The Fernhill Rising Main Bursts – What Went Wrong and What Was Done About It?

Uwe Kaeding[1], Steven Whichelo[1], Martin Ellis[2], Stuart Pile[1], Gerry Essenberg[2], Derek Falvey[1], John Mills-Ramage[1]

1. United Water International

2. Queenstown Lakes District Council

ABSTRACT

In July and August 2009 a rising main in the Fernhill water system in Queenstown burst on three separate occasions. The bursts resulted in significant damage due to washout of tracks and scouring around a reservoir, with significant costs being incurred for repairs of both private and council-owned infrastructure.

An investigation to determine the likely causes of these three bursts indicated two issues were of concern: the condition of the rising main itself, including the material it was made of and its bedding; and the absence of automated shut-off of the pumps and upstream reservoir in the case of a burst. The results of a pressure analysis of the rising main indicated operational pressures nearly equal to the pressure rating of the pipe. In addition a surge analysis indicated the potential for negative surge pressures in the area of the rising main where the majority of the bursts occurred. This could result in collapse of the main.

The Queenstown Lakes District Council has put in place a number of upgrades to the system, including the installation of automatic burst control valves on both rising mains and automatic shut-off of the pump station in the case of a burst. These upgrades were tested when a fourth burst of the rising main occurred shortly after commissioning.

KEYWORDS

Rising main, burst, uPVC , burst control valve, transient pressure analysis

1 THE FERNHILL WATER SUPPLY SYSTEM

The water supply to the town of Queenstown is sourced from Lake Wakatipu and is pumped from the lake at two water intakes: the main pump station at Two Mile and a second station on the Kelvin Heights peninsula. Water is chlorinated at both pump stations prior to entering supply.

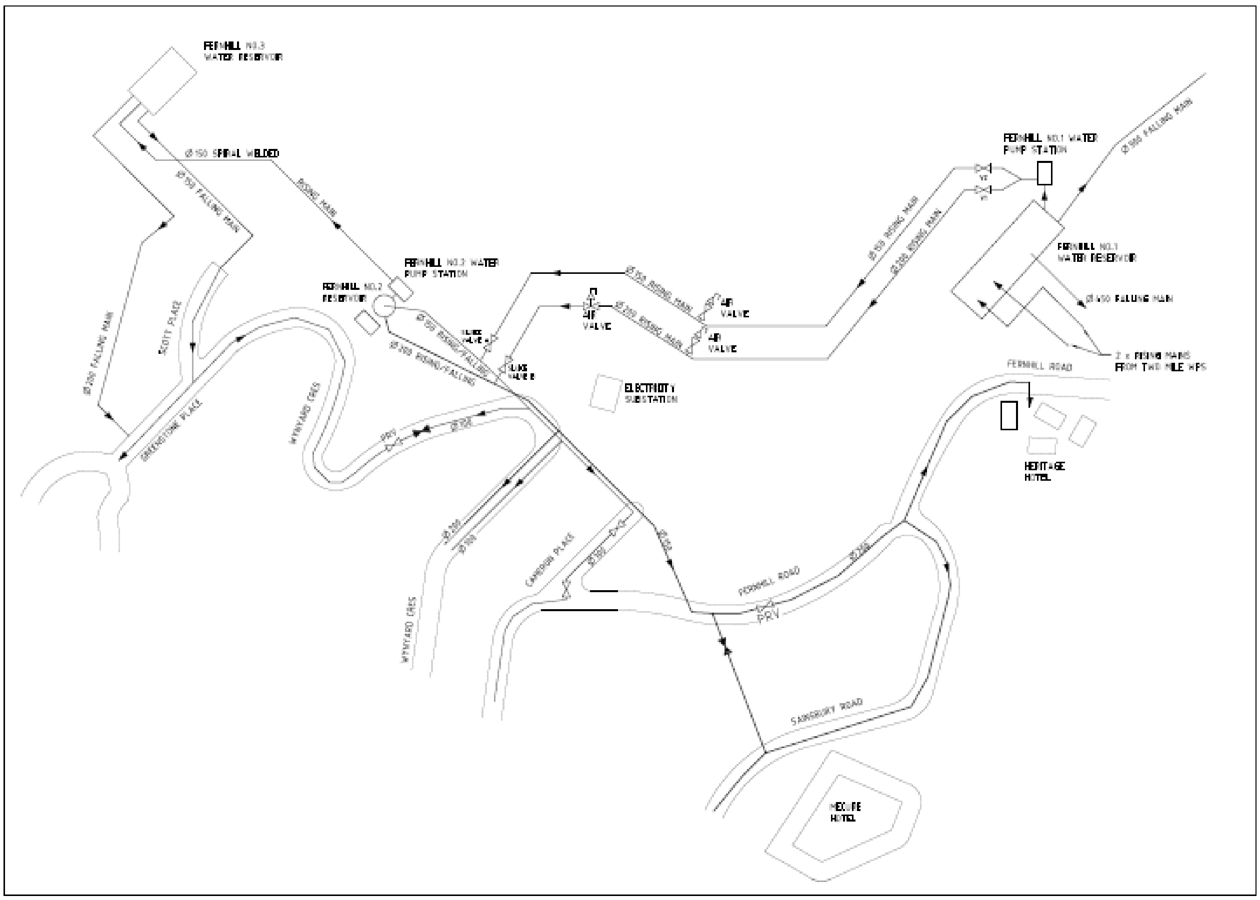
This water supply system is owned by the Queenstown Lakes District Council (QLDC) and has been operated on behalf of QLDC by United Water International (UW) since July 2008.

The Two Mile water intake pumps water up to the 8.6 ML Fernhill No.1 reservoir (TWL 407.2). This reservoir is the primary storage facility for the Queenstown central business district. In addition to supplying Queenstown, water from this reservoir is also pumped into the water supply system for the suburbs of Fernhill and Sunshine Bay, to the west of Queenstown, from the Fernhill No.1 water pump station (WPS, Figure 1).

The pump station includes two direct online TKL Hydro Titan HT 125x100-320 pumps with an approximate duty of 85 L/s at 115 metres pressure. There is a surge anticipating valve (SAV) fitted to the discharge of the pump station to mitigate the impacts of surge wave causing events such as a loss of power to the pump station. As soon as the header pipe from these pumps leaves the pump room at Fernhill No.1 WPS it splits into two rising mains. The 150 mm steel gibault jointed rising main (RM1) was the first line to be installed, in 1976. It is 648 metres in length and, when in use, transports water at approximately 20 l/s. The rising main connects into a 150 mm rising/falling main just below the Fernhill No.2 reservoirs and is fitted with one air release valve. The second rising main (RM2) is a 588 metre long 200 mm uPVC class 12 pipe constructed in 1990, with sections of 200 mm spiral welded steel in critical locations, and two automatic air valves at high points. It delivers approximately 60 l/s of water when in use. This main runs to connect into a 200 mm rising/falling main below the Fernhill No.2 Reservoirs. Both RM1 and RM2 can be isolated by closing sluice valves at the top and bottom of each main. Both rising mains run for the majority of their lengths under a steep walking track with no vehicular access.

Pumped water from Fernhill No.1 WPS will either recharge the two Fernhill No.2 reservoirs (total capacity 700 m^3, TWL 511.7) or feed directly into the Fernhill reticulation system, depending upon demand. Average daily flow from Fernhill No.1 WPS to Fernhill No.2 water reservoir is approximately 2500 m^3 per day. The Fernhill No.2 WPS, situated by the Fernhill No.2 reservoirs, pumps water to the higher Fernhill No.3 reservoir (500 m^3, TWL 587.0), which feeds the upper reaches of the Fernhill system.

Figure 1: Schematic of the Fernhill water supply system



2 RISING MAIN FAILURES

Three failures of RM2 occurred in a five week period in July and August 2009. The locations of these failures are shown in Figure 2. These three bursts are discussed individually below. Anecdotal evidence indicates that this rising main had previously burst in February 2008 (prior to UW taking over operation of the system), at a location close to the second burst.

Figure 2: Locations of rising main bursts

2.1 BURST NO.1 – 13 JULY 2009

At approximately 6:30 on the evening of 13 July 2009 the 200 mm uPVC RM2 burst. As a result of the burst, both the Fernhill No.2 and No.3 Reservoirs drained and water supplies were lost in the Fernhill and Sunshine Bay areas of Queenstown.

The loss of water supply was originally thought to be as a result of a failure of the SAV at Fernhill No.1 WPS and it was not until the valve was manually closed and recharge of the mains attempted several times with no success that the track between Fernhill No.1 and No.2 reservoirs was walked and the burst on RM2 was located at about 11:45. Repairs were complete at approximately 6:45 am on 14 July and water supplies to Fernhill No.2 reservoir reinitiated at 7 am, and water supplies to Fernhill No.3 reservoir were restored by 9 am. Water supplies to the entire Fernhill system were not restored until 15:00 due to problems with a failed pressure reducing valve (PRV) in one section of the system had allowed Fernhill No.3 reservoir water into the Fernhill No.2 zone.

This burst was the result of a catastrophic failure of a 6 m section of uPVC pipe (Figure 3) and resulted in significant scouring of the walking track under which the main runs, as well as damage to a nearby mountain bike track. The scouring also exposed the adjacent 150 mm steel rising main, with the result that it was not deemed possible to isolate RM2 and use RM1 for fear of damaging it during recharge.

The root cause of the burst is undetermined; however, there are two probable causes: excavation of the pipe revealed that there was a lack of bedding material used on the initial installation, and large pointed rocks were evident surrounding the pipe; and there was a lack of sufficient surge suppression on the pipe lines protecting them from the expected forces experienced during pump start and stop. Another factor which needed to be considered was that the current SCADA system lacks the ability to be interrogated rapidly for viable data in emergency situations.

Figure 3: Section of damaged pipe, 1st burst

2.2 BURST NO.2 – 28 JULY 2009

Two weeks after the first burst, on 28 July 2009, and before any of the suggested remedial work could even be started a second burst occurred. At 1:55 am a low level alarm was received for the Fernhill No.2 reservoir from the SCADA system. Shortly after the UW on-call operator was notified of a large flow of water down Fernhill Road. The operator and supervisor on site suspected a repeat failure of RM2 and at 3:30 am the burst site was located, immediately above the Fernhill No.1 reservoir.

Repair of the main was effected on 29 July 2009 and RM2 was re-charged and returned to use at 10 pm. This time, however, RM2 was able to be isolated and RM1 put into sole use until the repairs to RM2 could be completed, with the result that water supply to the Fernhill system was only lost for 2 to 3 hours.

This burst was again due to a failure of a section of the uPVC main (Figure 4) although the section involved was white PVC compared with the piece of blue PVC in the previous burst. The reason for the failure was suspected as being a sharp protuberance of rock near the pipe failure point. The pipe in this section was laid in a channel cut from bed rock.

The burst resulted in major scouring of an area around the Fernhill No.1 reservoir. Including the exposure of a section of the geo-textile support fabric underpinning the reservoir (Figure 5). The majority of this material was replaced by 30 July but a structural assessment of the area resulted in anchor points needing to be inserted below the reservoir to ensure stability of the shelf on which the reservoir sits. This work was only completed in early 2010.

Figure 4: (a) Section of broken pipe from 2nd burst, (b) Repair of second burst underway

(a) (b)

Figure 5: Scouring from from 2nd burst

(a) (b)

2.3 BURST NO.3 – 18 AUGUST 2009

Approximately 3 weeks after the second burst, on 18 August 2009, a third burst occurred. At 0:30 the on-call operator received a SCADA alarm indicating a low level at the Fernhill No.2 reservoir. Interrogation of SCADA revealed pumps at Fernhill No.1 WPS running but reservoir level at Fernhill dropping. En-route to Fernhill the operator was advised of water running down Wynyard Crescent and the supervisor and a second operator were called for assistance. Following arrival on site police were in attendance and a water "spout" was observed approximately 30m high at the rear of the transformer.

By 1 am RM2 had been isolated and RM1 was in sole use. Repair of the main began at 8:30 am. Once again water supplies to the Fernhill system were interrupted for only a very short period.

This burst was again due to the failure of a section blue uPVC pipe. However in this case the reason for the failure was more apparent. The failure occurred at the point at which a tapping band had been put on the pipe for an air valve. Removal of this section of pipe indicated that the tapping point had been chain drilled, resulting in the a number of potential weak points at which failure could occur (Figure 6).

Figure 6: Section of broken pipe from 3rd burst (a) in-situ, (b) showing method of drilling tapping point

(a) (b)

After this third burst RM2 was shut down until a full investigation could be completed on the main and processes could be put in place to, if not prevent further bursts on the line, at least minimize the number of bursts and mitigate their effects on the nearby environment.

2.4 COSTS OF BURSTS

Costs for the first burst on the Fernhill rising main were the costs for the repair and for the remediation of the walking track and mountain bike track. Costs for the third burst were only for the repair and remediation of the walking track following the repair. However the second burst caused a significant amount of scouring and therefore, in addition to the repair and walking track remediation costs, there were also cost incurred for the cleaning of the roadways and remediation of the scoured hillside, including stabilisation of the Fernhill No.1 reservoir platform. These costs are shown in Table 1.

Table 1 : Costs associated with the rising main bursts

Burst 1		
	- Repair	$7,490
	- Walking Track Remediation	$8,590
	- Mountain Bike Track Repair	$6.140
	- Total	$22,220
Burst 2		
	- Repair & Walking Track Remediation	$8,110
	- Scour Stabilisation	$110,550
	- Total	$118,660
Burst 3		
	- Repair	$2,680
	- Walking Track Remediation	$1,550
	- Total	$4,230

3 INVESTIGATIONS

Prior to these rising main bursts occurring the QLDC had already begun a review process of the design of the Fernhill water supply system. An outcome of this review was the need for non return valves on the system below the Fernhill No.2 reservoirs, which would have at least partially mitigated the effects of these bursts. However these recommended capital works had not yet been initiated before the bursts occurred.

Following the bursts a thorough investigation was undertaken on both the Fernhill No.1 WPS, particularly looking at the types of non return valves in use and the type of surge anticipation valve in use, and RM2 itself through pressure transient and surge analyses. These analyses were also undertaken on RM1 in order to determine whether there was any danger of future failures of this pipe as well.

3.1 FERNHILL NO. 1 WPS VALVES

An initial risk assessment of the Fernhill No.1 WPS undertaken following this series of bursts indicated two issues as possible contributing factors to the bursts. The first was the type of SAV in place at the pump station. The unit was a modified PRV and was operating on every pump start and stop and as a consequence was near to failure. Approval was received from QLDC to replace this unit with a more appropriate valve.

In addition to the SAV the non return valves at Fernhill No.1 WPS were found to be malfunctioning, potentially resulting in water hammer in the system. Approval was also received for the replacement of these units.

3.2 TRANSIENT ANALYSIS RESULTS

QLDC requested UW undertake a suitable risk assessment for the Fernhill No.1 WPS and rising mains with the purpose of investigating the security of the pipes and reservoirs and decide what is best suited to avoid future incidents. This section summarises the findings of a water hammer transient analysis performed on these systems using HAMMER transient modeling software, including:

- An assessment of the suitability of the rising main pipe materials to withstand pressure, cyclic loading etc;
- Surge analysis and required surge/ vacuum protection mechanisms;
- Systems that could be implemented for emergency shut off in the event of a rising or gravity main failure;
- Recommended works to provide protection against future failures; and
- Recommended works to pump direct to the water supply network in the event of failure of the water supply reservoirs.

3.2.1 ASSUMPTIONS

UW personnel in Queenstown provided as much As Constructed, GIS and operational information as was available at the time of the study, including pipe profiles, valve and fitting details, pump curves and momentum data, reservoir details and ground level contours. This data was used to create the pipe profile for the Fernhill No.1 WPS – Fernhill No.2 Reservoir system RM1 and RM2 in the HAMMER transient analysis. However, some additional information was required to be assumed for the formation of the transient model. The assumptions used in the construction of the model are listed below:

- Hazen-Williams steel pipe roughness coefficient C = 100
- Hazen-Williams PVC pipe roughness coefficient C = 150
- Fernhill No. 1 WPS Surge Anticipating Valve (SAV)

  Pressure Set Point = 130m

  Opening Time = 2 sec

Time Open = 5 sec

Closing Time = 10 sec

Discharge Coefficient = 0.03 $(m^3/s/mH_2O)^{0.5}$

- Rising / Falling Main Demands from customers were selected to provide approximately equal to the measured flows in each rising main:

  Rising Main No.1 Demand = 15 L/s

  Rising Main No.2 Demand = 25 L/s

- Automatic Air Valve Diameter = 80mm
- Time delay for pump shut down = 5 sec
- No pump reverse spin
- Check valve closure time = 0 sec
- Where there were inconsistencies between pipe profile data and As Constructed Drawings, the As Constructed Drawing details were used.

3.2.2 RESULTS

The results from the transient model for the Fernhill No.1 WPS to Fernhill No.2 Reservoir system RM1 and RM2 are shown in Figure 7 and Figure 8 below. These graphs show the results for the worst-case design scenario for a sudden loss of power at the Fernhill No.1 WPS, causing sudden pump shut down.

As can be seen in Figure 7 below, for RM1 the minimum pressure (dashed blue line) caused by the transient event is above the pipe profile (solid black line). This is good as significant negative pressures in pipework can cause air/water column separation and collapse of the pipe, particularly when negative pressures exceed -10 m.

The overpressure transient graph (red line) rarely exceeds the hydraulic grade line (dashed black line) for RM1, apart from a small peak in the section of rising main immediately prior to the Fernhill No.2 Reservoir inlet. This is unlikely to cause problems as the welded steel pipe materials used for RM1 are capable of withstanding very high pressures (up to PN 35). Therefore it is not expected that these higher surge pressures will be a cause of bursts unless the pipe is weakened by corrosion or other damage.

RM2 demonstrates significantly different results than RM1. Figure 8 shows that RM2 does not experience overpressure transient pressures (red line) higher than the hydraulic grade line (dashed black line). This is good as the operating pressures in this main are close to the pressure capacity of the uPVC class 12 pipe.

Significantly, however, the minimum pipe pressure (dashed blue line) caused by the transient event is below the pipe profile (solid black line), in particular immediately upstream of the first automatic air valve where negative pressures exceed -10 m. This is an indication that air/water column separation may occur in this section of RM2, potentially resulting in pipe burst or collapse. This correlates with operational experience recently where a number of bursts in this main have occurred at approximate chainages of 69, 230 and 373 metres from the WPS, as shown in Figure 2.

Differences between the actual and assumed values for equipment in the transient model can highlight potential problems not shown in the model results above. As a result, a number of scenarios were run in HAMMER to determine whether varying these assumed values would have any impact on the rising main to change its vulnerability to surge – related failure. However, no additional problems were discovered.

Figure 7:   Surge analysis results for RM1

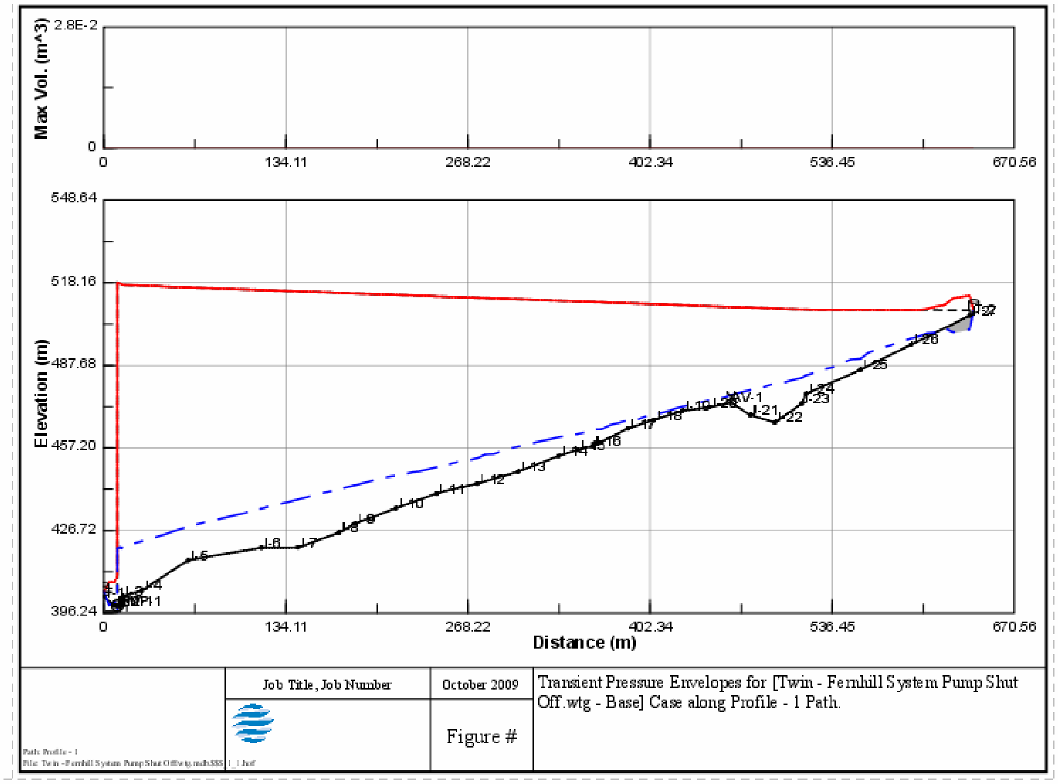
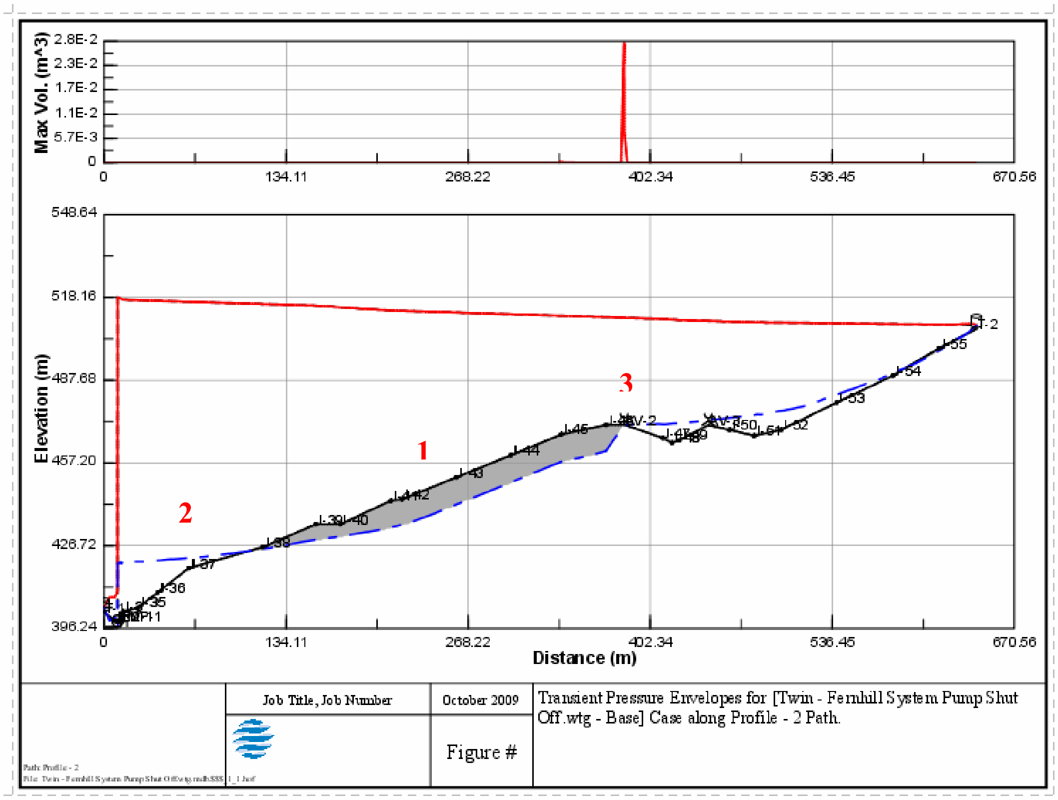


Figure 8: Surge analysis results for RM2



3.3 PIPE MATERIALS

The use of spiral welded steel pipe materials for RM1 is well suited to the operational pressures experienced in this system. Typically, these pipe materials would be able to withstand pressures of up to PN 35 (350 m).

The maximum and minimum pressure envelopes resulting from a transient event in RM1 have also been determined to be within the pressure capacity of the steel pipe. Therefore it is considered that this pipe material is also suitable for the surge profile of the system.

RM2, however, is constructed primarily of uPVC class 12 materials. The operational pressure in this main of up to approximately 115 metres is nearly equal to the pressure rating for uPVC class 12 of 120 metres. This material therefore is not suitable for use in this system and represents a risk of bursts. Pump shut off head can go as high as 150 metres, which would be even more likely to cause a burst in this main.

In addition, negative surge pressures within rising main 2 can drop below -10 metres, creating a risk of air / water column separation, vacuum and collapse of the uPVC pipe.

uPVC also suffers from a process known as 'cyclic derating' of the pipe, where over time pressure fluctuations such as those caused by a surge event can reduce the pressure rating of the pipe. This material would therefore represent a significant risk to the integrity of the system.

3.4 FAILURE MITIGATION

3.4.1 TRANSIENT PROTECTION

Transient protection is required for the Fernhill No.1 WPS – Fernhill No.2 Reservoir rising mains. The analysis recommended that this include the installation of approximately seven 80 mm double acting automatic air valves on RM2. The valves should be located at approximately chainage 140, 281, 299, 316, 318, 334 and 350 metres from the WPS. The air valves will prevent significant negative transient pressures in the rising main, therefore avoiding air/water column separation and potential pipe collapse.

The analysis also recommended that the SAV settings at the Fernhill No.1 WPS be checked and the valve opening time adjusted to between 2-5 minutes. This would allow sufficient time between a surge event and closure of the SAV to avoid the closure of the SAV to cause overpressure within the system.

In addition it was recommended that the pumps at the Fernhill No. 1 WPS be fitted with soft starters. This would mitigate the surge events in the system caused by pump start up and stop, therefore minimising the risk of a burst caused by surge. The soft starters should be set to allow the pump to ramp down slowly over approximately 2 minutes when powered, which should also allow the pump to spin to a stop over 5-10 seconds when power is lost to the WPS.

The resulting revised surge profiles with the above transient protection measures in place can be seen below in Figure 9 and Figure 10. Whilst these figures show an overpressure in the mains, this is an effect of the HAMMER modeling engine finishing the simulation and is not expected to happen in reality. The adjustment of the SAV settings will minimise this effect.

The results in Figure 9 and Figure 10 also show that there are still some slight negative pressures forming in RM2, in particular near chainage 317 and 350. Given that the HAMMER model is only an approximation, and that the material used in the construction of these sections of the rising main (uPVC class 12) is not well suited to these pressures and could be weakened by cyclic loading, it is considered a significant risk that the main in these areas could still collapse as a result of these pressures. Further mitigation measures to further reduce this risk are therefore required.

Figure 9: Surge profile for RM1 with 7 New Air Valves & Soft Starters

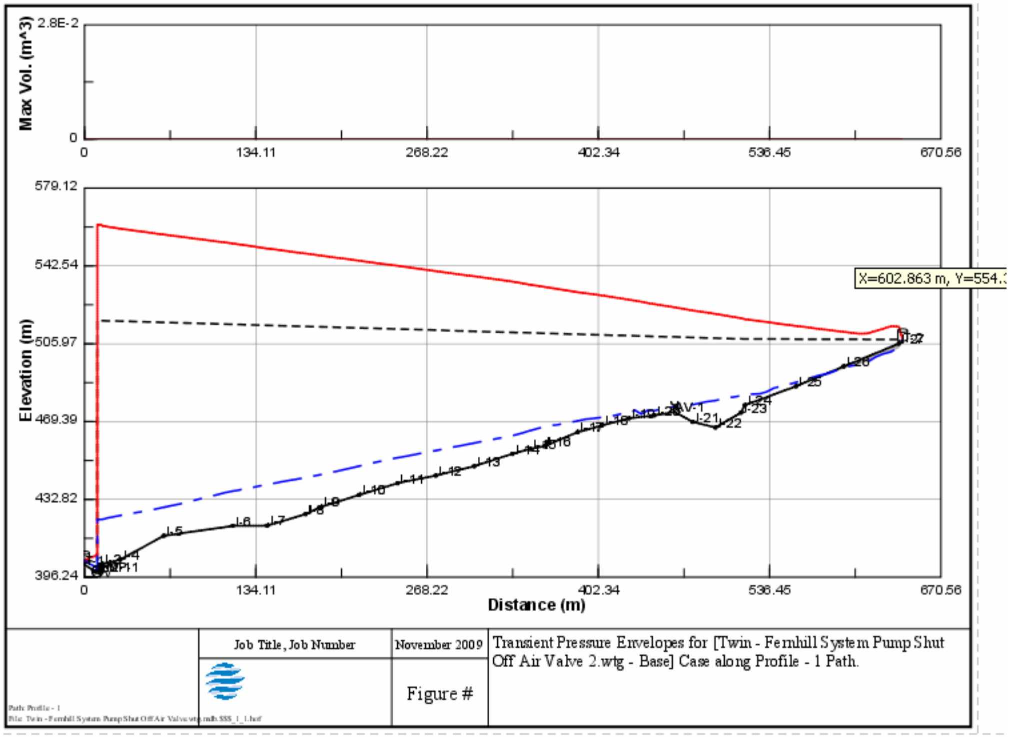
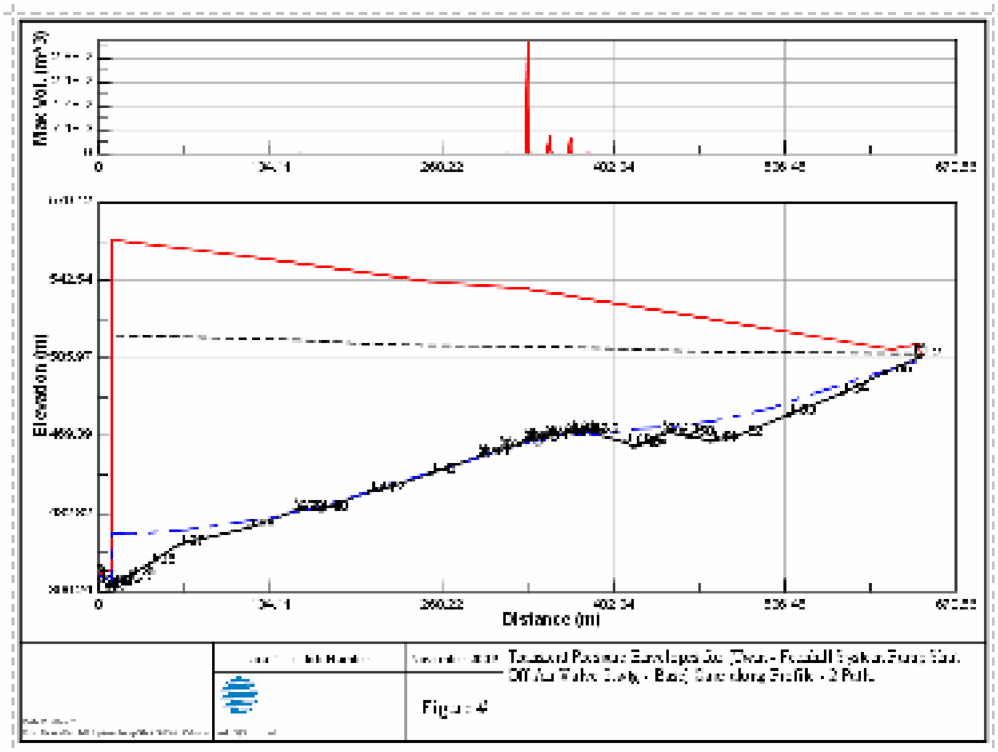


Figure 10: Surge profile for RM2 with 7 New Air valves & Soft Starters



3.4.2 PIPE MATERIALS

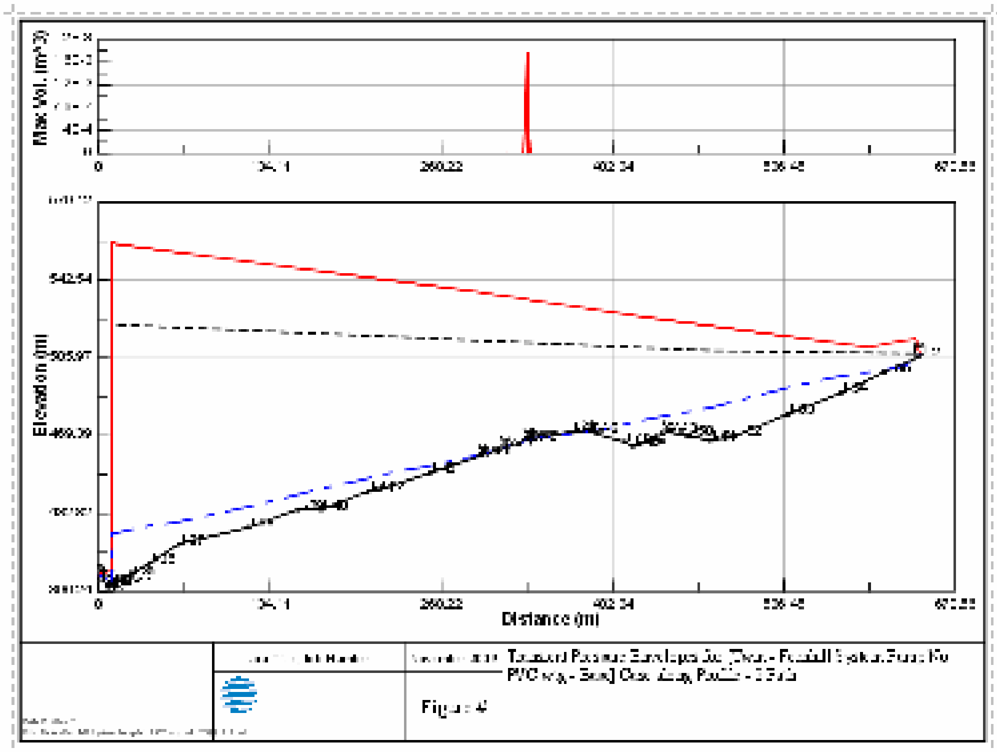
Steel pipe materials used in the construction of RM1 are considered adequate for the purpose used.

The uPVC class 12 pipe material used to construct RM2 should, however, be replaced as this represents a risk of bursting as a result of operational and surge pressures close to the pressure capacity of the pipe, and pump shut off head exceeding the pipe pressure rating. The effects of cyclic derating on the uPVC will increase the risk of burst in the uPVC pipe with time and therefore this replacement is considered a priority.

The replacement of this uPVC class 12 pipe is also important in mitigating negative transient pressures and their effects. Replacement of this pipe with steel pipe, in conjunction with the installation of approximately four additional 80 mm automatic air valves at approximate chainages 281, 299, 316 and 318 metres will produce the surge profile shown in Figure 11.

As can be seen, this recommendation will raise the minimum transient pressure envelope along the entire pipe route, minimising the potential for negative surge pressures to form, and eliminating virtually all of the negative transient pressures. The improved ability of steel pipe to withstand these negative pressures is also important, as small inaccuracies in the HAMMER model may mean that negative pressures may still form in reality. The steel pipe material would be better suited to withstand these pressures should they form in a surge event.

Figure 11: Surge profile for RM2 with steel pipe, 4 new air valves and soft starters.



3.4.3 TANK FAILURE

In the event of a failure of the Fernhill No.2 Reservoir, there are a number of capital works options that had been requested by QLDC to ensure that water supply can be maintained to customers. These included:

- Installation of tank bypass pipework between the rising mains and the Fernhill No.1 Reservoir outlet pipework (for Fernhill No.2 WPS suction, and the Lower Fernhill gravity main).
- Installation of isolation valves on the bypass pipework (valves to be normally closed, can be manually operated or automatically actuated to open if the reservoir fails).
- Installation of a pressure transducer on the bypass pipework.
- Installation of variable speed drives on the Fernhill No.1 WPS pumps.

- Installation of a telemetry link from the pressure transducer to the variable speed drive controller on the Fernhill No. 1 WPS pumps, to maintain a steady supply pressure to customers.

- Other modifications to the Fernhill No.1 WPS control philosophy as required.

4 REMEDIAL WORK

4.1 PUMP STATION

Two new Cla-Val Series 580 Silent Check (non return) Valves were installed vertically on the discharge outlet of each pump to replace the existing units. These valves prevent a reverse flow of water back into the pumps which can cause damage. They have a spring loaded poppet which allows the valve to close before flow reversal occurs, resulting in a silent, non-slam closure.

These new Silent Check valves replaced the previous faulty non return valves which were not functioning correctly and causing water hammer in the system.

The surge anticipation Line tee's off the 150mm header pipe and is designed to relieve any surge (negative) pressure that may occur in the system after pump stop. It is a 100 mm uPVC pipe that discharges excess surge (treated water) into the overflow manhole located outside on the bank behind the standby generator.

A SAV is fitted to ensure a fairly constant pressure is delivered into the system from the pump station and helps to prevent damage to the pump station and piping during unplanned pump stops.

The previous SAV was replaced with a 100mm Cla-Val 52-03 pressure relief & surge anticipator valve. The valve is fitted with both a low pressure and high pressure pilot which are both integral to its function. The SAV opens on an initial low pressure wave – in anticipation of a returning high pressure wave surge which can cause damage. The valve will then close slowly without generating any further pressure surges. Any liquid discharge from the SAV is expelled into the overflow drain that runs around the back of the reservoir, in front of the pump station building and out to the nearby Two Mile creek.

Installation of these new valves has significantly reduced the risk of rising main failure due to water hammer and other pressure surge events caused by the WPS. However the issue of the under-rated material of RM2 is still a major risk. As funds are not immediately available for replacement of this line other measures were put in place to reduce the risk of water loss from the upper reservoirs.

4.2 BURST CONTROL VALVES

The major costs associated with the three burst rising main events were not the repair of the main itself but the repair of environmental damage caused by water scour. In addition significant costs would have been incurred by individual households and businesses due to lack of water, particularly following the first burst. These effects could have been mitigated had burst control valves been installed on the inlet/outlet mains below Fernhill No.2 reservoir as such valves would have prevented the rapid emptying of the 700 m^3 water storage through the burst.

Therefore two Cla-Val excess flow valves (also termed 'burst control' or 'earthquake' valves) have been fitted to both the 150 mm and 200 mm rising/falling mains at the site of Fernhill No.2 reservoirs. Both valves have been installed in similar fashion and are housed in large diameter man hole chambers with secure hinged lids (Figure 12). The valves are pilot-operated and close when the flow rate exceeds the setting of the control. Each of the burst control valves is fitted with isolation valves on either side together with a bypass line should the burst control valves be taken out of service for maintenance. Installation of these valves was completed in March 2010.

These burst control valves also send signals when operating which allow automatic shut off of the pumps at the WPS in case of a rising main failure and for alarms to be sent to operators.

Figure 12: New burst control valves (a) during installation, (b) completed installation

(a)

(b)

4.3 BURST NO.4 – 2 APRIL 2010

Following the installation of the burst control valve on RM2 this line was returned to service so that the burst control valve could be installed on RM1. Shortly after the return to service, on the afternoon of Good Friday, 2 April 2010, a fourth burst occurred on the line. However all of the new valves performed flawlessly, shutting the burst control valve and retaining all the water in the upper reservoir, also shutting down the pumps and sending an alarm to the operator. Damage to the hillside was so minimal the operator had to walk the rising main six times before he found the burst. Furthermore no customers were put out of water at any time during this event as water was maintained in Fernhill No.2 reservoir until RM2 could be isolated and the WPS restarted using only RM1.

5 CONCLUSIONS

The series of three bursts on a single rising main over a period of five weeks was found to be due to a combination of water hammer caused by faulty valves in the Fernhill No.1 WPS, poor bedding of the rising main during construction and, primarily, incorrect material used in the construction of the rising main. Remedial work was able to be quickly completed to repair the faulty valves but the pipeline issues are waiting on the availability of funds to replace the rising main. In the meantime burst control valves have been installed below the Fernhill No.2 reservoir in order to minimize the effects of any future bursts.

The efficacy of these burst control valves was shown following a fourth burst, which occurred after their installation, where almost no scouring occurred following the burst and water supply was able to be fully maintained.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the technical assistance of Owen Foskett of HMA Valveco and Michael Apeldoorn of Cla-Val Pacific, and the Queenstown Lakes District Council for funding the work on which this paper is based.