

Monitoring of Pressure Transients in Water Supply Networks

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Received: 16 March 2015 / Accepted: 27 October 2015 /
Published online: 5 November 2015
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Abstract Ageing water infrastructure is one of the major problems faced by water utilities around the world at present, and urgent solutions are required in order to maintain the integrity of the water supply network. In order to use pipe failure prediction models, accurate information about loads acting on these pipes is important. Water pressure (steady-state and transient) is one of the key loads that needs to be estimated accurately in order to improve the predictability of pipe failures. This paper reports the results of a pressure monitoring program, which was conducted to measure pressure fluctuations during events of pressure transients in three selected network sections in Australia. Pressure measurements were conducted in network sections which were considered as susceptible to pressure transients. Potential sources of pressure transients were identified, and high speed data loggers were installed in selected locations of each network to measure and monitor pressure transients. Pressure transients that were generated during normal operation were measured for a period of one month in each selected section. Further, some of the pressure transients were manually made to simulate the different pressures due to pump start-ups within the network. Pressure fluctuations that could potentially lead to pipe failures were measured at many locations during the monitoring program (several selected failures were reported in this article). Therefore, the effect of pressure transients must not be ignored in pipe failure prediction.

Keywords Pressure transient · Pressure monitoring · Water supply systems · Pipe failure

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1 Introduction

1.1 Background

Many water supply networks around the world are very old, and have been subjected to different levels of deterioration due to corrosion. Furthermore, due to growing demand, water supply networks are subjected to a wide range of complex operational scenarios for which the networks were not originally designed and constructed. As a result, pipes fail frequently without prior warning. This is one of the main concerns among many water utilities around the world including Australia (Rajeev et al. 2014; Chan et al. 2007). The water industry is seeking urgent solutions to predict pipe failures because failure of a critical water main has significant impacts on both the water utility and the general public.

A pipe fails when ongoing pipe deterioration enhances the stresses in pipes causing pipes to reach their capacity or due to a combination of pipe deterioration and an event of unexpected loading (i.e., pressure transient). Many factors need to be considered for accurate prediction of water pipeline failures: pipe structural properties (including material type, pipe-soil interaction, and quality of installation), internal loads (steady-state pressure, transient pressure), external loads (soil overburden, traffic loads, frost loads), third-party interference, and material deterioration due to the external and internal chemical bio-chemical and electrochemical environment (Rajani and Kleiner 2001; Rajani and Makar 2000). Pipe network asset management tools were extensively used to make decisions on timely renew pipes prior to catastrophic failures (Large et al. 2014). In order to use such models, accurate information about the factors stated above is essential.

Internal water pressure can be sub-categorized as normal operational pressure and transient pressure. Estimation of steady-state pressure across an entire pipe network is relatively easy, since many water utilities have steady-state hydraulic models and pressure gauges installed covering the entire network. However, an estimation of the magnitude of pressure transients is particularly difficult, as the magnitude and propagation of a transient pressure wave will depend on additional factors including the rate of change of flow, the hydraulic characteristics of system components, pipe material, pipe geometry (wall thickness and diameter), and pipe wall friction (Wood et al. 2005), which are often relatively difficult to obtain accurately. Therefore, information on the magnitude of pressure transients is often neglected or conservatively assumed during pipe failure prediction due to lack of knowledge about pressure transients. However, it is pointed out that pressure transients can be a major contributor to pipe failures. The main thrust that this study undertook as part of the major project of Advanced Condition Assessment and Pipe Failure prediction project (www.criticalpipes.com) is based on the anecdotal evidence that pressure transients led to increased pipe failures. However, there is not much published material that reports detailed studies on this issue. The current paper therefore can be considered to fill the current research gap (Rajani and Abdel-Akher 2012; Rajeev et al. 2014). In addition, this is a unique opportunity to report and share monitored transient pressure changes during events of pressure transients (i.e., pump operation, valve operation, and vapour cavity collapse).

1.2 Effect of Pressure Transient on Pipe Failures

A pressure transient is a transitional phase between two steady states that occurs when a disturbance to the mean flow condition is introduced. The most common types of disturbances

are pump start/shutdown, valve open/closure, and a change in transmission conditions (e.g., main break or line freezing). In addition, when the internal pressure reaches the vacuum pressure in a pipe (below zero), vapour cavities can form inside the pipes. When the vapour cavities collapse during pressure recovery, large pressure fluctuations can occur (Collins et al. 2012; Jung et al. 2009; Kottmann 1995). A recent study conducted by Haghghi (2015) showed that fluctuations in water consumptions can also led to severe pressure transients. During a pressure transient event, most of the kinetic energy in the water mass is converted into pressure energy due to a sudden change of flow velocity. As a result, a travelling pressure wave is generated. The pressure wave will propagate at a speed of approximately 1000 m/s in rigid pipes, depending on the elasticity of water, the elastic properties of the pipeline, and other pipe properties (e.g., pipe material, wall thickness, and diameter), into the pipe network causing objectionable pressures until the energy in the travelling high pressure front is dissipated by means of acoustic, friction, vibration or other energy dissipation mechanisms. When all the energy in the wave is dissipated, a new steady-state condition will be established in the water supply network. A conservative estimation of the magnitude of a pressure transient can be obtained by using the Joukowsky formula (Wylie et al. 1993). According to the Joukowsky formula, every 0.3 m/s of velocity change can result in approximately 30 m pressure rise in metallic pipes.

1.3 Review of past Literature

Several research studies have measured the magnitude of pressure transients using high-speed pressure measuring equipment (e.g., Ebacher et al. 2010, Fleming et al. 2006, Friedman et al. 2004). During the study conducted by Fleming et al. (2006), pressure monitoring, and pressure transients modelling was examined in 16 selected network sections. A range of water network configurations were selected to examine the influence of system characteristics for occurrence of low/negative pressure. It was found that small systems (<38 million litres per day system delivery), systems fed by ground water sources, and the presence of a few floating storage facilitates were the main factors that contributed to significant pressure fluctuations. Even though the aim of the study was to find susceptible locations of negative pressure, the maximum measured transient pressure during pressure monitoring was provided. In one of the systems that pressure was monitored by Fleming et al. (2006), pressure rose to 729 kPa from the initial steady-state pressure of 429 kPa. The exact cause of this pressure rise was not clearly stated in the report produced by Fleming et al. (2006) (i.e., it could have either been caused by pump start-up or a sudden change in water demand condition). In another pump operational event monitored in Fleming et al.'s study, pressure rose to 587 kPa from a steady-state pressure of 348 kPa.

Friedman et al. (2004) conducted a large-scale monitoring program to verify the occurrence of low and negative pressure transients in real distribution systems. The study was conducted on eight water utilities, and it examined several different sources of pressure transients, such as pump operations, high demand situations, pipe breaks, and valve operations. The study reported significant pressure fluctuations (high, and low/negative) when pumps were turned on or off intentionally or unintentionally. Negative pressure was measured for 13 cases, and the cause of 12 of the negative pressure measurements were either intentional or unintentional pump stops. According to the report, a start-up of a pump that had a capacity of 76 million litres per day produced a 206 kPa pressure rise. In addition, a firefighting operation conducted by a local fire department using a pumper truck created an approximately 480 kPa pressure

rise. However, events such as valve operation, the action of a pressure-reducing valve, and a system flushing operation did not cause significantly high or low pressure transients during the study. Ebacher et al. (2010) conducted pressure monitoring in a large water distribution system to investigate how accurately a carefully calibrated numerical model can simulate field measured of low and negative pressure transients. Ebacher et al. measured three low pressure events (no high pressure events were reported) that included a minimum pressure of 36 kPa from an operating pressure of 442 kPa during a power failure at the pump station.

However, none of these studies attempted to correlate measured pressure transients in relation to pipe failure prediction. The main focus of each study was to investigate the susceptibility of the water supply networks to negative pressures during pressure transient events. In addition, pressure transient monitoring data obtained using high frequency data loggers was used to obtain possible negative pressure data that can be used to determine leaks, illegal branches, partial blockages, and partially closed valves (Christodoulou et al. 2010; Meniconi et al. 2011).

2 Objectives

Due to the complexity of operational scenarios and the size of water supply networks today, it is impossible to avoid pressure transients. Therefore, it is necessary to assess and quantify the possible magnitudes and locations of pressure transients in order to improve pipe failure prediction. One of the best ways to obtain this information is by measuring the pressure transients in the field using high-speed pressure monitoring equipment. Several research objectives were included in the present study. The main objective was to measure the magnitudes of pressure transients that occur in selected network sections due to various operational scenarios and to understand the behaviour of pressure transients (influence zone and dissipations mechanisms) within water supply networks. The specific aim of pressure monitoring in section A, and B was to examine the likely pressure rise that caused past pipe failures. The specific aim of pressure monitoring at section C was to investigate the occurrence of negative pressure, and subsequent pressure rise due to vapour cavity collapse.

3 Network Details

Sections A and B are sub-sections of pressure zones of water utility 1's pipe network. Water is supplied from a major zone and pumped into both sections via separate main pump stations. Section C is a small pressure zone from the second water utility (utility 2) involved in the monitoring program. Figure 1 shows all three sections (A, B, C) monitored for pressure transients, and the locations of monitoring sites. The pump stations are highlighted as circles, and water reservoirs as triangles in Fig. 1. Further information about network sections can be found in Table 1.

4 Methodology

The focus of the monitoring program was to capture transients generated due to the operation of pumps, valves, and pressure regulating valves (PRV). Monitoring locations were selected on

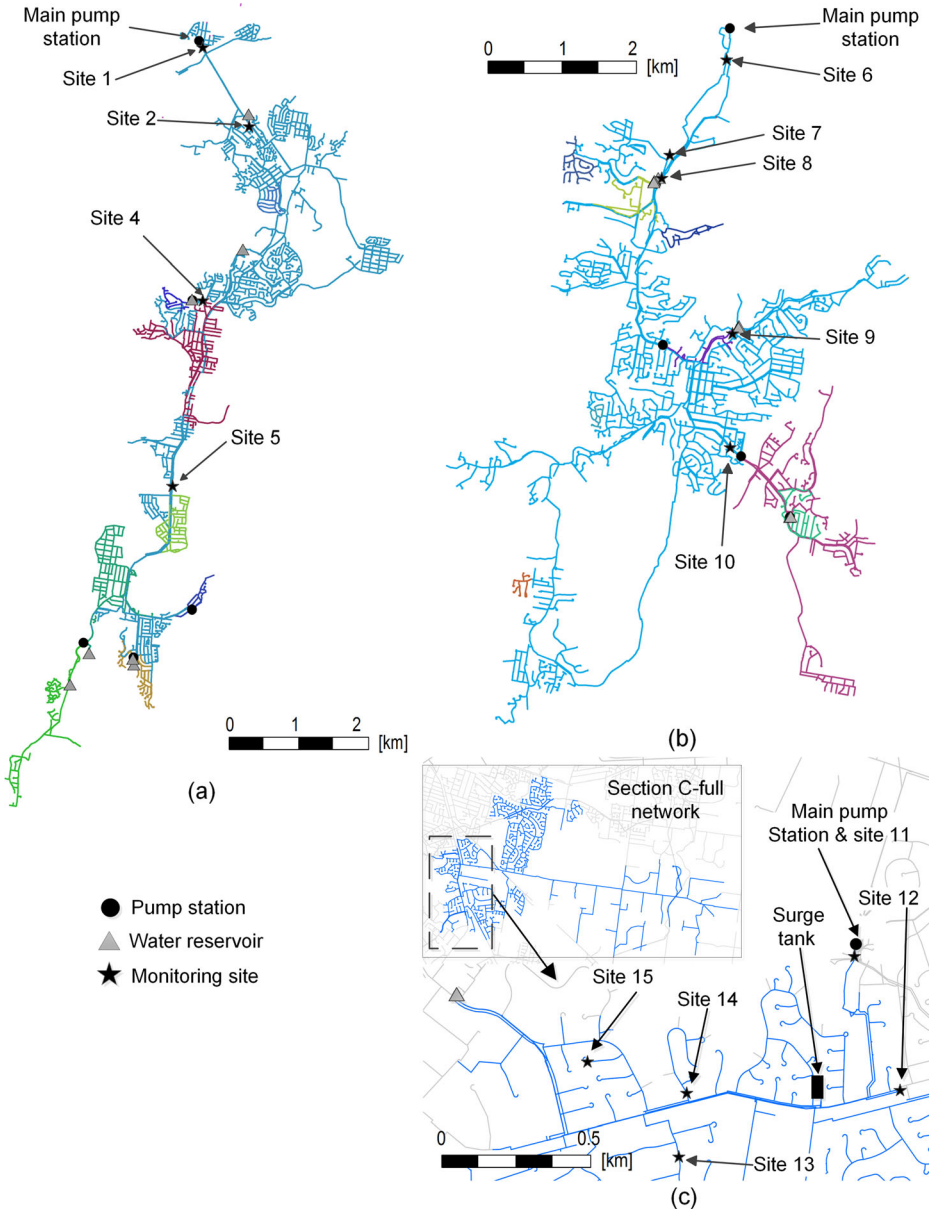


Fig. 1 Schematic of network sections involved in pressure monitoring program: **a** section A, **b** section B, and **c** section C

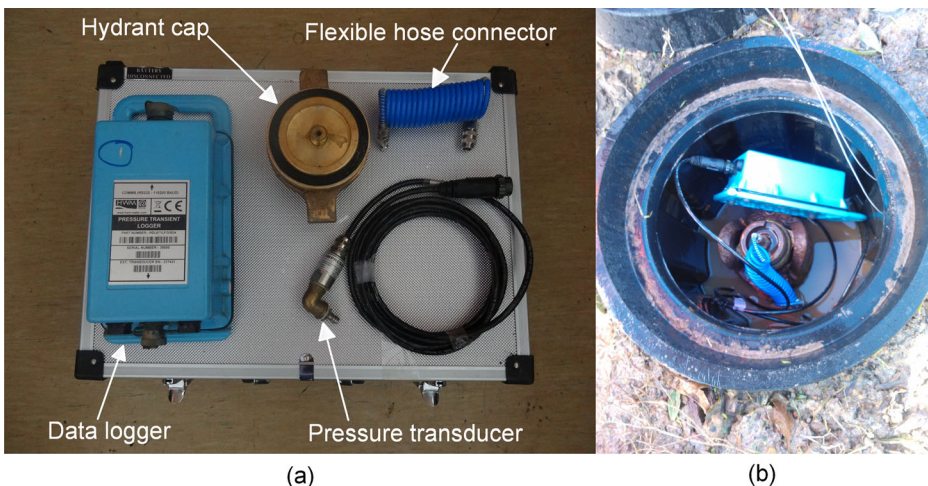
the basis of the operational experience of the water utility engineers and the results of preliminary pressure transient hydraulic modelling. In order to measure pressure transients in each network section, four to five high-speed data loggers were installed in each section. RADCOM pressure transient data loggers, developed by Halma Water Management (see Fig. 2a), were used to capture transients accurately. This particular pressure transient data logger has been used extensively in previous research work to measure pressure transients in

Table 1 Pipe network information

Type of Information	Section A	Section B	Section C
Total pipe length	332 km	257 km	96 km
Pipe material types ^a	CICL (61 %), DICL (17 %), PVC (15 %), and Other (7 %)	CICL (71 %), DICL (15 %), PVC (10 %), and Other (4 %)	PVC (68 %), MICL (6.5 %), DICL (5 %), AC (19 %), and other (1.5 %)
Diameter range	25 mm to 630 mm	25 mm to 750 mm	50 mm to 900 mm
Proportion of large diameter pipes(>300 mm)	12 %	11 %	23 %
Main material/materials in trunk main	CICL	CICL	AC, MICL
Total pumping capacity of main pump station	82 million litres per day	38 million litres per day	15 million litres per day
Storage capacity	20.7 million litres	20.4 million litres	unknown
Number of pressure zones	8	7	3

^a *CICL* cast iron cement-lined, *DICL* ductile iron cement lined, *MICL* mild steel cement lined

water supply networks (e.g., Ebacher et al. 2010, Fleming et al. 2006, Friedman et al. 2004). All data loggers and pressure transducers that were used to obtain measurements were factory calibrated. Prior to installment in the field, all data loggers, and pressure transducers were checked in the laboratory for accuracy and precision of measurements. Conventional pressure monitoring equipment is not suitable for the measurement of pressure transients because the wave propagation speed of a pressure transient in rigid pipes is close to 1000 m/s. The data logger used can record up to 25 readings per second and, it is robust, waterproof, submersible and equipped with a long-life battery, which enables the data logger to log continuously for long periods of time in remote locations. The data logger is equipped with one input for an external pressure transducer and one output to download data into a personal computer with the

**Fig. 2** a Pressure monitoring kit and b Equipment installed at a fire hydrant

aid of Radwin software. In this particular field work, the data logger was often connected to fire hydrants using a hydrant cap and flexi hose with a snap connection (Fig. 2b). In a few sites only, the data logger was installed upstream of the pressure regulating valve and directly on the trunk main using the small outlet taps. The frequency of the data logger was set to 20 readings per second with a tolerance setting of ± 5 kPa in this study. The tolerance setting was used to enable the data logger to save a longer recording duration without clearing the memory of the data loggers. Pressure was monitored for a period of approximately one month in each selected section. In addition, two sets of pressure transients (pump start-ups) were created in section A (one in the morning when water demand was high and another at night when water demand was low).

5 Results of the Monitoring Program

Information about each site, and summaries of maximum, minimum, and typical steady-state pressures measured at each site are given in Table 2, and the important measurements in each section is discussed in the following section.

5.1 Section A

In section A, two different types of pressure transient monitoring work were carried out. First, two sets of pressure transient events were manually created: one in the morning and the other one at night using a pump at the main pump station. Then, the loggers were kept for a period of three weeks at the same monitoring locations to measure pressure transients during normal operation.

The first series of pressure transients (event set 1) were created in the morning (starting from 8:15 AM on June 5 2013) and the second series (event set 2) were created at night (starting from 2:10 AM on 6 June 2013). According to the system's diurnal curve provided by water utility 1, the global demand factor during event set 1 (1.2) was considerably higher than that of set 2 (0.25). A single pump in the main pump station was started up (the pump motor speeded up to its full speed linearly) with four different start-up times (5 s, 10 s, 20 s, and 30 s). One of the 5 s pump start-ups created during these events generated a maximum pressure rise of 270 kPa at site 1 and 116 kPa at site 2. Increasing pump start-up time to 10s, 20s, and 30s significantly reduced the magnitude of the pressure transients generated. Although at site 1 similar magnitude and wave patterns were recorded for both event set 1 and 2, no sharp pressure pulses were recorded at site 2 during event set 2 compared to event set 1. However, a considerable rise of steady-state pressure was recorded at site 2 for event set 2 (see Figs. 3 and 4). Sites 4 and 5 (further downstream of sites 1 and 2) recorded no significant pressure transients during event set 1. A significant steady-state pressure rise was measured at sites 4 and 5 during event set 2, as shown in Fig. 4.

In section A, the closure of an automated valve (butterfly type), which was used to control the water level in the reservoir, generated a moderate magnitude of pressure transients at site 4 as shown in Fig. 6. Site 4 was located 300 m upstream from the control valve, on a fire hydrant connected to a 375 mm trunk main. The maximum pressure recorded at site 4 was 535 kPa, which is about a 182 kPa rise above steady-state pressure. No significant pressure fluctuations were observed at site 5 due to the valve spindle movement of the pressure regulating valve.

Table 2 Information about pressure monitoring sites and a summary of pressure monitoring program

Site number	Site information	Installation	Maximum pressure/kPa	Steady-state pressure before maximum pressure./kPa	Minimum pressure/kPa
Site 1	Section A: Main pump station	Hydrant	514	234	191
Site 2	Section A: 2.5 km downstream main pump station	Hydrant	252	136	39
Site 4	Section A: Upstream of reservoir 3 automated inlet valve	Hydrant	535	353	313
Site 5	Section A: Upstream of pressure reducing valve	PRV	1012	875	667
Site 6	Section B: 0.5 km downstream of main pump station	Hydrant	1486	1206	735
Site 7	Section B: 2.7 km downstream from main pump station	Hydrant	396	243	99
Site 8	Section B: 3.2 km downstream from main pump station	Hydrant	132	86	56
Site 9	Section B: Upstream of automated inlet valve	Hydrant	209	135	95
Site 10	Section B: Upstream of automated inlet valve	Hydrant	1079	474	400
Site 11	Section C: Main pump station	Outlet tap	1186	N/A ^a	-38
Site 12	Section C: Upstream of pressure reducing valve, 0.8 km from main pump station	PRV	646	466	190
Site 13	Section C: 1.8 km downstream from main pump station	Hydrant	621	451	134
Site 14	Section C: 2.2 km downstream from main pump	Hydrant	503	356	54
Site 15	Section C: 2.5 km downstream from main pump station, highest location of the system	Hydrant	704	255	-106

^a As logger was installed between pump and pump control valve it did not measure any transients. It measured only steady-state pressure head provided by pump operation

5.2 Section B

The purpose of measuring pressure at monitoring sites 6, 7 and 8 in section B was to capture the pressure transients generated at the main pump station. Significant pressure transients were observed during pressure monitoring when a pump was turned on and off at the main pump station. A single pump start-up event generated a pressure reading as high as 1489 kPa (rise of 274 kPa from the steady-state) at site 6. Although it is less important with regard to pipe failure, it should be noted that every pump shut-down event caused pressure to drop significantly (drop of 480 kPa). As shown in Fig. 5, the magnitude of the pressure transient measured close to the main pump station was reduced significantly (more than 50 % reduction) when the transient reached site 7 (2.2 km downstream). Furthermore, no pressure fluctuations were measured at site 8 due to pump operation. This observation is consistent with the study

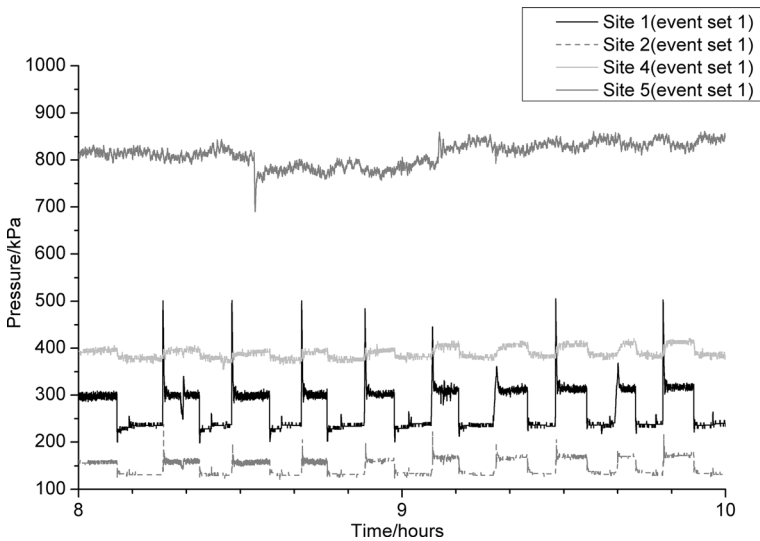


Fig. 3 Pressure transients generated during events created at section A main pump station: Event set 1

conducted by Fleming et al. (2006), in which the authors concluded that the presence/absence of water storage reservoirs can influence the magnitude of pressure transients.

Measurements at site 10 recorded several significant pressure transients due to the closure of an automated inlet valve and the combined action of the same valve and booster pumps. As shown in Fig. 6, during the closure of a butterfly valve controlling flow to a reservoir located a few kilometers downstream of site 10, a pressure gradient of approximately 100 kPa was generated. However, on three different days, very high pressure rises were measured. In one event, the pressure rose to a maximum of 1079 kPa from the steady-state value of 474 kPa on 18/06/2013 (see Fig. 7).

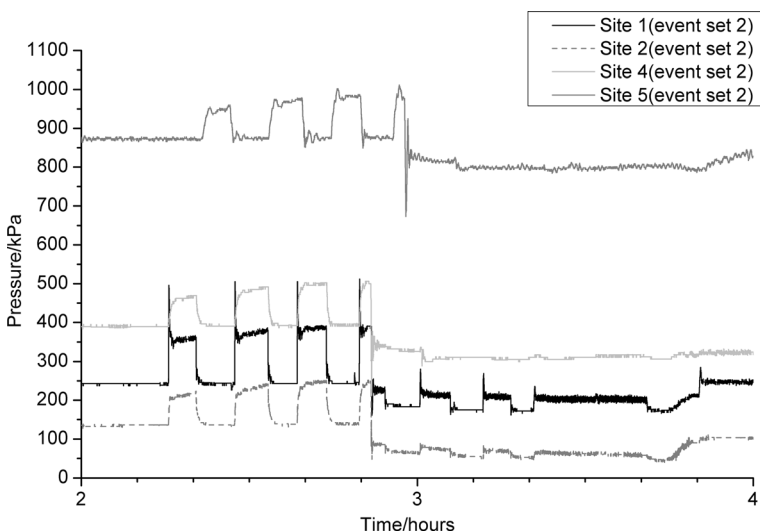


Fig. 4 Pressure transients generated during events created at section A main pump station: Event set 2

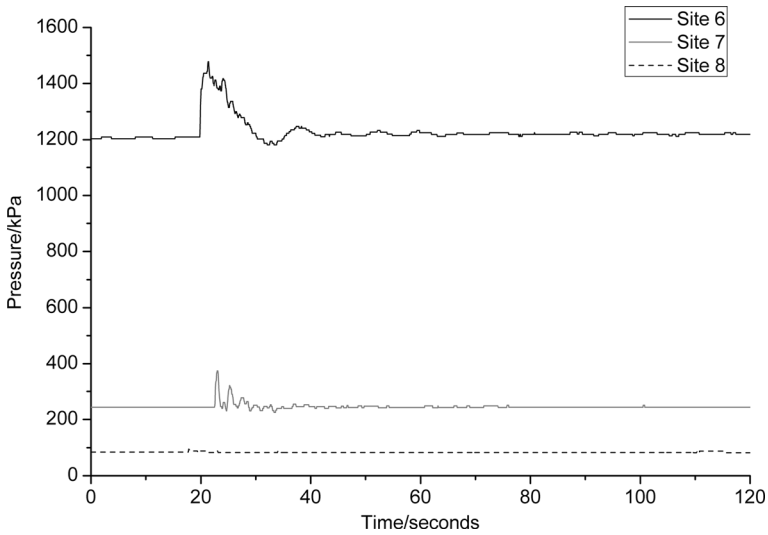


Fig. 5 Pressure transients generated during pump start-up at section B measured at three different sites located on the same trunk main

5.3 Section C

In section C, outflow from the main pump station is controlled by a control valve immediately on the downstream side of the pumps. After the pump is switched on, the control valve is opened slowly to avoid the generation of catastrophic pressure transients. A logger was installed between the pump and the valve used to control flow at the pump station (site 11). Therefore, site 11 did not record any significant transients, but the logger measured the pressure head provided by the pump during routine operation. However, site 12, located 800 m downstream from the main pump station, recorded approximately 180 kPa pressure

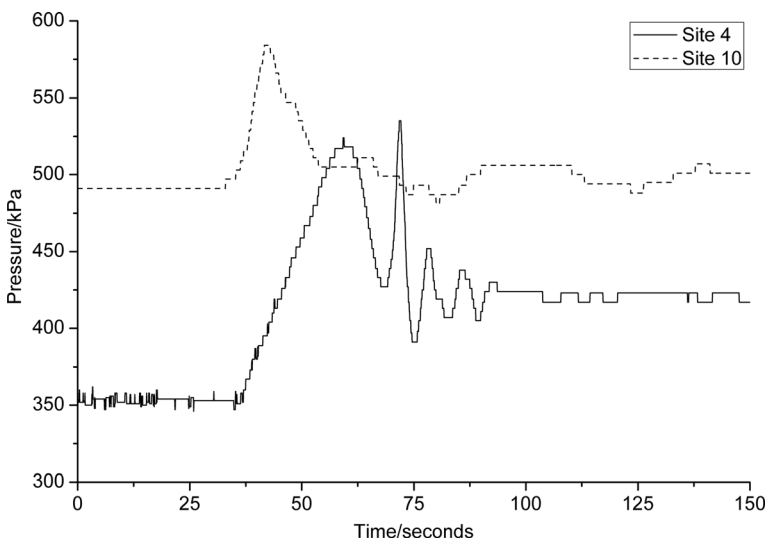


Fig. 6 Pressure transients generated due to valve operation

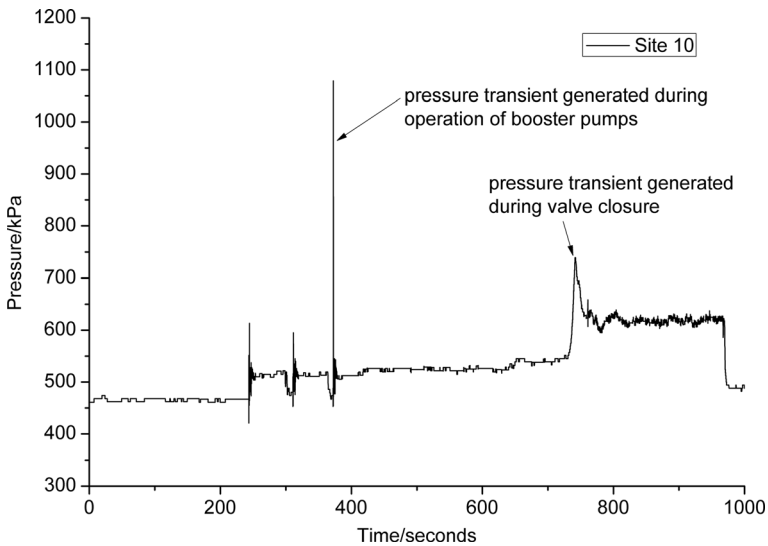


Fig. 7 Maximum pressure transient generated during monitoring program (site10)

transients and the magnitude of pressure rise was reduced before the pressure wave reached sites 13, 14 and 15 during this pump start-up event. Every pump shutdown event generated in section C showed significant pressure drops at all sites monitored during the period of pressure monitoring. At site 15, on 26 out of 33 days of monitoring the pressure reached negative values. The cause of the negative pressure was due to the pump stopping at the main pump station. The magnitude of the negative pressure transient generated was sufficiently high enough to lower the pressure to negative 100 kPa. At site 15, pressure was raised to 700 kPa when pressure recovered (vapour cavity collapse) after the low pressure event, which was approximately a 450 kPa pressure rise above steady - state pressure (see Fig. 8).

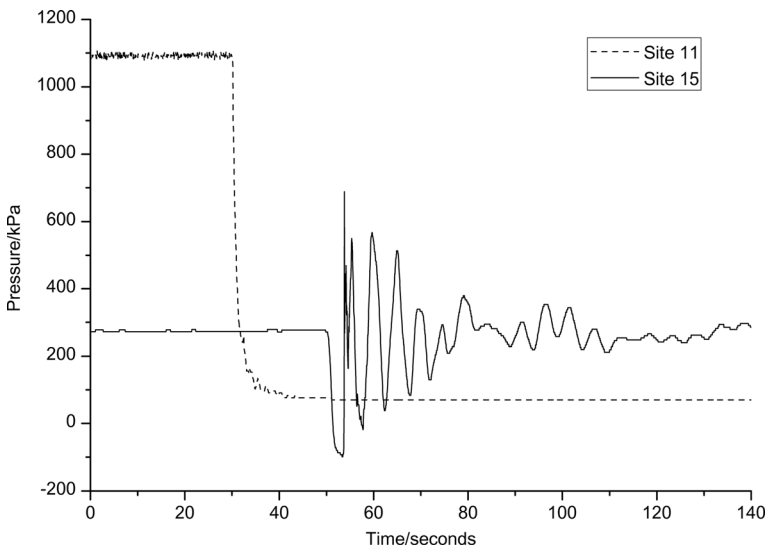


Fig. 8 Occurrence of negative pressure and cavity collapse at site 15

6 Discussion

Pressure transients are one of the main factors contributing to pipe failures; however, limited research work has been conducted on studying the causes of pressure transients, and their relation to pipe failures. Some researchers conservatively estimated the magnitude of pressure rise when calculating stresses on pipe to predict pipe failures (Rajani and Abdel-Akher 2012). On the contrary, the results of the pressure monitoring program conducted in this study showed that moderate to catastrophic pressure transients are possible in water supply networks during routine operation. A comparison of the supervisory control and data acquisition (SCADA) data and the time of pipe failure indicated that every failure that occurred in section A and B shown in Table 3 was associated with a system operational event such as pump start-up. Therefore the trigger event of all failures listed in Table 3 can be assumed as pressure transients, and the likely magnitude of each trigger event is listed in Table 3, which were based on monitoring conducted in this study (in most cases the pressure rise that produced the failure might be less than the given pressure in Table 3). The failure mode of many failed pipes are longitudinal fracture that indicates pressure driven failure (with the presence of corrosion). Therefore, a detailed understanding of location, magnitude, and the root of pressure transients in any water pipe networks are essential for failure prevention.

All measured pressure transients in this study can be categorized into three types: intentional, unintentional, and post resultant transients due to intentional or unintentional events based on measurements. The pressure transients shown in Figs. 3, 5, and 6 that occurred in section A, and B can be categorised as intentional pressure transients (planned events). However, pressure transients shown in Figs. 4, and 7 are unintentional because water utility 1 did not expect those pressure transients to occur in their pipe network. Unintentional pressure transients are caused by series of actions taken by an automatic network operational system to satisfy pre-defined conditions (e.g. to control reservoir levels). The likely reasons for a high pressure rise during event set 2 (Fig. 4) at all monitoring sites might be as follows: (1) The resultant friction head developed was high due to the automatic closure of some of the inlet valves in the water reservoirs close to the pump station that controls the reservoir water level (i.e. after closure of the inlet valves, the pump needs to operate at a higher head to send the water to the far end reservoirs), (2) During event set 2 there were fewer energy dissipation mechanisms present in the field, since event set 2 was performed during a period when water consumption and pipe flows were significantly low compared to event set 1.

In order to understand the cause of the very high pressure rise (unintentional event) shown in Fig. 7, real-time network operational data from the SCADA system for this particular day were obtained from water utility 1 and analysed. Figure 7 shows several pressure transients generated during the period from 10:50 AM to 11:07 AM on June 18 2013 at site 10. The pressure transients were created by the operation of the automated inlet valve and two booster pumps which were automatically controlled by the water level of the downstream reservoir. The automated inlet valve was set to open when the reservoir water level drops to 70 % of the maximum reservoir water level, and the valve was set to close when the reservoir water level reached 90 % of the maximum reservoir water level. When the reservoir water level drops to 55 % of the reservoir maximum water level, pump no. 1 in the booster pump station starts, and when the level drops to 35 % of the maximum water level, pump no. 2 starts to pump water to the reservoir. Pump no. 1 stops when the reservoir level reaches 85 % and pump no. 2 stops when the reservoir level reaches 80 % of maximum water level. The data obtained from SCADA showed that, although during this particular day the reservoir water level never

Table 3 Past pipe failures associated with pressure transients occurred in section A, and B

No.	Pipe material	Pipe diameter/ mm	Pipe age/ years	Failure mode	Closed monitoring site	Typical pressure rise at closest monitoring site/kPa	Time of failure	Cause ^d (according to failure inspection report)
A.	C/CL	300	57	Spiral fracture	1.8 km DS from Site 2, (section A)	116 ^a	2:52 AM	Pressure transient, and corrosion
B.	C/CL	500	41	Longitudinal split	0.8 m US from site 6, section B	153-280 ^b	10:50 AM	Pressure transient
C.	C/CL	500	47	Longitudinal split	1.85 km DS from Site 2, section A	70	6:04 PM	Pressure transient, and corrosion
D.	C/CL	250	55	Spiral fracture	0.76 km DS from Site 5, section A	137	5:35 AM	Pressure transient
E.	C/CL	375	55	Longitudinal split	2.1 km DS from Site 4, section A	182	8:03 AM	Pressure transient, and corrosion
F.	C/CL	375	55	Longitudinal split	2.2 km DS from Site 4, section A	182	8:03 AM	Pressure transient, and corrosion
G.	C/CL	150	46	Longitudinal split	2.2 km DS form Site 9, section B	103 ^c	6:51 AM	Pressure transient, and corrosion

^a Pressure was monitored when the failure actually occurred in the field

^b Failure occurred pipeline between site 6 and 7. Therefore, pressure rise may be between maximum pressure of each site

^c Pressure rise was provided based on typical pressure rise that occurred during period of pressure monitoring

^d Cause of failure was identified comparing time of pipe failure, and SCADA data

dropped below 65 % of the maximum water level, each pump at the booster pump station started two times. The first three pressure spikes occurred due to the booster pump operational events. The very high pressure spike observed in the third event resulted from two pump start-ups and one shut-down event, which occurred at the booster pump station within a period of 32 s. The fourth pressure spike was a direct result of the closure of the automated inlet valve (Fig. 7). Note that the fourth pressure spike event (a valve closure) showed a higher magnitude of pressure rise than the typical pressure transients at site 10 (see Fig. 6 for typical pressure transient due valve closure at site 10). Similar high pressure valve closures events (compare to a typical pressure rise shown in Fig. 7) were measured on June 11 2013, June 16 2013, and June 30 2013. Although the controls were set otherwise, the pump ran when the automated inlet valve was closing. This explains the reason (high flow rate) for the higher pressure rise due to the closure of the automated inlet valve on June 18 2013. In contrast to daily events (intentional events), unintentional pressure rises, such as mentioned above, are the most vulnerable for pipe failures as pipelines are not used to such rapid pressure changes. The pipe failure that occurred during the 4th 5 s pump event (after 13th pump event from the beginning of pump events) in event set 2 in section A provides an excellent example for the severity of unintentional pressure transients. The failure site was located between sites 2 and 4, approximately 750 m downstream from site 2.

Some of the common post resultant transients are vapour cavity collapse, and pressure transients after pipe bursts. The pressure transient event shown in Fig. 8 is an example of a pressure transient caused by vapour cavity collapse. The magnitude of the negative pressure transient generated during pump shut-down was sufficiently high enough to lower the pressure to negative pressure at site 15, which operated at a relatively low steady-state pressure (about 250 kPa) compared with all other monitoring sites. The pressure reached negative 100 kPa and stayed constant until pressure recovered when water entered the pipeline from the reservoir at the other end of the system (150 m elevation). During a period of negative pressure, all gas within the water is slowly released and the water starts to evaporate. When the pressure recovers, the vapour cavity can collapse creating catastrophic pressure transients. This was the reason for the observation of the very high pressure spikes at site 15 immediately after pressure went to negative values (see Fig. 8).

7 Conclusions

In this study, three different types of pressure transient events were identified (i.e. intentional, unintentional, and post resultant transients due to intentional or unintentional events). The generated transient pressure waves dissipated rapidly as they propagated along the trunk mains. In most cases, approximately 40 % to 50 % reduction of pressure was observed within a distance of 2 - 3 km from the event origin when pressure transients occurred in comparatively high demand periods. However, pressure transient dissipation may depend on the pipe network configuration, and other energy dissipation mechanisms available on the individual network, which can dissipate extra energy during a pressure transient event. Furthermore, a significant steady-state pressure rise occurred when the pumps were in operation during significantly low system demand. In addition, vapour cavities that occurred after negative pressure generated a catastrophic pressure rise upon collapsing of vapour cavities, which took place during pressure recovery. The pipe failures that occurred due to pressure transients (magnitude is estimated based on measurements) indicted that a moderate magnitude of pressure transients (50–200

kPa) are capable of failing deteriorated pipes in the field. Evidence was found through pipe failure pressure variations that intentional or unintentional cyclic pressure transients could also lead to a fatigue failure mechanism in deteriorated water pipelines.

Acknowledgments This publication is an outcome of the Advanced Condition Assessment and Pipe Failure Prediction Project funded by Sydney Water Corporation, Water Research Foundation (USA), Melbourne Water, Water Corporation, UK Water Industry Research Ltd., South Australia Water Corporation, South East Water, Hunter Water Corporation, and City West Water. The research partners are Monash University (lead), University of Technology Sydney and University of Newcastle. Author would like to acknowledge Yan Han, Matthew Drafter, Mike Guo, Valid Sourghali, and Duncan Sinclair for their valuable support in field work.

Compliance with Ethical Standards

Funding This study was funded by Advanced Condition Assessment and Pipe Failure Prediction Project.

Conflict of Interest The author(s) declare that they have no competing interests.

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