SEWER SYMPHONY: AN INVESTIGATION OF HYDRAULIC PHENOMENA IN A FALLING MAIN THROUGH ACOUSTICS.

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ABSTRACT

The Christchurch City Councils (CCC's) goal is to create a livable city with strong communities and healthy environments. In 2007 CCC engaged with the Lyttelton Harbour/ Te Whakaraupō communities on the future of wastewater management in the harbour. The response was clear – stop pumping treated wastewater into our harbour! By 2015 the concept design for what would become the Lyttelton Wastewater Scheme was underway. By 2018 consents were approved, Jacobs New Zealand Limited (Jacobs) had completed the detailed design, and Fulton Hogan were engaged as the constructor.

Figure 1: Lyttelton Harbour

This project was a transformational change for the Lyttelton Harbour communities, ending the practice of disposing wastewater into the harbour that had taken place for nearly 200 years. The scheme comprised conversion of the existing Diamond Harbour, Governors Bay, and Lyttelton Treatment Plants into transfer pump stations, as well as construction of a new terminal pump station, and a combination pumped/gravity wastewater transmission pipeline. The transmission pipeline conveyed the wastewater to PS15 in Woolston and on to the Christchurch Wastewater Treatment Plant at Bromley. For the purposes of this paper, we refer

to the gravity section of this pipeline, from the tunnel's northern portal through to PS15 as the Heathcote Gravity Main. The Heathcote Gravity Main is a 4.6 km DN450/350 pressurized gravity sewer.

During initial commissioning of the terminal pump station, surges and backflows occurred in the Heathcote Gravity Main under certain flow conditions, leading to overflows at the transition chamber where the pressure main transitions to the gravity main. The hydraulic design and behaviour of the pipeline had well considered during the design process, however understanding of the cause of the surging overflows required moving beyond conventional theoretical assessment into developing and testing of hydraulic hypotheses.

Innovative techniques to ground-truth engineering theory were applied such as the use of a ground microphone to track the filling front of the pipeline to enable the project team to "see" inside a buried pipe that was otherwise inaccessible. After identifying the hydraulic phenomena causing the surging backflows, Jacobs were responsible for establishing and implementing a solution that enabled the safe operation of the scheme without any physical alteration to the pipeline. This led to the successful completion of commissioning of this asset and hand over to CCC.

This paper details the unexpected overflows from the top of the gravity sewer transmission main and the series of investigations that were undertaken, both in the field via physical testing and using engineering hydraulic principles, to identify the causes and characterise the hydraulic behaviour in the pipeline under various conditions. This work brought together both in house and independent, local, and international hydraulics experts who, combined with the teamwork of the CCC operations and management staff, Fulton Hogan Site staff, and project management team, were able to come together as a high performing team and resolve this commissioning challenge.

KEYWORDS

Commissioning, teamwork, hydraulics, acoustics, wastewater overflow, Lyttelton Wastewater

PRESENTER PROFILES

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Joe's background is primarily in construction, and he has worked for Jacobs since June 2021 as a Senior Associate Project. He most recently worked as Mechanical and Electrical Manager for Fulton Hogan at the Waimea Community Dam in Nelson. Prior to this Joe worked for Fletcher Construction Infrastructure.

Matthew Sheppard

Matt's background is primarily in the planning, design and construction of water and wastewater infrastructure, with a strong focus and specialism in conceptual hydraulics and more than 30-year's experience in this field. Matt was the design manager for the Lyttelton Wastewater project.

INTRODUCTION

Christchurch City Council's (CCC) long term strategy for management of wastewater in the Lyttelton Harbour aims to remove all wastewater discharges to the harbour by collecting and conveying untreated wastewater to Pump Station PS15 in Woolston, for onward transfer to the CWTP at Bromley. A major part of achieving this goal is the recently completed design, construction, and commissioning of the Governor' s Bay, Diamond Harbour and Lyttleton Wastewater Scheme (commonly referred to as the Lyttelton Wastewater Project).

The scheme design consists of a series of new wastewater pump stations around Lyttelton Harbour with associated buffer storage tanks and includes decommissioning of the existing Wastewater Treatment Plants (WWTP)'s at Governors Bay, Diamond Harbour and Lyttelton. The completion of this transformational project has successfully resulted in the removal of all treated wastewater discharges into Lyttleton Harbour. Wastewater is now being conveyed by the system to CWTP at Bromley.

The Lyttelton wastewater Scheme includes 6.8km of submarine and 2.6km land based pipelines which transfers wastewater from the Lyttelton Harbour pumpstation locations to a new terminal pump station in Lyttleton. From there a 1.9km pressure main passes through the Lyttelton Road Tunnel and connects to 4.6km of pressurized gravity main to Pump Station 15. The existing PS15 pressure main carries flows on to the CWTP.

The general process description for the scheme components is as follows:

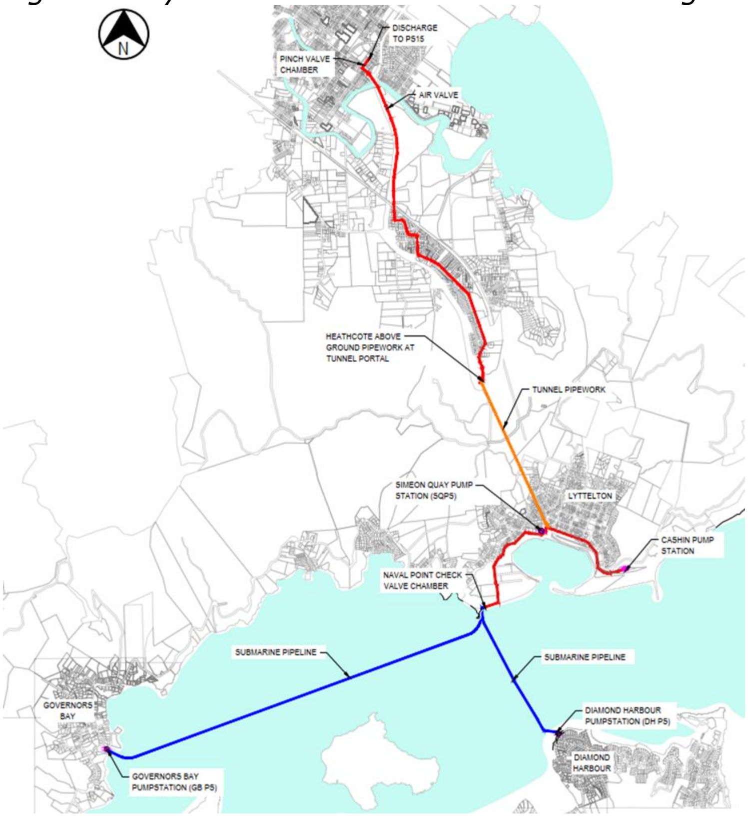
- Governor's Bay pumping station with buffer storage transferring wastewater via a submarine pipeline, and then section of overland pressure main to a new terminal pump station at Simeon Quay
- Diamond Harbour pumping station with buffer storage transferring wastewater via a submarine pipeline, and then section of overland pressure main to a new terminal pump station at Simeon Quay
- Lyttleton pumping station at Cashin Quay with buffer storage transferring wastewater via overland pipeline to a new terminal pump station at Simeon Quay
- At the Simeon Quay terminal pump station, wastewater from the western part of Lyttelton is directly received into the pump station wet well.
- From Simeon Quay, wastewater is pumped via a pressure main, through the Lyttleton Road tunnel.
- At the Simeon Quay pump station excess flow can be diverted into the Lyttelton gravity wastewater network where it is conveyed to the Cashin Quay buffer storage to prevent overflows
- At the Heathcote portal of the tunnel, wastewater transitions from the pressure main to a pressurized gravity main, that passes down the Heathcote valley and under the Heathcote River to wastewater pump station PS15.
- A flow control valve station, MV3202, is located on the pipeline at Alport Place, shortly before the discharge at PS15.
- At MV3202 Valve Station in Alport place, twin control valves placed in parallel regulate the control of the flow. Normally the valves are both open however periodically, 3 to 4 times per day, they close to allow the pipeline to fill before opening to achieve scouring flows within the pipeline. This

purposeful design enables effective management of sedimentation within the pipeline that would otherwise occur due to the flat grades.

- Odour treatment is included at 2 locations- at the Simeon Quay wet well with a mechanically ventilated activated carbon scrubber, and at the Heathcote flow transition point (discharge chamber) with a mechanically ventilated biofilter.

The overall Lyttelton Wastewater scheme arrangement is presented schematically in Figure 2 below.

Figure 2: Lyttelton Wastewater Scheme Arrangement



SCHEME COMPONENTS

Governors Bay Pump Station/35 Jetty Pump Station (PS0629), Diamond Harbour Transfer Pump Station/Otamuhua Pump Station (PS0630), Submarine pressure mains and Lyttelton township onshore pressure main Scheme components are not discussed here. The elements of the Lyttelton Wastewater scheme that have relevance to the incidence and resolution of the observed hydraulic phenomena are discussed briefly below:

LYTTELTON TRANSFER PUMP STATION – PS0628 – CASHIN PUMP STATION

A new wastewater pumping station was constructed including a buffer storage tank and conversion of the existing boat clarifier to a second buffer storage tank at the Lyttelton WWTP site. The pump Station has a pump capacity of 65 L/s and a combined buffer storage of 2100 m3. Two dry-mounted submersible centrifugal pumps in a duty/standby configuration in an open-air pump station. The permanent emergency standby generator and fuel tank has capacity to power the new pump station and the upgraded Lyttelton Lift pump station on the site.

SIMEON QUAY PUMP STATION – PS0631 – SIMEON PUMP STATION

A new wastewater pumping station was constructed at a new site on Simeon Quay, with a maximum pump capacity of 120 L/s. The installation includes three progressive cavity pumps that operate in a duty/duty/duty configuration, surface mounted in a concrete pump station building with a below-ground concrete wet well. Additional features include two surge vessels, an odour scrubber and A permanent emergency standby generator and fuel tank, with sufficient capacity to power the new pump station at a capacity of 80 L/s.

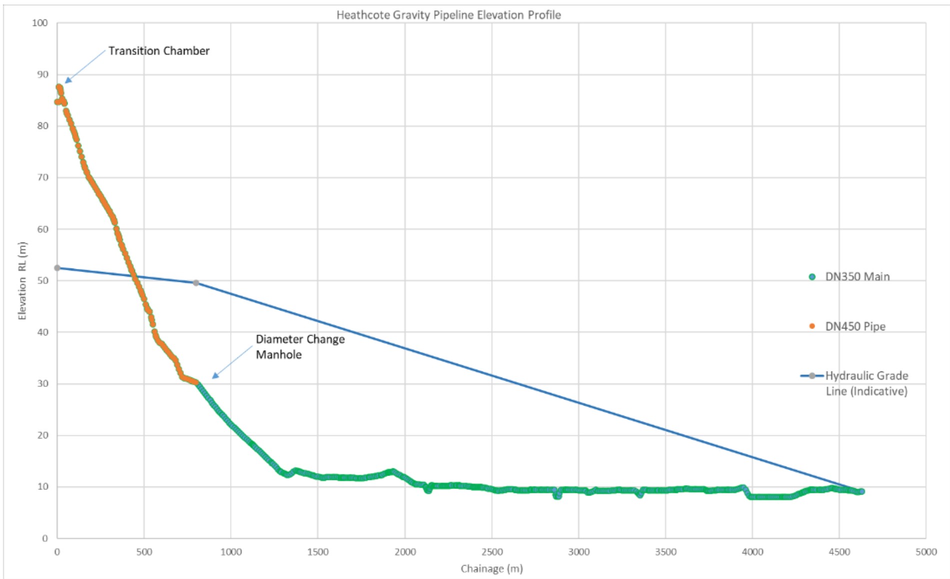
PINCH VALVE STATION MV3202

Pinch Valve Station MV3202 is located in Alport Place and houses two electrically actuated pinch valves and a flow meter in a below-ground chamber. The pinch valves are installed in series and operate in a duty/duty configuration. Gate valves are provided on both sides of the Pinch Valves to enable manual isolation for maintenance. Each pinch valve has a pressure transducer that monitors the gravity main pressure, and a pressure switch that provides hard-wired over-pressure control redundancy. Combined, this pressure instrumentation is used for control of the pinch valve station.

HEATHCOTE GRAVITY MAIN

The Heathcote Gravity main connects to the transition chamber at the Heathcote Tunnel Portal (Chainage 0) and runs down the Heathcote Valley, across the flat land beside Tunnel Road, under the Heathcote River and through to Pump Station PS15. The initial 50m consists of above ground DN450 stainless steel pipe which transitions to buried DN450 HDPE pipe down to the diameter change manhole in Port Hills Road (Chainage 725) then DN355 HDPE pipe to the Pinch Valve Station MV3202 (Chainage 4500) and on to PS15 (Chainage 4635). As can be seen in Figure 3, The upper sections of the pipeline are steep with the lower reaches of the pipeline having much flatter grades.

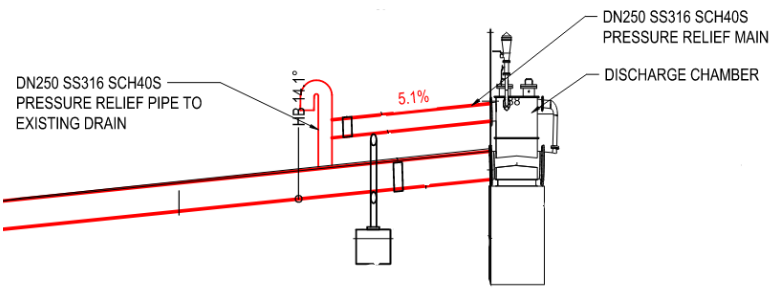
Figure 3: Simplified Longitudinal Section of the Heathcote Gravity Main



The initial 725m of DN450 PE pipe (orange in Figure 3) is designed as a gravity main, with provision of air space within the pipe to enable air to exhaust back up the pipeline to the transition chamber, where it is then piped to the air treatment biofilter. The balance of the pipeline is DN355 PE pipe (green in Figure 3) and is designed assuming full-pipe flow as a pressurised gravity main. The indicative hydraulic grade line (HGL) at peak design flow of 120 L/s is shown in blue in Figure 3. The Transition chamber, pipe diameter change chamber and valve station MV3202 are located where noted.

As can be seen in Figure 4 , the upper section of the above ground stainless steel pipe has an air-bridge pipe to avoid pipeline pressurization if a hydraulic jump was to form at the pipe entry, and the transition chamber has an overflow pipe to the nearby stormwater drain in the event of a pipe blockage.

Figure 4: Overflow point for Heathcote Gravity Main



HEATHCOTE GRAVITY MAIN OPERATIONAL PHILOSOPHY

HYDRAULIC CHARACTERISTICS

As identified in Figure 3, the elevation of the pipeline slopes from chainage CH00 to CH2100 and thereafter is relatively flat gradient to the discharge at PS15. Atmospheric venting of the pipeline at the transition chamber means that flows pumped into the pipe will drain by gravity once inflows cease, down to the invert level of outlet pipework at PS15. The anticipated full-pipe interface location is around chainage CH2100.

When Simeon Pump Station PS0631 operates in non-peak conditions, there is intermittent pumping at reduced pump flow rates. The pipeline starts to fill while inertial forces to get the full-pipe contents moving are overcome and then equilibrium is reached until the pumped flows cease, and the pipeline drains under gravity back down to its natural equilibrium level. Under this scenario, which could be for weeks and weeks at a time, the peak flow velocities are insufficiently high or frequent to manage long-term sedimentation risk and are also potentially insufficient to maintain forward movement of any accumulated air in the pipeline.

When Simeon Pump Station PS0631 operates continuously at the design peak flow rate of 120 L/s, friction losses within the pipe results in the HGL shown in blue in Figure 3, with the full-pipe interface occurring around CH350 and elevation RL 58 m. Under this situation, the flow velocity in the DN450 PE pipe is approximately 1.076 m/s and 1.730 m/s in the DN355 PE pipe. These flow velocities are sufficiently high to manage long-term sedimentation risk and to reliably maintain forward movement of any accumulated air in the pipeline.

To ensure reliable long-term operation without sediment or air accumulation in the pipeline, Pinch Valve Station MV3202 was incorporated to enable the pipeline to be periodically closed and filled to a level that achieved the flow velocities required to provide good scouring of the pipeline and forward movement of air.

MV3202 OPERATIONAL ARRANGEMENT

The operational arrangement of MV3202 was designed as follows:

- Two actuated pinch valves operating in a duty / standby configuration.
- Flow meter at MV3202 sees minimum flow and signals valves close (Q_{min}= 371 m^3/hr, adjustable). Duty valve closes (standby valve already closed).
- Pipeline fills as Simeon Pump Station PS0631 periodically operates.
- Pressure transducer at MV3202 sees target pressure and signals valve open ($P_{trigger}$ = 64.2m head, adjustable). Duty valve opens (standby valve remains closed).
- Pipeline drains. Flow meter at MV3202 sees minimum velocity and signals valves close. Duty valve closes (standby valve remains closed). Valve duty changes.
- Repeat

The original design intention was that this closing / filling / opening / draining cycle happen repeatedly and independently of Simeon Pump Station PS0631.

MV3202 MONITORING AND CONTROL

The following monitoring and control was integrated into the design:

- Two pressure transducers and a flow meter installed at MV3202 to control routine operation as discussed above.
- Two pressure switches installed at MV3202 that provide hard-wired over-pressure control that will open the duty valve if they are triggered. The hard-wired aspect means these switches remain effective in the event of RTU failure.
- A Level Switch is installed in the transition chamber to provide an overflow/high level alarm.
- Two pressure transducers installed at the pipe diameter change chamber at CH700. These have no control functionality and are for information only.

Changes to this operational philosophy were required to overcome the challenges observed during commissioning and these are discussed generally later.

SCHEME COMMISSIONING & PROBLEM IDENTIFICATION

INITIAL COMMISSIONING

Initial wet commissioning of Simeon Pump Station PS0631 with treated wastewater was successfully undertaken between 10 May 2022 and 26 May 2022. This utilized relatively short pump runs that were aimed at testing the Simeon Pump Station PS0631 functional controls while the valve station MV3202 was run in automatic mode. All pumped flows discharged through the Heathcote Gravity Main without any overflow events being observed.

During witness commissioning of Simeon Pump Station PS0631 with valve station MV3202 running in automatic mode, overflows were observed on two occasions at the transition chamber overflow (refer Figure 4 above). Overflow events did not occur in all commissioning tests, and it was not immediately obvious what situation or combination of events resulted in overflows. This meant that further controlled testing was required to determine the cause of the overflows and to test the hypothetical solutions developed.

INITIAL DESIGN REVIEW

Inputs were initially sought from Jacobs Advanced Hydraulics team in the US, who undertook an independent and theoretical review of the Heathcote Gravity Main, using as-constructed levels, gradients, and bends. This review utilized various methods of analyses for mixed air and water flow in pipe systems and targeted hydraulic phenomena including free-flow siphon inlet conditions, free vent pipe sizing, vent size recommendations, air pocket movement in sloped pipes, and a gradually varied flow analysis.

The Advanced Hydraulics team's work included reviewing the original hydraulic and transient assessment which used a Manning's n approach for full pipe head loss. In general, the analysis showed the system should have plenty of hydraulic head capacity available when considering conventional gravity sewer design principles and did not pin-point ant areas of concern.

To provide Christchurch City Council an independent perspective, an independent specialist hydraulic designer was engaged to oversee design review and testing activities.

FIELD TESTS

OVERVIEW

After the initial overflows were observed during Witness Commissioning, the balance of the commissioning process was put on hold and a series of field tests were progressively developed and undertaken to investigate and characterize the problem and to test hypothetical solutions that were developed. In total, five rounds of physical testing were undertaken by a team assembled from Jacobs, CCC and the Contractor Fulton Hogans' staff.

To prevent overflows discharging to the environment, an overflow capture system was installed that included pipework connected to the overflow point at the transition chamber (hidden from view) and temporary storage tanks, as shown in Figure 5.

Figure 5: Overflow capture system

ROUND 1 TESTING – VERIFY THE STATION FLOWRATES AT PUMP SPEED SET POINTS AND CONFIRM THE DISCHARGE CHAMBER CAN RECEIVE THE FLOWS

Objectives

The objectives of the first round of testing were to:
- Verify pump flow rates at selected pump speeds against the design basis
- Verify the hydraulic performance of the transition chamber

Test Schedule

The test schedule in Table 1 was undertaken to verify Round 1 testing objectives.

Table 1: Round 1 Test Schedule

	Test Description	Pump 1	Pump 2	Pump 3	Pinch Valves Setting	Purpose of Test
1	Pump 1 at 38Hz	38Hz	Off	Off	Auto	Confirmation of P1 flow rate 33 L/s
2	Pump 2 at 38Hz	Off	38Hz	Off	Auto	Confirmation of P2 flow rate 33 L/s
3	Pump 3 at 38Hz	Off	Off	38Hz	Auto	Confirmation of P3 flow rate 33 L/s
4	2 pump combinations at 38Hz				Auto	Confirmation 2 pump combinations achieve 66L/s
5	3 pumps at 38 Hz	38Hz	38Hz	38Hz	Auto	Verify discharge chamber flow of 97l/s
6	3 pumps at 41 Hz	41Hz	41Hz	41Hz	Auto	Verify discharge chamber flow of 102l/s
7	3 pumps at 43 Hz	43Hz	43Hz	43Hz	Auto	Verify discharge chamber flow of 110l/s
8	3 pumps at 46Hz	46Hz	46Hz	46Hz	Auto	Verify discharge chamber flow of 120l/s
9	3 pumps at 46 Hz with staged start (2min delay to each pump start)	46Hz	46Hz	46Hz	Auto	Establish if rate of increase of flow or max pump speed/max pumped flow is issue causing overflow

Test Observations

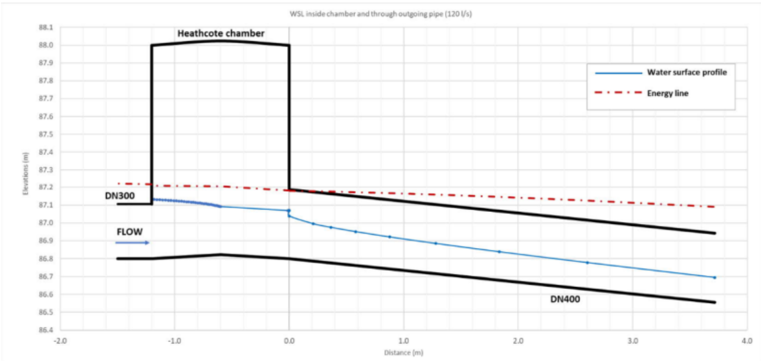
Flow Rate

The initial four tests confirmed that the pumped flows were as expected and in accordance with the design basis. Higher flow rates than designed was therefore eliminated as a potential cause.

Transition Chamber Hydraulic Performance

The field testing objective was to determine if a hydraulic jump could form at the outlet of the discharge chamber that could restrict displaced air travelling back up the pipeline from discharging, resulting in the observed surging backflow and overflow as the trapped air eventually forced its way through the hydraulic jump. The designed flow condition inside the discharge chamber at the design flow of 120 L/s is shown in Figure 6.

Figure 6: Design flow condition inside the transition chamber



This demonstrated that a hydraulic jump should not be occurring to sufficient an extent to block the return air passage in the pipeline.

To enable observation of the hydraulic performance within the transition chamber, a clear observation port was installed on the transition chamber to enable visual observation within the chamber as shown in Figure 7.

Figure 7: View port installed on the transition chamber

Testing across a range of flows up to the peak design flow of 120 L/s confirmed that no hydraulic jump was occurring and flow through the chamber was smooth and consistent and had sufficient clear space to enable air release to the chamber.

Poor hydraulic performance at the transition chamber outlet was therefore eliminated as a potential cause.

<u>Additional Observations</u>

Tests 8 and 9 (refer Table 1) resulted in overflows however the mechanism of overflow was different for the two events. The overflow in Test 8 occurred after 5-minutes of continuous running of the pumps at 115L/s before the line backed up and overflowed. In Test 9, the pumps were run for 9-minutes without overflow and then stopped. Immediately thereafter a surging release of air was expelled from the pipeline resulting in a small overflow.

Round 1 Testing Outcomes

Following completion of the initial round of testing the following key outcomes were observed:

- PS0631 pump rates were consistent with design expectations
- There was no hydraulic jump occurring inside the transition chamber that had the potential to choke air release

The method of overflows observed in Test 8 and 9 demonstrated that air was surging back up the pipeline, suggesting that a momentary hydraulic jump or pipeline blockage downstream was occurring. The inconsistent timing of overflows however increased uncertainty of the likely cause.

ROUND 2 TESTING – DETERMINE OTHER CONDITIONS THAT CAUSE OVERFLOWS/EXTENT OF ISSUE

Objectives

The next stage of investigations shifted focus to characterizing the performance of the pipeline downstream of the transition chamber, including consideration of the operational status of Valve Station MV3202. By virtue of this broad objective, the range of tests were also varied.

The working hypothesis was that hydraulic jumps and/or roll-over at bends in the steeper gravity-flow section of the pipeline were causing an air lock in the pipe, restricting free passage of air back up the line to the discharge chamber. The locations of interest included horizontal bends and changes in pipeline slope in the upper sections of the pipeline from the transition chamber down to the diameter change chamber at CH926.

As the pipeline is buried and continuous (no manholes or other points of access), physical observation was not possible. CCTV inspection was considered to visually inspect the pipeline for partial blockages or flow obstructions and to observe flow at the locations of interest, however the long pipeline length meant that this was not feasible.

Recognizing the necessity of gaining some insight to what was physically occurring within the pipeline and recognizing that it was likely to result in turbulence, a novel method of utilizing acoustic sensing to listen for changes in flow behavior was considered and trialed. This was achieved using a hand-held ground microphone positioned above the pipeline feature of interest and then listening for excess noise generated by the turbulence of a hydraulic jump when the pumping commenced.

The objectives of the Round 2 testing were therefore to:

- Verify that acoustic sensing enabled "observation" of the hydraulic behavior in the buried pipeline and determine how this technology is best utilised
- Identify if there was abnormal turbulence at the identified pipeline features
- Assuming that acoustic sensing would prove useful, undertake tests across a range of flow rates and Valve Station MV3202 operational status to observe and record hydraulic performance

Test Schedule

The test schedule in Table 2 was undertaken to verify Round 2 test objectives. For this testing the Valve Station MV3202 operation was left in automatic.

Table 2: Round 2 Test Schedule and observations

Description of test	Flow rate (L/s)	Gravity Line Press. (kPa)	Overflow Notes	Pinch Valve Notes
3 Pumps at 38Hz	98	67	No	Opened within 20s test start
3 Pumps at 41Hz	102	417	No	Opened in Middle of test
3 Pumps at 46Hz, non staged start	116	416	No	Opened in Middle of test
3 Pumps at 46Hz, staged start	114	115	Yes - after pump shut down	No Actuation During Test
3 Pumps at 46Hz, staged start	116	435	Yes - after pump shut down	Opened 2 min before end of test
3 Pumps at 46Hz, Non staged start	114	115	No	No Actuation During Test
3 Pumps at 43Hz, non staged start	109	277	No	Opened 2min before end of test
3 Pumps at 43Hz, non staged start	108	240	Yes - While Pumping	No Actuation during test
3 Pumps at 48Hz, non staged start	121	522	No	Opened within 30s of start of test
3 Pumps at 48Hz, non staged start	121	120	Yes - While Pumping	No Actuation During Test

Test Observations

Applicability of acoustic sensing and presence of increased turbulence at bends

Testing demonstrated that the flow in the pipe could be clearly heard however there was no difference in the sound observed between straight pipe sections and bends. It was not possible to determine whether this meant that there was no additional turbulence at bends or that any increase in turbulence was not identifiable.

Testing however demonstrated another very useful outcome that had not been contemplated, which was an obvious change of sound between a flowing pipe and one that was full.

This meant we were able to use the ground microphone to track the filling front, or free surface inside the pipeline, but were not able to verify if there was increased turbulence at bends. We recognized however that the absence of increased noise at bends could be because there was no significant increase in turbulence.

Additional Observations

The test scenarios canvased a range of operational settings of Valve Station MV3202 and differing pump flow rates. There were no clear outcomes however the testing did identify that:

- Opening of the Valve Station MV3202 immediately prior to or during filling of the pipeline reduced the likelihood of overflow
- The location of the free surface inside the pipeline, identified by the gravity line pressure reading and acoustic sensing, affected the timing to overflow, with this being short the higher the starting location of the free surface

Round 2 Testing Outcomes

Following completion of Round 2 testing, the following key outcomes were observed:

- Acoustic sensing was a useful and reliable tool to identify the free surface within the pipeline
- The extent of filling of the pipeline affected the likelihood of overflow, with this reducing when open and increasing when closed and the pipe was increasingly full
- Additionally but not conclusively, the absence of additional hydraulic noise at bends suggested that hydraulic jumps and resulting air locks may not be occurring at these features.

This led to development of a revised hypothesis, that rather than a specific pipeline feature or flow rollover at a bend causing a hydraulic jump, the fluid in the pipeline was becoming aerated during its descent down the pipeline and this could be causing the flow in the pipe to bulk. Further testing was then planned to investigate this.

ROUND 3 TESTING – CHARACTERISE AND LOCATE HYDRAULIC BLOCKAGE OR FLOW BULKING

Objectives

This phase of testing became a more focused exercise targeting the specific objective of determining if flow bulking were occurring in the upper steep section of the pipeline. Where the previous round tested a broad range of flow and pipeline filling conditions, this round aimed to reduce the number of variables that were influencing performance.

The objectives of the Round 3 testing were therefore to:

- Determine if flow bulking was occurring in the upper section of the pipeline and if so, attempt to isolate any specific locations where this was occurring

Test Approach

The general test approach adopted was to pump at constant rate until overflow occurred, into a closed pipe of known storage volume, then to retrospectively determine the actual volume pumped into the pipe by using the difference in static pressure (after resting 5-minutes) between start and stop free-surface levels and therefore understand the amount of air entrained by comparing this against the pipeline test section volume.

This was repeated for shorter and lengths of pipeline with lessor and lessor volume, but with constant pump rate, so that the results from subsequent tests could be deducted from the preceding test to determine the behaviour that occurred in the section of pipeline isolated by this process.

The location of the pipeline free-surface at the commencement of the test was identified by using the static pressure (at rest) to determine starting elevation. The location of the pipeline free-surface at the end of the test was identified both by acoustic sensing of the filling front and by using the static pressure (at rest) to determine finishing elevation.

The reliability of this testing approach was considered to be reasonable as:

- The pressure gauges enabled accurate determination of elevation
- The acoustic sensing provided in-field validation of elevation
- The internal volume of the pipes can be reliably determined
- The pumping run duration was sufficiently long that any additional pumped volume resulting from a minor delay (fraction of a second) in stopping the pumps was insignificant

The test sections were selected to include one bend within each section, as presented in Figure 8.

Figure 8: Plan of Heathcote Pipeline upper sections showing chainages and bends

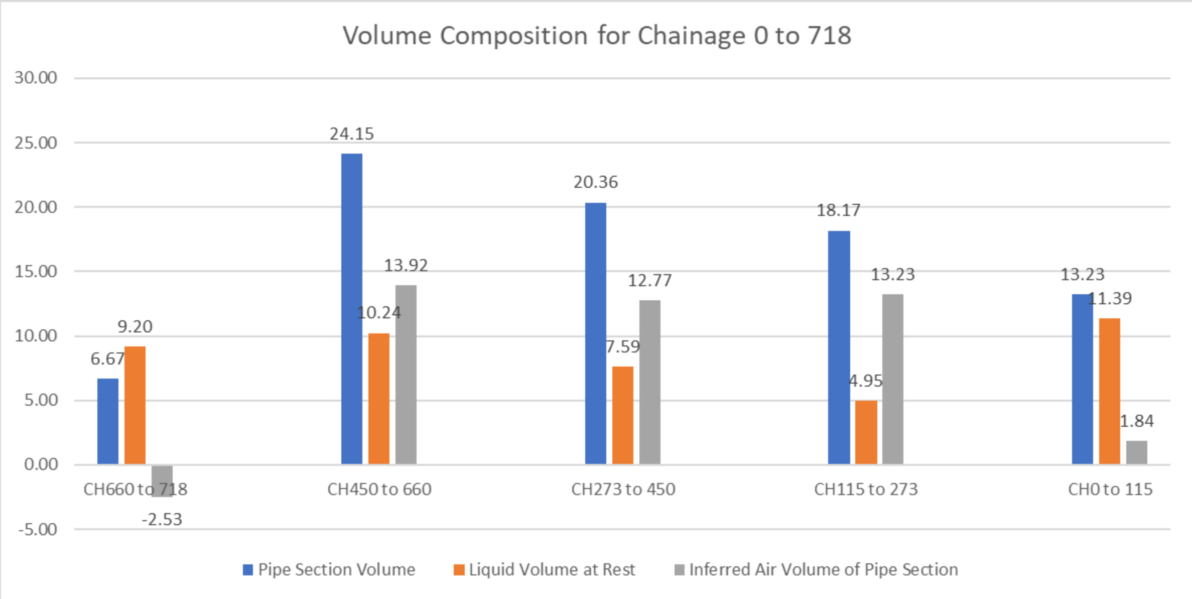
The general characteristics of each of the test sections include:

- CH000 to CH115 – relatively short section, 11.5 degree horizontal bend
- CH115 to CH273 – relatively short section, 35 degree horizontal bend
- CH273 to CH450 – relatively long section, long smooth horizontal bend
- CH450 to CH660 – long section, LR 45 degree Segmented horizontal bend
- CH660 to CH718 – very short section, no bends

Test Observations

Analysed test results showing the pipe section volume, liquid volume and air volume for each of the test sections are presented in Figure 9.

Figure 9: Proportion of entrained air by volume for the upper pipe sections



Performance observations derived from these results include:

- Air entrainment through the three steepest sections from CH115 to CH660 is significant, with the following observed:
    - CH115 to CH273 – 267%
    - CH273 to CH450 – 168%
    - CH450 to CH660 – 136%
- Only a small proportion of air is entrained in the upper flatter section from CH00 to CH115 – 16%

The results from the lower section incorrectly suggest that more volume was pumped than could be stored and it is considered that specific result is inaccurate due to the very short test section and deduction of the larger volumes from the subsequent test section. It does however demonstrate that the results as presented should be considered generally rather than exactly.

Further consideration of these results and the pipeline characteristics for each test section yield further conclusions:

- Section CH115 to CH273 has a sharp bend and steep gradient so understandably has the greatest air entrainment and significantly more than the preceding and subsequent sections
- Sections CH273 to CH450 and CH450 to CH660 still have significant air entrainment, despite slightly less steep slopes and no sharp bends, this suggests air entrainment occurring at the turbulent free-surface interface.

Further consideration of the likely hydraulic behaviour at the turbulent free-surface interface indicates that the flow velocity down the pipe is likely to be in the order of 1.5 m/s to 3.0 m/s and that the free-surface interface is filling upwards at a velocity in the order of 1.5 m/s to 3.0 m/s (depending on the location and percentage air entrainment), so the resulting closing velocity at this interface is often upwards of 6 m/s and therefore highly turbulent.

The hypothesized significance of the identified fast pipe filling rate is that by the time the entrained air separates into bubble form, it can no longer escape as the pipeline is filling faster than the escape velocity of the air bubbles.

The hypothesized outcome is that air bubbles form, accumulate and occupy pipe volume and continue to proceed upwards and get increasingly pressurized until there is sufficient buoyancy for them to pass the inflow above, resulting in the energetic and turbulent overflow observed.

Round 3 Testing Outcomes

Following completion of Round 3 testing, the following key outcomes were observed:

- Air entrainment appears to be occurring in the steep upper sections of the pipeline
- Air entrainment appears to be occurring at the 35-degreebend at CH200
- The free-surface filling front moves up the pipe faster than air can escape, therefore trapping the air temporarily

Assessment of gravity flow velocities at a pumped flowrate of 80 L/s indicates these are only slightly lower than at 120 L/s, supporting the testing through observation of some overflows at lower pump rates when the free-surface was within the steeper upper pipeline sections.

Overall these outcomes demonstrate that having the free-surface within the upper sections, likely anywhere within CH00 to CH650, is likely to result in flow bulking and overflow if pumping continues and the Valve Station MV3202 does not open.

To achieve safe and reliable operation, the free surface inside the pipeline needs to be kept in the lower sections of the pipeline with flatter pipe grades, or, the pipeline could be modified to operate completely as a full pipe.

ROUND 4 TESTING – STEADY STATE AND AUTOMATIC OPERATION

Objectives

The fourth round of testing was devised to verify the steady state performance of the pipeline with sustained peak design flow (120 L/s) with unconstrained outflow (pinch valves fully open). The purpose of this test was to verify pipeline capacity at steady state and confirm if in a fully open system the air entrainment was still an issue.

The second purpose of this round of testing was to verify the performance of the pipeline when operated with the free surface below the steep upper pipe sections. This involved adjusting the set points for the pinch valve controls to ascertain if revised (lowered) operational set points would resolve the overflow issues.

Test Approach

The test approach adopted was to track the free surface location along the pipeline under steady state flows using the ground microphones. This was achievable due to the clear audio signal of the noise generated by the plunging jet created by the water flowing down the pipe under gravity colliding with the free surface moving up the pipeline as the pipe fills.

Tests were undertaken at 80 L/s to validate the testing approach and to test the lowest acceptable peak flow. Testing was then repeated at 120 L/s to validate performance at the peak design flow.

Testing was also undertaken trialing lower set-points for the opening of Valve Station MV3202 valves.

Valve station MV3202 was open for all tests.

Test Observations

The initial test at 80L/s was sustained for approximately 67 minutes and achieve steady state conditions before stored wastewater in the Lyttelton network was used up. The ground microphone reliably tracked the free surface inside the pipe to Chainage 730. This was well below the identified area of concern (CH00 to CH650) and well below the overflow located at Chainage 00.

The next test at 120L/s had insufficient stored wastewater to achieve steady state conditions and the testing was rescheduled to enable supplementing of the wastewater by fire hydrants and storage in the buffer storage available at the Cashin Pump Station.

Subsequent tests were then conducted with sustained pumping and the pinch valves in automatic control mode, with adjustments made to Pinch Valve operational set points. In order to limit the free surface during filling to the lower sections of the pipe with flatter grades and allow entrained air to escape during the filling process, the set point for opening the pinch valves was reduced progressively from the original design set point of 537kPa to 217kPa. While the testing showed that the reduced opening set point triggered valve opening correctly and there were no overflow issues, the installed control logic limited the commissioning team's ability to filter out nuisance valve opening due to pressure transients in the pipeline and ultimately further tests were abandoned.

It was observed that while the PS0631 pumped flows were being applied to the gravity pipeline and after successful closing of the pinch valves at the completion of a scour cycle the pressure transient generated on valve closing triggered the valve to open immediately again. The control logic contained a persistence delay to require the opening pressure to be maintained for a set period of time however the logic applied this same persistence delay to both opening and closing. Therefore, any increase in persistence delay to filter out transient pressure on closing also delayed valve opening leading to the pipeline filling further and increased risk of overflow due to rapid bulking.

Round 4 Testing Outcomes

At the completion of the fourth round of testing the commissioning team had proved that the system was able to operate at a sustained flow rate of 120 L/s when valves are open, subject to further confirmatory testing when sufficient test water supply is available.

ROUND 5 TESTING – 120L/S STEADY STATE TESTING AND SUSTAINED AUTOMATIC OPERATION TO A FULLY OPEN RECEIVING PIPELINE TO INFORM SCOURING CYCLE

Objectives

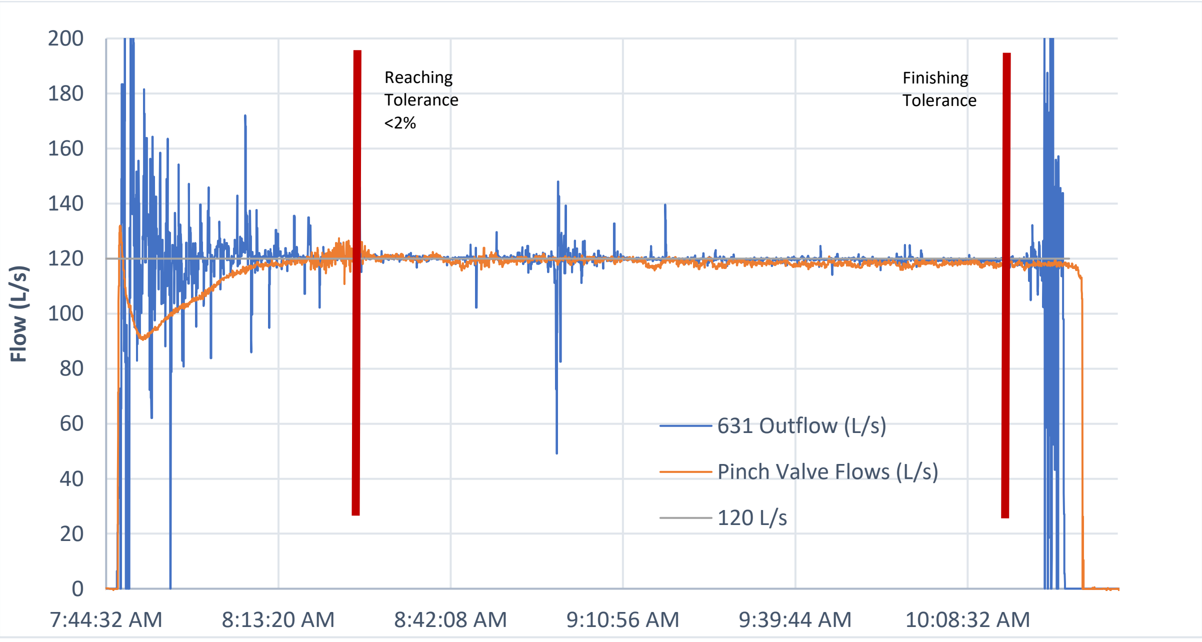
The two key objectives of the fifth round of testing were:

- To run PS0631 at 120 L/s for an extended period to achieve steady-state conditions and observe that air entrainment and flow bulking would not generate an overflow. This would prove the system could cope with steady state operation at peak flow rates.
- Secondly to run PS0631 for an extended period of time, pumping in automatic mode and with Valve Station MV3202 valves open, to determine the peak and average flow velocity achieved and evaluate if this was sufficient for scouring or if a dedicated scour cycle was required.

Test Observations

Figure 10 shows a comparison of the flow meter data from PS0631 and the flow meter data at MV3202. The data from the two flow meters was used to verify that the inflow and outflow reached equilibrium and record the duration that this was maintained.

Figure 10: Comparison of PS0631 and MV3202 Flow meters to verify 120L/s Steady State Flow (Inflow matches outflow)



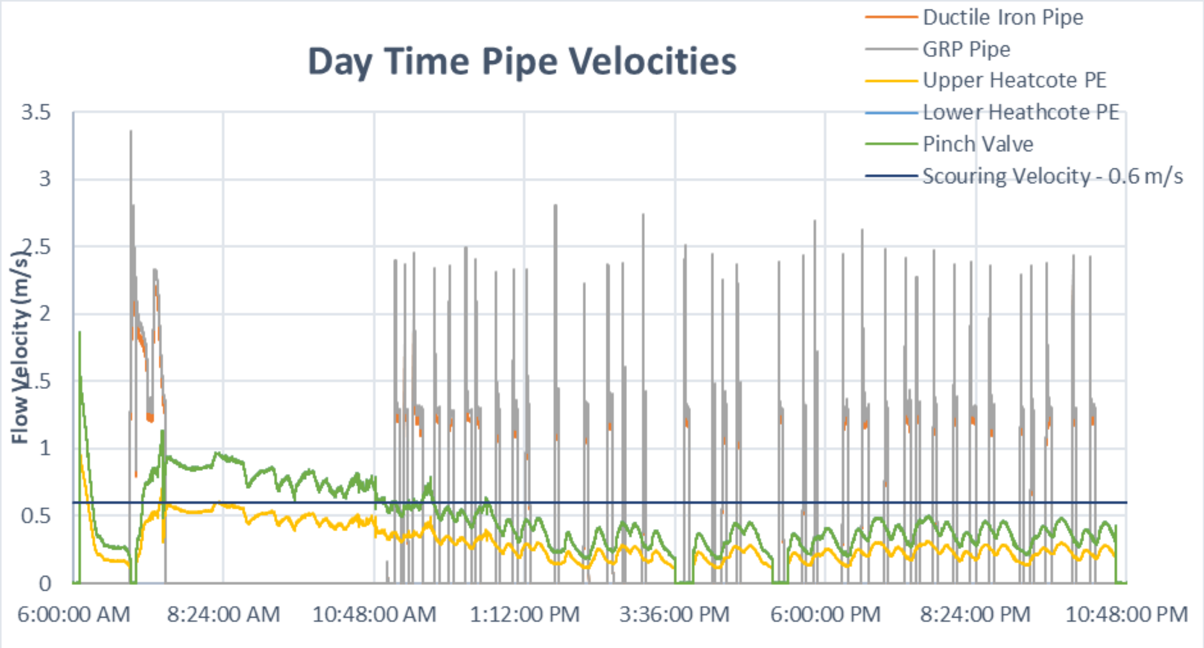
As can be seen from the graph, the inflow and outflow of the gravity pipeline was maintained in steady state equilibrium (+/-2%) for 2 hours and 9 minutes. Using the ground microphone, the pipe free surface was tracked and observed to be located at approximately Chainage 724, which equates to RL31. It is noted that this was only minimally above the steady state location for the free surface observed (Chainage 730) in Round 4 testing at 80 L/s.

The pump test duration was long enough to provide assurance that continued pumping at the design flow was sustainable.

It is noted that to achieve the volume of test water required for the sustained pumping at 120L/s, a significant effort was required that combined Christchurch City Council Operations staff form the Three waters team, Jacobs staff, as well as Fulton Hogan and their subcontract staff. CCC operational staff were on site to control remote stations around the harbour to manage flows to the terminal pump station (PS0631) as well as using 3 fire hydrants controlled by Fulton Hogan and their subcontractors to empty into the local gravity sewers. This team effort allowed sufficient incoming flows to enable the required testing to be undertaken.

Testing with multiple repeated automatic operations of Simeon Pump Station PS0631 demonstrated repeated reliable operation. Figure 11 below shows the resulting pipe flow velocity plot with the horizontal bar showing the minimum scouring velocity as defined in the Design.

Figure 11: Typical Daytime fluid velocity in the Heathcote Gravity pipeline from 16h operating period (7am to 11pm)



From Figure 11 you can see that flow velocities in the Lyttelton pressure main of up to 2.4 m/s were achieved on pump start and sustained at 1.25 m/s once the pumps ramped down to minimum flow. Flow velocities in the Heathcote gravity / pressure main peaked at around 0.8 m/s and sustained above 0.6m/s for an extended period over the morning peak network flows however this could have been affected by the full buffer storage tank providing a higher than normal base flow to PS0631.

Figure 12 below gives the minimum scour velocity for the gravity pipeline of 0.7m/s in the upper steep sections of DN450 HDPE and 1.1m/s in the lower flatter sections of DN355 HDPE.

Figure 12: Required minimum scour velocity in the Heathcote Gravity Pipeline

Component	Design method	PS0629-35 Jetty	PS0630-Otamuhua	PS0628-Cashin	PS0631-Simeon	Tunnel to CH1400	CH1400 to PS15
Flow rate	From design flow assessment in Section 4.4	12-15 L/s	30-40 L/s	33-65 L/s	75-120 L/s	75-120 L/s	75-80 L/s
System head	Friction loss determined using Colebrook white, local losses using fittings factor, static head being the height difference from normal mean wet well level to pressure main IL at termination location or intermediate high point	95 m	44 m	28 m	127m	22 m	42 m
Minimum velocity	Minimum velocity of 0.6m/s	0.9 m/s	0.8 m/s	0.8 m/s	2.3 m/s	0.7 m/s	1.1 m/s
Minimum shear	Minimum shear of 3 Pa to scour sediment and 4 Pa to scour slime growth	3.3 Pa	2.5 Pa	1.9Pa	4.1 Pa	1.1 Pa	2.9 Pa
Pipe material and pressure rating	HDPE PE 100 or GPR design guidance.	PE100 PN16	PE100 PN12.5	PE100 PN12.5	PN20 GRP	PE100 PN12.5	PE100 PN12.5

Round 5 Testing Outcomes

The outcome of the fifth round of testing is that the Heathcote gravity main demonstrated an ability to pass a sustained flow rate of 120 L/s through the WP4 Gravity pipeline when the pinch valves are open and that with pinch valves open PS0631 can operate with no observed overflows for sustained periods of time.

This testing also confirmed that under normal dry weather daily flows, the pipeline had insufficient scouring velocities on a daily basis and that a regular scour cycle was required.

SUMMARY OF ANALYSIS AND FINDINGS AT THE CONCLUSION OF ALL ROUNDS OF TESTING

A summary of the outcomes of the analysis and testing undertaken includes:

- Analysis by Jacobs Advanced Hydraulics Team in the US indicated low risk of hydraulic jump and flow rollover at discrete points in the upper sections of the Heathcote gravity line.
- Test results and analysis drove the formation of a hypothesis that there was no single hydraulic jump or air lock forming that blocks flow down the pipe and causes an overflow.
- Overflows were believed to primarily be caused by flow bulking due to turbulence induced air entrainment at the filling interface in the pipe, which cannot escape due to the speed of pipe filling.

- A likely additional cause of air entrainment is the turbulent flow at bends, particularly the 35-degree bend at CH200.
- Flow velocities above 0.6m/s in the Heathcote gravity / pressure main are achieved consistently and for several hours during the morning peak network flow period and reach peak flows in the order of 0.8 m/s. These are consistent with the original design expectations and confirm that a scour cycle is required to ensure that scour velocities in excess of 1.0 m/s are achieved at least once per day.
- Sustained pumping from PS0631 at the peak flow condition of 120L/s with the pinch valve open has been demonstrated as being repeatedly achievable. This validates that it is safe to operate PS0631 at peak design conditions without an increase in overflow risk when the pinch valves are in the open position.
- PS0631 was operated for two periods of approximately 16 hours across morning and afternoon peaks and midday and late evening shoulder periods with the pinch valves in the open position validating safe operation of PS0631 under typical dry weather operating conditions when the pinch valves are in the open position.

DEVELOPMENT OF AN ALTERNATIVE OPERATIONAL MODE FOR VALVE STATION MV3202 AND SIMEON PUMP STATION PS0631

REVISED OPERATIONAL PHILOSPHY OF MV3202 AND PS0631

Following the conclusion of testing and completion of the analysis of test results, the below key changes to the original operational philosophy were made to enable safe operation of the Lyttelton Wastewater Scheme via the Heathcote Gravity main:

- Change MV3202 Pinch Valves from normally closed to normally open, with a periodic scouring cycle implemented when pre-set conditions prevail
- Introduce a scouring operational mode at PS0631 during which the pump station will operate at reduced speeds/flows and pump into the Heathcote Gravity main with the MV3202 Pinch Valves closed. This reduces air entrainment in the gravity flow and reduces likelihood of overflows
- Include communications between MV3202 and PS0631 to establish when preconditions for a scour cycle are met and control the initiation and execution of the scouring cycle itself and including return to normal operational mode
- Institute an observational period following recommissioning and review operational data to verify the satisfactory operation of the revised Scour Cycle philosophy

RECOMMISSIONING RESULTS AND OPERATIONAL DATA REVIEW

Following the agreement of the Client to the revised operational philosophy, the revised functional descriptions were developed. The software changes were rigorously tested via Factory acceptance tests followed by Site acceptance tests.

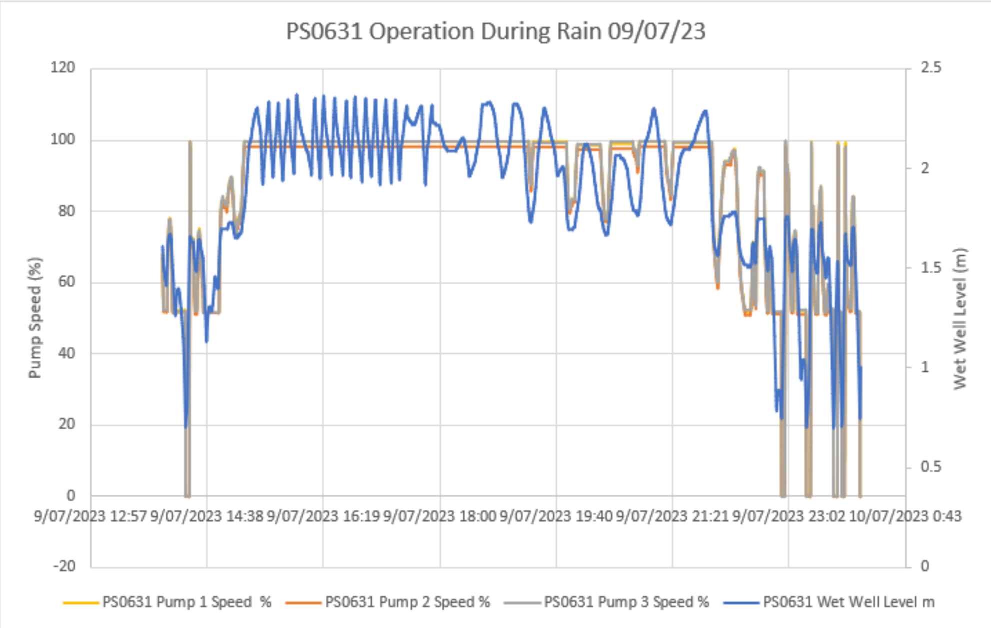
Field Commissioning Witness testing was successfully completed with no overflows.

The scheme was then run for a period of two weeks to verify the revised operational philosophy prior to handover to the client CCC.

WET WEATHER PROVING

Since handover the scheme has had several wet weather events occur that have been handled without any overflows at any point of the scheme. Figure 13 below shows the performance of PS0631 during a recent wet weather event, the most significant since it was commissioned and handed over. The pump station pumped at 100% (120L/s) for approximately 7 hours into the Heathcote Gravity main.

Figure 13: PS0631 performance during Rain Event (Jess Carruthers)



CONCLUSIONS

IMPACT ON SYSTEM FOR CCC/OWNER

Through the combined teamwork of the Commissioning and design teams, including the CCC Operations staff, the Contractor and designer, the cause of the overflows were able to be thoroughly investigated and the solution implemented involved only changes to automation software with no physical changes to the scheme required.

The original intent of the Pinch valve control was to complete regular scouring, and this has been maintained through the revised operational control. The system still operates as intended with the added benefit of reduced actuation movements for the pinch valves which will extend their operational life for the asset owner.

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