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 1

Introduction

Condition assessment of pipeline assets has been a focus for water authorities, and operators of other oil and gas pipelines, for many years. Condition assessment is not narrowly defined and can include a range of investigations from “desk-top” studies using available historical failure, pipe material and age, soil and maintenance data to specific physical examination using either destructive sampling or non-destructive testing technologies. Condition assessment programs are often designed to provide different levels of confidence based on the strategic outlook of a particular water authority. “Desk-top” studies provide general information, over longer lengths of pipeline, whereas specific tests provide detailed information regarding the condition of particular sections of pipeline.

The balance between broad investigation and specific testing is driven by relative costs. Broad investigation costs less than specific destructive or non-destructive tests and so tends to be adopted more frequently. The cost and inconvenience of destructive and non-destructive testing act as a significant deterrent when condition assessment programs are designed. Furthermore, the ratio between the cost of conducting specific tests and the consequential savings in rehabilitation and/or replacement has not justified extensive specific testing in the past. That said, as the rate and extent of deterioration of pipeline assets increases in the future, the cost benefit ratio, even based on the assumption that developing non-destructive technologies will not provide greater information at less cost, will reach a point at which more costly and extensive condition assessment programs are justified.

Transient response analysis, including Inverse Transient Analysis (ITA), are potential methods for performing non-destructive tests that will provide relatively specific physical information regarding the condition of pipelines over broader scales than existing technologies. The information derived from transient response analysis will be less specific than that obtained from invasive and disruptive technologies but much more specific than that from “desk-top” studies. In this regard, transient response analysis has the potential to fill the statistical deficit left when limited destructive or non-destructive tests are performed because of cost and “desk-top” information is too general. Furthermore, transient response analysis has the potential to identify specific faults, such as blockages, air pockets and leaks, which are often associated with deteriorating pipelines, when limited invasive and disruptive investigation miss such faults.

The basic concept involves the induction of a controlled transient in a pipeline and the measurement and interpretation of its pressure response. The pressure response is a function of the condition of the pipeline wall (which also governs the speed of propagation of the transient wavefront) and reflections and damping from any fault may be observed. If an accurate transient model can be developed then it may be possible to isolate particular parameters in it (relating to the wall thickness of the pipeline or faults such as blockages, air pockets and leaks) and fit these to give optimal matches between the predicted and measured response of the pipeline. This process is often referred to as inverse analysis (and hence the derivation of the name Inverse Transient Analysis (ITA)).

While a significant amount of numerical and laboratory investigation has been carried out focussing on the use of ITA for leak detection, limited field studies have been undertaken. The laboratory investigation has been necessary and has provided qualified evidence regarding the viability of transient response analysis and ITA for condition assessment and fault detection. However, in a number of regards, the experimental apparatus tested in the laboratory have been simplified to eliminate physical uncertainties (which are unavoidable in the field) and relatively magnify the effect of leaks upon transient responses.

In the case of leaks, this simplification has enabled a clear relationship between the presence of a leak and its effect on the transient response of a laboratory pipeline. This simplification is not possible when testing field pipeline and network systems. As a consequence, there are many physical uncertainties that may affect measured transient responses to differing degrees. It has been necessary to attempt to identify and quantify the effect of these physical uncertainties in this research. The author has adopted a strategy of identifying all the available evidence and then systematically eliminating or quantifying the physical effect of physical uncertainties. This has involved a lengthy negation of the possible effects of some physical uncertainties before the certainty with which conclusions regarding others can be improved. This process is inherently less certain than that which occurs when laboratory experiments are conducted to investigate one or two phenomena at a time. The physical complexity of field systems dictates that this is so.

1.1 Objectives of the research

The goal of this research is to determine whether transient response analysis and Inverse Transient Analysis (ITA) can be applied to field systems to obtain useful information regarding the presence of specific faults such as blockages, air pockets and leaks and the condition of pipeline walls (roughness and/or changes in wall thickness). Considerable uncertainty exists regarding the outcomes of the research because no previous attempt has been made to implement transient response analysis and ITA in the field apart from two investigations in the United Kingdom relating to leak detection (which were conducted after this research began and were completed before this research had been completed). The results from the studies in the United Kingdom indicated that the theoretical potential of transient response analysis and ITA might not be able to be realised because of difficulties in interpreting measured responses from the field.

The first aim of this research is to therefore conduct controlled transient tests on field pipelines and collect measured responses with which to assess the accuracy of current transient models (which it is intended to use to perform inverse analysis). Field tests are conducted on transmission pipelines, distribution pipelines and a network in order to obtain a broad view of the likely nature of the measured transient responses at each scale and to identify any common characteristics. The next aim is to develop existing or new transient models that are capable of accurately replicating the measured field responses. Given the anticipated physical complexity of field pipelines, the development of parameterised and/or conceptual transient models, which can be calibrated to measured responses using inverse methods, will be investigated. The final aim is to perform transient response analysis and/or ITA, using the parameterised and/or conceptual transient models, to locate and characterise artificial blockages, tuberculation, air pockets and leaks on transmission and distribution pipelines, and closed valves and bursts in a network, and assess the roughness and wall condition of a transmission pipeline.

1.2 Scope of the research

The scope of this research is identified by briefly describing each chapter. Chapter 2 contains a review of the economic motivations for condition assessment and identifies current “desk-top” assessment methods and specific destructive and non-destructive technologies. The cost of existing non-destructive technologies is identified as a major deterrent in their application. Furthermore, their sparse deployment means that while the level of information regarding a pipeline wall is excellent over a short length the deficit in information over the remainder of the pipeline is statistically problematic. Chapter 3 reviews the numerical and laboratory investigation conducted to date relating to transient response analysis (direct reflection methods) and/or Inverse Transient Analysis (ITA) for fault detection. Most of the previous research has focussed on leak detection with a lesser focus on blockage detection. The main problem with the laboratory work is that each experimental apparatus has been simplified to eliminate or minimise the effect of physical complexity not related to the leak or block. This means that positive results in the laboratory will not necessarily translate to the field.

Chapter 4 introduces the principles of inverse analysis and least squares regression analysis. Concepts of random observation and systematic model error are explained and given context in relation to ITA. In this regard, systematic model error is identified as the most likely dominant influence upon ITA given low random measurement error and a deficit of models capable of replicating measured transient responses. The NLFIT suite of regression analysis programs is introduced and it is explained that they will be applied to perform inverse analysis throughout the research. Chapter 5 identifies a number of physical complexities that cannot be modelled using the existing theoretical algorithms and hypothesises that they are likely to result in significant dispersion and damping of measured transient responses from the field. In particular, the effects of mechanical motion and vibration at restraints, flexible joints and soil/pipe (joint) interaction, together with a proliferation of similar effects at water service connections (in the case of distribution systems), are thought to be responsible for significant dispersion and damping and the transmission of energy from pipelines (whether above or below ground) to external surrounds (in contrast to fluid friction losses within a pipeline).

Chapter 6 describes the method of generating controlled transients on each system together with the instrumentation used to record pressure responses at high speed. Different methods for synchronising the measurement of pressure at multiple locations are described as they developed throughout the research. The methods used to simulate artificial faults, including discrete blockages, air pockets and leaks, are described for the transmission and distribution pipelines. Calibration information for the device used to generate transients, in-line gate valves for blockage simulation, compressed air chambers for air pockets and nozzles for leaks is presented or referenced.

Chapter 7 is the first of the results and analysis chapters. Details of two transmission pipelines are provided. The tests conducted on the transmission pipelines are reported together with the results of the analysis performed using a traditional explicit transient model developed by the author. The purpose is to identify any discrepancies between the measured and predicted transient responses from the transmission pipelines before undertaking transient response analysis and/or ITA. Chapter 8 describes attempts to develop transient models that can be calibrated to the measured transient responses for the transmission pipelines. Different calibration mechanisms are identified, including pipe roughness, entrained air and mechanical dispersion and damping, and parameterised models are calibrated to assess whether field responses can be better predicted. The feasibility of the physical parameters derived during each model calibration is assessed. Inverse analysis is performed to calibrate the models using modified subroutines developed by the author and a suite of non-linear regression analysis programs. Chapter 9 describes an attempt to use the calibrated transient models from Chapter 8 to perform ITA for leak detection for one of the transmission pipelines subject to tests. The results of tests and modelling for another transmission pipeline, with an artificial discrete blockage, are also presented. Chapter 10 presents the results of the transient tests on one of the transmission pipelines, known to have significant wall lining damage and corrosion, and investigates a hypothesis that changes in lining and wall thickness at the location of the damage give rise to reflections in the measured transient response that can be used to interpret the damage to a resolution of approximately 10m. This potential technology relates directly to the overall aims of the research.

Chapter 11 presents the details of two distribution pipelines. The tests conducted on the distribution pipelines are reported together with analysis performed using a traditional explicit transient model developed by the author. The purpose is to identify any discrepancies between the measured and predicted transient responses before undertaking transient response analysis and/or ITA for fault detection. Additional insight into the mechanisms that might disperse and damp transients in distribution systems, but which are not currently anticipated, is sought. Chapter 12 describes attempts to develop transient models that can be calibrated to the measured transient responses for the distribution pipelines. The failure of the traditional transient models developed in Chapter 11 is confirmed and conceptual calibration models, with increased spatial complexity and parameterisation, relative to that developed for the transmission pipelines, are developed. The sensitivity of the model to the number of conceptual calibration parameters, and to the representation of water service topology, is investigated. Inverse analysis is performed to calibrate the proposed models using similar subroutines to those developed by the author for the transmission pipelines. Chapter 13 describes an attempt to use the calibrated transient models from Chapter 12 to perform ITA for discrete blockage detection. The sensitivity of the analysis to the pressure loss across a constriction, and the possibility that a no-blockage response is not required for calibration purposes, are investigated. The details of, and tests performed on, another distribution pipeline, with extensive tuberculation, are presented. The use of transient response analysis for extended blockage (i.e., tuberculation) detection is investigated. Chapter 14 presents the results of an attempt to use the calibrated transient models to perform ITA for air pocket and leak detection.

Chapter 15 presents the details of a distribution network. The tests conducted on the network are reported together with analysis performed using a traditional implicit transient model modified by the author. The purpose, as for the transmission and distribution pipelines, is to identify any discrepancies between the measured and predicted transient responses. Strict physical controls exerted over the network, with regard to demands/leakage, air pockets and/or entrained air and the network's physical extent, are described. Chapter 16 describes the development of a series of conceptual transient models, based upon parameterised physical mechanisms, with the purpose of improving the comparison between measured and predicted responses. Some of the conceptual models that are investigated are based on previous research while others are novel. The results are used to identify a conceptual model that is capable of replicating measured network responses with reasonable accuracy. Particular attention is paid to the development of a conceptual model comprising a Kelvin-Voigt "viscous" mechanism that can be calibrated for mechanical dispersion and damping. Chapter 17 describes the use of the calibrated conceptual model identified in Chapter 16 for the diagnosis of inadvertently closed valves. The results of the tests and analysis are used to assess the robustness of the calibrated conceptual model. A burst detection method, based on continuous monitoring and the interpretation transients initiated by bursts, is also presented. Chapter 18 presents the conclusions from the research.

Chapter 2

Motivation and Problem Definition

Condition assessment and fault detection in water supply pipelines have the potential to provide system operators with information with which to prioritise planning and rehabilitation work. Traditional condition assessment methods for water systems have involved, in addition to examination of historical information, visual, steady state hydraulic, external soil resistivity or destructive inspection and sampling procedures. In contrast, numerous non-destructive technologies have been developed for the inspection of oil and gas pipeline systems. This development has been motivated by regulations that govern environmental damage from oil and gas facilities and the severe economic consequences of the failure of these energy supply pipelines. Some of these non-destructive technologies are being adapted for use on water pipelines as deterioration of these assets becomes more problematic. However, there have been difficulties that have restricted their application in water transmission and distribution pipelines and networks.

This chapter contains a summary of the main mechanisms by which water pipelines and networks deteriorate and the consequential effects. Justifications for condition assessment are reviewed in the context of a changing legislative environment and an increasing rate of deterioration of many systems. The economic incentive for developing new condition assessment technologies, which can be used by operators to provide information that will reduce rehabilitation costs, is explained in the context of specific pipeline faults and general wall condition. South Australian water system operators have been consulted to determine their general attitude towards condition assessment and which pipeline faults and failure mechanisms are the causes of greatest concern. Finally, non-destructive technologies, which have already been adapted from the oil and gas industries, are reviewed.

2.1 Deteriorating condition of pipeline assets

2.1.1 System composition

A recent American Water and Wastewater Association (2004) report indicates that water systems in the USA and Europe comprise, on average, cast iron (48%), ductile iron (19.2%) and asbestos cement (15.1%). The research presented in this thesis focuses on Cast Iron (CI), Ductile Iron (DI), Mild Steel (MS) and Asbestos Cement (AC) pipes as they represent the bulk of pipeline materials in Australia (although the percentage use of each material varies from utility to utility: for example, the distribution network for the City of Adelaide and surrounding suburbs comprises over 60% AC pipelines). The installation of High Density Polyethylene (HDPE) and Non-Plasticised Polyvinyl Chloride (uPVC) pipes in new suburbs and during relaying (i.e., replacement of old pipes) has occurred in Australia over the last decade. However, pipelines constructed from these materials still represent less than 5% of pipes in Australian water networks.

2.1.2 Pipeline deterioration

Assuming that a Cast Iron (CI), Ductile Iron (DI) or Mild Steel (MS) pipeline has been properly constructed, the most common contributor to failure is external and/or internal corrosion. When corrosion occurs in cast iron, the iron content goes into solution leaving graphite flakes in a process known as graphitisation. Williams et al. (1984) have shown that, in aggressive soil environments, the rate of wall thickness loss to external corrosion can be as high as 0.52mm/year. Typical rates of wall thickness loss to internal corrosion, in the absence of any protective lining, are in the order of 0.18mm/year. Ductile iron pipes tend to have lower corrosion rates because of the provision of protective linings. Rates of external corrosion for unprotected steel pipelines, if buried below ground, are in the order of 0.2mm/year. Cathodic protection systems are commonly used to reduce this rate of corrosion. Table 2-1 lists the main forms of deterioration for CI, DI and MS pipelines.

Asbestos Cement (AC) pipelines generally fail following lime leaching caused by either external or internal exposure to soft or aggressive water (Nebesar 1983). The cement matrix contains lime ($Ca(OH)_2$) and is alkaline. When exposed to soft (acidic) water the lime is leached in a chemical reaction with dissolved carbon dioxide in the soft water in a process known as carbonisation (the lime is converted into calcium carbonate). Coupon sampling and phenolphthalein tests are normally used to gauge the extent of deterioration and give a measure of the remaining pipe wall elasticity (rather than wall thickness). Table 2-1 includes the main forms of deterioration for AC pipes.

Table 2-1 – Summary of forms of deterioration affecting CI, DI, MS and AC pipelines

Mechanism	**Pipeline Material**			
	Cast Iron	**Ductile Iron**	**Mild Steel**	**Asbestos Cement**
Lining (if lined)	Yes	Yes	Yes	NA
Internal corrosion	Yes	Yes	Yes	NA
External corrosion	Yes	Yes	Yes	NA
Pitting corrosion	Yes	Yes	NA	NA
Delamination	NA	NA	NA	Yes
Softening	NA	NA	NA	Yes

NA = not applicable

2.1.3 Failure modes for pipes

Typical factors that are likely to have a significant impact upon deteriorated pipelines include external structural loading (e.g., traffic and overburden surcharges), internal pressures (e.g., system pressures and waterhammer), ground conditions (e.g., loss of pipe or joint support due to ground movement) and cyclic temperature variations including freezing. These factors, in combination with pre-existing deterioration, are likely to cause either pipe cracking (e.g., longitudinal, circumferential, splitting or spiral) or joint failures (e.g., displacement, pull-out or misalignment). Ultimately, cracking or joint failures will manifest as leaks and/or bursts. Alternatively, a pipeline may remain structurally intact, but tuberculation (the deposition of nodules and protrusions of iron oxide from dissolved iron in solution) may develop to a stage where a pipeline can no longer deliver potable water at required flows and pressures or of satisfactory quality. In this regard, the severity and distribution of specific faults such as blockages, air pockets and/or leaks may be indicative of a more general problem with the condition of a pipeline such as corrosion, cracking or joint failure.

2.1.4 Affects on water quality

Water quality is a function of the condition of the distribution pipelines and networks (amongst other things). For United Water International Pty Ltd (hereafter United Water) and the South Australian Water Corporation, the operator and owner of the water pipeline and network assets in South Australia, respectively, the problem of tuberculation is significant. Local operator experience, together with direct observation throughout the five years of testing conducted in this research, has confirmed that biofilms, and potentially bacteria, are found in sections of the network where low flows and a lack of circulation have reduced residual chlorine levels.

As tuberculation and other corrosion products continue to reduce the capacity of pipelines to supply water at adequate pressures, and of appropriate quality, the relation between the condition of the assets and water quality is likely be confirmed. Furthermore, legislative requirements relevant to water quality are likely to become more prescriptive as systems continue to deteriorate and the frequency of complaints from the public increases.

2.2 Fault detection and condition assessment goals

The goal for water system operators is to deliver the required quantity and quality of potable water at least cost. However, as water pipeline infrastructure deteriorates the capacity of operators to achieve their goal cost effectively is reduced. The American Water and Wastewater Association has recognised that in the USA and Europe many water supply pipelines are old and failing and that conducting condition assessment provides a means by which the extent of the problem can be assessed. Planning and investment steps can then be taken, such that the efficient delivery of the required quantity and quality of water can be achieved.

2.2.1 Operational justifications for condition assessment

Condition assessment can be used to predict the remaining operational life of a water pipeline. This prediction is based on the known time of installation, the condition of the deteriorated pipeline at the time of assessment and a projected minimum condition at which failure will occur. Various probabilistic models can be applied to draw relationships between location specific estimates of remaining wall thickness and pipe capacity and for the prioritisation of rehabilitation or repairs. The accuracy of these probabilistic models is dependent upon both the accuracy of location specific estimates of remaining wall thickness and the number of estimates or the length of pipeline over which the estimate applies.

Condition assessment can also be used to improve the operation of, and operational costs associated with, a pipeline system. For example, the cost of maintaining adequate pressure will increase with the extent of tuberculation (blockage) or leakage. Operators currently compensate for these forms of deterioration by increasing pumping heads or flows. Condition assessment can be used to intelligently guide the repair or rehabilitation of sections of pipe and avoid potential failures, including bursts, and the operational problems and costs associated with such events. Alternatively, where condition assessment has identified problematic pipes, but repair or rehabilitation has not been scheduled, system operation can be modified to increase efficiency and minimise the risk of failures.

Condition assessment and leak reduction are interrelated. The benefits of leak reduction programs include less potable water loss, deferral of capital expenditure, a reduction in operating costs and meeting regulatory targets. Undetected leaks can become bursts and, on critical mains, these bursts have significant consequences in terms of security of supply. Condition assessment on critical mains is already recognised by operators as important in minimising disruption and allowing rehabilitation measures to be strategically undertaken.

2.2.2 The changing legislative environment

The legislative environment within which water supply system operators function is changing, as concerns over the deterioration of assets increase amongst policy makers and the public, and decisions are being taken out of the sphere of the technical judgement of operators and are instead being made by regulatory bodies. In the United Kingdom, the Office of Water Service (OFWAT) and the Drinking Water Inspectorate (DWI) have legislated roles in ensuring water operators maintain minimum levels of service and water quality standards, respectively. In the USA, the Governmental Accounting Standards Board (GASB) revised statement number 34 in 1999 to require all water supply operators to report on the condition of their assets by either:

- Calculation using historic cost depreciation
- Using an asset management system including a requirement for condition assessment on a three yearly cycle

In South Australia, United Water operates the water supply and sewage assets of the City of Adelaide and surrounding suburbs for the South Australian Water Corporation (the government entity that owns the infrastructure). United Water operates the water supply system under the terms of a contract with the South Australian Government. This contract stipulates numerous performance standards pertaining to minimum flows and pressures and United Water are required to annually report on the number of interruptions to, and water quality complaints from, the public. The statics regarding these problems have direct financial consequences in contractual renegotiations.

2.2.3 Economic case and rehabilitation rationale

The business case for condition assessment has been a point of conjecture, largely because of the lack of cost effective condition assessment technologies and the incomplete collection of evidence of increasing rates of failure. That said, evidence of an accelerated deterioration of pipeline assets, rather than any significant drop in the cost of condition assessment, is driving a current shift in emphasis towards proactive investigation. Issues including the structural condition of systems, leak reduction, rehabilitation planning, operational expenditure and risk are, in most cases, receiving greater attention amongst operators than in the past.

In terms of cost recovery from the public through the price charged for potable water, or making application to government for capital grants for repair and rehabilitation, an accurate estimate of the condition of the water supply asset and its rate of deterioration is crucial. At the moment, there is a significant gap, in most jurisdictions around the world, between the rate of deterioration and renewal for water pipelines. The USEPA (2001) found that $139 billion would be required over 20 years to maintain the delivery of potable water in accordance with minimum standards in the USA. Of this quantum, $81.9 billion would be for transmission and distribution pipelines. More recently, the American Water and Wastewater Association (2004) has reported that:

> *"The average cost of replacing the water pipe network to comply with the required standards in the USA over the next 20 years has been estimated to cost around one trillion dollars. The potable transmission water pipe network would require around $325 billion to upgrade and replace failed pipes, which equates to $16.25 billion annually. There is currently an $11 billion annual shortfall between current spending and the overall necessary spending."*

The above costs cannot currently be passed onto the public for a myriad of political and economic reasons and, more specifically, because there is no sensible justification for replacing the entire system (at random). The role of condition assessment is becoming crucial in providing an intelligent basis upon which to take arguments for pipeline rehabilitation or replacement to economic and political decision makers.

United Water operators currently rely upon complaints of low flow and pressure and/or poor water quality, as well as records identifying pipes with a history of significant maintenance expenditure, as a guide to problematic pipelines within the system supplying the City of Adelaide and surrounding suburbs. However, United

Water's experience is that problems, such as poor wall condition, deteriorated joints, blockages, leaks and sometimes air pockets, associated with corrosion or cement leaching, tuberculation and aggressive external or internal pipe environments, are not uniformly distributed along the length of transmission or even individual distribution mains. This leaves United Water, and other operators, in a difficult situation in which, without a more complete understanding of a problematic pipe, and variations in its condition along its length, they need to decide on a remedial course of action. The options include:

- do nothing
- clean the pipe
- repair damaged sections
- rehabilitate damaged sections
- rehabilitate the entire pipe
- replace the entire pipe

It is clear that most of the above decisions require more detailed information regarding the nature and spatial distribution of changes in the condition of the problematic pipe. The ability to prioritise pipeline repairs, rehabilitation and replacement, or indeed to even decide upon the most suitable option, is crucial if unnecessary costs are to be avoided in closing the gap between the projected expenditure in asset maintenance and the actual expenditure required to maintain standards of supply. This prioritisation depends, in turn, upon specific knowledge of the condition of the asset. The difficulty is the cost of deploying current condition assessment technologies.

Traditional sources of pipeline condition information are not detailed enough to inform decisions as to whether particular pipes need to be replaced or can be rehabilitated. United Water operators can get an overall "feel" for the condition of a pipeline from its history of repairs, hydraulic performance (including specific flow/pressure or Hazen Williams C-Factor tests to gauge internal pipe roughness) and number of water quality complaints. However, they are then left to decide whether to replace the pipe or do further condition assessment, potentially involving coupon sampling or closed circuit television (hereafter CCTV) camera work, and this work is currently costly and operationally inconvenient. Non-destructive condition assessment technologies, which can be applied to identify specific faults or weaknesses, and identify specific rehabilitation and repair measures, need to be developed such that the combined cost of the investigation and specific remedial measures can be justified relative to the cost of replacing the entire pipeline. The development of such cost effective condition assessment technologies is crucial if the cost of replacing entire systems is to be mitigated over the next 20 years.

2.2.4 Incentive to develop condition assessment technologies

The combined effect of legislative and economic imperatives mentioned above makes the need for the research and development of condition assessment technologies increasingly relevant. Water operators struggling with increasing rates of leaks and/or bursts, complaints from the public regarding water flow, pressure or quality, and their economic and regulatory obligations in respect of each of these problems, can use condition assessment to help monitor the deterioration of assets and thereby better manage such difficulties.

At the moment, the bulk of research is directed towards adapting specialised technologies from the oil and gas industries for application to water systems. While more cost effective applications are emerging from this process, a lack of generality and the cost of deployment have remained significant obstacles to the wide scale implementation of detailed condition assessment programs in water supply systems. In this regard, there are crucial differences between the applicability of various technologies at different scales within water supply systems. In the case of long and large diameter transmission pipes, the option of replacement is a last resort and considerable condition assessment can be justified relatively easily. Furthermore, the transfer of technologies from the oil and gas industries to water transmission pipelines has been made easier because they are of a larger diameter and match the size, and so technological limitations, of the devices currently used on oil and gas pipes.

However, this leaves the problem of the assessment of the bulk of the smaller diameter distribution pipes. In total, the replacement cost of these distribution systems outweighs that of the larger transmission pipelines (American Water and Wastewater Association, 2004). However, the decision whether to replace shorter and smaller diameter pipelines or conduct condition assessment, and partially repair or rehabilitate, is finely balanced. The cost of deploying oil and gas pipeline technologies at this scale is prohibitive and only CCTV camera investigations are periodically used (partly because the existing non-destructive technologies are not well suited to the detection of internal blockage or tuberculation).

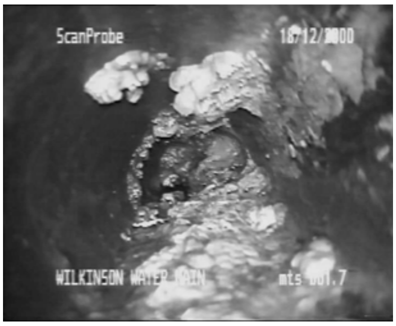
2.2.5 Effect of blockages, air pockets and leaks

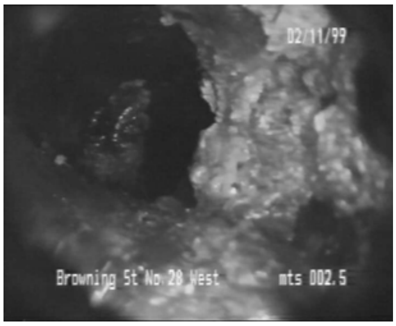
Water utilities expend up to half their annual budgets on pumping and treatment costs. In turn, pumping costs are proportional to the hydraulic efficiency (or the in-situ condition) of the water distribution system. The hydraulic efficiency of a system is directly proportional to the roughness of its composing pipes (i.e., their frictional resistance), blockages (either in the form of closed valves, discrete partial strictures or extended pipe constrictions), leakage (i.e., water that is lost and that needs to be pumped again) and, occasionally, trapped air pockets. Blockages affect efficiency by obstructing water supply routes either during pumping to network storage facilities or during periods of demand when water may be forced to take indirect and high loss routes to meet consumptive demands. Furthermore, the presence of blockages and air pockets are often related to water quality problems. Finally, blockages can be a precursor to, and are often associated with, leakage. If a blockage has evolved over time at a particular location then system pressure may be elevated at nearby locations. Such elevated pressures, over extended periods, stress water distribution systems and any weakness (eg. a problem joint) may well evolve into a more serious problem, such as a leak or burst, because of the elevated pressures.

Blockages

Blockages can reduce the overall redundancy in a network to the point where dead ends or backwater areas are created. This directly reduces the water supply pressure to the public. It also creates water quality problems because stagnant water is left for extended periods in such dead ends. Occasionally, high demands or natural transient events lead to the emergence of water from stagnant sections and severe water quality problems occur. The result is complaints from the public and these are often characterised by descriptions of low pressure and discoloured water. To date, such complaints have been one of the primary mechanisms for the detection of blockages. Unfortunately, the blockage is usually in a highly evolved state by the time such complaints are recorded.

Figures 2-1 and 2-2 show two typical blockages that were discovered after complaints from the public. Steady state tests were unable to confirm whether the blockage was discrete or extended. Furthermore, the location of the hydraulic inefficiency could not be specified beyond saying that it was located between the two nearest fire plugs (over 70m apart in both cases). CCTV camera investigation required that the pipelines be isolated and drained before they were cut open to allow the entry of a camera. However, there was uncertainty regarding where to focus the investigation. After making several cuts to improve access to the pipelines the CCTV camera was able to visually verify the size of the blockages and that they were discrete in nature.





Figures 2-1 and 2-2 – Examples of discrete blockages identified in the Wilkinson Road and Browning Street water mains, respectively, in Adelaide, South Australia

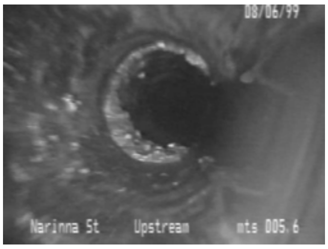
United Water operators confirmed that it was difficult to successfully deploy the CCTV camera to determine the extent of the blockages because associated smaller blockages (tubercules) obstructed the camera. As mentioned above, numerous cuts needed to be made to achieve sufficient access for the CCTV camera to properly define the extent of the main blockages. Unfortunately, by the time all the cuts had been made the replacement of the entire pipeline was, in both cases, required. The condition assessment was not cost effective because CCTV camera investigation was unable to cope with multiple blockages of variable severity and because the investigation was left too late.

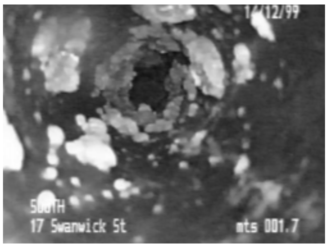
The decision to use CCTV cameras to investigate suspected blockages is significant for operators because considerable costs and disruption to supply are usually involved with no guarantee that the information obtained will be useful. That said, recent advances in technology now permit CCTV camera inspection of "live" systems in certain circumstances. Regardless of whether supply needs to be disrupted, the effectiveness of CCTV cameras is often reduced by a lack of access (and limited range) and complex topology (including suspected blockages). Numerous inspection points will typically be required in order to overcome these problems.

Continuous spectrum from roughness to blockage

Blockages, as distinct from inadvertently closed valves, can occur in a large number of forms ranging from discrete to non-discrete pipe constrictions, which occur over short or extended lengths of pipelines, respectively. The severity of the blockage can vary from rougher than usual pipes to complete topological obstruction. United Water has obtained, over the past decade, CCTV camera footage of numerous problem areas within the system supplying the City of Adelaide and surrounding suburbs in South Australia.

Figures 2-3, 2-4 and 2-5 show the early, mature and final stages of the process of internal corrosion and formation of tuberculation in three different 100mm diameter Cast Iron (CI) pipes (axial views along sections of the pipelines). Figure 2-3 shows that, in its early stages, internal corrosion can either begin at a joint or generally along the inside face of a metal pipeline. At this stage of development, the corrosion is akin to increased roughness along the inside of the pipe. Flow and pressure tests did not identify any significant drop in hydraulic capacity. CCTV camera investigation followed persistent complaints from the public regarding water quality problems that were believed to be associated with biofilm formation. Rehabilitation was performed economically by cleaning and the insertion of a non-structural liner.





Figures 2-3, 2-4 and 2-5 – Examples of the spectrum of roughness/blockage development due to internal corrosion and tuberculation

Figure 2-4 shows that, in its mature stages, internal corrosion and tubercules have continued to develop from pit and joint locations. At this stage of development, flow and pressure tests confirmed a significant reduction in hydraulic capacity. Again, CCTV camera investigation followed persistent complaints from the public regarding water quality problems. Rehabilitation was performed economically by replacing sections that exhibited a significant degree of internal deterioration.

Figure 2-5 shows that, in its final stages, internal corrosion and tubercules can develop into almost complete blockages in a pipeline. In contrast to the other two cases, fewer complaints from the public were recorded. Those complaints that were recorded related to slight reduction in pressure. The pressure in the pipeline was maintained at a reasonable level because it was located in a grided network with supply available from both ends. This masked the development of the blockage in terms of its effect on steady state flows and pressures. Furthermore, low flow through the blockage itself reduced associated tell-tale water quality problems. This case illustrates how difficult the identification of blockages can be and the totality of considerations that affect the assessment of a particular pipeline. As it transpired, the extent of the blockage as relatively limited and replacement of a 3m length of pipe was all the rehabilitation that was required.

Air pockets

Sources of air include entrainment during pumping, release during rapid pressure variations, residuals following pipeline maintenance with inadequate flushing and egress through seals at joints and fittings. Once air is entrained in a pipeline or network system it migrates to high points, such as under risers from valves and other fittings, at which it can accumulate. The accumulation of relatively small quantities of air at fire plugs was regularly observed throughout the testing program described in this research.

Air pockets can cause both hydraulic capacity and water quality problems. Air pockets trapped along individual pipelines have the potential to throttle flow and reduce hydraulic efficiency. Instances of this behaviour were confirmed after consultation with United Water operators. Furthermore, air pockets may remain trapped and accumulate over long periods of time. As an aerobic interface within a pipeline, there is the potential for bacteria to thrive in the proximity of an air pocket. Combinations of high and/or low pressure occasionally allow portions of trapped air pockets to escape and become re-entrained in flow. These circumstances can give rise to a reduction in water quality.

Leaks

Leak detection in water pipelines at all scales has been the focus of extensive research for decades. Historically, steady state methods have been employed. However, acoustic leak detection technologies have become commercially available over the last decade and are now extensively used by system operators around the world. These acoustic technologies are generally limited in range to distances of up to approximately 200m. However, they are extremely accurate for leaks as small as 0.1L/s (or an approximate equivalent orifice diameter of 0.5mm). Because of range limitations, detailed acoustic investigation is undertaken in combination with steady state volumetric monitoring by operators in the United Kingdom. The results of the volumetric testing, usually performed at night, are used to identify areas in which more detailed investigation using acoustic technologies is warranted. This procedure helps reduce the time and costs involved in carrying out acoustic investigation.

2.2.6 Operator consultation

The condition assessment and maintenance philosophies of operators vary with the needs and condition of different water systems assets, such as materials and construction methods used, environmental conditions, age, and regulatory environment. On-going discussions between the author and a number of experienced operators within United Water between 2001 and 2004 has provided valuable insights into the nature of the problem of fault detection and condition assessment in water pipeline and network systems. Their experience has helped define the problems investigated in this research.

Blockages

United Water operators were consulted regarding the range of sizes of discrete blockages they were interested in detecting. They indicated that constrictions up to 100% of pipeline diameter were typical of obstructions that could only be conclusively identified using CCTV camera investigation. As mentioned previously, redundancy in a network often masked the development of such severe obstructions because pressure and flow could be supplied from either side in a grided network, typical of that throughout the City of Adelaide and surrounding suburbs in South Australia. Furthermore, while isolation valves were typically manipulated to remove this redundancy during steady pressure and flow tests, the nature and extent of the blockage, and its precise location, could not be determined without follow up CCTV camera inspection.

Leaks

United Water operators were interested in techniques that could detect both very small and relatively large leaks at network scales. The ability to detect small leaks is important if improvements in water conservation are to be sustained. Acoustic leak technologies have been proven commercially and have the capability to locate leaks as small as 0.1L/s. However, operators were also interested in the accurate location of relatively large leaks (up to 1.5L/s) because visual evidence, if any, was often misleading and did not lead repair crews to the point of failure along a pipeline. Where a pipeline is particularly inaccessible and/or buried in porous material, or the discharge flows to drains before detection, operators are interested in the location of leaks exceeding 1.5L/s.

2.3 Non-hydraulic methodologies and technologies

2.3.1 Fault detection

The typical methods of non-hydraulic fault investigation are summarised, in terms of faults that can be detected, specificity of information obtained and spatial extent of information, in Table 2-2 below (and discussed in detail in Appendix A). Despite the correlation between the general deterioration of a pipeline and the manifestation of faults such as blockages, air pockets and leaks, and the direct impact of these faults, methodologies for obtaining specific information on the location and severity of a fault have been mainly pursued for leaks. In terms of blockage and air pocket detection, there is a clear impetus for the development of alternative non-invasive techniques.

Table 2-2 – Summary of non-hydraulic fault detection technologies

Method / Technology	**Detectable Fault**	**Specificity of information**	**Extent of information**
Visual (external)	Pipe displacement, bursts, leaks	Confirmation of location and nature of fault requiring immediate maintenance	Location specific
CCTV camera	Blockages, closed valves, tuberculation	Definition of extent and severity where access gained	Limited by severity of obstructions
SAHARA	Leaks	Location and size specific	Leak location to within 20m and flow down to 1L/hr
Acoustic correlators	Leaks	Location and size specific	Leak location if within 200m and size down to 0.5mm

2.3.2 Wall condition assessment

The typical capabilities of the non-hydraulic pipeline wall condition assessment methodologies and technologies are summarised, in terms of applicable materials, cleaning requirements, dewatering, inspection range and speed, in Table 2-3 below (and discussed in detail in Appendix A). Apart from the direct economic cost of wall condition assessment, the level of operational inconvenience (indirect economic cost) has a bearing on the decision to use particular condition assessment methods and technologies. Traditional condition assessment methods (i.e., those more commonly applied) have probably attained that status by being inexpensive and operationally convenient.

Table 2-3 – Summary of key characteristics of wall condition assessment techniques

Method / Technology	**Pipe material**	**Cleaning**	**Dewatering**	**Range**	**Speed**
Pipe history	All	None	No	Not applicable	Not applicable
Visual	All	External	No	Point specific	Not applicable
Coupon sampling	All	None	Yes	Sampling frequency	Not applicable
Soil resistivity	CI, DI, MS	None	No	Sampling frequency	5 samples and tests per day
CCTV camera	All	Internal	No (if "live" inspection)	400m limited by topology	400m per day
Broadband electromagnetic	CI, DI, MS	Internal	Yes	Limited by topology	2m per day for larger pipes
Guided wave ultrasonics	MS	External	No	30m	30m per day
Standard ultrasonics	CI, DI, MS	External	No	Point specific	1 test per day
Magnetic flux leakage	CI, DI, MS	External	No	Point specific	1 test per day
Remote field eddy current	CI, DI, MS	Both	Yes	900m limited by topology	6m per minute
Seismic pulse echo	Concrete	None	Yes	Point specific	1-3 tests per day

Internal access is required for CCTV camera, broadband electromagnetic, remote field eddy current and seismic pulse echo investigations. Where complex topology (i.e., changes in direction or junctions), fittings or tuberculation are present, the range and access for such technologies will be curtailed. Where external or internal cleaning is required before a technology can be applied, excavation and pipeline dewatering/cutting are also required, respectively. In this regard, technologies requiring internal cleaning or access are not non-destructive and are at least as operationally inconvenient as coupon sampling. All of these factors combine with cost to reduce the uptake of the listed condition assessment technologies and provide an impetus for the development of alternative non-invasive techniques.

2.4 Summary

The mechanisms by which water pipelines and networks deteriorate have been summarised in this chapter. Furthermore, information has been presented indicating that the current rate of rehabilitation and replacement of water supply infrastructure, including transmission and distribution pipelines and networks, is too low if economic and/or physical crises with regard to water systems are to be avoided. Legislators and policy makers have become aware of the problem and new regulations stipulating mandatory condition assessment programs are beginning to emerge in some jurisdictions. In the absence of such regulations, only some water system operators are taking a proactive approach to the problem of the deteriorating condition of the water systems they operate. In this context, the uptake of condition assessment technologies by operators has been restricted by cost versus benefit considerations. To date, these have shown that emerging condition assessment technologies are too difficult to apply to water systems and provide information which is either not sufficiently useful and/or too location specific (and so cannot be used without significant statistical extrapolation to gauge the condition of a pipeline or network more generally). The clear exception to this has been the reaction of operators in the United Kingdom and elsewhere to legislated leak reduction targets and the successful application of acoustic technologies to achieve goals.

However, in the context of other faults that affect pipeline and network systems, and the condition of pipeline walls, current technologies are not widely applied because of the difficulties described in this chapter. This is despite the fact that the information provided by Guided Wave Ultrasonics, Magnetic Leakage Flux and Remote Field Current Eddy technologies is generally accurate and detailed. These technologies continue to be widely neglected because operators cannot justify the cost of their application. Alternative technologies, that are less difficult to apply, and which yield more general information regarding faults or pipeline wall condition, are required to give operators more cost effective means of performing condition assessment over large geographical scales.

In this regard, numerous researchers have investigated the potential application of hydraulic transient testing to the problem of leak detection over the last decade as described in Chapter 3. As mentioned above, acoustic technologies have now been successfully applied to this problem. However, the application of hydraulic transient testing to the detection of other faults and pipeline wall condition assessment has not been previously investigated in the field. This research is undertaken in this thesis. The results presented in later chapters suggest that hydraulic transient testing may provide a cost effective tool for operators to intelligently diagnose faults, wall condition or other forms of deterioration in pipelines, without incurring the costs associated with existing non-destructive technologies.

Chapter 3

Background Literature and Previous Research

Numerous researchers have investigated the application of hydraulic transient testing to the problem of leak detection over the last decade. The use of hydraulic transient testing for leak (and other fault) detection, as well as pipeline wall condition assessment, is attractive because there is a need for such condition assessment which current technologies do not satisfy (to varying extents). Leak detection has received significant attention and been the subject of regulatory changes that have motivated the development of the acoustic technologies, described in Chapter 2, and also the research described in this chapter. As a consequence, most previous research focuses on the application of hydraulic transient methods to the problem of leak detection and there is little reported literature relevant to the use of hydraulic transients for the diagnosis of other faults or pipeline wall condition.

3.1 Potential role for controlled transient testing

3.1.1 Desirable condition assessment criteria

The American Water and Wastewater Association (2004) has indicated, in its "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains", that new condition assessment technologies should:

- minimise any excavation by deployment through any existing access points such as valves and hydrants

- be non-interruptive and be deployed on the outside of pipes or not interrupt pressure and flow if inside the pipe
- operate without the need for pre-cleaning to allow the tool to negotiate the pipe or to have intimate contact with the pipe wall
- not involve the introduction of something into the pipe that could potentially cause problems with water supply or quality

Although this list of requirements is onerous, it represents the thinking of water operators when considering proposed condition assessment technologies. Most of the conventional technologies transferable from the oil and gas industry, as mentioned in Chapter 2, do not meet all of these criteria.

The use of transient tests, as elaborated in the remainder of this thesis, meets all of the American Water and Wastewater Association's practical requirements. As described in more detail in Chapter 6, existing valves and hydrants are used for access, no excavation is required, the flow and pressure in a pipeline or network system is only slightly perturbed and not disrupted, there is no need for cleaning external or internal pipe surfaces and nothing is introduced to the pipeline that could cause problems with water supply or quality. The outstanding question is what information transient tests yield.

3.1.2 Transient testing for fault detection and condition assessment

The transient response of a pipeline or network system is a function of the type of transient induced and the physical condition of the system. Any fault (such as a blockage or leak) or change in pipe wall condition will affect measured flow and pressure responses during a transient and contain specific reflection and damping information that may be able to be used to diagnose the fault or pipe condition. If a fault is significant, and/or a relatively large transient pressure rise or change is applied, then direct reflections will be observed. If the fault is less significant then tell-tale damping may be observed in the absence of any direct reflections. A further precondition to the observation of direct reflections is that the incident transient wave be sufficiently sharp.

Reflection and damping information in a transient response

Regardless of whether a fault or defect in pipe condition is present, reflection and damping information are simply two manifestations of the response of a pipeline or network system to an induced transient. When a transient wave arrives at a fault (such as a blockage or leak) a loss of energy occurs coupled with a reflected wave. The size of the reflected wave is proportional to both the size of the fault and transient pressure change. If the reflected wave is large, relative to reflections from other sources, it may be usefully interpreted. However, if the reflected wave from a fault is small, or the induced transient wavefront is insufficiently sharp, then the direct reflection information may be obscured by reflections from other physical elements and/or dispersion and damping. Nevertheless, energy is removed by the fault with each pass of the transient wave despite the fact that direct reflections may be difficult to discern. This energy loss manifests as damping that equates to the cumulative effect of indistinct reflections. An understanding of non-fault related sources of dispersion and damping in a pipeline or network system is required if the damping contribution from a relatively small fault, with indistinct direct reflections, is to be isolated.

3.1.3 Theoretical potential of inverse transient models

The theoretical potential of using inverse transient analysis, and the reflection and damping information contained in the response of a pipeline or network with a leak, was first numerically explored by Liggett and Chen (1994). Inverse analysis was performed by minimising the sum of the squares of the differences between predicted responses, obtained using a transient model, and measured data (numerically generated using the same transient model), at a fixed number of measurement points, for each set of leak parameters (i.e., a least squares minimisation criteria was applied). The leak parameters were varied during the optimisation process using a Levenberg-Marquardt gradient search algorithm. Once the sum of the squares of the differences was minimised (i.e., a minimum objective function was identified), the accompanying leak location and size was taken to represent the true leak location and size. Vitkovsky et al. (2000) performed further numerical research implementing a genetic algorithm to perform optimisation for leak location and size parameters

The key to the theoretical success of the technique was the fact that the same numerical model was used to generate artificial measured data as was used to perform the inverse analysis. In essence, a perfect model that accurately replicated the measured response was assumed. Subsequent laboratory and field investigations, as summarised below, have displaced the assumption that the transient behaviour of real systems can be easily replicated using existing transient models. Nevertheless, the potential application of inverse transient analysis remains attractive because transient models are capable of being used to interpret measured responses from field systems and provide additional insight into different phenomena that would otherwise prevent the identification of a fault.

3.2 Leak detection using transients

3.2.1 Direct reflection methods in the time domain

Leaks along pipelines produce reflected signals within transient responses. If the leak reflection(s) are discernable, then the time of arrival of these reflections at known measurement locations can be used to locate the leak(s). This form of analysis is sometimes referred to as Time Domain Reflectometry. Jonsson and Larson (1992), Brunone (1999), Covas and Ramos (1999), Jonsson (2001), Vitkovsky (2001) and Brunone and Ferrante (2001) have all used this form of analysis to locate leaks using reflection information from transient responses obtained using laboratory apparatus. Each researcher, together with a summary of the experimental equipment used and results obtained, is listed in Table 3-1. Provided the wave speed of a pipeline can be accurately estimated, and leak reflections are sufficiently distinct, the travel time of the leak reflected waves, over the first 2L/a or 4L/a seconds of the response following the induction of the transient (depending on system boundary conditions), can be used to determine the location of any leak(s).

Table 3-1 – Laboratory research using direct reflection information and analysis

Researcher	Laboratory apparatus	Sharpness of transient and sampling rate	Size of leak(s) and/or leak flowrate (L/s)	Type of analysis
Jonsson (1995)	Galvanised steel 133.25m long 40 to 50mm (ID)	25ms incident wavefront 640Hz sampling rate	0.04L/s (1.3mm) to 0.21L/s (2.9mm) under approximately 600kPa	Damping used for qualitative assessment and reflections used for locating leak
Brunone (1999)	Polyethylene 352m long 93.8mm (ID) (single pipe in concentric loops)	Incident wavefront not specified 200Hz sampling rate	C_dA_L = 3.17x10^{-5}m^2 minimum leak discharge coefficient	"As new" or "no leak" signal used for comparative reflection analysis
Vitkovsky (2001)	Copper 37.2m long 22mm (ID)	9ms incident wavefront Sampling rate up to 2000Hz	1.0mm minimum leak diameter	Reflection based methodology used akin to Time Domain Reflectometry
Brunone & Ferrante (2001)	Polyethylene 352m long 93.8mm (ID) (single pipe in concentric loops)	Neither incident wavefront nor sampling rate specified	Small leak defined as A_L/A_{pipe}<0.03 Smallest leak was 4.9mm in diameter with 1.0m reflected wave for 16m overpressure	Reflection based methodology used akin to Time Domain Reflectometry

where ID is internal diameter, A_L is leak area, A_{pipe} is pipeline area and A_L/A_{pipe} is the ratio of leak area to pipeline area

Covas and Ramos (1999), Brunone (1999), Jonsson (2001) and Vitkovsky (2001) have all developed formulae for the determination of the size of a leak using the size of the incident transient wavefront and leak reflected waves. All of these formulations neglect the effect of friction along a pipeline and this is only appropriate in laboratory systems where friction losses can be minimised. The formulation used by Vitkovsky (2001) is presented below. Providing the initial steady pressure, transient pressure rise (or change) and drop (or change) in pressure at the location of a leak are known the size of the lumped leak coefficient $C_d A_L$ can be approximated using the relation:

$$C_d A_L = \frac{A}{a}\sqrt{\frac{g}{2}}\frac{\left(H_1 - H_2\right)}{\left(\sqrt{\frac{1}{2}\left(H_1 + H_2\right)} - \sqrt{H_0}\right)} \tag{3-1}$$

where C_d is the leak discharge coefficient, A_L is the area of the leak, A is the pipe area, a is the wave speed, g is the gravitational constant and the values for H_0, H_1 and H_2 are equal to the steady state pressure, the magnitude of the incident wavefront and the magnitude of the wavefront transmitted after interaction with the leak, respectively

The researchers listed in Table 3-2 have measured the size of leak reflected waves and reported C_dA_L values for their laboratory apparatus, respectively. Predicted C_dA_L values have been determined using Equation 3-1 and information regarding the physical configuration of each laboratory apparatus. The predicted C_dA_L values are listed in the last column of Table 3-2 and are in agreement with the measured C_dA_L values except for the results reported by Covas et al. (2003).

Table 3-2 – Measured and predicted leak coefficients for previous researchers

Researcher	H_0 (m)	H_1-H_0 (m)	H_1 (m)	H_2 (m)	Leak reflection (m)	C_dA_L (m^2) x10^{-5} (measured)	C_dA_L (m^2) x10^{-5} (predicted)
Jonsson (1995)	60.0	50.0	110.0	108.6	1.40	0.0117	0.0117
Covas et al (2002a)	41.0	19.0	60.0	59.35	0.65	0.5712	0.5687
Brunone & Ferrante (2001)	10.0	16.6	26.6	25.86	0.74	1.6420	1.6325
Vitkovsky (2001)	27.0	19.0	46.0	44.76	1.24	0.0521	0.0518
Brunone (1999)	1.3	9.5	10.8	9.37	1.43	3.1681	3.1615
Covas & Ramos (2001)	25.5	7.0	32.5	30.27	2.23	2.9954	2.9923
Covas et al (2003)	3.0	9.5	12.5	12.0 (approx)	0.5 (approx)	4.5620	0.6025

The general consistency between the measured and predicted C_dA_L values obtained using the frictionless formulation developed by Vitkovsky (2001) suggests that friction losses are not significant in the laboratory apparatus. The wave speed and size of the leak reflections are not specified in the work reported by Covas et al. (2003) and this partially accounts for the discrepancy between the measured and predicted C_dA_L values. More significantly, the tests were performed using the 1.3km long Thames Water quasi-field "Torus" rig (located near Reading in the United Kingdom) and significant effects related to friction and air pockets were neglected. These influences combined to significantly distort the reflection associated with the leak.

3.2.2 Inverse transient methods in the time domain

Inverse transient methods, including inverse transient analysis (ITA), can be applied over short or long time periods to interpret the reflection and damping information contained within a measured transient response from a pipeline with a leak. The researchers listed in Table 3-3 have previously applied inverse transient analysis to interpret results from their laboratory apparatus and determine whether leaks can be successfully located and sized. A number of the researchers are the same as those who conducted research into the application of direct reflection methods.

The application of inverse transient analysis to interpret the results from the laboratory tests, identified in Table 3-3, required calibration of forward transient models except for the results presented by Vitkovsky et al. (2001). Vitkovsky et al. (2001) found that the inclusion of the effects of unsteady friction was all that was required to accurately reproduce the measured responses from the laboratory apparatus. The calibration of steady state friction factors, unsteady friction weighting functions and viscoelastic creep coefficients, using measured responses without any leak(s), was required for the other experiments conducted on apparatus comprising PVC or polyethylene pipes.

Table 3-3 – Laboratory research using leak reflection and damping information and inverse transient analysis (ITA)

Researcher	Laboratory apparatus	Sharpness of transient and sampling rate	Size of leak(s) and/or leak flowrate (L/s)	Calibration and type of analysis
Vitkovsky (2001)	Copper 37.2m long 22.1mm (ID)	9ms incident wavefront Sampling rate up to 2000Hz	1.0mm minimum leak diameter	Inclusion of unsteady friction effect
Covas & Ramos (2001)	PVC PN 10 4m x 6m loops 45 mm (ID)	80ms incident wavefront 600Hz sampling rate	C_dA_L = 3.0x10^{-5}m^2 minimum leak discharge coefficient 0.67L/s	Steady friction factor and wave speed adjustment calibration with leak damping effect
Covas et al (2002a)	HDPE 277m long 50.6mm (ID)	Not specified Sampling rate up to 9600Hz	2.7mm to 6.0mm effective leak diameters	Concurrent viscoelastic creep compliance calibration with leak damping effect
Covas et al (2003)	MDPE 1.3km long 70mm (ID)	Not specified Sampling rate up to 9600Hz	C_dA_L = 4.44x10^{-5}m^2 minimum leak discharge coefficient 0.35L/s	Concurrent viscoelastic creep compliance calibration with leak damping effect

Covas and Ramos (2001) performed pre-calibration by manipulating steady state friction factors and using wave speed adjustment. Later, Covas et al. (2002a) calibrated transient models for their apparatus by fitting creep coefficients for a viscoelastic function. The last set of experiments listed in Table 3-3 was conducted on a quasi-field pipeline called the "Torus" rig owned and operated by Thames Water. This pipeline exhibited a complex transient response including multiple reflections from air pockets and joints. Covas et al. (2003) were able to perform creep coefficient calibration for this apparatus but were unable to replicate all of the reflections in the measured responses.

While inverse transient analysis has the theoretical potential to provide the location and size of leaks with no calibration effort, the results of the laboratory experiments demonstrate that calibration effort is required even under controlled conditions. Furthermore, the forward transient model, even once calibrated, becomes less accurate with increasing system complexity. A number of researchers (notably Covas et al. (2002a)) have emphasised the critical importance of the accuracy of the forward transient model when performing inverse transient analysis.

3.2.3 Dimensionless leak parameter comparisons

The determination of dimensionless leak parameters is useful because it clarifies the sensitivity with which leaks can be detected given variations in the wave speed, pipe area, pressure at the leak and the size of the lumped leak coefficient for each laboratory apparatus. The following expression for a dimensionless leak parameter is based on the derivation presented by Wang (2002). It is applied to each of the laboratory apparatus, described above, to determine the dimensionless parameters listed in Table 3-4:

$$F_L = \frac{\dfrac{C_d A_L}{A} \dfrac{2ab}{(2gH_0)^{1-b}}}{\left(\dfrac{H_{L0}}{H_0}\right)^{1-b}} = \frac{C_d A_L}{A} \frac{2ab}{(2gH_{L0})^{1-b}} \qquad (3\text{-}2)$$

where C_dA_L is the lumped leak coefficient, A is the area of the pipeline, a is the wave speed, b is taken as 0.5, H_0 is a reference pressure and H_{L0} is the initial pressure at the leak

The smaller the dimensionless leak parameter the greater the sensitivity of a particular configuration of apparatus to leaks. Table 3-4 exhibits a decreasing trend in sensitivity to leaks as the configuration of the apparatus became less favourable to leak detection (due to the effects of either larger pipeline diameters, lower wave speeds and/or smaller leak pressures). The last listed results are for the Thames Water quasi-field “Torus” rig which has the least sensitivity to leaks and, notably, most closely approximates a real field pipeline.

Table 3-4 – Dimensionless leak parameters for previous researchers

Researcher	C_dA_L (m^2) x10^{-5}	Area of pipe (m^2) x 10^{-3}	Wave speed (m/s)	Initial pressure (m)	Leak discharge (L/s)	Dimensionless leak parameter (F_L)
Jonsson (1995)	0.0117	1.2566	1234	60.0	0.040	0.0034
Covas et al (2002a)	0.5712	2.0109	385	41.0	0.162	0.0386
Brunone & Ferrante (2001)	1.6420	6.9103	354.0 (avg)	10.0	0.230	0.0601
Vitkovsky (2001)	0.0521	0.3836	1319	27.0	0.012	0.0779
Brunone (1999)	3.1681	6.9103	340	1.3	0.160	0.3087
Covas & Ramos (2001)	2.9954	1.5904	475	25.5	0.670	0.4001
Covas et al (2003)	4.5620	3.8485	400 (assumed)	3.0	0.350	0.6182

3.2.4 Limits to controlled transient pressure rise (or change)

The transient pressure rise (or change) required to detect a leak is as critical as the size of the leak itself. That said, the pressure rise following a deliberately induced transient cannot be increased above the safe working limits for pipeline and network systems. Furthermore, the magnification of non-leak related reflections, as the transient pressure rise (change) is increased, may continue to obscure leak reflections.

Transient pressure rise (change) for tests performed using an abrupt valve closure

The tests listed in Table 3-4 (above) were all performed using either abrupt in-line or side discharge valve closures to reduce steady flow along each pipeline apparatus to zero. This generated step increases in pressure (i.e., transient pressure rises). Unfortunately, the transient pressure rise is not directly taken into account when determining the dimensionless leak parameters. That said, the dimensionless leak parameters have been determined using the minimum C_dA_L values reported by each researcher and these, in turn, are a partial function of transient pressure rise. Figure 3-1 confirms an indirect relationship between the dimensionless leak parameters and the corresponding transient pressure rise for each laboratory apparatus.

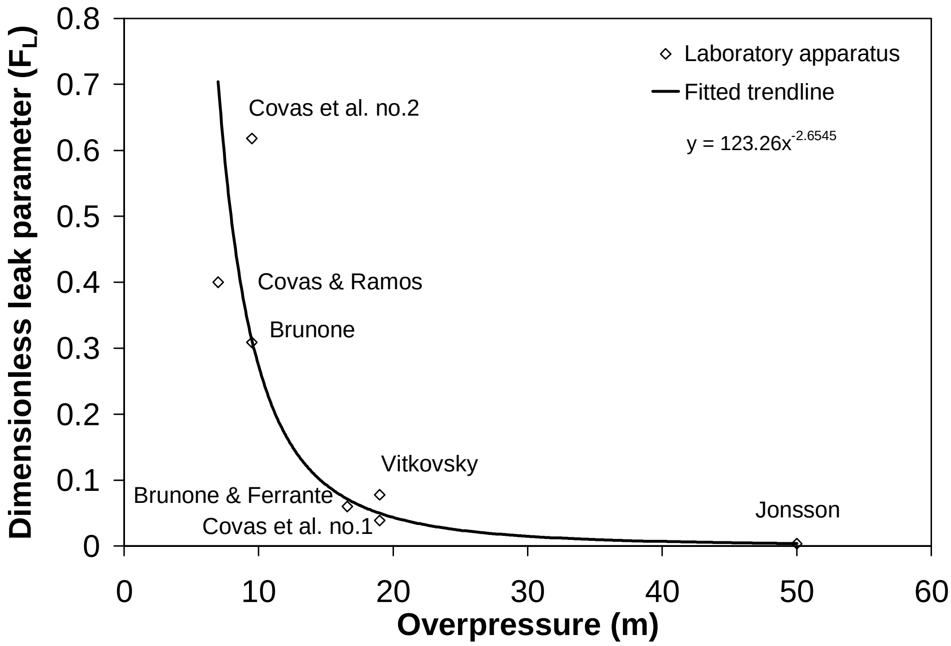


Figure 3-1 – Relationship between dimensionless leak parameters and transient pressure rise for laboratory apparatus used by previous researchers

The apparatus used by Jonsson (1995) could be used to detect the smallest leaks because a very large transient pressure rise was generated. However, transient pressure rises of up to 50m, as used by Jonsson (1995), are not acceptable on field pipelines with components that may be in deteriorated condition and/or in a location where pressure magnification occurs such that safe working pressure limits are exceeded. The maximum transient pressure rise that the operators of water pipelines and networks will permit may vary.

However, the consensus amongst United Water and South Australian Water Corporation personnel was that approximately 10m was an appropriate limit.

Use of Psuedo Random Binary Signals (PRBSs)

A potentially important alternative to the use of an abrupt in-line or side discharge valve closure is the use of a Psuedo Random Binary Signal (PRBS). PRBSs typically comprise a series of pulses, spaced at random intervals, which are periodically repeated. The minimum period of the pulse sequence is set to the time for the response from the first pulse in the series to attenuate to zero. The advantage of the PRBS is that the same energy as a step or abrupt signal can be input to a pipeline system over a longer period of time.

Martin and Chen (1986) explored the superposition of low amplitude constrained white noise, with a periodic signal (with the result being an input analogous to a PRBS), upon normally operating pipeline systems, for the purpose of leak detection. Both impulse and frequency response functions were subsequently extracted from numerical and laboratory data. The laboratory apparatus comprised a 6.26m long by 15.7mm diameter oil filled pipeline with an off-line servo valve to impose a PRBS with a frequency of 2640Hz. The location and size of a 2mm diameter leak was experimentally verified. Subsequent research by Lee (2005) has demonstrated that a PRBS can be successfully generated on laboratory water pipelines and used to detect leaks. While the use of PRBSs is potentially important, the devices required to generate the input pulses are difficult to construct with limitations as observed in the laboratory by Lee (2005). The construction of a device suitable for field application was beyond the scope of the research described in this thesis.

3.2.5 Frequency domain transient damping method

Wang et al. (2002) and Wang (2002) developed a frequency domain method for the identification of the location and size of a leak based on observed transient damping related to the leak. An analytical solution describing the decay of individual harmonic components in the frequency response of a pipeline to a transient, when a leak was present, was derived and the following equation obtained for the determination of the location of the leak:

$$\frac{R_{n_2L}}{R_{n_1L}} = \frac{\sin^2\left(n_2\pi x_L^*\right)}{\sin^2\left(n_1\pi x_L^*\right)} \qquad (3\text{-}3)$$

where $R_{nL} = \frac{C_d A_L}{A}\frac{a}{\sqrt{2gH_{L0}}}\sin^2\left(n\pi x_L^*\right)$ is the leak induced damping for each harmonic and C_dA_L is the lumped leak discharge coefficient, A is the area of the pipeline, a is the wave speed, H_{L0} is the steady state pressure at the leak, n is the harmonic number and x_L^* is equal to x_L/L (i.e., the dimensionless leak location with x_L equal to the distance of the leak from upstream boundary and L equal to the length of the pipeline)

The method relies on the fact that a leak damps different harmonic components of the transient response at different rates. This enables the location of the leak to be determined from the ratio of the magnitudes of leak induced damping for two harmonic components as shown in Equation 3-3. The magnitudes of the leak induced damping are determined as the difference between the measured damping for the relevant harmonics for the pipeline system with and without a leak. Once the dimensionless leak location has been determined the size of the leak can be estimated using the equation relating the leak induced damping to the lumped leak discharge coefficient (Wang, 2002).

The technique has two limitations that inhibit its application to field pipelines. Firstly, it is necessary to to accurately determine the non-leak related damping in the pipeline system without a leak. Secondly, the analytical solution is limited to single pipelines with constant head boundary conditions (i.e., tanks/reservoirs or valves at either end). This means that the technique cannot currently be applied to branched pipe or network systems.

3.2.6 Frequency domain response function method

The frequency domain response of a pipeline is known as its frequency response function. The traditional method for obtaining the frequency response function for a pipeline is called frequency sweeping. This process involves establishing a sinusoidal oscillation (flow and pressure) in a pipeline by means of a fluctuating discharge valve. Once a steady oscillation is established, at a particular frequency, the magnitudes of flow and pressure oscillation within the pipeline are measured (and provide a point on the frequency response function). This process is repeated for different frequencies until a sweep at the desired resolution of the frequency response function is complete.

Mpesha et al. (2001, 2002) simplified this procedure by replacing the need for a steady oscillatory forcing function with the use of a non-periodic transient. By measuring both the input to (e.g., valve perturbation) and output from (e.g., pressure variation) the pipeline system, the frequency response function could be obtained by determining the autocorrelation of the input and cross correlation with the output, taking the Fourier transform of the cross correlation and dividing the Fourier transform obtained for the output by that for the input. The resulting frequency response function can be expressed in terms of the pressure response at each frequency per unit perturbation of the valve.

Results presented by Brunone and Ferrante (2001), Lee (2003c) and Lee (2005) confirm that while leaks do not induce specific frequencies they do alter the relative magnitudes of the harmonics in a frequency response function. This observation was used by Lee et al. (2004) to develop an inverse technique for locating and sizing leaks using frequency response functions extracted from single pipelines. Unfortunately, the same problems inhibiting the application of the transient damping method in the field apply to frequency response function methods. Another problem, specific to frequency response function methods, is the need for the source of the induced transient and pressure measurement stations to be at fixed relative locations.

3.2.7 Impulse response function methods

Liou (1998) numerically demonstrated a methodology whereby the time domain impulse response of a pipeline to a controlled transient could be extracted at a series of measurement points along a pipeline, and the maximum amplitude plotted, to identify a change in the friction slope at the location of the leak. The procedure for extracting the impulse response function involved firstly extracting the frequency response function for the pipeline system, as described above, applying filtering algorithms to reduce the impact of high frequency noise not related to the system response, and inverting the result using an inverse Fourier transform to obtain a real data series representing the impulse response function of the pipeline.

Lee (2005) applied impulse response methods to show that the measured response from a pipeline system, including any leak reflections, could be reduced to a series of sharp pulses. Unfortunately, the impulse responses function does not distinguish between leak and non-leak reflections and sharp pulses will be observed at locations that correspond with system boundaries and, more problematically, any other reflective phenomena in a pipeline. As Vitkovsky (2003a) and Lee (2005) point out, the sign of the pulse will indicate whether the reflection is coming from either a low or high impedance element along the pipeline. However, the technique provides no additional interpretive benefit apart from improving the accuracy with which the origin of all reflections can be estimated.

3.3 Blockage detection using transients

3.3.1 Direct reflection methods in the time domain

Zhou and Adewumi (1999) and Adewumi et al. (2000) numerically demonstrated that a multiphase hydrodynamic model for gas-condensate two-phase flow could be used to detect extended blockages in gas pipelines (i.e., blockages with axial length). Adewumi et al. (2000) traced the theoretical behaviour of a transient pulse in an example pipeline and adequately predicted the arrival of the first reflection from a blockage. However, the predicted behaviour was significantly complicated by reflections propagating from both the upstream (constriction) and downstream (expansion) ends of the blockage. In the case of multiple blockages the interaction of the initial pulse with blockage entry (constriction), blockage exit (expansion) and boundary condition reflections was even more complicated. Nevertheless, decomposition of the response was numerically undertaken and revealed the location of multiple blockages.

The main problem with the methodology proposed by Adewumi et al. (2000) is the sensitivity with which pressure measurements need to be taken to detect the reflections from the blockages. The reflection from a blockage is proportional to its severity (and pressure loss across the blockage). The numerical experiments conducted by Adewumi et al. (2000) assumed an initial constant pressure of 1000psi in the pipeline. Unfortunately, the pressure variation associated with a 65% blockage in the pipeline was only ±0.005psi or 0.0005% of the background pressure.

3.3.2 Blockage reflections and dimensionless parameter

Wylie and Streeter (1993) presented equations that can be iteratively applied to determine a lumped loss coefficient for a discrete blockage (in-line orifice) using measured transmitted and reflected transient wavefronts (assuming that a step incident transient wavefront is induced). It is apparent from these equations that a significant baseflow through the discrete blockage will non-linearly magnify the reflection from it (assuming the incident transient pressure rise (change) remains constant). Establishing a significant baseflow may be crucial in extracting discernable blockage reflections in the field. In this regard, the conduct of transient tests with baseflow to magnify reflections from discrete blockages is analogous to the existing practice of performing steady state Hazen-Williams pipe roughness C-Factor tests.

Calculation of lumped loss coefficient for discrete blockage

The size of the block coefficient (K) can be determined iteratively using Equations 3-4 and 3-5, as presented by Wylie and Streeter (1993), provided the loss under steady conditions, transmitted and reflected pressures and the transient pressure rise (change), at the location of a discrete blockage, are known:

$$\Delta H_T = \frac{-\left(1 + H_V / BQ_V\right) + \sqrt{\left(1 + H_V / BQ_V\right)^2 + Kg\Delta H_W / a^2}}{Kg / 2a^2} \qquad (3\text{-}4)$$

$$\Delta H_R = 2\Delta H_W - \Delta H_T \qquad (3\text{-}5)$$

where ΔH_T is the transmitted transient pressure through the discrete blockage, ΔH_R is the reflected transient pressure from the discrete blockage, Q_V is the underlying flow through the blockage along the pipeline, H_V is the pressure loss across the blockage under steady conditions, $B = a/gA$ is the pipe impedance (with A = pipeline area), ΔH_W is the incident transient pressure rise (change), g is the gravitational constant, a is the wave speed and K is the block coefficient (and is assumed to be quasi-steady)

When there is no underlying baseflow through the blockage Equation 3-4 reduces to:

$$\Delta H_T = \frac{-1 + \sqrt{1 + Kg\Delta H_W / a^2}}{Kg / 2a^2} \qquad (3\text{-}6)$$

Dimensionless blockage parameter (F_B)

The determination of dimensionless blockage parameters is useful because it clarifies the sensitivity with which blocks can be detected given variations in the wave speed, pipe area, steady pressure loss and underlying baseflow for different pipeline configurations.

The following expression for a dimensionless discrete blockage parameter is based on the derivation presented by Wang (2002):

$$F_B = \frac{KQ_0}{2aA} = \frac{K\dfrac{Q_0^2}{2gA^2}}{\dfrac{aQ_0}{gA}} = \frac{\Delta H_{orf}}{H_S} \tag{3-7}$$

where K is the block coefficient, A is the area of the pipeline, a is the wave speed, Q_0 is a reference flow (underlying baseflow along the pipeline), ΔH_{orf} is the pressure loss across the discrete blockage (represented as an in-line orifice) and H_S is the Joukowsky pressure rise (change)

3.3.3 Unsteady inertia and minor losses

The block coefficient used in the above equations is usually applied during transient analysis in a quasi-steady manner. This means that the loss coefficient applicable to the discrete blockage or orifice is determined for the steady state conditions prior to the transient and then re-determined, at each computational time step, as the magnitude of flow through the discrete blockage or orifice varies throughout the transient. The instantaneous flow is used to assign a corresponding steady state loss coefficient at each computational time step. Other minor loss elements, such as bends and tees, are treated in a similar quasi-steady manner. Zero-time computational elements, which incorporate pressure losses, are traditionally used to represent minor loss elements, as explained in more detail in Appendix B.

The quasi-steady approximation of the minor losses through an orifice, and other elements, is inappropriate when there are severe geometric constrictions in a system. Daily et al. (1956) observed extra pressure loss (in addition to that predicted using a quasi-steady approximation), fluid inertia and a momentum flux, when an in-line orifice, forming a severe constriction, was subject to accelerating and decelerating flow (i.e., transient flow conditions). The extra pressure loss, fluid inertia and momentum flux correspond to frictional shear losses, submerged jet formation and destruction, and changes in the volume of water in the control volume, associated with the formation of separated regions, respectively. For intense jet formation, associated with severe constrictions, Daily et al. (1956) observed that unsteady flow conditions were not comparable to any steady state condition.

Funk et al. (1972) confirmed that the assumption that in-line orifices follow their steady state characteristics during transient events could lead to significant errors if the in-line orifice severely constricted a pipeline. The authors developed an equation relating the flow through an in-line orifice to the pressure drop across it during unsteady conditions:

$$p_1 - p_2 = \frac{\rho}{\sqrt{\frac{C_D A_0 \pi}{2}}} \left[\frac{dq}{dt} \right] + \frac{\rho q^2}{2(C_D A_0)^2} \tag{3-8}$$

where p_1 and p_2 are the pressures upstream and downstream of the in-line orifice, C_D is an unsteady discharge coefficient that is approximated using a steady discharge coefficient determined for the initial flow conditions, A_0 is the area of the in-line orifice, q is the unsteady flow and ρ is the density of the relevant gas or fluid

Under steady conditions, Equation 3-8 reduces to the familiar form of the steady state equation describing the head loss across an in-line orifice. Funk et al. (1972) experimentally calibrated the above equation. In doing so, they confirmed that the unsteady effect was limited to high frequency transients and relatively severe in-line orifice geometries (i.e., very small orifices). The authors concluded that the use of the steady state or quasi-steady equation was adequate to describe the behaviour of most orifices subject to unsteady conditions.

Washio et al. (1982) isolated non-linearity in oscillatory flow through an in-line orifice. Observed hysteresis was explained by describing a process of eddy formation and destruction whereby non-linear energy dissipation occurred. This process of eddy formation and destruction lagged the oscillating changes in flow and the resistance to the physical change in state was labelled “eddy inertia” (the effect was confirmed by Zielke (1983)). Washio et al. (1982) suggested that an analytical approach to describing the phenomena would not be successful and instead presented an empirical formulation for calibration to experimental measurements:

$$\Delta H = K_U \frac{Q(t-T_0)|Q(t-T_0)|}{2gA^2} \tag{3-9}$$

where H_U is a calibrated unsteady loss coefficient and the flow used is lagged by time T_0 to account for the inertial effects of the unsteady eddies (i.e., “eddy inertia”)

More recently, Prenner (2000) has conducted a comprehensive set of laboratory experiments using a 12m long by 100mm diameter steel tube, with a range of in-line orifice to pipe area ratios from 1:16, 1:32, 1:64 to 1:100, to determine the conditions over which a quasi-steady approximation of the behaviour of the in-line orifices remains valid. Prenner (2000) found that the use of the quasi-steady approximation remained accurate until the ratio of the in-line orifice to pipe area exceeded 1:50.

3.3.4 Frequency domain transient damping method

Based on the method developed for leaks, Wang et al. (2002) developed an analytical solution describing the decay of individual harmonic components in the frequency response of a pipeline to a transient, when a discrete blockage was present, and the following equation for the determination of the location of the discrete blockage:

$$\frac{R_{n_2 B}}{R_{n_1 B}} = \frac{\cos^2(n_2 \pi x_B^*)}{\cos^2(n_1 \pi x_B^*)} \tag{3-10}$$

where $R_{nB} = 2G\cos^2\left(n\pi x_B^*\right)$ is the blockage induced damping for each harmonic

and $G = KQ_0/2aA$ is the blockage resistance parameter (and is equal to F_B in Equation 3-7), K is the block coefficient, Q_0 is the initial baseflow, a is the wave speed, A is the pipeline area, n is the harmonic number and x_B^* is equal to x_B/L (i.e., the dimensionless blockage location with x_B equal to distance of the blockage from upstream boundary and L equal to the length of the pipeline)

The location of the discrete blockage is determined from the ratio of the magnitudes of blockage induced damping for two harmonic components as shown in Equation 3-10. The magnitudes of the blockage induced damping are determined as the difference between the measured damping for the relevant harmonics for the pipeline system with and without a blockage. Once the dimensionless blockage location has been determined the size of the discrete blockage can be estimated using the equation relating the blockage induced damping to the blockage resistance parameter (Wang, 2002).

3.3.5 Frequency domain response function method

Based on the method developed for leaks, Lee (2005) explored the effects of both discrete and extended blockages upon the frequency response function of a pipeline. As for leaks, discrete blockages do not result in any additional blockage induced frequency in the frequency response function. However, the extended blockage did result in shifts in the induced frequencies in the frequency response function. The distortion of the positions of the harmonic peaks in the frequency response function increased with the length of the extended blockage.

Mohapatra et al. (2006) presented a method for determining the size and location of a discrete blockage using the frequency response function of a pipeline, by making assumptions regarding system linearity, and using transfer matrices to relate an input (forcing) function, from an oscillating valve at the end of a single pipeline supplied by a tank/reservoir, to the output pressure and flow at the oscillating valve. Mohapatra et al. (2006) acknowledged that uncertainty in the values of friction factors, diameters, demands, pipe properties and system topologies would be significant challenges in the field.

3.4 Field implementation of transient leak detection methods

The application of reflection and inverse transient methods in the laboratory has confirmed that leaks affect hydraulic transients and that reflection and damping information can be used to locate and size them under controlled conditions. That said, a number of researchers (notably Brunone (1999)) have predicted that field measurements are likely to contain reflection and damping information, from non-leak related physical complexities within a pipeline, which may make the identification of a leak difficult. Brunone (1999) speculated that an “as new” or “no leak” transient response from pipelines would need to be obtained, shortly after installation, to provide a basis for comparison and enable the isolation of any new leak reflections contained in subsequent transient measurements. However, even this measure will not account for changes in pipeline condition that occur coincidentally with the development of leaks and give rise to reflections.

3.4.1 Transient testing on field pipeline systems

The application of reflection and inverse transient methods in the field is difficult where there are significant physical complexities. Examples of these complexities include demands, air pockets and/or entrained air, roughness or pre-existing blockage, topological variation (and potential model skeletonisation error), pipe wall thickness or lining variations, soil/pipe interaction for buried pipes, unsteady phenomena (both in the context of friction and minor losses), pipe joint behaviour and fluid structure interaction effects (including mechanical motion and vibration). These uncertainties will contribute to observed reflections and damping in measured transient responses from the field.

Unfortunately, laboratory researchers have not, to date, simulated the effect of these complexities when using hydraulic transients for leak detection.

Leak detection techniques using hydraulic transients remain in their infancy in terms of their application to field pipelines. Two research investigations have been completed, during the period over which the research presented in this thesis has been undertaken, in which attempts were made to apply reflection and inverse transient methods to the problem of leak detection at the transmission pipeline scale. No research investigation has been reported in the literature, verifying the usefulness, or otherwise, of reflection and inverse transient methods at the scale of water distribution pipelines or networks. That said, network field tests have been undertaken by McInnis and Karney (1995) for the purpose of transient model development and are summarised below.

3.4.2 Reported field tests using hydraulic transients for leak detection

Stoianov et al. (2003a) and Covas et al. (2004a) have published two field studies conducted on different transmission mains in the United Kingdom. Together, the results of these studies provide a basis upon which to make a preliminary assessment of the practicality and usefulness of reflection and inverse transient methods for leak detection in transmission mains.

Essex to Suffolk transmission main – Stoianov et al. (2003a)

The “Essex-Suffolk” Transmission Main (ESTM) is made of carbon steel lined with bitumen, is 23.14km long and has an external diameter of 860mm. Stoianov et al. (2003a) identified a section of the ESTM (7.40km long) which contained four branches and tests were conducted along this section at times with minimal demand. Transients were induced using pump trips. The wave speed was estimated as approximately 1000m/s. The results indicated that the presence of an artificial 9L/s leak did not create any discernable reflection or damping information in the measured transient responses. Stoianov et al. (2003a) pointed to physical complexities including reflections from branches, changes in pipe diameter and the operation of surge protection devices and concluded that leaks up to 9L/s could not be detected in transmission mains.

The author of this thesis contends that this conclusion should have been qualified and restricted to the ESTM for the conditions under which it was tested. In particular, the pump trips took approximately 15s to fully develop and it is unrealistic to expect to observe leak reflections for such a slow transient event. Furthermore, it is difficult to draw any conclusion about possible leak damping effects without knowing the precise impact of branches and surge protection devices.

Balmashanner branch transmission main – Covas et al. (2004a)

Covas et al. (2004a) identified the “Balmashanner” Branch Main (BBM) for testing. The BBM is made of ductile iron and has an estimated Hazen Williams friction coefficient of 130. It is 5.94km long and has a nominal diameter of 300mm. Transients were induced near the location of a downstream boundary by manually closing a side discharge fire hydrant valve over approximately 0.5s. The wave speed was estimated, using the period of the measured transient responses, as approximately 1190m/s.

A 25mm diameter leak was installed on the BBM approximately 2.8km from the upstream boundary junction with a larger transmission main (this information was obtained by the author from Scottish Water’s Mr Alan Young). Covas et al. (2004a) used a hybrid reflection and inverse transient technique, applied over a limited time scale corresponding to the first half period of the system response (i.e., 2L/a seconds), to estimate the location of the leak. The forward transient model was unable to replicate the damping and period of the measured responses beyond a time of 2L/a seconds.

Summary of reported transient field tests for leak detection

Unfortunately, neither Stoianov et al. (2003a) nor Covas et al. (2004a) could identify or account for non-leak related sources of damping in the measured transient responses they obtained from the field (thereby making it impossible to identify leaks using damping information in the measured responses). Complexities such as existing mechanical devices and non-ideal boundary conditions (despite the careful selection of the test pipelines and/or isolation of the sections under investigation) were significant problems. Furthermore, “in-situ” air pockets and demands through lateral pipes were problematic.

These reported difficulties give an important insight into the likely practicality of applying non-model based approaches when using hydraulic transients to identify leaks (and other faults). In particular, the identification and interpretation of non-fault related sources of reflections, dispersion and damping in measured transient responses is critical if faults are to be successfully isolated. Reflection methods and impulse response analysis, and frequency domain damping and response function analysis, cannot currently be adapted to the physical complexities, and system configuration restraints, which have been identified. Inverse transient methods have the potential, given the development of accurate and/or calibrated forward transient models, to distinguish between fault and non-fault related field complexities (and thereby become a tool for the detection of faults or other changes in pipeline condition).

3.4.3 Reported network field tests for transient model development

McInnis and Karney (1995) applied a traditional transient model, based upon an explicit Method of Characteristics (MOC) solution, to replicate the measured responses of a relatively large Canadian water distribution network called the Bearspaw Network. Problems were encountered with the quantity and distribution of demands, skeletal representation of the system and the discretisation of the pipes in the model. Unfortunately, the measured responses of the Bearspaw Network could not be satisfactorily replicated (except for the magnitude of the initial surge following the transient event).

McInnis and Karney (1995) identified a number of physical complexities, applicable to pipe networks, which could account for the failure of their model. Unfortunately, the large size and physical complexity of the Bearspaw Network limited the authors' ability to isolate and individually investigate the effect of each potential complexity. A detailed description of the Bearspaw Network, including the physical complexities affecting it, is presented in Chapter 16. The study by McInnis and Karney (1995) did not seek to apply transient response analysis or ITA for fault detection or condition assessment.

3.5 Summary

Reported literature describing the development of hydraulic transient techniques for fault detection and, in particular, locating and sizing leaks, has been summarised in this chapter. While not specifically addressing field complexities, the laboratory based research has revealed that there are limits to the size of leak that can be successfully located using reflection and inverse transient methods (even under controlled conditions). A number of researchers have also pursued frequency domain methods that provide for improved extraction of leak (and other fault) related information from measured responses. While these techniques, including transient damping and response function methods, have been successfully tested under controlled laboratory conditions they cannot currently be adapted to account for effects from unsteady friction, fluid structure interaction, mechanical motion and vibration, variable roughness, flexible joints, topological complexity (including branched pipeline systems), fittings, variable demands and entrained air.

Two field tests investigating the potential application of hydraulic transient techniques to the problem of leak detection have been summarised. The results of these tests and the analysis reported in the literature demonstrate the importance of developing accurate forward transient models that can replicate the effects of physical complexities upon measured transient responses from the field. The results also demonstrate the importance of developing techniques that have the flexibility to incorporate any or all of the physical complexities described above. Inverse transient methods and inverse transient analysis have such flexibility but are premised on the use of an accurate forward transient model that includes all relevant fault and non-fault related phenomena. The results presented by

Stoianov et al. (2003a) and Covas et al. (2004a) demonstrate that the development of accurate forward transient models for transmission pipelines is not straightforward. The results presented by McInnis and Karney (1995) indicate that current models are not able to accurately replicate measured responses from field networks.

Chapter 4

Inverse Methods and Field Complexities

Physical complexities such as unsteady friction, fluid structure interaction, mechanical motion and vibration, variable roughness, flexible joints, topological complexity, fittings, variable demands and entrained air all affect the transient responses of a field pipeline or networks. In many cases, significant spatial and temporal variability means that an impractical level of physical description is required if measured responses are to be accurately replicated. Inverse procedures are adopted in other fields of engineering in such circumstances and parameterised models are developed and calibrated. It is argued in this thesis that similar inverse procedures need to be applied when modelling the response of a field pipeline or network.

It is also recognised in other fields of engineering that conceptual models are required to explain physically complex phenomena for which there are no existing analytical bases upon which to include them in a model. The physics of many phenomena defy complete explanation and conceptual models are regularly employed in such circumstances (e.g., the use of a Kelvin-Voigt mechanical model to replicate viscous pendulum damping during oscillatory motion through air). In the context of transient analysis, mechanical motion and vibration, flexible joints and soil/pipe interaction are significant physical complexities that affect the measured response of field systems. Unfortunately, no analytical models exist for these phenomena (which are inherently physically variable and defy precise quantification). In these circumstances, conceptual models (such as the Kelvin-Voigt model introduced in Chapter 5) need to be developed and inverse procedures applied to test each model's appropriateness and to calibrate model parameters.

This chapter sets out the inverse procedures and tools that will be used in this thesis to calibrate for physical complexities that can be analytically described, but not physically quantified, and to test and calibrate conceptual models that can replicate the effects of physical complexities for which no analytical description exists.

4.1 Motivation for improved application of inverse methods

The principles and application of inverse methods have been comprehensively described in other fields of engineering, such as groundwater hydrology, by Neuman (1973), Yeh (1986) and Carrera and Neuman (1986a, b, c), where it is recognised that subsurface environments are heterogenous and spatially variable in terms of hydraulic conductivity, transmissivity and storativity. Structural error in models (i.e., models that ignore physical phenomena relevant to the behaviour of a system the model purports to predict) and associated parameter uncertainty are recognised problems in the field of groundwater hydrology. If a model's structure does not account for important physical phenomena capable of affecting measured responses then the parameter estimates obtained for the mechanisms that have been included will be inherently unreliable. That said, there is a limit to the number of mechanisms and parameters that can be included in a model if over-parameterisation is to be avoided. Over-parameterised models include more than enough mechanisms to replicate a phenomena but have too many parameters for the calibrated values to take on any unique and/or physically relevant meaning.

Inverse Transient Analysis (ITA), as first proposed and numerically tested by Liggett and Chen (1994), has been subject to numerous subsequent numerical and laboratory trials. In the case of the laboratory experiments, the apparatus used has been simplified to eliminate most of the physical complexities likely to affect field pipeline and network systems. Unfortunately, this process has delayed the recognition of the importance of physical complexities that make the application of ITA difficult in the field. This lack of recognition has led to the neglect of phenomena that affect the accuracy of forward transient models. In the context of using hydraulic transients for leak detection, there has been little systematic effort to include effects from the previously mentioned physical complexities encountered in field systems (whether analytically describable or not). The research presented in subsequent chapters illustrates these issues in the context of the calibration of complex analytical and conceptual transient models to measured field responses for a variety of pipeline and network systems.

4.2 Inverse methods applicable to field systems

To date, numerical assessment of the performance of Inverse Transient Analysis (ITA) has been typically facilitated by the optimisation of a single parameter at a time, assuming that the forward transient model “perfectly” replicates all other aspects of the measured responses (which they do because the measured responses are numerically generated). Gradient search algorithms, such as the Levenburg-Marquardt technique, have been successfully applied because of the simplicity of the inverse problem that is posed with numerical data. Nash and Karney (1999) extended this approach, in the context of a numerical investigation of demand and friction factor calibration in a single pipeline, by introducing numerical error to the artificially generated measurement data.

During the transition from numerical to laboratory investigations, the use of genetic algorithms for the inverse optimisation was developed by, amongst others, Tang et al. (1999), Vitkovsky et al. (2000b) and Covas and Ramos (2001). While this represented an improvement, in terms of the robustness of the search algorithm used for the inverse analysis and parameter determination, regression diagnostics were not used to assess model structure or parameter certainty because model error was minimised in the context of numerical or controlled laboratory experiments.

In the context of the analysis of measured transient responses from the field, with all of the potential physical complexities mentioned previously, the successful application of inverse analysis will depend upon the implementation of parameterised analytical, where they are available, and conceptual formulations for known physical complexities. Regression diagnostics will need to be examined to assess the structure of proposed models and the certainty of parameter estimates. The basis upon which inverse analysis is performed, and regression diagnostics are determined, is described below.

4.2.1 General principles of regression analysis

The successful application of a model to predict the transient response of a pipeline or network will depend upon how well it is calibrated. That said, the accuracy of the calibration is dependent upon the inclusion of mechanisms in the model structure that are capable of replicating system processes by taking all relevant phenomena into account. The robustness of parameter estimates is also important in that the calibrated parameters must be unique and physically sensible. A regression model includes both random observation and systematic model errors in the form:

$$G_{obs} = G_{pred} + E_r + E_s \tag{4-1}$$

where G_{obs} is the vector of actual observations, G_{pred} is the prediction from the model (which, in turn, is a function of a model parameter vector B elaborated below), E_r is random error in the observations (measurement error) and E_s is systematic error due to an incorrect physical model (model error)

The regression and physical models are distinct. The physical model comprises the relatively familiar forward transient model and solution of the applicable analytical and conceptual formulations. The regression model bundles the physical transient model together with random observation and systematic model errors introduced by inadvertently using the wrong physical transient model. Unfortunately, there is no way of distinguishing between random observation and systematic model errors prior to performing inverse calibration to obtain parameters for a set of observations. Both forms of error are lumped into a common residual. However, examination of regression diagnostic statistics after calibration can reveal different forms of error.

Least squares error model and optimisation criteria

The least squares error model is most commonly selected to guide regression analysis and predictive model parameters are fitted until the square of the difference between measurements and model predictions is minimised. A derivation of the least squares error model from maximum likelihood theory is presented in Appendix C. The least squares error model has been applied from the 1970s to present in numerous fields of inverse engineering, including groundwater hydrology, but was first applied for the inverse analysis of the transient response of networks by Liggett and Chen (1994). The selection of a least squares error model presumes that the predictive model correctly predicts, on average, the measured response (i.e. that the expected value of the errors is zero), the variance of the errors is constant, the errors are statistically independent and the errors are normally distributed.

Random observation and systematic model error

Perfect observations are never obtained in field systems. That said, in the case of the measurement of transients in field systems, the random error in observations is relatively low. Barring a problem with the pressure transducer used to measure pressure at a particular location, the random error will be limited to the purely stochastic component of behaviour in the field system that is difficult to model in detail (e.g., temporal and/or spatial variations in demands or entrained air).

The assumption that a physical model is correct is usually inappropriate for field pipeline and network systems. Two sources of systematic model error occur – namely, errors from the rationalisation of physical complexity, even when accurate analytical descriptions are available, and errors from the theoretical approximation of physical phenomena (i.e., inherent simplifications in existing analytical descriptions and/or the use of a conceptual model where no analytical description is available). These two types of systematic model error have been previously recognised in other fields of engineering, including groundwater hydrology, by, amongst others, Knopman and Voss (1987).

Model discrimination problem and parameter estimation

The first step in regression analysis is to select a suitable model from which system parameters can be estimated. If the model is flawed, or unable to replicate the fundamental processes contributing to the response of the system, then this error will dominate the parameter estimation process and reduce the ability of the calibrated model to replicate field measurements. In the case of transient modelling, the objective of model discrimination is to identify the dominant physical phenomena that affect a pipeline or network system and include parameterised analytical or conceptual mechanisms that can be calibrated to replicate observations. The robustness of each of the hypothesised mechanisms can be assessed, after calibration, in terms of the predictive capability of the model and the uniqueness and physical feasibility of estimated parameters.

An example of the type of problem that can occur, if a forward transient model is incorrectly structured, is illustrated by recent laboratory work and model calibration performed by Covas et al. (2004b). Two fundamental dispersion and damping mechanisms, namely unsteady friction and viscoelasticity, were required to adequately model the measured transient response of a polyethylene pipeline. Initially, Covas et al. (2004b) attempted to use unsteady friction to calibrate for viscoelastic effects and vice versa. However, the use of the wrong model process made the calibration unworkable. Satisfactory results were only obtained when Covas et al (2004b) included, and calibrated parameters, for both unsteady friction and viscoelasticity.

4.2.2 Need for realistic calibration mechanisms

Steady state calibration precedents

Calibration of the steady state friction factors in pipeline and network systems has been the focus of considerable research (including that by, amongst others, Lansey et al. (1991)). The inverse calibration process involves fitting steady state model parameters (typically demands or roughness) until differences between measured and predicted responses are minimised. Typically, gradient search algorithms such as the Levenburg-Marquadt technique have been used to guide the inverse calibration. However, more recently, global search algorithms have been utilised.

Steady state calibration is affected by some of the physical complexities that are relevant to transient models. For example, the effect of topological complexity is often rationalised by grouping steady state friction factors for pipes that are of a similar age or material and diameter (Mallick et al. (2003)). This skeletonisation process is weakly analogous to that used to simplify transient models. However, the skeletonisation of a transient model is more likely to introduce significant model error because of the greater sensitivity of the transient response of a network to its topology.

Calibration for physical uncertainties affecting transients

The theoretical power of Inverse Transient Analysis (ITA) lies in the additional temporal information that is contained in the transient rather than steady state response of a system. The neglected disadvantage is the development of modelling tools capable of interpreting this additional information in the context of significant physical complexities and their effects upon the transient response of field systems. Researchers investigating the use of inverse calibration for the determination of steady state friction factors have recognised that the accurate replication of the effects of all of the physical complexities in field systems is unrealistic. This reality also applies to the inverse calibration of forward transient models and/or when conducting ITA.

A broad range of elements, which are typically either spatially uncertain, or both spatially and temporally uncertain, can affect the transient response of a pipeline or network. In this context, accurate transient modelling is more difficult than steady state modelling. Demands and leakage, roughness, pipeline restraints, discrete air pockets and/or entrained air, quasi-steady and unsteady friction (roughness), fluid structure interaction and mechanical motion and vibration, flexible joints and soil/pipe interaction are all spatially variable. In addition, demands and entrained air are temporally variable (over time scales comparable with those of transient events).

McInnis and Karney (1995) acknowledged that "…. it is virtually impossible to know the precise conditions existing in (a) system with respect to some important physical parameters ….". These difficulties have thus far prevented the successful application of ITA to any field pipeline or network system, for fault detection or calibration, apart from the results presented by Covas et al. (2004a) summarised in Chapter 3. If the measured transient response of a pipeline or network system is to be accurately modelled then the model must include, or be calibrated for, the physical conditions that exist at the time the measurements are obtained. This is achieved by introducing parameters for physical complexities that can be calibrated to the measurements. The calibration of such parameters represents a significant challenge for the various field pipeline and network systems investigated in this research.

4.2.3 Available optimisation algorithms and NLFIT

Unfortunately, most of the analytical and conceptual formulations describing relevant physical complexities are not linear functions of their associated parameters. Furthermore, different formulations are applied simultaneously and have correlated effects upon predicted pressure responses. Consequently, there are often a number of non-unique calibrations, with different parameter values, that give similar minimum objective functions after optimisation. This problem is likely to become more severe as the transient model increases in complexity and the number of parameters increases.

A number of evolutionary optimisation algorithms have been applied to the problem of inverse calibration for transient model parameters. As mentioned previously, Tang et al. (1999), Vitkovsky et al. (2000b) and Covas and Ramos (2001) have all applied genetic algorithms to the optimisation of parameters describing demands and leaks. Alternative algorithms, including particle swarm algorithms, have been investigated by, amongst others, Jung and Karney (2004). The Shuffled Complex Evolution – University of Arizona (SCE-UA) optimisation algorithm is generally used to conduct the inverse analysis presented in this thesis.

Shuffled Complex Evolution Algorithm – University of Arizona

The Shuffled Complex Evolution – University of Arizona (SCE-UA) global optimisation algorithm was first developed by Duan et al. (1992). 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 CCE algorithm requires the construction of a sub-complex by randomly selecting a number of points from within each complex using a specified probability distribution (either triangular or trapezoidal). The probability distribution is specified such that the point with the largest criterion value has the greatest probability of being selected to form the sub-complex (and the point with the smallest criterion value has the least probability of being selected). The point with the smallest criterion value is then identified and the centroid of the sub-complex determined excluding this point. The point with the smallest criterion value is then reflected through the centroid to generate a new point within the feasible space (or alternatively a new random point is introduced). If the new point has a criterion value greater than the previous point then it is retained and the previous point is discarded. If not, then a point midway between the centroid and the point with the smallest criterion value is computed. If this new point has a criterion value greater than the previous point then it is retained and the previous point is discarded. If not, then the point with the smallest criterion value is replaced with a randomly generated point within the feasible space.

Bayesian Non-Linear Regression Program (NLFIT)

A Bayesian Non-Linear Regression Program Suite (NLFIT) has been adopted to conduct the inverse calibration of parameterised analytical and conceptual forward transient models, and the Inverse Transient Analysis (ITA) for fault detection and condition assessment, presented in this research. NLFIT was developed by Kuczera (1994) and provides options for the application of numerous search algorithms for parameter optimisation including the SCE-UA global optimisation algorithm. NLFIT has the capacity to fit predictive model parameters to multiple measured responses. Furthermore, NLFIT has options allowing prior information to be specified in the form of a mean and standard deviation for each parameter or, alternatively, a co-variance matrix for the predictive model.

NLFIT provides an unbiased sample variance of the residuals after fitting (i.e., an objective function) and an estimate of the mean and standard deviation for each model parameter. This information provides for a comparison between models on the basis of the fit between predicted and observed transient responses and the stability of the parameter estimates obtained from the regression fitting. NLFIT also produces a series of diagnostic statistics and plots that can be used to assess structure in the error residuals (Draper and Smith, 1981), that may be contrary to the assumptions of randomness and normality made when applying the least squares criterion. The residual error is standardised in NLFIT by dividing by the standard deviation of the residual error. NLFIT is coupled to explicit and implict forward transient models, including analytical and conceptual formulations, developed by the author in this research and as described in later chapters.

4.2.4 Need to rigorously determine regression diagnostics

Discrimination between hypothesised models is based on four criteria – the fit between measured and predicted transient responses, the stability of the parameter estimates obtained, the presence of systematic error in the residuals and the examination of regression diagnostics to check that least squares and other error model assumptions have not been violated. As mentioned above, NLFIT produces a series of regression diagnostics including an error variance and standard deviation for each parameter, measured versus predicted scatter response plots, residual error versus time plots and residual error versus normal deviate plots to provide a posterior gauge of the level of violation of the assumptions, as listed in Table 4-1, that support the use of a least squares optimisation criterion. Violation of the assumptions may indicate systematic model error.

Table 4-1 – Least squares assumptions and corresponding regression diagnostics

Least Squares Assumption	Regression Diagnostic
Expected value of errors is zero	Measured v predicted “scatter” plot
Errors are independent	Residual error v time plot
Errors are normally distributed	Residual error v normal deviate plot

Calculated error variance and parameter standard deviation

The calculated error variance, or unbiased sample variance of the regression model residuals after fitting (i.e., the objective function), is determined using:

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

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

The square root of the calculated error variance is called the standard error. Smaller values of both the calculated error variance and standard error indicate a closer fit between measured and predicted responses and are preferred providing the residuals do not reveal significant model error. The calculated error variance is reported as the objective function value throughout the remainder of this thesis.

The standard deviation for parameters provides a measure of the stability of the estimate and values an order of magnitude smaller than the fitted mean values are preferred. Relatively large standard deviations may indicate over-parameterisation. Both the calculated error variance and parameter standard deviations will be determined following the inverse calibration of each potential forward transient and conceptual model proposed in subsequent chapters. Similarly, calculated error variances will be reported, and used in helping to determine whether faults have been successfully detected, when ITA is performed.

Diagnostic plots from NLFIT following regression analysis

The plot of the measured versus predicted transient response, following regression analysis, should ideally fall along a line with a slope equal to unity and an intercept of zero. The coefficient of determination may be determined from such a plot and when less than 90% (0.9) suggests model inadequacy. The plot of the residual errors versus time should appear random and reveal no discernable patterns. If a distinct pattern is observed, or if a sequence of residual errors with the same sign is observed (called a "run"), then the likelihood is that the residual errors and time are not independent and that there is systematic model error. The plot of the residual error versus normally distributed deviate (based on the assumption that the residual errors are statistically independent and normally distributed) should fall along a line with a slope equal to unity and an intercept of zero. However, deviations from linearity are common and determining whether the residual errors are non-normally distributed is difficult.

4.3 Summary

Researchers investigating the use of Inverse Transient Analysis (ITA) for leak detection in water pipelines have not explicitly recognised physical complexities that affect the response of field pipeline and network systems. Simplifications during numerical analysis, and the subsequent isolation of problematic phenomena during laboratory research, have enabled spatial and temporal variability, which are inherent in the field, to be avoided. As a consequence the inverse procedures developed during previous numerical and laboratory studies are not robust enough to deal with the level of complexity encountered in field measurements.

A review of the approach adopted in fields of engineering such as groundwater hydrology has illustrated the type of inverse procedures that should be applied when modelling field systems with significant physical complexity. Evolutionary optimisation algorithms are commonly used in combination with regression models, that combine random observation and systematic model error, and a parameterised physical model, to facilitate the calibration of suitable parameters that describe the behaviour of the system. Conceptual physical models are often used because the phenomena involved defy analytical description or are spatially or temporally complex. A least squares criterion is usually assumed when performing model calibration and this implies that the measurement and structured model errors are, on average, zero and normally distributed.

Random observation error is not significant when calibrating inverse transient models to measured pressure response data. However, difficulties in rationalising the spatial and temporal information, which is required if existing analytical descriptions are to accurately replicate measured responses, lead to significant systematic model error. Furthermore, for some physical complexities, discussed in more detail in Chapter 5, conceptual models have to be developed because no existing analytical descriptions exist.

As recognised in other fields of inverse engineering, the posterior assessment of different conceptual models for representing a physically complex field system is crucial in identifying systematic model error. The NLFIT suite of programs is introduced and has been applied in later chapters to undertake Bayesian non-linear regression analysis when assessing proposed conceptual forward transient models. NLFIT is subsequently used to perform ITA using the calibrated conceptual models for fault detection and condition assessment. A least squares criterion has been adopted for the regression modelling performed in this research. NLFIT produces posterior regression diagnostics that can be used to determine whether the assumptions supporting this regression model are significantly violated when calibrating or performing ITA using the various conceptual models that are presented.

Chapter 5

Including Mechanical Damping in Transient Models

While existing algorithms describing a number of physical complexities are available, complexities such as spatial and temporal variability in demands and leakage, discrete air pockets and entrained air, unsteady friction and fluid structure interaction effects, blockages and unsteady minor losses, combined with a lack of deterministic algorithms for effects from mechanical motion and vibration, inelastic behaviour of pipe walls, flexible joints and viscoelastic confining soils, often prevent accurate modelling of transient responses from field systems. Furthermore, the successful application of transient response analysis, including inverse transient analysis (ITA), for fault detection and pipeline wall condition assessment is dependent upon accurate transient modelling. In the author's opinion, the physical complexities faced in the field require a shift from deterministic to conceptual thinking, as has occurred in other fields such as, for example, groundwater hydrology, if transient modelling is to improve.

It is hypothesised, based on evidence from researchers investigating dynamic damping phenomena in other fields of structural and hydraulic engineering, that significant dispersion and damping of transient responses in the field occurs as a result of mechanical motion and vibration at restraints, the response of flexible joints to dynamic internal loading and the influence of viscoelastic soils confining pipelines subject to dynamic loads. The theoretical basis for the development of a conceptual calibration model is presented, initially placing reliance on the laboratory work of Budny et al. (1991) (but expanding to propose a more general and conceptual model), to suggest that complex dispersion and damping influences can be replicated using equivalent calibrated "viscous" damping. In this context, the equations relating to viscoelastic pipeline wall behaviour are presented, together with an efficient formulation for the calculation of the viscoelastic effect (which is vital if inverse calibration is to prove feasible), to provide the theoretical background to the different conceptual models that are developed and calibrated in later chapters for transmission pipelines, distribution pipelines and networks, respectively.

The word “viscous” is used in physics and other fields of engineering to describe the replication of the effects of, amongst other things, mechanical damping and friction (e.g., a common term that is used is “viscous” damping). It is in this sense that it is used in this research and it is not used in the sense of viscous fluid friction effects.

5.1 Sources of “viscous” damping of transient responses

5.1.1 Mechanical damping and joints

As pipe systems become more complex, elements including reservoirs, tanks, valves, joints, bracing or brackets and bends, other minor loss elements, changes in the thickness or material comprising pipe walls and mechanical elements can all potentially generate transient reflections and contribute to the dispersion and damping of transient waves. The laboratory investigations summarised in Chapter 3 generally relate to simple pipelines with pressurised tank and/or valve boundary conditions. The apparatus were comprised of uniform pipe materials and joints were generally formed using welds (metal) or solvent (plastic). Specific detail regarding the bracing/bracketing arrangements for each apparatus are not emphasised or reported in the published research results. However, in the case of the research performed by Vitkovsky (2001), the author has visually inspected and confirmed the bracing/bracketing arrangements for the pipeline apparatus comprising single clamp braces at 2.4m spacing with each of the brackets bolted to an adjacent wall. Lee (2005) upgraded the bracing support, due to concerns over a lack of support and potential fluid structure interaction, such that supports were provided at 0.6m spacing.

Mechanical damping related to restraint conditions

Williams (1977) confirmed that pipes with flexible joints, which are not completely restrained, and which are therefore able to move axially, will absorb a significant proportion of the energy of any internal fluid transient. Budny et al. (1991) subsequently performed a series of laboratory experiments on a 47.7m long copper pipeline system investigating the impact of restraint conditions on transient damping. Anchoring a downstream valve and clamping the pipeline at 3.7m intervals along its length established a relatively rigid system. Conversely, releasing the downstream valve and removing the clamps established a "free" system. For the rigid system, mechanical motion was suppressed and a structural damping ratio of up to 5% was required to calibrate sufficient equivalent "viscous" damping to achieve a match between the measured and predicted responses. For the "free" system, motion was not restricted and significantly greater vibrations were observed in the measured responses. Budny et al. (1991) also investigated the configuration where the clamps were installed but not tightened. This had the effect of restraining the pipe against lateral motion. Coulomb damping (sliding friction), acting to partially restrain longitudinal motion, was induced between the untightened clamps and the pipe.

The transmission pipelines subject to controlled transient testing in this research are aboveground and are supported by saddle supports and restrained by concrete collar rings. Figure 5-1 shows a typical arrangement for one of the pipelines. Both lateral and longitudinal motion and vibrations are feasible and the degree of support and restraint provided by the saddles and collars varies.

Figure 5-1 – Typical saddle supports for transmission pipeline (with collar restraint at right hand edge of picture)

Mechanical damping related to joints

Flexible joints typically occur at 3m to 10m intervals along buried metal and cement pipelines, depending on the diameter of the pipeline, and are used for small distribution as well as large transmission pipelines. Each flexible joint, at which longitudinal and lateral movement is possible through circumferential expansion and longitudinal sliding, has the potential to introduce significant additional damping. Elastomeric gaskets or rubber rings are typically used to seal the joints while permitting axial movement and rotation up to approximately 3 to 4 degrees. The degree of damping related to individual joints will vary with the condition of joint and gasket materials and surrounding restraint. Figure 5-2 shows a typical spigot and socket joint used for Cast Iron (CI)/Ductile Iron (DI) distribution pipelines in South Australia.

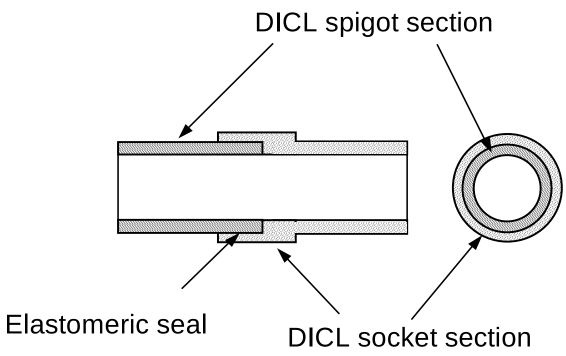
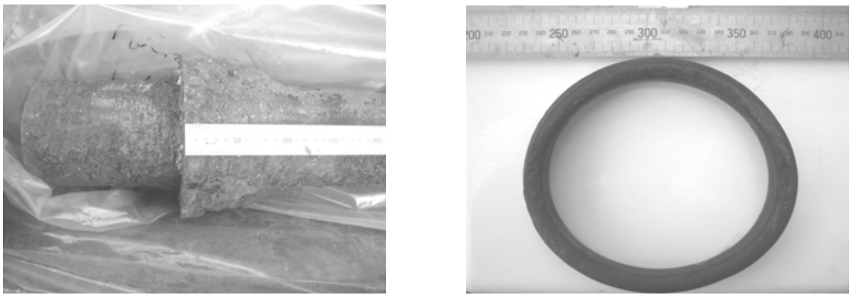


Figure 5-2 – Typical flexible joints used for CI/DI pipes in South Australia

Segments are slid, and then forced together, to form an interference fit between the socket and spigot. An elastomeric gasket is inserted during this process to provide a positive seal. When the pipeline is filled with water and exposed to the “in-situ” system heads, the CI/DI pipe segments expand and compress the elastomeric seal further while simultaneously tightening the interference fit between the sockets and spigots. In the case of transmission pipelines, an additional weld is sometimes provided around the circumference of the socket and spigot.

Figures 5-3 and 5-4 show a dismantled flexible spigot and socket joint for a CICL (cast iron cement lined) pipeline with the elastomeric gasket in good condition.

Connections between pipe segments and at junctions are typically formed using these flexible joints.



Figures 5-3 and 5-4 – Dismantled CICL pipe spigot and socket flexible joint with elastomeric gasket/rubber ring in good condition

In the case of Asbestos Cement (AC) pipes, segments are butted together and an AC collar is then positioned at the point of the discontinuity to provide structural support. The collar is notched such that rubber rings can be inserted. These rubber rings have a diameter approximately equal to the outside diameter of the AC pipe segments and the collar's position is adjusted until the notches and rubber rings are located equidistantly from the point of discontinuity between pipe segments. When the pipeline is pressurised, the AC pipe segments expand and compress the rubber rings against the collar thereby forming a seal at the joint. Figure 5-5 shows a typical rubber ring joints used for AC distribution pipelines.

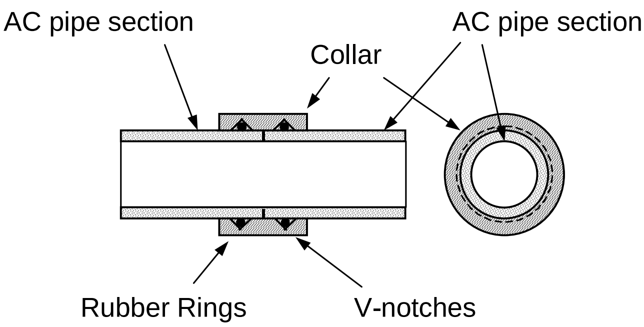


Figure 5-5 – Typical flexible joints used for AC pipes in South Australia

Mechanical damping related to other fittings/restraints

Apart from frequent flexible joints, other recurring elements within water distribution systems that restrain a pipeline include junctions, gate valves (for isolation), fire plugs and thrust blocks. The degree of restraint and damping associated with each of these elements will depend on their original installation and current condition. Figures 5-6 and 5-7 show typical installations of a gate valve and a fire plug in below ground/road level access chambers. The fire plugs typically have 80mm diameter vertical risers of various lengths between 0.3m and 1.5m in order to achieve a standard depth of 0.9m in the associated access chamber.

NOTE: These figures are included on page 72 of the print copy of the thesis held in the University of Adelaide Library.

Figures 5-6 and 5-7 – Typical installation of a gate valve and a fire plug in access chambers (from standard United Water drawings)

Thrust blocks are usually specified in design documentation and should be cast into undisturbed "in-situ" soils. However, if the pipe embedment and backfilling is inadequate, or thrust blocks have not been properly constructed (or omitted), then the potential for axial and/or lateral pipe movement and vibration becomes significant.

Previous implementation of a viscous transient damping model

Budny et al. (1991) adopted a scheme of four hyperbolic partial differential equations relating fluid pressure, axial fluid velocity, axial pipe stress and axial pipe velocity, incorporated a viscous damping mechanism, and solved the system in the usual manner using a Method of Characteristics (MOC) scheme. The scheme of equations is at the less complex end of the spectrum of schemes typically utilised by researchers of

Fluid Structure Interaction (FSI) phenomena and ignores additional equations incorporating bending and torsion effects. However, the incorporation of a viscous damping mechanism was novel and recognised that a combination of complex physical interactions contributing to the damping of the experimental pipeline could not be deterministically explained. Budny et al. (1991) confirmed that viscous damping models, incorporating a damping force proportional to the structural velocity and acting in the opposite direction, were commonly used in numerous fields of engineering (e.g., dynamic analysis of structures). Budny et al. (1991) calibrated their viscous damping coefficient to approximate experimentally measured damping caused by mechanical motion and vibration for different restraint conditions applied to their apparatus.

Non-viscous forms of damping, including inertial, structural or Coulomb damping, can all be represented as equivalent viscous damping. Budny et al. (1991) noted some loss of accuracy in the shape of the damped response, for the case with Coulomb sliding friction at the clamps, because the viscous approximation only produced a condition of equivalent energy dissipation. However, they concluded that damping caused by an untightened clamp (similar to a saddle support for an aboveground pipeline) could be modelled using distributed viscous damping or viscous dampers located at supports.

As for the saddle supports investigated by Budny et al. (1991), equivalent viscous damping can be used to represent sliding friction in joints. Ferri (1988) confirmed that the approximation of the damping at joints using viscous elements, whether due to Coulomb sliding friction or some other mechanism, could lead to considerable simplifications in analytical and computational analyses. Ishibashi et al. (1989) modelled energy dissipation at flexible expansion joints using a calibrated non-linear spring stiffness expressed as a function of velocity. The purpose was to test the energy dissipating characteristics of flexible joints under cyclical dynamic loads and they confirmed that relatively simple rheological models, using combinations of springs, dashpots and sliders, could be used to replicate dynamic losses in flexible connections.

5.1.2 Soil/pipe interaction and viscoelastic damping

In addition to damping at flexible joints, buried pipelines can be, depending on the pipeline material and condition, subject to damping proportional to the characteristics of the surrounding soil. The damping of structures supported in or on soil stratum, when subject to dynamic loading, has been investigated in the fields of structural dynamics and geotechnical engineering by, amongst others, Datta et al. (1984) and Michaels (1998). Under dynamic loads, soils behave in a viscoelastic manner. For buried pipelines, the presence of continuous soil strata in contact with the pipe walls provides a direct external viscous damping mechanism. A pipeline subject to an internal transient will dissipate a variable amount of energy to the surrounding soil stratum and the damping will be viscoelastic in nature.

Furthermore, the soil is an important factor when assessing the restraint of the pipeline. Recognising the effect of soil restraint upon field pipelines highlights an important distinction with regard to the laboratory work conducted by Williams (1977) and Budny et al. (1991). Their research was aimed at investigating the effect of mechanical motion and vibration under controlled laboratory conditions with mechanical restraints. Buried field pipelines are restrained by surrounding soils and thrust blocks. Soil strata provide variable support to buried pipelines such that the degree of restraint, and potential motion and vibration, are a function of variations in soil strength and compaction (degree of contact). This added complexity is discussed below when presenting a justification for a conceptual transient model.

Static soil/pipe interaction model

Larson and Jonsson (1991) first suggested, in the context of a series of transient tests on sewer pipes, that the soil surrounding a buried pipe would enhance its strength. Rajani et al. (1996) confirmed that where the ratio of the elastic modulus of the pipe to surrounding soil is less than 500 a lower circumferential stress develops in the pipe wall as load is transferred to the soil. Rajani and Tesfamarian (2004) reconfirmed that the circumferential stress developed in a pipeline could be tempered by the influence of the surrounding soil. Typical elastic moduli were presented for Cast Iron (CI) and

Ductile Iron (DI) pipes together with those for typical sand soils. These parameters, together with the elasticity for Asbestos Cement (AC) pipe determined in the laboratory at the University of Adelaide (refer to Appendix D), are listed in Table 5-1 together with corresponding pipe to soil elasticity ratios.

Table 5-1 – Typical pipe and soil elastic moduli (Ranjani and Tesfamarian (2004))

NOTE: This table is included on page 75 of the print copy of the thesis held in the University of Adelaide Library.

Assuming that the trench backfill around a buried pipeline typically comprises a gravelly sand (standard practice in South Australia), and that the ratio of the elastic modulus of the pipe to surrounding soil needs to be less than 500 for the soil to have a significant effect, soil/pipe interaction is anticipated for AC pipes. That said, any deterioration of the elastic moduli of a CI or DI pipeline, to less than an equivalent value of 50 GPa, or higher elastic moduli for the trench backfill, will permit significant soil/pipe interaction. Furthermore, the restraint of any buried pipeline with flexible joints will be a function of the joint structure, thrust blocks and the support from surrounding soils. This means that even though direct soil/pipe interaction along the wall of a buried CI or DI pipeline may not occur, unless it has deteriorated, the dynamic response of the supporting soils are still important via the mechanism of pipeline restraint.

Rajani and Tesfamarian (2004) quantified the interaction between the viscoelastic response of soils and axial, flexural and circumferential stresses upon a buried pipeline using a Winkler model. The objective was to develop a model capable of being used to assess the capacity of buried CI, DI, AC and plastic water pipelines, at various stages of deterioration, subject to external loads such as soil movement (i.e., loss of bearing or reactive movement), traffic (i.e., live loads), frost (i.e., loads induced by temperature differentials) and, finally, static internal pressure.

The model developed by Rajani and Tesfamarian (2004) for soil/pipe interaction, under internal pressure, is shown diagrammatically in Figure 5-8. The mathematical details of this Winkler elastoplastic material model are given by Rajani and Tesfamarian (2004). The purpose in presenting this conceptual model is to illustrate the recognition that the load response of jointed CI, DI and AC pipes is governed, at least partially, by a combination of soil and pipe interaction.

NOTE: This figure is included on page 76 of the print copy of the thesis held in the University of Adelaide Library.

Figure 5-8 – Rajani and Tesfamarian (2004) Winkler model for soil/pipe interaction with pipeline under internal pressure

The Winkler model presented by Rajani and Tesfamarian (2004) relates to static stresses and does not take time variable behaviour, under transient conditions, into account. The influence of the soil on the circumferential stress in the walls of AC pipe, or deteriorated CI/DI pipe, will be elastoplastic in nature under static (or steady state) conditions. The soil/pipe interaction is complicated, in the case of internal transient pressure, by the time dependent variation of the internal pressure and the viscoelastic nature of the response of soils under dynamic loads. For a buried pipeline, with a sufficiently low modulus of elasticity, the soil in contact with the pipe wall will provide a direct external viscous damping mechanism.

Viscoelastic modelling of pipelines buried in soils

Chua et al. (1989) considered the time dependent behaviour of soil loads on buried pipelines (cement and plastic) and developed a viscoelastic model to replicate the long term creep behaviour of both the pipe wall and soil materials. Both the elastic properties of the soil and pipe materials, although the cement pipes were effectively rigid and not inherently viscoelastic, were recognised as variable over long time scales and slow stress changes. The distinction with the current problem is the time-scale over which the changes in stress occur. Chua et al. (1989) were considering creep behaviour over a period of years rather than seconds or minutes (as applies in the case of a transient).

Subsequent research by Makris and Zhang (2000) has confirmed that soils subject to pulse type dynamic loading should be modelled viscoelastically, using concepts of equivalent viscous damping, rather than traditional Rayleigh damping. Michaels (1998) confirmed that Kelvin-Voigt viscoelastic models are currently used to undertake the dynamic analysis of soil/foundation systems subject to seismic loading. The use of a Kelvin-Voigt viscoelastic model for determining the equivalent viscous damping of the soil/foundation system, subject to dynamic loading, is important and forms part of the justification for the development of a series of different Kelvin-Voigt models, used to replicate the combined damping effects of mechanical movement at restraints, flexible joints and soil/pipe interaction, in subsequent chapters of this thesis.

5.2 Application of a general viscoelastic damping model

5.2.1 Using equivalent "viscous" damping

It is difficult to model the effect of restraints, flexible joints and soil/pipe interaction upon the damping of the measured transient response of a pipeline. For example, the shear and sliding mechanisms which lead to the dissipation of energy in a single flexible joint are so difficult to comprehensively include in a physical model that Ferri (1988) resorted to the application of an equivalent viscous damping mechanism to represent predicted energy losses. In the context of their laboratory experiments on water pipelines, Williams (1977) and Budny et al. (1991) noted that, in the absence of a more detailed understanding of the physics of the damping mechanisms affecting a pipeline, and the practical level of physical information required to model all of the potential energy losses, viscous damping mechanisms and coefficients could be introduced to a forward transient model to incorporate an equivalent dispersion and damping mechanism.

In the case of even a short length of water distribution pipeline, there are many more restraint uncertainties and flexible joints than for the laboratory apparatus tested by Williams (1977) and Budny et al. (1991). The likely contribution of each of these effects to the damping of a transient response is difficult to practically anticipate because of uncertainties in the initial construction and current condition of a pipeline as listed, for example, in Table 5-2.

Table 5-2 – Practical issues affecting the damping caused by restraints, joints and soil/pipe interaction

Pipeline element	**Initial construction uncertainties**	**On-going deterioration and uncertainties**
Direct restraints (thrust blocks)	What size and number? What are the bearing conditions?	Have the bearing conditions deteriorated or changed?
Lateral pipelines (water services)	What number and size? What materials?	Do these services have leaks or blocks?
Joints (flexible)	What number and type? What deflection tolerances?	Has the condition of the seals changed? Has soil movement exceeded deflection tolerances?
Other fittings (fire plugs)	What number? What degree of constraint?	Has the condition of the seals changed?
Soil/pipe interaction	What level for cement and plastic pipes?	Has the condition of a CI/DI pipe deteriorated such that soil/pipe interaction is significant?

Furthermore, there is the potential for damping from soil/pipe interaction (either directly through pipe walls with lower elastic modulii or via secondary influences related to the interaction of supporting soils with flexible joints and other pipe restraints). It is therefore necessary to develop transient models with equivalent viscoelastic damping mechanisms if calibration to include the losses exhibited in field systems is to be facilitated.

The reaction of a pipeline to a transient is both a spatial and temporal phenomena. As a consequence, it is not possible to apply a Winkler-like elastoplastic model to account for the deformation related effects of soil/pipe interaction, or more significant restraint or joint related effects, without taking into account the time variable nature of the response to a transient. In this context, it is necessary to develop a transient model that can be calibrated to give a varying magnitude of viscous damping in space (along a pipeline) and over time.

5.2.2 Rationale for applying a “viscous” model to non-plastic pipes

While viscoelasticity has been discussed above in terms of the viscous damping influence of variable pipeline restraint, movement at flexible joints and soil/pipe interaction, another typical context is the viscoelastic response of plastic pipes to transients. The polymers in the walls of plastic pipes often behave elastically at low stress (or under the slow application of stress) but like viscous fluids at high stress (or under the rapid application of stress). This is why the term viscoelastic is applied to describe the behaviour of, amongst other things, the walls of plastic pipes.

The underlying physics relate to the ability of long polymer chains in plastics to clump together and deform elastically until a stress threshold is reached over which they unravel (without breaking) to stretch and slide past each other. In this regard, the equations describing the behaviour of the polymer chains in the walls of plastic pipes describe similar phenomena to those that occur when, at a much larger scale, restraints or flexible joints elastically retard movement up to a threshold and then permit sliding movement that can be viscously replicated.

5.2.3 Details of the Kelvin-Voigt mechanical model

Viscoelastic models for the stress/strain relationship in the walls of plastic pipelines, under transient and other pressure conditions, have slowly developed since the introduction of such pipelines in the mid-1970's. Gally et al. (1979) elaborated the basic equations for fluid transients including the incorporation of a time dependent creep compliance function as described below.

The effect of a viscoelastic pipe wall response is incorporated in the governing continuity equation:

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}+\frac{2a^2}{g}\frac{\partial \varepsilon_r}{\partial t}=0 \qquad (5\text{-}1)$$

where the only unfamiliar term is ε_r = the circumferential strain in the pipe wall

The third term in Equation 5-1 incorporates a retarded strain effect in the pipe wall. The calculation of the rate of change of retarded strain requires a mechanical model representing the creep behaviour of a viscoelastic material. A one-element Kelvin-Voigt mechanical model, comprising a single spring and dashpot element as shown in Figure 5-9, can be applied to determine the creep compliance function used in the calculation of the retarded strain term in the modified continuity equation:

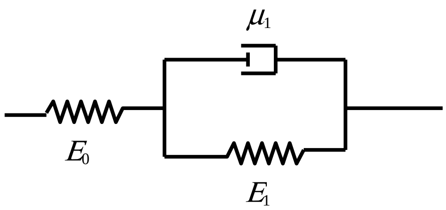


Figure 5-9 – A one-element Kelvin-Voigt mechanical viscoelastic model

where E_0 is the elastic modulus of the pipe wall, with J_0=1/E_0, the compliance of the elastic spring, and E_1 the modulus of elasticity of the creep deformation spring. The viscosity of the dashpot μ_1 represents the viscous creep behaviour. Further parameters J_1 and τ_1 are defined as J_1=1/E_1, the compliance of the creep deformation spring, and

$\tau_1 = \mu_1/E_1$, the retardation time of the dashpot. These later two components appear in an expression describing the creep compliance function for the pipe wall:

$$J(t) = J_0 + J_1(1 - e^{-t/\tau_1}) \tag{5-2}$$

Multi-element Kelvin-Voigt mechanical models can be used to refine the form of the creep compliance function and improve the replication of the retarded strain in the modified continuity equation. The evaluation of the rate of change of strain in a pipe wall, as required for the calculation of the third term in Equation 5-1, can now be performed using equations originally presented by Gally et al. (1979) and re-expressed by Covas et al. (2005):

$$\varepsilon_r(x,t) = \frac{\alpha D}{2e}\gamma\int_0^t [H(x,t-t') - H_0(x)]\frac{J_1}{\tau_1}e^{\frac{-t'}{\tau_1}}dt' \tag{5-3}$$

$$\frac{\partial \varepsilon_r(x,t)}{\partial t} = \frac{\alpha D}{2e}\frac{J_1}{\tau_1}\gamma[H(x,t) - H_0(x)] - \frac{\varepsilon_r(x,t)}{\tau_1} \tag{5-4}$$

where

$\varepsilon_r(x,t)$ = the strain in the pipe wall, $\partial\varepsilon_r(x,t)/\partial t$ = the rate of change of strain in the pipe wall, α = wall thickness factor, D = internal pipe diameter, e = wall thickness, γ = specific gravity of water, $H(x,t)$ = pressure head, $H_0(x)$ = steady state pressure head and the remaining terms have been previously defined

Gally et al. (1979) performed laboratory experiments on a 43.1m long polyethylene pipe with a diameter of 50mm and wall thickness of 4.2mm to obtain transient responses after closing an end in-line valve over 12ms to stop flow along the pipeline with a velocity of 0.57m/s (the flow was supplied from a pressurised tank with an initial head of 25m). Gally et al. (1979) then modelled the anticipated response of the pipeline using an experimentally calibrated creep compliance function (determined by stress/strain testing) and a three-element Kelvin-Voigt model as shown in Figure 5-10.

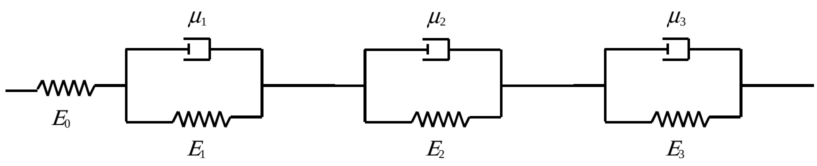


Figure 5-10 – Three-element Kelvin-Voigt mechanical model used by Gally et al. (1979)

The use of a three-element Kelvin-Voigt model meant that three creep compliance spring and three retardation time dashpot parameters were used to describe the viscoelastic response of the pipe. Covas et al. (2005) performed similar laboratory experiments on a 277m long polyethylene pipe with a diameter of 50.6mm located at Imperial College, London. Instead of using an experimentally calibrated creep compliance function, Covas et al. (2005) used the measured transient responses to determine approximate creep deformation and retardation parameters using inverse methods.

5.2.4 Development of an efficient solver for viscoelastic calculations

The calculation of the integral in Equation 5-3 involves a convolution of the change in pressure head (relative to the steady state pressure head H_0 (x)) with the function describing the non-elastic creep of the pipe wall (i.e., a creep compliance function). Equation 5-3 can be expressed in the form:

$$\varepsilon_r(x,t) = \frac{\alpha D}{2e}\gamma\left(\frac{\partial H}{\partial t} * J\right)(t) \qquad (5\text{-}5)$$

where J represents the creep compliance function that is convolved with pressure head changes throughout the transient event

Equation 5-5 is analogous to the equation developed by Vitkovsky et al. (2004), used in the efficient calculation of unsteady friction with a one-dimensional weighting function (as described in Appendix E), and both equations involve the calculation of a convolution integral. As a consequence, the recursive approximation developed by Kagawa et al. (1983) for the efficient calculation of unsteady friction can be applied to the calculation of the strain in the wall of a pipe exhibiting viscoelastic behaviour:

$$\varepsilon_r(x,t) = \frac{\alpha D}{2e}\gamma\sum_{m=1}^{N} y_m(t) \tag{5-6}$$

in which N = the number of elements in the mechanical model and the variables y_m are defined as:

$$y_m(t+\Delta t) = e^{-\Delta t/\tau_m} y_m(t) + \frac{J_m}{\tau_m} e^{-\Delta t/\tau_m}\left[H(t+\Delta t) - H(t)\right] \tag{5-7}$$

which reduces to:

$$y_1(t+\Delta t) = e^{-\Delta t/\tau_1} y_1(t) + \frac{J_1}{\tau_1} e^{-\Delta t/\tau_1}\left[H(t+\Delta t) - H(t)\right] \tag{5-8}$$

for a one-element Kelvin-Voigt model with a creep compliance function defined by:

$$J(t) = J_1\left(1 - e^{-t/\tau_1}\right) \tag{5-9}$$

where J_1 is the compliance of the creep deformation spring, τ_1 is the retardation time of the dashpot, y_1 is the recursive variable and $J(t)$ is the creep compliance function for a one-element Kelvin-Voigt model. The elastic component of the wall deformation (i.e., J_0) is removed so that only the viscous component of the viscoelastic behaviour is replicated (in the context of transient analysis, the elastic component of the pipe response is determined in the normal system of equations and is proportional to the wave speed)

Values for the parameters J_1 and τ_1 can be determined by mechanical testing of viscoelastic pipes. The values of y_1 need to be stored and updated on an on-going basis to enable the re-calculation of strain at each time step. The calculated strain may be substituted in Equation 5-4 (the rate of change of strain equation) to enable the rate of strain to be calculated for the current time step and included in Equation 5-1 (the modified governing equation of continuity). The method can be applied to multiple Kelvin-Voigt element mechanical models.

5.2.5 Application to non-plastic pipelines

The incorporation of the mathematical algorithms outlined above for the calculation of a viscoelastic effect are normally used to replicate creep deformation of plastic pipes but can be also be calibrated to account for viscous dispersion and damping caused by imperfect restraint and mechanical motion and vibration, flexible joints and soil/pipe interaction. Kelvin-Voigt viscoelastic models are commonly used to replicate (not physically describe) damping phenomena in numerous fields of engineering involving dynamic loads and the one-element model described above is used to develop conceptual transient models throughout this research.

5.3 Summary

Deterministic algorithms cannot be incorporated in transient models for the effects of sources of spatial and temporal uncertainty such as mechanical motion and vibration, associated with the restraint of pipelines, flexible joints and soil/pipe interaction. Literature has been identified in each case that indicates that associated dispersion and damping has been unable to be analytically described in other disciplines of engineering and that, given the damping is either viscous or viscoelastic in nature, replication using a conceptual mechanical model, such as the Kelvin-Voigt model, is employed. Gally et al. (1979) developed a Kelvin-Voigt model to describe the viscoelastic behaviour of plastic pipelines. This model can readily be adapted to develop conceptual transient models that provide for viscous damping from the physical complexities described above (for non-plastic pipelines). An efficient algorithm for solving the convolution in the equations describing viscous has been developed by adapting the methodology presented for unsteady friction by Vitkovsky et al. (2004). The creep compliance and retardation time parameters in the Kelvin-Voigt mechanical model (i.e., the basis for conceptual models developed throughout this research) can be calibrated to measured transient responses using inverse procedures as described in subsequent chapters.

Such conceptual models are not without precedent in the field of transient research as confirmed by Williams (1977) and Budny et al. (1991). However, the conceptual models developed and calibrated in this research are novel and cannot be physically traced to a single physical dispersion or damping mechanism. Budny et al. (1991) used equivalent "viscous" damping to conceptually replicate a single physical uncertainty (mechanical damping related to degree of restraint). In this research, the application of much broader conceptual models is proposed to replicate the effect of spatially and temporally variable physical complexities that influence field measured transients including mechanical motion and vibration, flexible joints and soil/pipe interaction. In this regard, these phenomena are not separate, particularly when a pipeline is buried, and coupled effects are likely. For example, the degree of mechanical motion and vibration for a buried pipeline is a function of both the type and number of flexible joints and the support from surrounding soils at each joint and restraining thrust block.

Chapter 6

Generating Transients and Field Instrumentation

The concept of generating controlled transients by rapidly closing established steady side discharges has evolved during the laboratory tests described in Chapter 3. Transients were initially generated in laboratory apparatus using in-line valve closures. This method followed the classic numerical configuration for transient analysis using a tank/reservoir and in-line valve boundary conditions. Most recently, Vitkovsky (2001) presented results, obtained using laboratory apparatus maintained at the University of Adelaide, where a mechanical torsion spring had been adapted to facilitate the closure of an in-line valve on a 22mm diameter copper pipeline in 10ms.

However, practical difficulties have emerged in generating sharp transient wavefronts when using in-line valve closures. Furthermore, the development of mechanical or other apparatus capable of rapidly closing an in-line valve on field pipelines with diameters ranging between 100mm and 1500mm is prohibitive. Alternative methods for generating controlled transients have been considered including resonating diaphragms, vacuum shocks and controlled explosions. These alternatives were not pursued in this research. Another alternative is the use of "in-situ" or naturally occurring transients. However, as Stoianov et al. (2003a) discovered, transients from normal pumping operations do not produce sufficiently sharp wavefronts to give rise to discernable (or any) reflections from faults.

In response to this, many of the researchers mentioned in Chapter 3 have moved to the use of side discharge valve apparatus in order to generate controlled transients with sharp wavefronts. This chapter describes the methods contemplated and used for generating controlled transients in field pipeline and network systems, the equipment used for the high speed and synchronised measurement of pressure responses, the acquisition of data and the method of introducing known faults to each pipeline and network system.

6.1 Mechanical torsion spring transient generator

Solenoid valves were used to rapidly close side discharges in the laboratories at the University of Adelaide. Unfortunately, direct action solenoid valves could not be manufactured economically for field conditions and pilot operated solenoid valves distorted the side discharge, giving rise to associated hydraulic losses, and more significantly, had relatively slow response times. Hence, pilot operated solenoid valves failed to induce sufficiently sharp transient wavefronts. The development and field application of a transient generator using pilot operated solenoid valves is described in Appendix F.

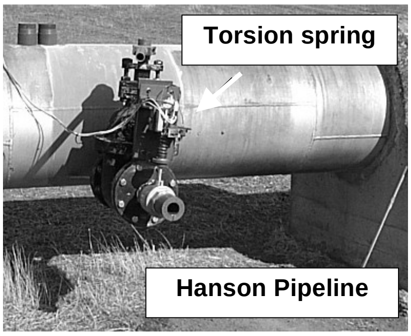
The development of a mechanical device capable of performing rapid valve operations was pursued. A torsional spring device was adapted from the laboratory apparatus used by Vitkovsky (2001). In turn, Vitkovsky (2001) had adapted the torsional spring device from that used by Bergant (1992) when conducting cavitation experiments. The spring device comprised a base plate with a torsion spring encircling and attached to a steel axis mounted in brackets protruding from the base plate. The rotation of the steel axis was coupled with either coiling or uncoiling of the attached torsion spring. The torque generated rapidly rotated the steel axis against considerable resistance.

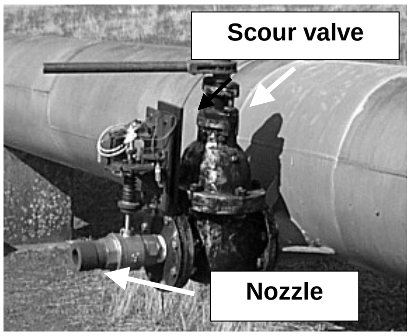
The rotation of the steel axis could be used to turn the axis of a ball or other valve against significant differential pressure and shutoff flow. This required the alignment of the steel axis enclosed by the torsion spring with the axis of the coupled valve and for the base plate of the device to be fixed to some support (the transient generator). This was achieved in different ways for different transmission and distribution pipelines. In the case of the above ground transmission pipelines, the transient generator could be welded, as described below, to a flange plate capable of being bolted to existing scour valve flanges. In the case of the below ground distribution pipes, the requirement that a standpipe be connected to the system meant that the transient generator needed to be mounted on the standpipe as described below. Below ground transmission pipelines have not been tested in this research but have been tested in subsequent work using a scaled-up version of the standpipe used for distribution pipelines.

Once the transient generator was installed and braced, the torsion spring could be coiled up by a 90 degree turn, and the steel axis similarly rotated, to open the connected ball valve and establish a side discharge. The torsion spring was held in this coiled position by restraining a lug fixed to the steel axis using a “bombslip” trigger. Once a steady discharge was established through the ball valve and any downstream nozzle, and other data logging preparations were complete, the “bombslip” trigger was released and the torsion spring uncoiled while simultaneously rapidly turning the steel axis 90 degrees and closing the coupled ball valve.

6.1.1 Transient generator for transmission pipelines

Controlled transients were induced in transmission pipelines by closing a relatively large side discharge ball valve (75mm diameter), over a period of approximately 10ms, using the custom modified transient generator. The speed of the closure was measured using a voltage potentiometer attached to the shaft of the ball valve. Figures 6-1 and 6-2 show the connection of the transient generator to an exiting scour valve on an above ground transmission pipeline. Figure 6-3 shows the side discharge jet established through the transient generator as mounted on a scour valve. The torsion spring proved capable of closing the side discharge ball valve mounted downstream of the in-situ scour valve across a maximum differential pressure of approximately 700kPa. Nozzle sizes downstream of the side discharge ball valve could be varied and a 50mm diameter nozzle was ultimately used for the transient tests described in later chapters. Unfortunately, the size of the 50mm diameter nozzle prohibited calibration using the laboratory apparatus described above. However, the flow rate in the transmission pipelines that were tested could be measured using in-stiu insertion flowmeters and compared with that estimated using the orifice equation.





Figures 6-1 and 6-2 – Torsion spring powered transient generator as mounted on an existing scour valve on an aboveground transmission pipeline

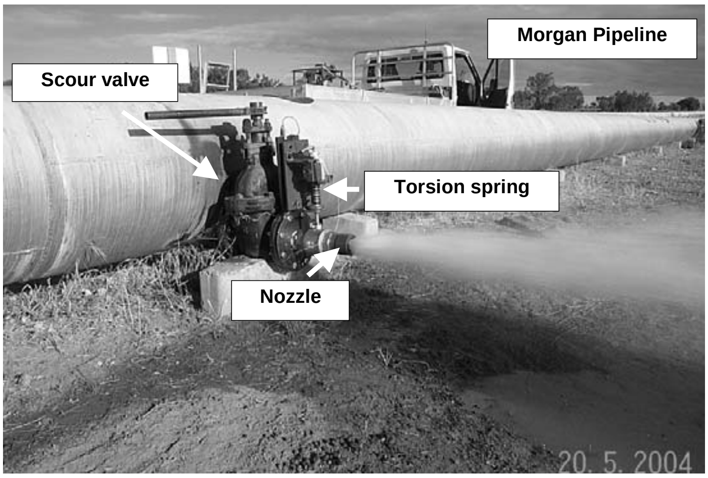
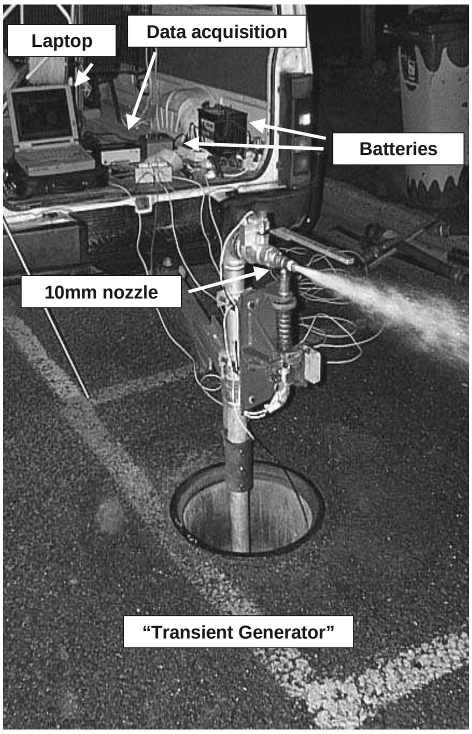


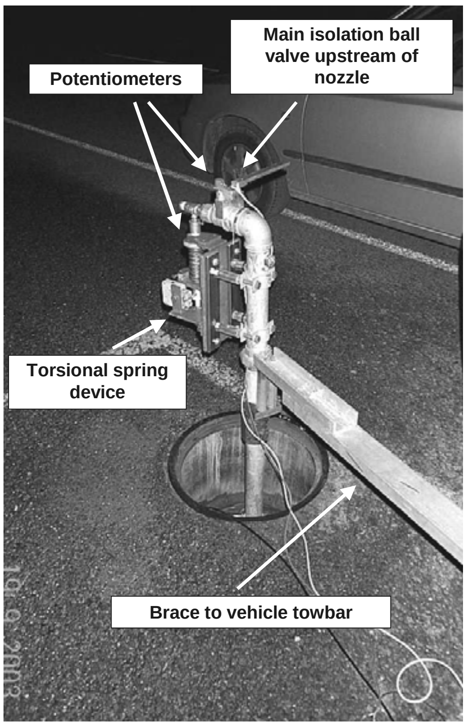
Figure 6-3 – Side discharge jet established through the transient generator as mounted on an existing scour valve on the Morgan Transmission Pipeline (MTP)

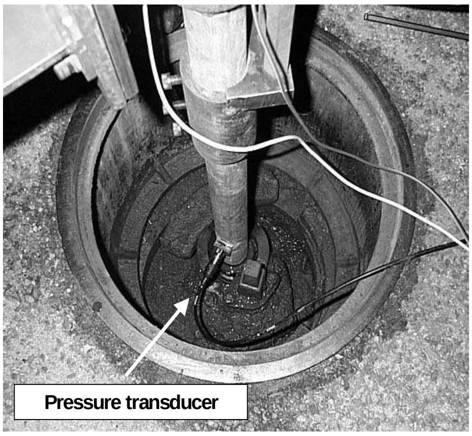
6.1.2 Transient generator for distribution pipelines and network

Controlled transients were induced by either closing or opening a small ball valve (15mm), located immediately upstream of a discharge nozzle (size varies), on the end of a 1.25m high standpipe (which is, in turn, mounted on existing fire plugs). The torsion spring was mounted near the end of this standpipe and coupled to the 15mm ball valve used to regulate discharge. Figures 6-4, 6-5, and 6-6 show the typical installation of the transient generator during the tests on distribution pipelines and a network. Figure 6-4 shows a typical side discharge through a 10mm nozzle. The base plate, steel axis (mounted in brackets) and the torsion spring are visible. Data acquisition equipment including a laptop computer, a Dasport logger and batteries are apparent in the background and are described in more detail below.

Figure 6-5 again illustrates the components of the transient generator including the coupling between the steel axis (enclosed by the torsion spring) and the 15mm ball valve behind the 10mm discharge nozzle, the main 25mm isolation valve upstream of the 15mm ball valve, the connection between the base plate supporting the torsion spring brackets and the standpipe and, finally, bracing from the towball of the nearby vehicle. A potentiometer on top of the main isolation valve was used to track its position during manual operations. The maximum speed at which manual closure and opening operations could be performed was approximately 250ms. A second potentiometer (not visible) was mounted below to track the motion of the steel axis enclosed by the torsion spring. This potentiometer confirmed that closure and opening operations, powered by the torsion spring, were completed within a time of 4ms.







Figures 6-4, 6-5, 6-6 and 6-7 – Photographs of the transient generator as installed, bracing arrangement, base connection and valve/torsion spring arrangement

Figure 6-6 shows the installation of a Druck PDCR-810 pressure transducer at the base of the transient generator such that the pressure variations at the location of the transient source could be monitored. The physical constraints at this location required the installation of the pressure transducer 200mm above the point of connection between the base of the transient generator and the fire plug. Figure 6-7 focuses on the "head" of the transient generator. A vertical rod and coupling, connecting the steel axis enclosed by the torsion spring to the 15mm ball valve mounted upstream of a 6mm discharge nozzle, is apparent.

6.2 Generation of positive and negative transients

The generation of a controlled transient by the rapid closure of a valve through which a steady discharge has been established has been labelled a positive transient because the resulting initial pressure surge increases the pressure in the pipeline or network system. Conversely, the generation of a controlled transient by the rapid opening of a valve through which a discharge becomes established has been labelled a negative transient because the resulting initial pressure surge decreases the pressure. The generation of negative transients is attractive because they place less stress on the pipeline or network system under investigation (the initial pressure surge is negative and the subsequent positive waves are attenuated by the open discharge through the transient generator). Furthermore, negative transients do not require the discharge of potable water while waiting for steady conditions to establish prior to inducing a controlled transient. However, there is an underlying change in the steady state conditions following a negative transient upon which the transient response is superimposed.

A coupling was developed, linking the steel axis enclosed by the torsion spring with the 15mm ball valve, which could be adjusted to configure the ball valve in either an open (discharging) or closed (not discharging) position, for the generation of positive and negative transients, respectively. Figure 6-8 shows the adjustable coupling that could be reorientated by simply removing two “Allen Key” screws, turning the coupling 90 degrees and re-inserting the “Allen Key” screws. Negative transients were used in the tests reported and analysed in Chapters 11, 12 and 14.

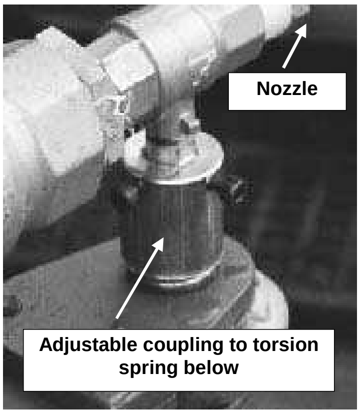


Figure 6-8 – View of adjustable coupling used to alternate between the induction of positive and negative transients

6.3 Risks from induction of controlled transients

6.3.1 Transmission mains

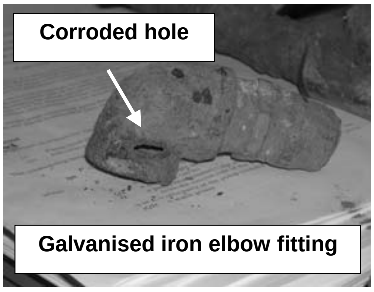
The specification of a maximum transient pressure rise is a critical constraint in the application of transient response analysis or Inverse Transient Analysis (ITA) as discussed in Chapter 3. In the case of larger transmission pipelines in South Australia, the South Australian Water Corporation and United Water operators considered a maximum overpressure of 10m, given likely variations in the condition of fire plug/air valve and scour valve fittings, as an appropriate limit for repeated testing over a period of one or two days. This limit takes into account the magnification of the transient pressure rise to 20m (approximately double the incident wavefront) at boundaries such as closed in-line valves.

During the course of the transient tests on transmission pipelines conducted during this research, no damage to the pipeline infrastructure was observed or subsequently reported after checks by South Australian Water Corporation operators. Despite the fact that the purpose of the transient tests was to investigate specific faults (artificially introduced) and the condition of the walls of pipes constructed between the mid-1940s and 1950, it was thought that the overall condition of the pipelines would be adequate to withstand the relatively small pressure rises associated with the tests. Indeed, normal pumping operations often resulted in surges that, while not as sharp as those induced using the transient generator, were of a greater magnitude and occurred more frequently.

6.3.2 Distribution pipelines and network

A pressure rise limit of 10m was determined for distribution pipelines and networks in consultation with United Water operators. Nevertheless, two pipe failures were initiated in water service connections during the transient tests conducted during the research. This was despite the total head at all locations within the system remained orders of magnitude below design limits.

The reason for the failures, subsequently discovered during repairs, was the deteriorated condition of the domestic plumbing. In the first case, a galvanised iron elbow had been used in a copper service and had corroded such that less than 0.1mm of metal remained at the bend in the elbow. The rise in pressure in the adjacent street main was sufficient to rupture the corroded metal and a small leak, external to the residence, occurred. In the second case, a galvanised iron section of plumbing in a private yard was heavily corroded with only 0.1 to 0.2mm of metal remaining in numerous locations. As for the first failure, the rise in pressure in the adjacent street main was sufficient to rupture the corroded metal and a small leak, again external to the residence, occurred. Figures 6-9 and 6-10 show the corroded elbow and the corroded section of galvanised pipe removed while undertaking repairs, respectively. Interestingly, well-developed turberculation was observed in the section of pipe removed from the second residence.



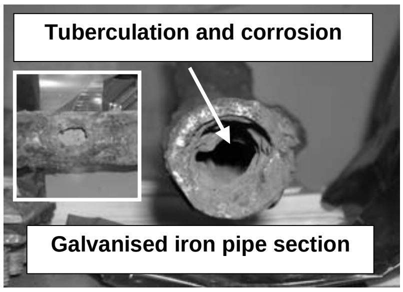


Figure 6-9 and 6-10 – Water service failures within a corroded galvanised iron elbow and section of pipe, respectively

Both failures occurred within private water services during the tests and were more of a nuisance to the research program than inconvenience to the owners who acted very reasonably during the repairs. Approximately 500 transient tests (not all reported in this thesis) were performed in the months and years subsequent to the two failures, which occurred early in the testing program, suggesting that older systems are typically in sufficiently good condition to withstand the relatively small pressure rises induced during the testing.

Furthermore, the recorded responses taken between transient tests, indicated that the systems tested were relatively dynamic and that natural transients in the order of 5m were common (and exceeding 10m were not uncommon). These transients were generally initially negative (becoming positive after half a wave cycle) with sudden pressure drops associated with demands. Given this level of dynamism, it was surmised that the induction of small controlled transients would generally have insignificant impact.

6.4 Issue of discharge to environment

In South Australia, the Environment Protection Agency (EPA) has developed regulations limiting the discharge of chlorinated potable water to the public stormwater drainage system. While the issue of discharging potable water to the environment did not prevent the development of a field testing program based on the use of side discharge valves for the generation of controlled transients, environmental regulations limiting the use of the technique have been discussed with United Water and South Australian Water Corporation operators.

Although comparable with the discharge of potable water during flushing maintenance or C-Factor tests, the discharge of considerable quantities of water while waiting for steady conditions to develop, prior to inducing a controlled transient via a side discharge valve closure, is undesirable. In this context, side discharge valve openings, rather than closures, have been investigated, because they potentially minimise discharge to the environment, as explained in later chapters. Furthermore, since the time of this research, further development of the equipment has occurred and discharges prior to side discharge valve closures are now captured via a pipeline connected to a water tanker.

6.5 Pressure measurement and data acquisition systems

6.5.1 Use of rapid response pressure transducers

Druck PDCR-810 15bar (approximately 1500kPa) flush face style pressure transducers were originally purchased to measure the transient response of all the pipeline and network systems. Flush face transducers were obtained to avoid small air bubbles becoming trapped in the port of the non-flush face style pressure transducers. Druck Limited confirmed the linearity of each pressure transducer before shipping them from the United Kingdom in February 2003.

Unfortunately, one of the three flush face transducers failed upon testing (lack of watertightness) and the only available replacement was a non-flush face style pressure transducer. Throughout the tests, two flush face and one non-flush face pressure transducer were used. The non-flush face pressure transducer was consistently installed in the transient generator standpipe for the tests on distribution pipelines and the Willunga Network. Precautions were taken when installing the non-flush face pressure transducer to ensure no air was trapped in its port. The characteristics of the flush/non-flush face Druck PDCR-810 pressure transducers are listed in Table 6-1:

Table 6-1 – Characteristics of the Druck pressure transducers (PDCR-810)

Characteristic	Values
Pressure range	0 to 15bar
Supply voltage	10V
Output voltage	0 to 100mV
Accuracy	0.06% of pressure range
Temperature range	0°C to 50°C

The Druck PDCR-810 pressure transducers were coupled with amplifiers to magnify their small output voltages. Strain-Gauge Transmitter WT127s were purchased from Analog Process Control Services Pty Ltd in Sydney, New South Wales, Australia, for this purpose. The WT127 amplifiers were custom matched with each of the pressure transducers. This process of custom matching involved sending the pressure transducers to Sydney where the excitation voltage for the amplifiers was matched to the pressure transducer specifications, the offset signal was zeroed, the output was zeroed for zero pressure and, finally, the range of output was adjusted for the full range of pressure (a hand held pressure pump and gauge were used to pressurise the transducers). Figure 6-11 shows a typical Strain Gauge Transmitter WT127 amplifier in the field.

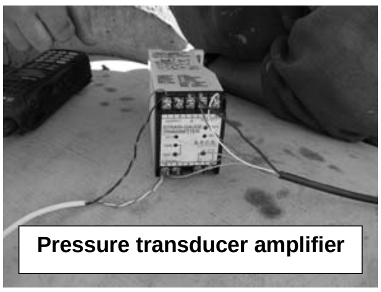
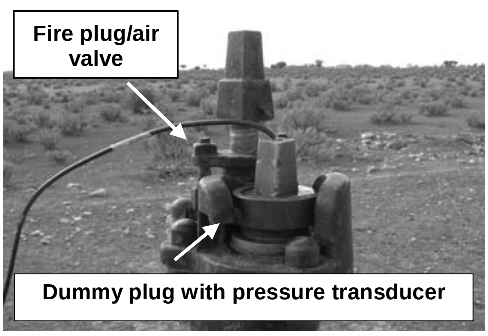


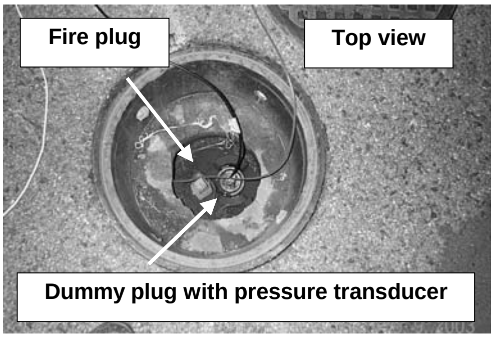
Figure 6-11 – Strain Gauge Transmitter WT127 used to amplify signals from Druck PDCR-810 pressure transducers

Once the pressure transducers and amplifiers were custom matched, it remained necessary to calibrate the transducer/amplifier combinations before and after each round of field tests. The field test dates, transducer calibration dates and the results of the calibration of the transducers are summarised in Appendix G. The calibrations confirmed a linear relationship between the amplified pressure transducer output and changes in pressure over a range up to 900kPa. This relationship was consistent over the period of testing.

6.5.2 Coupling to existing fire plug/air valves and other fixtures

The locations at which pressure measurements can be taken on field systems, including transmission pipelines, distribution pipelines and networks, without custom installed tappings, are limited to existing fire plug/air valves, fire plugs, scour valves and pump station tappings. Figures 6-12 and 6-13 show typical installations on a fire plug/air valve for an aboveground transmission pipeline and belowground distribution pipeline, respectively. The pressure transducers were mounted inside “dummy” plug connectors that are normally used to blank-off a fire plug/air valve or fire plug discharge outlet. The “dummy” plugs were cored-out to create a void in which the pressure transducer could be accommodated and sealed.





Figures 6-12 and 6-13 – “Dummy” plug pressure transducer installations on an existing aboveground fire plug/air valve and a belowground fire plug, respectively

The sensor face of the pressure transducer penetrated a new front plate for the “dummy” plugs such that, once installed, the face of the pressure transducer was exposed to the full system pressure after the fire plug/air valve, fire plug or scour valve was opened. In this way, pressure measurements could be taken without any discharge of water. Air trapped in the fire plug/air valves, fire plugs or scour valves was carefully flushed before installing the “dummy” plugs.

The location and condition of existing access points were a complication when designing and executing the field tests reported in this research. Even when suitable access points were identified their condition often made them ineffective after the installation of “dummy” plug connectors. This was caused by the corrosion of tightening bolts and deterioration of seals and subsequent leaks. This problem also affected the installation of the transient generator.

6.5.3 Data acquisition system and synchronisation

Data acquisition systems for water pipeline and network systems are evolving as the need to better understand the behaviour and condition of systems is recognised by operators. However, little published work exists on data acquisition systems for the collection of synchronised high speed pressure measurements apart from that presented by Stoianov et al. (2003b). The data acquisition system used for the collection of pressure data during the field tests described herein evolved from the equipment developed by Vitkovsky (2001) in the laboratories of the University of Adelaide. The basic components are the Druck PDCR-810 pressure transducers, Strain-Gauge Transmitter WT127 amplifiers and laptop computers.

The synchronisation of pressure transducers is not an issue in the laboratory because of their close proximity to each other and the ability to directly connect them, via cables, to a single data acquisition card and computer. In the field, the distances between pressure measurement stations means that individual laptop computers and data acquisition systems are required at each location.

Portable Dasport units, supplied by Intelligent Instrumentation, were used for data acquisition. Each Dasport unit accepts up to 16 single-ended analogue input channels. The conversion of these analogue signals to digital signals was performed with 12-bit resolution. A 0V to 10V range was used to log the output from the pressure transducer/amplifier combinations. Visual Designer software was used to program a data acquisition sequence for each Dasport unit and provide a graphical interface with which to establish the number of input channels, signal ranges, recording devices and rates, and specify output storage. Three input channels were required for the data acquisition system at the transient generator to record pressure, a synchronisation signal and the output from a potentiometer used to track valve operation profiles. Two input channels were required for data acquisition at other measurement stations to record pressure and a synchronisation signal.

While the specification for the Dasport unit indicated that a single channel could be successfully sampled and recorded at 100,000Hz, this sampling rate dropped of significantly when attempting to sample and record three channels simultaneously. Experiments were conducted in the laboratory confirming that to avoid buffering problems a sampling rate of 500Hz was the maximum that could be used while recording three channels simultaneously. In the case of two channels, a sampling rate of 2000Hz was the maximum that could be used.

Physical cable system for synchronisation

Figure 6-14 shows the typical equipment used for data acquisition for the water distribution pipeline and network tests. A Pentium 166MHz laptop, Dasport logger and associated batteries are visible in the foreground. In addition, cables on barrels and a synchronisation trigger are visible in the background and foreground, respectively. While synchronisation issues were managed in the laboratory using direct cable connections to a single data acquisition unit and computer, the expansion of this system for field testing was difficult and labour intensive because of the greater distances between pseudo independent data acquisition stations. The main reason for pursuing a scaled-up version of the cable synchronisation system was that it was known to work and, given that there were limited opportunities to conduct the field tests, reliability was very important.

However, signal degradation was a concern in the case of direct transmission of the output from the pressure transducer/amplifier combinations at remote measurement stations to a single data acquisition unit and laptop computer. Hence, laptop computers and Dasport units were deployed in pairs at each of three measurement stations. The problem then became how to synchronise these data acquisition stations to within 1ms. McInnis and Karney (1995) had simply relied on the internal clocks of their laptops in order to synchronise the time at which pressure measurements were logged. Laboratory investigation at the University of Adelaide confirmed that the relative accuracy of the laptop clocks was in the order of 100ms to 1000ms. In the context of obtaining accurately synchronised pressure measurements at the scale of milliseconds over individual lengths of distribution pipeline, this level of accuracy was inadequate.

A cable synchronisation system was developed such that a common voltage pulse could be transmitted to all measurement stations. Signal degradation was not important provided the pulse could be detected at each data acquisition unit. Separate wires were run out, over hundreds of metres, from a central control station to the other data acquisition stations. Radio messages were sent to individual operators at each data acquisition station to start data recording. A voltage pulse was then triggered at the central control station that transmitted virtually instantaneously to the other stations where it was recorded. This voltage signal was recorded on the second input channel at each data acquisition station. In the case of the central control station, usually located near the transient generator, a third channel recorded the signal from the potentiometer mounted on the steel axis enclosed by the torsion spring.

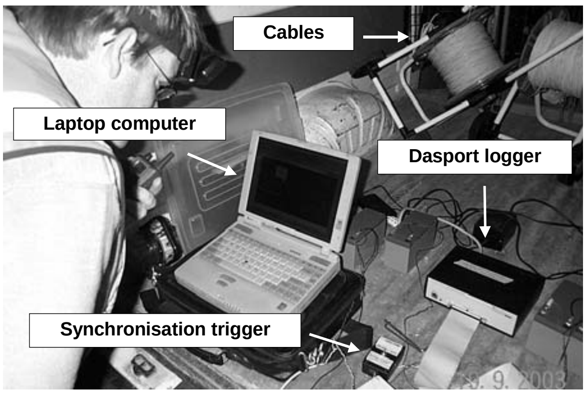


Figure 6-14 – Central control data acquisition station used with cable synchronisation system

Radio system for synchronisation

The cable system of synchronisation was very intensive and limited the range of locations at which data acquisition stations could be deployed to within one kilometre of the central control station (because of the physical limitation to the amount of cable that could be stored on a series of cable barrels). While this system was workable, and provided reliable results, it was not practical for tests on longer transmission pipelines. Hence, the author, in conjunction with staff from the University of Adelaide's laboratories, developed a radio synchronisation system.

The concept is the same as that for the cable synchronisation system. A central radio at, or near, the control station was used to transmit an audio signal of a known frequency to all measurement stations. A custom built emitter was held close to the central radio and triggered to generate and transmit the audio signal. Receiving radios at each of the remote data acquisition units were set to receive this audio signal at a particular frequency. Once the signal was received it was converted to a voltage pulse that was recorded on the already active data acquisition record. The data acquisition was initiated earlier by a radio instruction from the central station operator. Figure 6-15 shows the laptop computer, Dasport logger and radios for communication and synchronisation at the central control station for the tests on a transmission pipeline.

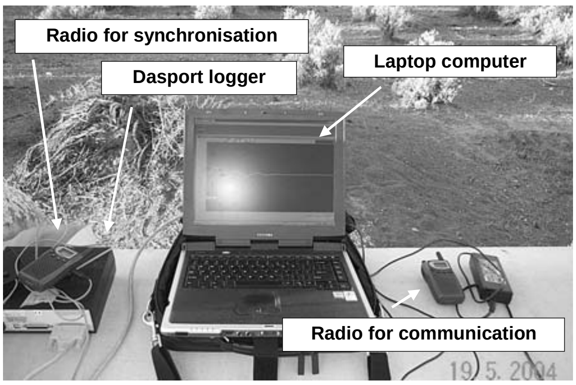


Figure 6-15 – Central control data acquisition station with radio synchronisation system for tests conducted on an aboveground transmission pipeline

Since the time of this research, a GPS synchronisation system has been developed to further increase the range between data acquisition stations to over 10kms. This system has been developed by the University of Adelaide and is currently being used to measure transient responses from transmission and distribution pipelines for the South Australian Water Corporation and United Water.

6.6 Methods of introducing known faults to the systems

6.6.1 Operator thresholds of interest for different faults

The thresholds of interest, held by operators, in detecting different faults in pipeline and network systems vary considerably with the nature of the fault and alternative detection methods that may be available. It was necessary to consider these thresholds when deciding how best to artificially simulate the various faults either using in-situ field fittings or custom fabricated pieces of equipment.

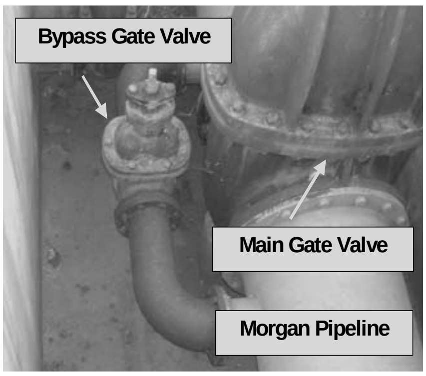
United Water operators are interested in the detection of discrete and/or extended blockage of any size up to the total constriction of a pipeline. The case of total constriction is of interest where network redundancy means that pressure and flow is maintained to residences from either end of a pipeline despite a total blockage forming in the middle. In the case of air pockets, United Water operators considered volumes up to 10 litres typical of that which could potentially accumulate in riser pipes under fire plugs along distribution pipelines and within networks. Finally, in the case of leaks, South Australian Water Corporation operators considered methods for detecting leaks up to 10L/s of interest in remote areas or along sections of pipe that were underwater or buried in porous materials. United Water operators considered methods for the detection of leaks up to 1.5L/s as potentially useful on water distribution pipelines and networks (as alternatives to the deployment of acoustic leak correlators).

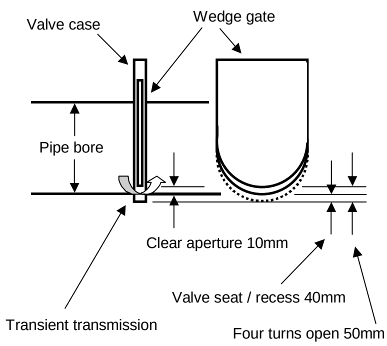
6.6.2 Simulation of 2D discrete blockages – existing gate valves

In the case of oil and gas pipelines, Adewumi et al. (2000) confirmed that techniques for the detection of discrete or 2D blockages were important. While 3D tuberculation is the main form of blockage that occurs in distribution pipelines and networks, it was decided to begin by conducting transient tests for 2D blockages formed by partially closing in-line gate valves to form constrictions of known severity.

As described in Chapter 9, field tests were conducted on a transmission pipeline with an artificial discrete blockage formed by the partial closure of an in-line gate valve. Unfortunately, it was not possible to calibrate large diameter in-line gate valves in the laboratory. Hence, knowledge of the wedge mechanism for such valves was used to estimate the applicable discharge coefficients. A typical in-line gate valve, and bypass pipe and valve, are shown in Figure 6-16. Figure 6-17 shows the geometry of the valve, gate and potential flow path when the valve is partially open.

As described in Chapter 11, further field tests were conducted on a distribution pipeline with a 100mm diameter in-line gate valve. A similar valve was retrieved from United Water's storage depot and taken to the University of Adelaide's laboratories where it was calibrated using the roof and volumetric tank system described and illustrated in Appendix H. The gate valve was calibrated as described in Appendix I.





Figures 6-16 and 6-17 – Typical large in-line gate valve used to simulate discrete blockage along a transmission pipeline and internal geometry, respectively

6.6.3 Simulation of air pockets at existing fire plugs

As described in Chapter 11, field tests were conducted on a distribution pipeline with an artificial air pocket formed by attaching a 1.65m high by 85mm nominal diameter pipe section, sealed at the top with a welded plate, to an existing fire plug valve. A 600mm long Perspex window was built into the side of the pipe section and a manual pressure gauge was fitted. The pipe section was attached to the existing fire plug in the same manner as a typical standpipe and tightened until a seal was achieved. The isolating valve on the fire plug was then opened to allow the pressure in the pipeline to compress the air in the pipe section. Figure 6-18 shows the pipe section used to form the artificial air pocket.

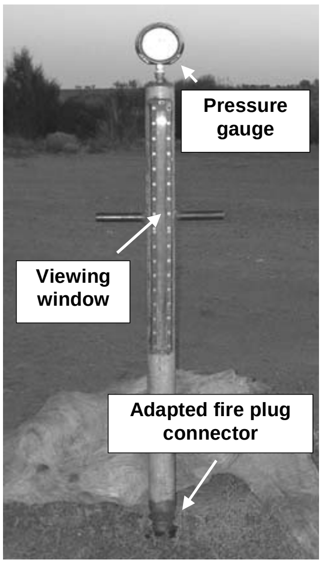


Figure 6-18 – Galvanised steel pipe section used to create artificial air pocket on distribution pipelines

6.6.4 Simulation of leaks – fire plug/air valves, nozzles and standpipes

Figure 6-19 shows a typical simulated leak that was introduced to a transmission pipeline at the location of an existing fire plug/air valve. A galvanised steel pipe section, 850mm long by 55mm nominal diameter, was connected to the fire plug/air valve and the valve opened to establish a vertical discharge. The fire plug/air valve has a maximum aperture of approximately 1.5 inches (i.e., an equivalent orifice diameter of 38mm) across its seating section. The fire plug/air valve was only opened 6.5 of 10 turns, giving an equivalent orifice diameter of approximately 25mm across the seat of the valve, so as to control the magnitude of the leak discharge.

Artificial 10mm leaks were introduced to distribution pipelines by attaching a 1.25m high by 50mm nominal diameter standpipe, with a 90 degree bend, 25mm ball valve and 10mm fitted nozzle, to existing fire plug valves. The standpipe was attached to the existing fire plug in the same way as a typical standpipe and tightened until a seal was achieved. The isolating valve on the fire plug was then opened to allow the standpipe to fill with water. The 25mm ball valve mounted at the top of the standpipe was then closed to prevent any discharge until it was time to establish a leak discharge.

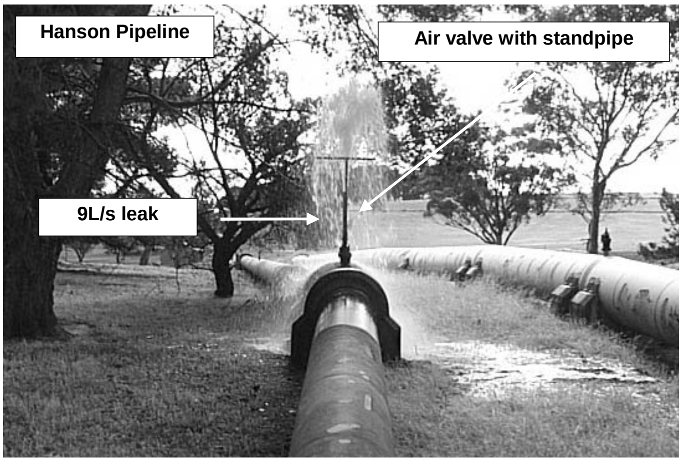


Figure 6-19 – Simulated leak at existing fire plug/air valve on a transmission pipeline

6.7 Summary

Different methods for inducing controlled transients in pipeline and network systems have been investigated with side discharge valve manoeuvres preferred because sharp wavefronts could be generated. A mechanical device, including a torsion spring, is adapted to operate side discharge valves mounted on scour valves on the transmission pipelines and at the end of standpipes attached to fire plugs on distribution pipelines. Different discharge nozzles can be mounted in the mechanical device, called the transient generator, and these were calibrated in the laboratories at the University of Adelaide. In the case of the transmission pipelines, larger nozzles were calibrated in-situ using existing insertion flowmeters in transmission pipelines.

The risks from the induction of controlled transients in both the pipeline and network systems tested appear to be minimal. Consultation with United Water and South Australian Water Corporation operators assisted in setting the level of transient pressure rise to be applied. No infrastructure failures occurred during the field tests conducted on the transmission pipelines. Two minor failures of deteriorated private plumbing occurred during the field tests on distribution pipelines.

The details of the pressure measurement instrumentation and data acquisition systems have been presented including a description of the use of separate Dasport data acquisition units and laptop computers at individual measurement stations. Druck PDCR-810 pressure transducers and Strain-Gauge Transmitter WT127 amplifiers are used for pressure measurement and have been regularly calibrated between field tests. A cable synchronisation system, used to transmit a synchronising voltage pulse to remote measurement stations, for the field tests conducted on the distribution pipelines, has been described. Furthermore, a radio tone synchronisation system, for the field tests conducted on the transmission pipelines, has been developed.

Different pre-existing faults or artificially introduced faults are described in this chapter. A leak was artificially introduced to a transmission pipeline using an existing fire plug/air valve. The discharge through this artificial leak was confirmed using an existing insertion flowmeter. The details of an existing in-line gate valve along another transmission pipeline, used to introduce an artificial discrete blockage, have been presented. The results of field tests performed on transmission pipelines with artificial faults are presented in Chapter 9.

A discrete blockage was artificially introduced to a distribution pipeline using an existing in-line gate valve. An equivalent valve was retrieved from United Water and calibrated to obtain loss factors for different incremental openings. The details of the valve and its calibration have been presented in Appendix I. As described in this chapter, an artificial air pocket was introduced to another distribution pipeline using the pipe section attached to existing fire plug valves. Similarly, artificial leaks were introduced to the same distribution pipeline by attaching a standpipe with a calibrated nozzle to an existing fire plug valve. The results and analysis of the field tests performed on the distribution pipelines, either with artificial or in-situ faults (e.g., pre-existing tuberculation), are presented in Chapters 13 and 14.