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TRANSIENT REFLECTION ANALYSIS TO IDENTIFY PROBLEMS WITH A RAW WATER PUMPING MAIN

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Abstract

Transient analysis has been shown to have applications for the detection of discrete anomalies such as leakage, blockage and air pockets within pipelines. This technique may be extended to the investigation and assessment of the condition of pipelines. The issues associated with the field implementation of this technique, such as field measurement equipment, synchronization of measurements, lack of reliable system information, low pressures, the presence of air valves and operational issues also require further investigation.

This paper presents the analysis of a raw water pumping main using field data collected during transient testing. This composite main of Acrylonitrile-Butadiene-Styrene (ABS) and Ductile Iron Cement Lined (DICL) pipe was designed to deliver 105 L/s and at the time of testing was capable of delivering only 87 L/s. Online and offline testing was undertaken with transients generated by the fast closure of a valve connected to the system via a standpipe. Both openings and closures of the valve were recorded, as were varying nozzle sizes. Online transients were also initiated by pump failures.

A combination of transient and steady state analysis is used to determine the presence and location of anomalies within the pipeline with the aim to discover possible causes of the reduced flow capacity and assess the condition of the pipeline. An emphasis on the analysis of transient reflections, from system components and anomalies, is made including investigation of the consistency of results between openings and closures and varying nozzle sizes. The correspondence between reflection size and timing as measured at different locations is used to determine anomaly presence. Issues associated with applying this technique to a real world system are also investigated and discussed.

Keywords
Condition Assessment, Hydraulic Transient, Field Applications

1. INTRODUCTION

Condition assessment of pipelines is gaining importance in the water industry as pipelines age and deteriorate. It is also important in the diagnosis of problems with pipelines that do not perform as designed or expected. The condition of pipelines and hence the performance may be impaired through the presence of faults such as leaks, blockages, trapped air and pipe wall deterioration.

The use of the response of a system to hydraulic transients to diagnose faults was initially proposed by Liggett and Chen (1994). Since 1994, a large amount of theoretical development of several transient based techniques has been undertaken (Brunone 1999; Vítkovský 2001; Lee et al. 2002; Wang et al. 2002). However, limited investigation of the field application of techniques has been undertaken, it has only been recently that transient techniques have been applied to field data for detection of faults. Transient analysis has been applied in the field for leak detection in water transmission mains by Stoianov et al. (2003) and in networks by Covas (2004). Stephens et al. (2004) has applied inverse transient analysis to locate and detect simulated leaks, blockages and air pockets within a field water distribution system. The potential of transient analysis for the detection of simulated and naturally occurring blockages has also been shown (Stephens et al. 2005) and hence its applicability to condition assessment has been identified.

2. FIELD TEST PIPELINE

The single pipeline pumps water from the river where the water level is approximately 16.5 m through two submerged pumps to a PAC (Powdered Activated Carbon) tank with typical water level at 25.6 m. The main is a composite pipeline of 315 mm diameter ABS (ID 278 mm) and 250 mm diameter DICL (ID 255 mm) with design roughness heights of 0.007 mm and 0.03 mm respectively. ABS extends from the PAC tank at chainage 0 m to approximately chainage 109 m and from chainage 708.42 m to the pump intake pipes at chainage 725.45 m, while the remainder of the pipe is DICL. A magnetic flow meter is present in the first section of ABS between chainages 63 m and 109 m, however the exact location is unknown.

Air valves are present at several locations along the pipeline and two scour tees exist, although scouring of the pipeline is not undertaken on a regular basis due to Environmental Protection Authority restrictions. A schematic of the pipeline is shown in Figure 1.

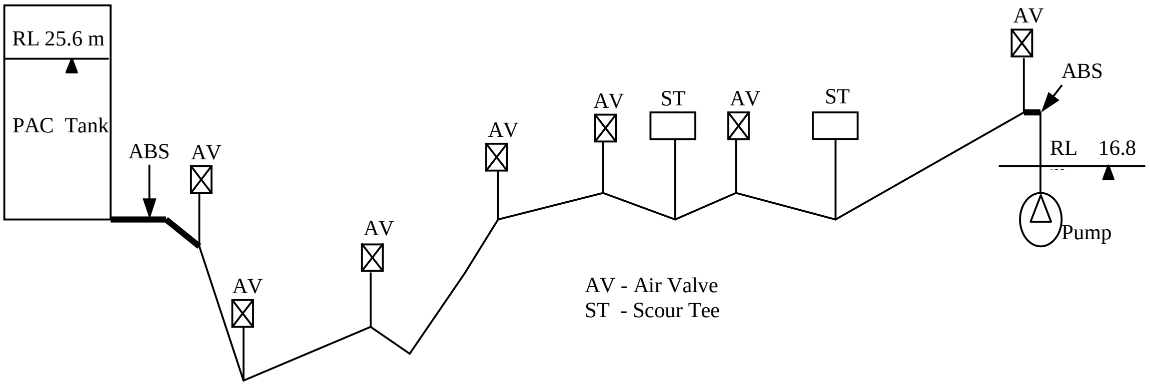


Figure 1. Schematic of pipeline

The typical operation of the pipeline is at low discharge (approx. 30 L/s), particularly in winter, however the higher designed discharge of 105 L/s is required to meet growth and peak demands. The raw water pumping main was identified for the application of transient analysis for condition assessment as the pipeline at the time of testing was capable of delivering only 87 L/s, a significant reduction from the expected design discharge. Transient testing was undertaken to identify and locate any anomalies in the system such as blockages, leaks or air pockets that could account for the reduced discharge.

3. TRANSIENT TESTING OVERVIEW

Transient testing of the system was undertaken on two separate occasions in November 2005. Preliminary investigation utilized emergency pump shutdowns to generate hydraulic transients, and the hand closure of a 25 mm ball valve attached to the air valve at approximately chainage 67 m. Pressure measurements were recorded at chainages 301.56 m and 708.42 m.

More detailed testing was carried out on the second occasion when the pipeline was isolated from the pumps. Controlled hydraulic transients were generated by the fast closure or opening of a 25 mm valve mounted on a 55 mm diameter 1.8 m high standpipe connected to the existing scour tees (at chainages 439.55 m and 565.38 m) as shown in Figure 2(a). A custom-built quick release torsional spring device was used to close/open the valve with a closing/opening time of 5 ms. Pressure measurements were taken at chainages 67 m, 386.01 m and 489.95 m.

(a) (b)

Figure 2. a) Torsional spring transient generator and b) transducer measurement connection

Synchronized measurement of pressure at several locations was possible through the use of the data acquisition system consisting of a 16 bit A/D converter sampling at 2000 Hz, a 1000 Hz low pass filter and GPS (Global Positioning System) time synchronization at each pressure transducer measurement station. Druck 810 pressure transducers (15 bar) were connected to the system using existing air valve connection points as shown Figure 2(b). The air valves were bled to remove any existing air pockets before testing.

4. PRELIMINARY TESTS

4.1 Emergency pump shutdowns

The transient response of the system during an emergency pump shutdown was recorded twice on the first testing occasion. The testing configuration including measurement locations is shown in Figure 3.

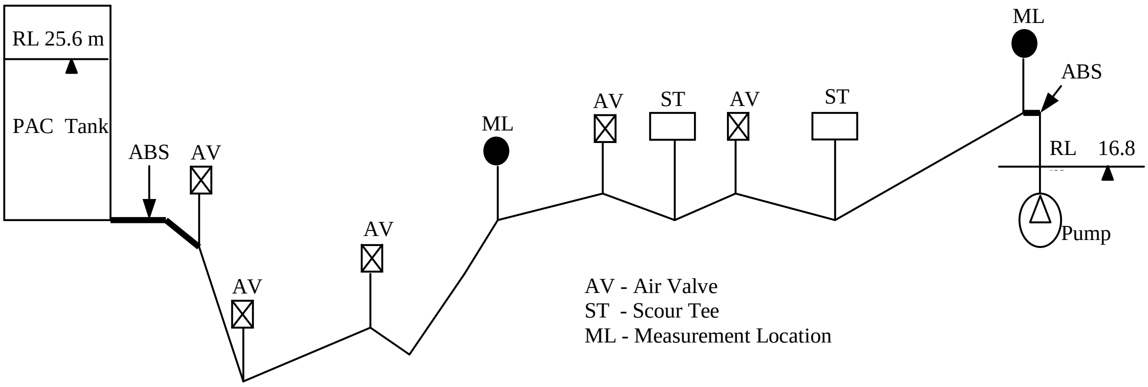


Figure 3. Emergency pump shutdown testing configuration

The transient analysis undertaken focused on the reflection information obtained in the first period of the transient response, not the periodic damping information. Hence it is necessary to use a fast transient generation, that produces a sharp transient front, to obtain clear reflections as noted by Stephens et al. (2004).

The transient response of the system as produced by an emergency shutdown and shown in Figure 4 is not of sufficient speed to produce clear reflections as the pump takes time to slow to a stop. At the first measuring station at a distance 17 m from the pump reflections occur prior to the 1.2 second transient completely passing the measurement location. Hence the magnitude of the transient and the reflection are unknown due to the superposition of the two transient waves at that point. While the effect of this may have been limited through the use of a different measurement location it indicates the potential problem with using a slow transient for transient analysis.

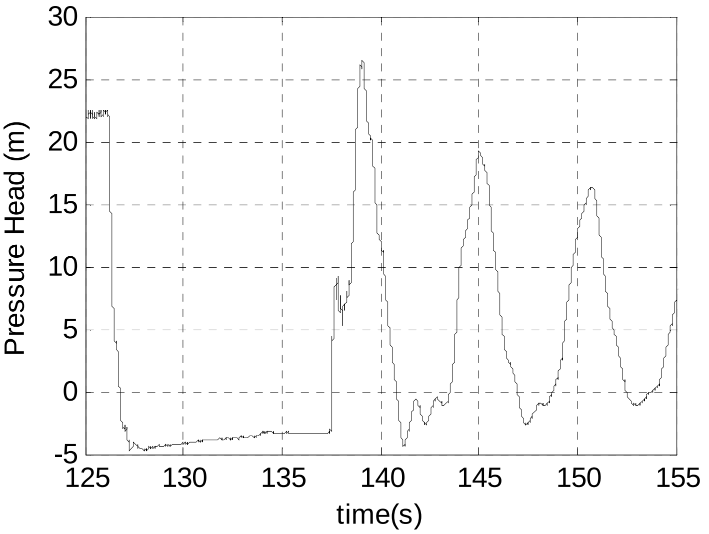


Figure 4. Emergency shutdown transient response at pump side measurement station over 20 seconds

Analysis of emergency pump shutdown responses also requires accurate modeling of the pump shutdown including the moment of inertia and is not preferred. Transient analysis of these results is however investigated to confirm the conclusion of the analysis from the detailed testing.

4.2 Hand Closure

Hand closures of a side discharge valve were performed on the initial testing day. Closures were performed with the pump on and offline. For offline testing the pipeline was isolated from the pumps due to the check valves on the pump intake pipes and hence the testing configuration was as shown in Figure 5.

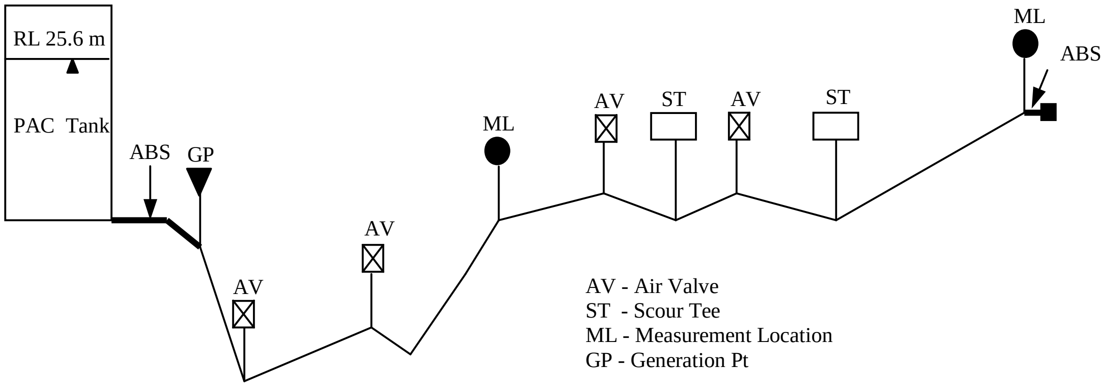
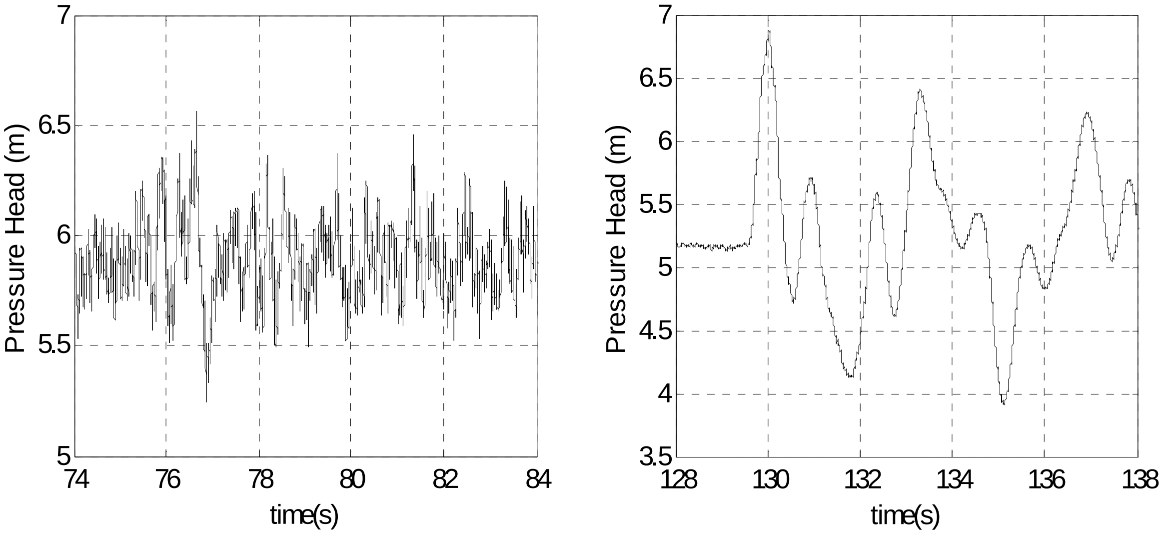


Figure 5. Hand Closure testing configuration

The transient generated by the hand closure of the valve was of insufficient size to be distinguishable from the oscillations in the transient response produced when the pump was online, as shown in Figure 6. Hence online testing of the system with hand generation of transients is not advised for transient analysis. Offline testing using hand closure transient generation produced small transients in the system, however these transients were not of sufficient sharpness for clear reflection information to be gained. Hence a faster transient generation method was required.



(a) (b)

Figure 6. Hand closure transient response at pump side measurement location over 10 seconds with pump a) online b) offline

5. DETAILED TESTING

On the second testing date the torsional spring generation device was used for all tests to obtain a faster closure and hence sharper transient. The testing configuration is shown in Figure 7. Openings and closures were undertaken with the generation device to obtain different transient responses. A range of nozzle sizes (5-25mm) were used to produce transients of different sizes and online testing was undertaken.

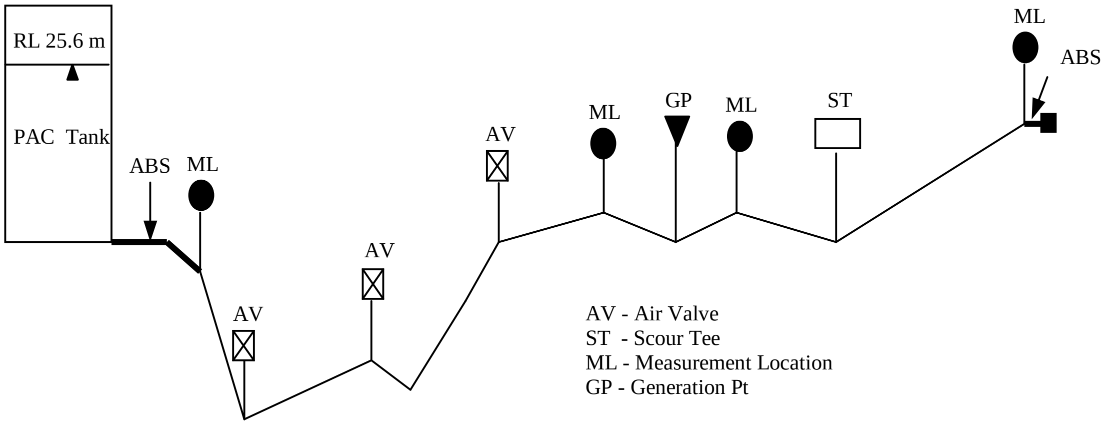


Figure 7. Generation device testing configuration

5.1 Transient Response from Generation Device

The torsional spring generation device resulted in a sharper hydraulic transient response (0.04 seconds), as required and shown in Figure 8. The transient produced was deemed of sufficient speed to produce clear reflection information and hence was found to be applicable to transient analysis. The response recorded is very complex in character with initial high frequency oscillations and will be shown later to be different from the expected modeled response.

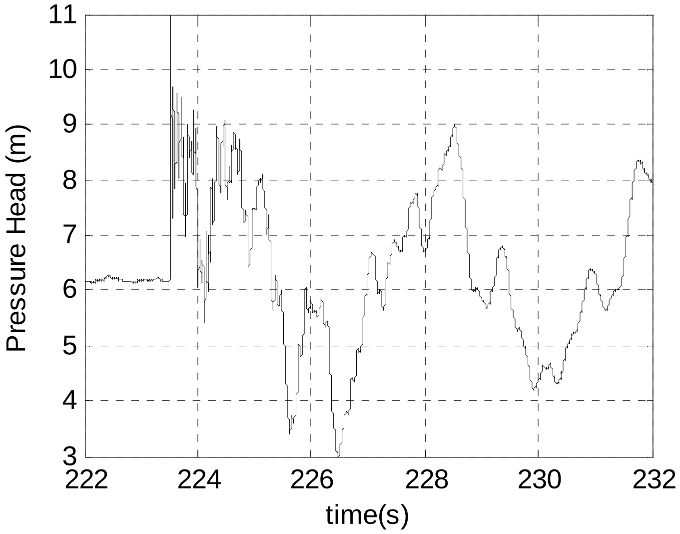


Figure 8. Typical response to torsional spring generation at tank side measurement location

The response of the system was found to be consistent between tests. Figure 9 shows the comparison of the responses for two tests undertaken with slightly different nozzle sizes and hence transient magnitudes. The location of the peaks, and hence timing of the reflections, does not differ indicating the consistency of the results between tests and that limited testing is required to gain sufficient information from the system. The magnitude of the nozzle should be such that the transient generated is of sufficient magnitude that reflections are identifiable but within the limit set by the system operators.

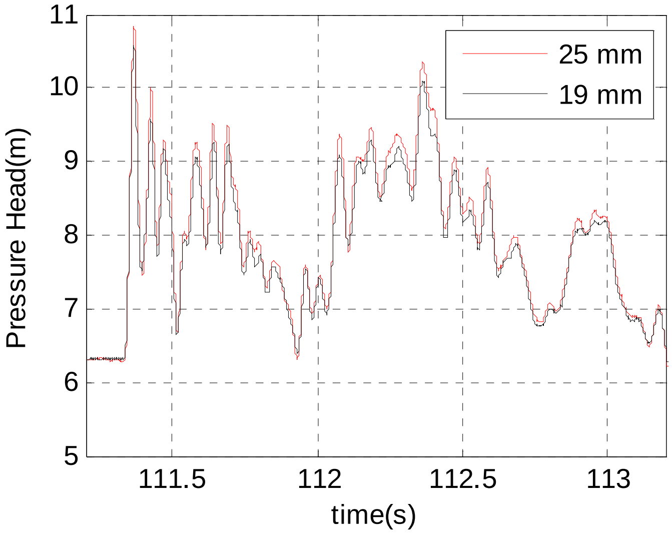


Figure 9. Comparison of transient response with 25 mm and 19 mm nozzle sizes

Both fast openings and closures were undertaken and the consistency of the reflections in the transient response between these can be seen in Figure 10. Again the location of the peaks and hence timing of the reflections was consistent indicating that either openings or closure could be used in identifying anomalies, however as shown the impact of the high frequency oscillations is reduced for the openings. These oscillations are inferred to be due to the generator standpipe. As the generator standpipe is of sufficiently different diameter and material to the pipeline at the generator, reflections occur from the junction between the standpipe and the pipeline. Due to the length of the standpipe these additional reflections are of a high frequency when compared to the reflections within the pipeline under consideration as shown.

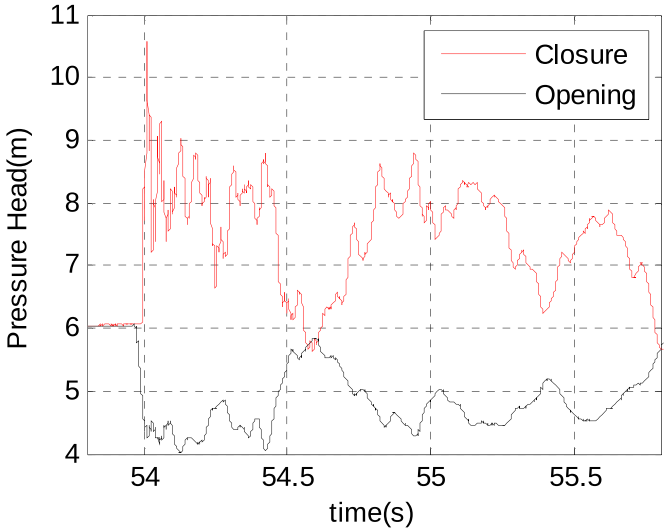


Figure 10. Comparison of valve opening and closure transient response

To limit these reflections and hence reduce the added complexity input by the generator into the induced transient it is necessary to attach the generator as close as feasibly possible to the pipeline. Feasible locations are limited due to access to buried pipelines and hence available tappings and valves. In the system analyzed here the scour tees were the only available connection locations, although it may have been possible to reconfigure the pipeline by connecting the generator directly to the end of the above ground section of pipeline near the pump station in place of the pipeline to the pumps, this would have been difficult due to time and cost constraints. Thus reducing the length of the generator standpipe represents the only method to reduce the added complexity and attaching the generation device directly to the scour tee would be beneficial if feasible. However the scour tees exist on a standpipe of reduced diameter from the pipeline hence the effect cannot be completely removed. It is recommended to attach the generation device as close as feasibly possible to the pipeline and if a standpipe is necessary then if possible construct the standpipe of similar diameter and material to the pipe section to which it will be attached.

When an opening is used for generation a leak is introduced into the pipeline at the generator and thus the unwanted reflections are damped, limiting the effect of the standpipe on the transient response as shown in Figure 10. Hence it is recommended to undertake valve openings if a generator standpipe that introduces added complexity to the induced transient is unavoidable.

5.2 Online Testing

Testing was also conducted as the pump was brought online and up to speed. As seen in Figure 11 the noise due to the pump interferes with the identification of reflections in the measured transient response. A significantly larger transient, made possible by a larger nozzle, would be required to accurately identify reflections, however operator limits on transient magnitudes set to protect pipelines restrict the allowable magnitude. Hence the feasibility of performing online transient testing with the generation device is restricted and offline testing is recommended.

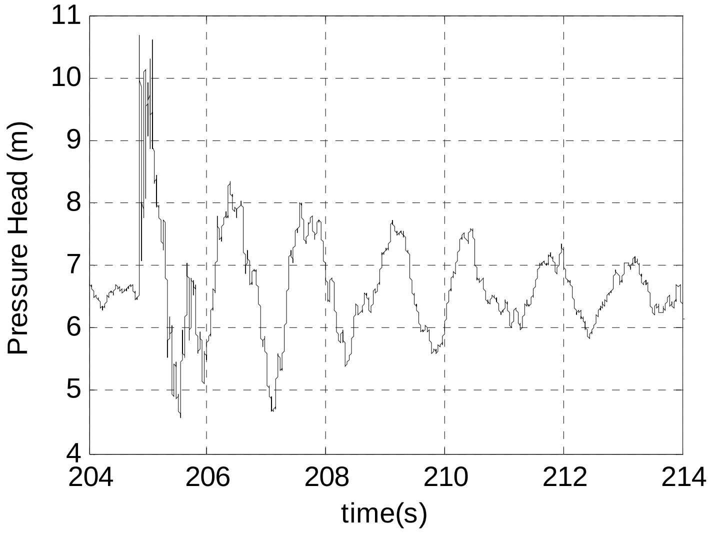


Figure 11. Online test transient response for closure

5.3 Effect of Bleeding Air Valves

The air valves not used for pressure measurement were bled after several tests had been undertaken. The effect of this is shown in Figure 12, where it is clearly shown that air was entrapped and the release of this air had a small affect on the transient response. In this case only a small amount of air was removed as noted during the bleeding process and it can be inferred that if a larger amount of air were present in the system a larger impact on the transient response would occur. Thus it is recommended that if possible air be bled from a system before transient testing is undertaken.

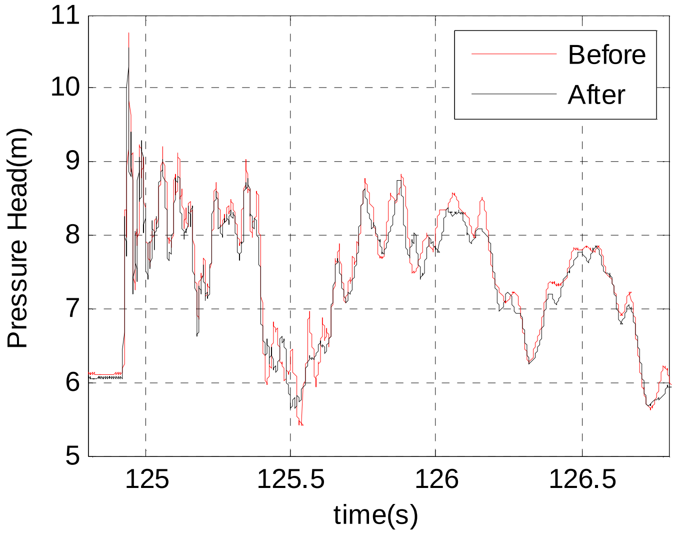


Figure 12. Transient response before and after air release

6. TRANSIENT ANALYSIS

Although the generator standpipe introduces additional reflections into the transient response the traces recorded using the torsional spring generation device are sharper in nature and hence preferable for use in transient analysis. The use of the results recorded for valve openings reduces the impact of these additional reflections and hence the transient responses from the offline valve openings using the torsional spring generation device were used as the basis of the transient analysis.

6.1 Wave speed

The high accuracy of the GPS time synchronization of the stations (accurate to within 90 nanoseconds) allows calculation of the wave speed in the pipeline through comparison of the arrival times of the induced transients. The wave speed in the 250 mm diameter DICL (ID 255 mm) section of the pipeline was calculated directly through the comparison of the arrival times within this section as approximately 1242 m/s. The calculated value was within the range expected for DICL of this diameter and wall thickness (1150-1250m/s).

The wave speed in the ABS sections could not be calculated directly as only one measurement station was located within this material. The exact location of the change in material was unknown although it was approximated at chainage 109 m. The wave speed of the ABS was determined through frequency analysis.

The system can be conceptualized as a reservoir-closed valve system and hence has a period of $4L/a$, where L is the length of the system 725.45 m and a is the wave speed. The corresponding dominant frequency of the spectrum obtained by performing a Fast Fourier Transform on the recorded data is 0.265 Hz, which is equivalent to a period of 3.77 s. Hence the effective wave speed of the system is 769 m/s.

Through use of the previously calculated wave speed for the DICL system the approximate wave speed for the ABS system was thus calculated as 275 m/s, this value is low compared with the estimated 352 m/s calculated using the standard wave speed equation,

$$a = \sqrt{\frac{K/\rho}{1 + [(K/E)(D/e)]c_1}}$$

with bulk modulus of water K = 2.2 Gpa , density of water ρ = 998.2 kg/m^2 , wall thickness e = 18.5 mm, modulus of elasticity of the pipe material E = 2.2 Gpa, and c_1 dependent on the pipe restraint. For a thick-walled elastic pipeline (D/e < 25) with expansion joints throughout its length as in this case Wylie and Streeter (1993) give c_1 by,

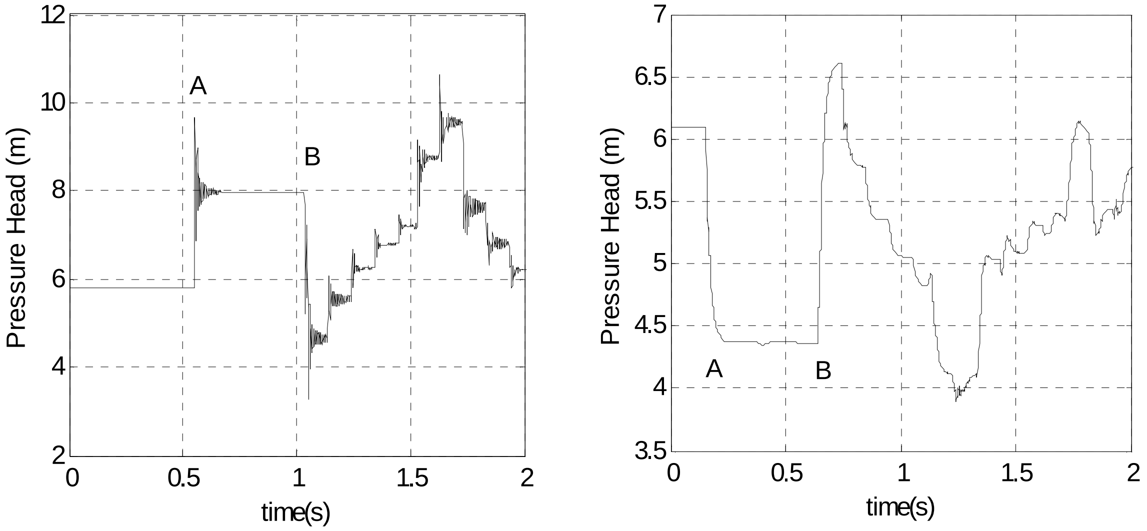
$$c_1 = \frac{2e}{D}(1+\mu) + \frac{D}{D+e}$$

where Poisson's ratio μ = 0.35.

The wave speed within the ABS and the approximate location of the change in the material were confirmed by comparison of the observed time of arrival at the measurement station located in the ABS section and the calculated arrival time. The expected arrival time based on the calculated wave speed in the ABS, the observed wave speed in the DICL and the approximated location of the material change differed by 0.1% to the observed arrival time.

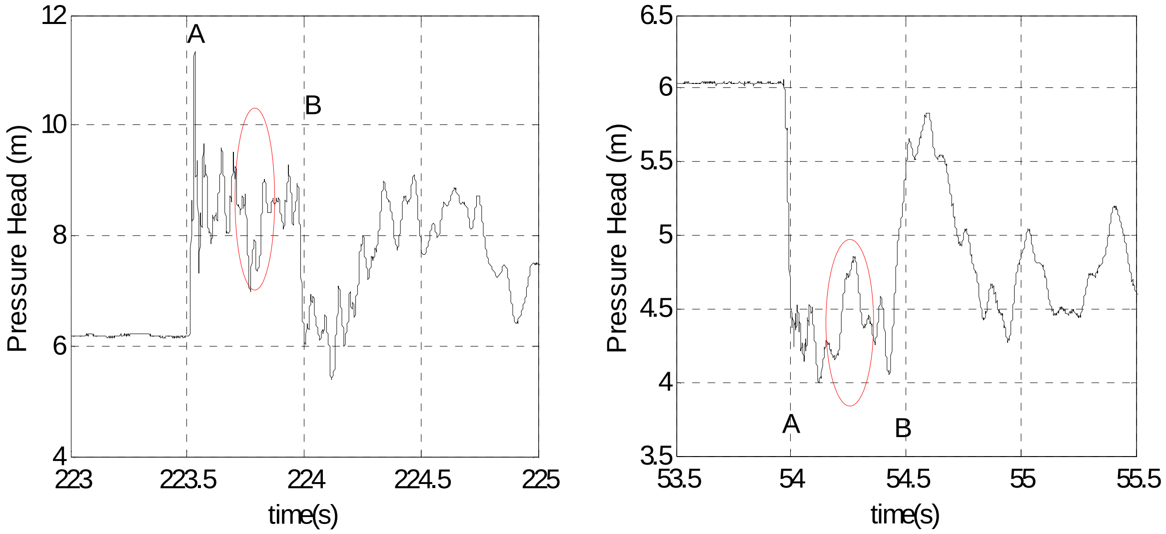
6.2 Detection of Anomalies

Preliminary modeling before the testing produced the expected traces for a closure and opening as shown in Figure 13 for generation at the given location. The recorded traces were expected to approximately follow this trend if the condition of the pipeline was good, the pipeline was constructed as per the plans provided and no significant anomalies were present. In essence the transient generator should produce a sharp rise (or drop for an opening) at A for a valve closure and remain at this level until reflections from the change in pipe material from DICL to ABS occurs at chainage 709 m occurs at B. This corresponds to travel distance of 437.4 m from the air valve situated between the scour valves and hence the trace recorded here was expected to stay relatively level for 0.35 s after the generated transient reached this point (the initial drop/rise). After this point, as shown in Figure 13 a complicated series of reflections occur due the change in pipe material at both ends of the pipeline and the closed reflux valves at the pump station. It is observed however, that none of the recorded traces exhibited this initial plateau, indicating the presence of an anomaly within the system. All of the tests recorded exhibit a large unexpected reflection between A and B as circled in Figure 14 indicating the presence of an anomaly.



(a) (b)

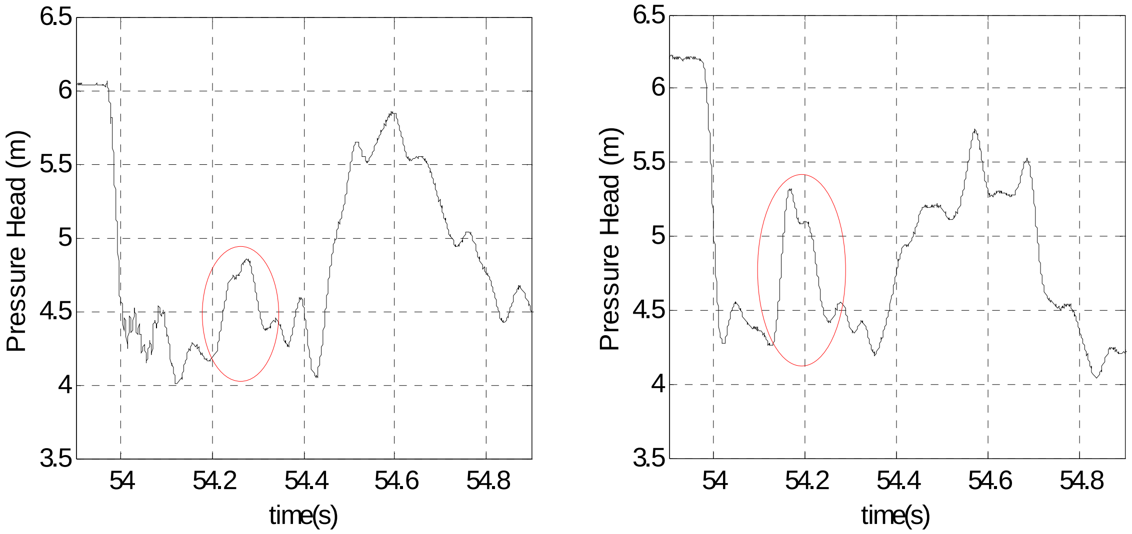
Figure 13. Expected transient response at tank side measurement location for a closure) b) opening



(a) (b)

Figure 14. Recorded transient response at tank side measurement location a) closure b) opening

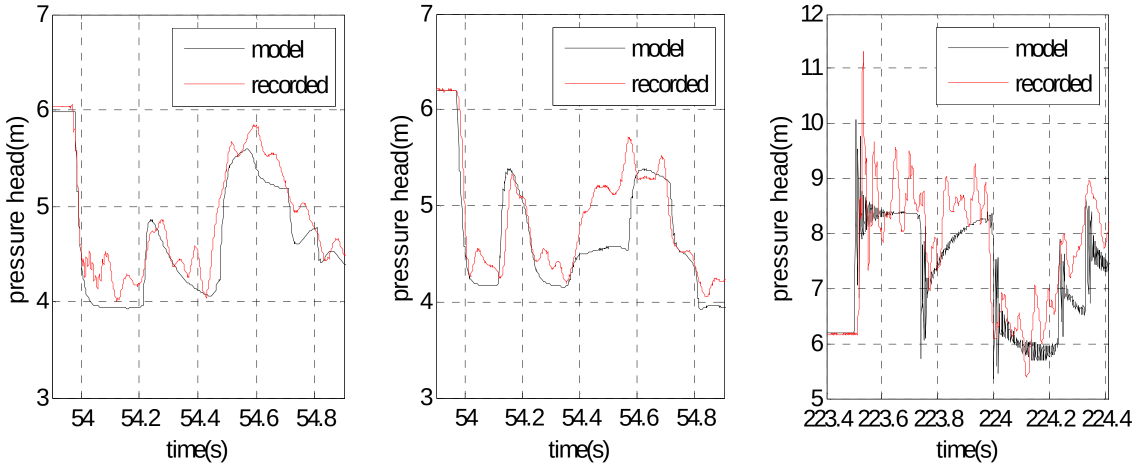
The timing of the unexpected reflection can be used to indicate its distance from the measurement locations as the speed of the transient within the system has been previously calculated. As shown in Figure 15 the reflection occurred in the response of the measurement recorded on the pump side of the generator early than in the measured response from the tank side, indicating that the reflection was from an anomaly located toward the river. Thus the approximate location of the anomaly could be calculated as 135 m from the generator in the direction of the river, that is chainage 575 m.



(a) (b)

Figure 15. Recorded transient response for measurement station a) tank side b) pump side of generator

The characteristics of the anomaly, namely the pulse-like reflection, indicate that the anomaly is not a blockage or leak as these anomalies are characterized by a step change (Stephens et al. 2004). The characteristics indicate that the anomaly is most probably an air pocket or a section of lower elasticity pipe. Figure 16 illustrates the effect of an air pocket (volume of 0.0025m^3) situated at chainage 575 m and shows the comparison of this model with three different recorded responses.



(a) (b) (c)

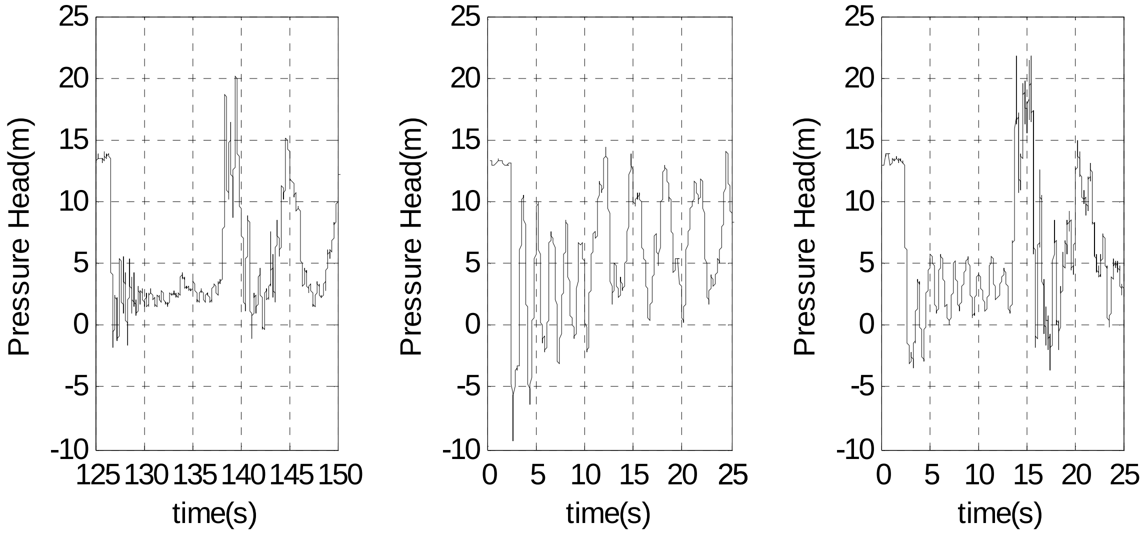
Figure 16. Comparison of air pocket model response and recorded response for a) opening measured tank side of generator location b) opening measured pump side of generator location c) measured tank side of generator location

While this one air pocket does not account for the entire variation of the recorded response with the modeled response it accounts for the largest anomaly in the transient response. There do not exist any large step changes in the response as characteristic of a leak or blockage and hence it is inferred that these anomalies are not present. The lack of leakage can also be confirmed by the steady water level in the PAC tank when pumps are offline. Any other air pockets in the system are also inferred to be significantly smaller than the air pocket modeled due to the lack of additional large pulse changes in the transient response. The slight variations in transient response may be attributed to other phenomena in the system such as the air valves and pipe joints.

The anomaly as detected by transient analysis does not account for the reduction in the capacity of the system, thus transient analysis has not identified the cause of the system problems. However the transient analysis has shown the lack of blockages (and leaks) that were thought to be the cause of the reduced discharge and thus the potential for this technique to be used for condition assessment of pipelines has been indicated.

6.3 Emergency pump shutdown

The transient response recorded from the emergency pump shutdown transient generation does not allow transient analysis as described above as the slow transient generation reduced the identifiably of reflections within the response. The presence and location of the air pocket is unable to be determined from the response due to the difference in characteristics of the response. However modeling of the scenario indicates the presence of air due to the reduction in the initial transient oscillations in the response of the furthest measuring station as shown in Figure 17. The presence of an air pocket as located by analysis of the fast transient reflections is clearly a closer match to the recorded response and confirms the previous analysis.



a) (b) (c)

Figure 17. Emergency shutdown responses at measurement location nearest to pump a) recorded b) modeled no air c) modeled with air pocket at chainage 575m

7. STEADY STATE ANALYSIS

Steady state analysis of the system using EPANET required a high overall roughness along the pipeline to match the recorded pressures and flow rates. The pipeline was found to have an average Hazen-Williams roughness coefficient (C) of 86. Figure 18 shows the approximate Hazen-Williams roughness coefficients necessary to match the head friction losses over each section of the pipeline and the discharge of 87 L/s. A minor loss of coefficient K = 20 is also incorporated to account for losses associated with the elbows and magnetic flowmeter, which is in an extended reduced section of pipe (ID 198mm), near the PAC tank. The comparison between the modeled and recorded pressures is shown in Figure 19.

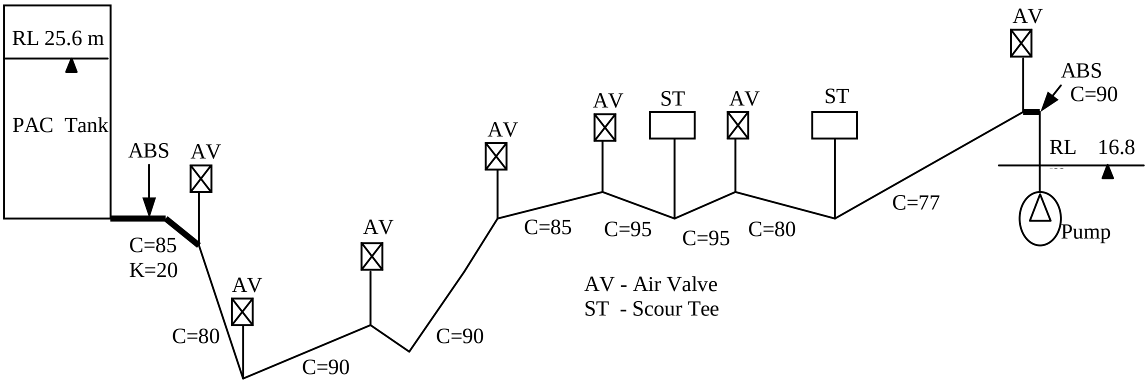


Figure 18. Schematic showing Hazen Williams roughness coefficients

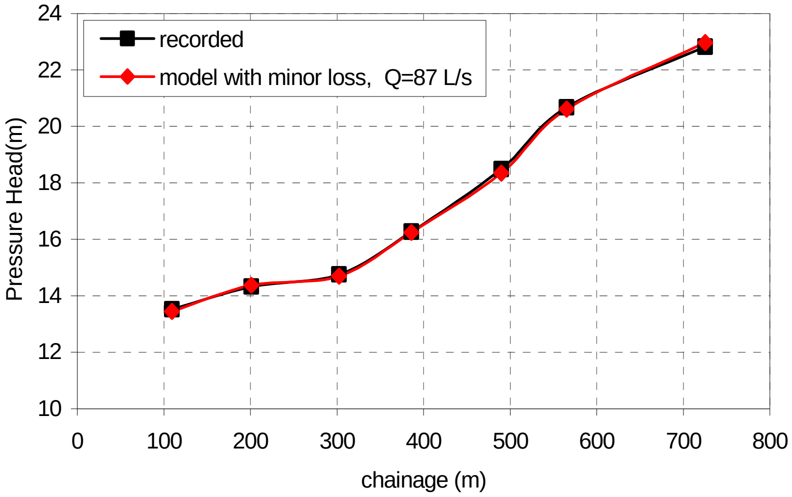


Figure 19. Comparison of recorded and modeled steady state pressures

Hazen-Williams roughness coefficients ranging from 77 to 95 are lower than expected for ABS and DICL pipe of this age, design values in the range of 130-150 and 120-140 respectively are typically used although a slight reduction due to the raw water would be necessary. The calculated C values correspond to roughness heights of over 4 mm, significantly higher than the 0.007 mm and 0.03 mm recommended for design by manufactures of ABS and DICL respectively. The roughness height is specifically high for the ABS section for which manufactures state does not need to be “over-sized” in the design stage to allow for performance losses as the smoothness and chemical resistance of the material prevents corrosion.

The usual mechanisms for increased roughness are pipeline deterioration, corrosion, tuberculation, biological growth and sedimentation. In this instance, due to the usual operating procedure of running the pumps at a low discharge, biological films may be an issue due to the low average velocities that would allow for growth of significant films. Accumulating quickly, biological films are very persistent and may require high velocities to remove them. The operational practices along with the raw water quality may be creating an environment that facilitates biological growth. Biological films have been found to increase hydraulic roughness directly and through a decrease in pipe area. Previous studies of raw water pumping mains in the surrounding area have shown that reduced flow capacity has occurred due to a thin coating of mud and biological growth. Sharp (1954) found that a thin coating of mud and biological growth in the form of a species of freshwater sponge, *ephydatia fluviatilis*, and a species of Bryozoa was responsible for an increase in friction and hence reduction in flow capacity of a raw water pumping main.

8. CONCLUSION

Transient analysis of the recorded responses indicated that no significant leak or blockage was present in the test pipeline. An air pocket was found to be present, however the impact of this fault did not account for the reduction in capacity of the pipeline. The pipeline was found to have a significantly high roughness, most probably due to the presence of a biological film. The untreated and possibly high nutrient water and the low typical pumping rates encourage the growth of a biological film in the system. The presence of a 4mm biological film layer was shown to account for the reduction in capacity experienced.

The potential use of transient techniques for condition assessment has been shown, however several limiting aspects have been identified. The first is the requirement of an adequate generation device to input a sharp step impulse into the system. The torsional spring generation device described here is an improvement on emergency pump shutdowns and hand closures in this regard however the standpipe arrangement facilities the production of higher frequency oscillations that complicate the transient response. The use of fast valve openings reduces the impact of the standpipe through damping the oscillation however further improvement of the generation device is required. It is recommended to attach the generation device as close as feasibly possible to the pipeline under investigation with a standpipe of like diameter and material if necessary.

The second limiting aspect is the ability to accurately model the given system. Knowledge of a pipeline may be incomplete, as in this case, increasing the modeling effort and time. The pipeline investigated in this paper is a single pipeline, however the composite nature and unknown elements indicate that even a simple pipeline may require a complicated analysis. A more complex pipeline consisting of several branches or possibly loops will increase the complexity of the analysis, as will varying pipe properties due to pipe section replacement. A good representation of the system is required in order to use transient analysis to identify faults in the system as the expected behavior of the fault free system is required for comparison with the recorded response.

The use of transient analysis is also limited by the current understanding of transient behavior and system response under transient conditions. As this understanding increases the potential for the technique to be used to identify faults in the system and the overall condition of the pipeline will increase. Currently the technique can only identify discrete faults such as leaks, blockages and air pockets but there is potential to extend the technique to other faults.

The analysis undertaken has shown the potential of transient analysis to assess the condition of pipelines in the field. However there are still many improvements to be made in the areas of transient modeling and field application, including the generation mechanism, as well as the analysis technique itself.

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