows that the wall thinning detected by the ultrasonic survey coincides with images of significant internal loss of cement mortar lining (CML) and corrosion in the vicinity of chainages 15273m to 15282m. Further internal damage is indicated by the ultrasonic survey in the direction of increasing chainage but no CCTV camera footage is available for comparison.

The CCTV camera footage is useful because it shows the nature of the internal damage to the pipe wall and the variability of the distribution of loss of CML and wall corrosion both along a pipe section and around the pipe circumference. The information obtained by the CCTV camera inspection and the inspection of cut out sections of the MTP from locations remote from the test length (refer to Figure 1) have assisted in characterising the problem of internal pipe wall lining loss and corrosion.

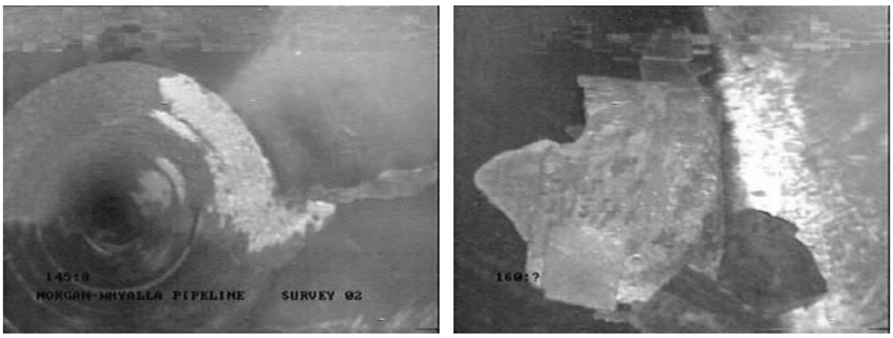

Figure 19 – CCTV Camera Footage between Chainage 15273m and 15282m – damage along approximately 9m of pipeline and focus on local damage

Summary and Conclusions

This paper reports the development of Inverse Transient Analysis (ITA) for determining the location and magnitude of internal wall damage, including the loss of protective linings and wall corrosion, along pipelines. A transient model is developed in which the speed of propagation of transient waves along the pipeline (i.e., the wave speed) can be varied along 15m lengths of the pipeline to simulate the effect of a loss of wall thickness and/or stiffness. This transient model was combined with a Shuffled Complex Evolution University of Arizona (SCE-UA) inverse search algorithm to form an inverse transient model. A least squares minimisation criterion was applied to guide the optimisation of wave speed variation for each 15m length along the MTP, using the inverse transient model, and measured pressure transient responses obtained for the Morgan Transmission Pipeline (MTP). The method of generating hydraulic transient pressure waves in the MTP, and the method of measurement and signal analysis to remove long term oscillations created by the initiation of the transient, are reported.

Significant prior information about the physical configuration and transient response of the MTP had been obtained between 2004 and 2008 which enabled the physical influence of valves, junctions, blockages and leaks to be either assessed and included or ruled out. Further information about the response of the MTP to in-situ and deliberately introduced air pockets indicated that the potential effects of air were likely to minimal (but could not be eliminated). Information about the magnitude of the measured pressure reflections enabled the range for the inverse determination of the wave speed of the 15m long sections of the MTP to be reduced to between 700m/s and 1100m/s. Numerical approximations introduced by the interpolation scheme used in the transient model and by not fitting pipeline roughness, or including the effects of unsteady friction, were assessed. While each of these modelling issues had some significance, the errors introduced did not account for the main discrepancies between measured and predicted responses of the MTP (after ITA).

Finally, the fitted pattern of wave speed variations (indicative of sections of damaged pipeline with either lost cement mortar lining or wall corrosion) was compared with ultrasonic measurements taken along the 6km section of the MTP at 5m intervals and 8 points around the circumference of the pipeline. The comparison indicates that the locations at which the fitted wave speed is depressed, and where damage is hence inferred, generally correspond, although not always, with locations at which the ultrasonic survey confirmed internal damage to the MTP. The limited closed circuit television (CCTV) camera footage that was available also confirmed the predicted damage between chainage 15273m and 15282m.

It is not claimed that no other combination of fitted wave speeds would not have improved the fit (reduced the error variance). Given the difficulty of the inverse problem attempted, which was simplified by reliance on prior information and model simplifications, it is almost certain that the optimal "solution" was not found because:

- the ITA could have been run longer to find a better optimised solution
- the inverse algorithm used (the SCE-UA) is powerful but not able to perfectly derive predicted responses (tuning the optimisation parameters of the algorithm may also have assisted)
- the use of prior information to greatly simplify the transient model is an approximation and may have resulted in the neglect of some influences (including the possibility of a small percentage of entrained air)
- the transient model involves a number of numerical approximations of known influences including the interpolation scheme, pipeline roughness and unsteady friction
- the transient model could have used a finer discretisation or the inverse model could have fitted wave speeds for shorter lengths of pipeline (<15m) if sufficient computational capacity existed
- the transient model does not take into account the influence of other physical mechanisms such as Fluid Structure Interaction (FSI) that may contribute to the measured pattern of reflections

While the method proposed is able to approximately identify the location and approximate magnitude of internal pipeline wall damage, further development of the technique is likely to significantly improve the accuracy with which damage can be located and characterised. Overall, a balance between model sophistication, inverse analysis effort and the required accuracy with which damage can be inferred is required.

Acknowledgements

The authors would like to gratefully acknowledge the assistance of the South Australian Water Corporation in supporting and facilitating this research and the field tests. In particular, we would like to thank Mr Jim Braendler and Mr Greg Milsom for attending and assisting with the field tests.

Notation

a = wave speed

c_1 = pipe restraint factor

D = internal diameter of pipe

E_C = elastic modulus of cement mortar

E_S = elastic modulus of metal pipe wall

e_{eq} = composite wall thickness of lined pipe

g = gravitational acceleration

H = piezometric head

K = bulk modulus of water

t_C = thickness of cement mortar lining

t_S = thickness of metal in pipe wall

t_{eqS} = thickness of equivalent metal in pipe wall

$v = v_S$ = Poisson ratio for steel

ρ_W = density of water

ρ_S = density of steel

References

Brunone B., Ferrante M. And Meniconi S. (2008) “Portable Pressure Wave-Maker for Leak Detection and Pipe System Characterisation”, *Journal of American Water Works Association (AWWA)*, 100(4), 108-116.

Covas D., Ramos H., Brunone B. and Young A. (2004) “Leak detection in water trunk mains using transient pressure signals: field tests in Scottish Water”, 9th International Conference on Pressure Surges, BHR Group, Chester, England, UK, 185-198.

Duan Q., Sorooshian S. and Gupta V.K. (1994) “Optimal Use of the SCE-UA Global Optimisation Method for Calibrating Watershed Models”, *Journal of Hydrology*, 158, 265-284.

Duan Q., Sorooshian S. and Gupta V. (1992) “Effective and Efficient Global Optimisation for Conceptual Rainfall-Runoff Models”, *Water Resources Research*, 28(4), 1015-1031.

Hachem F.E. and Schleiss A.J. (2012) “Detection of Local Wall Stiffness Drop in Steel-Lined Pressure Tunnels and Shafts of Hydroelectric Power Plants Using Steep Pressure Wave Excitation and Wavelet Decomposition”, *Journal of Hydraulic Engineering*, 138(1), 35-45.

Kuczera G. (1994) “NLFIT: a Bayesian Nonlinear Regression Program Suite”, *the Department of Civil Engineering and Surveying*, the University of Newcastle, Newcastle, NSW, Australia.

Liggett J.A. and Chen L.C. (1994) “Inverse transient analysis in pipe networks”, *Journal of Hydraulic Engineering*, 120(8), 934-955.

Meniconi S., Brunone B., Ferrante M. And Massari C. (2011) “Potential of Transient Tests to Diagnose Real Supply Pipe Systems: What Can Be Done with a Single Extemporary Test”, *Journal of Water Resources and Planning Management*, 137(2), 238-241.

Meniconi S., Brunone B., Ferrante M. And Massari C. (2011) “Small Amplitude Sharp Pressure Waves to Diagnose Pipe Systems”, *Water Resources Management*, 25(1), 79-96.

Misiunas D., Simpson A.R., Lambert M.F. and Olsson G. (2005) “Hydraulic Transients for Diagnosis of Inline Valves in Water Transmission Pipelines”, Proceedings of the CCWI (Computing and Control in the Water Industry Conference, Exeter, England, UK), 293-298.

Stephens M.L., Simpson A.R. and Lambert M.F. (2008) "Internal Wall Condition Assessment for Water Pipelines Using Inverse Transient Analysis", Proceedings of the 10th Annual Symposium on Water Distribution Systems Analysis, ASCE, Kruger National Park, South Africa.

Stephens M.L. (2008) "Transient Response Analysis for Fault Detection and Pipeline Wall Condition Assessment in Field Water Transmission and Distribution Pipelines and Networks", PhD Thesis, School of Civil, Environmental and Mining Engineering, the University of Adelaide, Adelaide, South Australia.

Stephens M.L., Lambert M.F., Simpson A.R., Vitkovsky J.P. and Nixon J. (2004) "Field Tests for Leakage, Air Pocket and Discrete Blockage Detection Using Inverse Transient Analysis in Water Distribution Pipelines", Proceedings of the 6th Annual Symposium on Water Distribution Systems Analysis, ASCE, Salt Lake City, USA.

Taghvaei M., Beck S.B.M. and Boxall J.B. (2010) "Leak Detection in Pipes Using Induced Water Hammer Pulses and Cepstrum Analysis", *International Journal of COMADEM*, 13(1), 19-25.

Taghvaei M.S. (2009) "Fast Leak Detection and Location of Water Pipelines Based Using Orthogonal Wavelet Transform", Proceedings of the International Conference on Pipelines and Trenchless Technology, ICPTT 2009, 361, 186-192.

Taghvaei M., Beck S.B.M. and Staszewski W.J. (2006) "Leak Detection in Pipelines Using Cepstrum Analysis", Measurement Science and Technology (Institute of Physics Publishing), 17, 367-372.

Thyer M. And Kuczera G. (1999) "Probabilistic Optimisation for Conceptual Rainfall-Runoff Models: A Comparison of the Shuffled Complex Evolution and Simulated Annealing Algorithms", *Water Resources Research*, 35(3), 767-773.

Vitkovsky J.P., Stephens M., Lambert M.F., Simpson A.R. and Bergant 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, England, UK.

Wylie E.B. and Streeter V.L. (1993) *Fluid Transients in Systems*, Prentice Hall, Englewood Cliffs, New Jersey, USA.