THE USE OF HYDRAULIC TRANSIENT MODELLING IN THE DESIGN OF RESILIENT PIPELINES

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ABSTRACT

Pressure surges during the start up, shut down, or sudden power failure of a pipeline can cause operational problems if a pipeline is not designed properly. The issues of buckling under negative pressure and positive pressure peaks which exceed rated pressures can cause a pipeline and its mechanical components to fail much sooner than necessary. The technical challenges encountered when configuring a pipeline for efficient and resilient operation will be looked at.

A long, large diameter polyethylene pipeline exhibits different behaviour to a shorter thin walled mPVC pipeline. The paper will discuss the Surge Analysis of a range of pipelines, solutions to mitigate large surges in pressure, and the analysis and reduction of fatigue loading to extend asset life.

Modelling of such pipelines will be demonstrated through on screen animations and the results of which will be discussed in depth.

Thus, it will be shown how hydraulic transient modelling can be an effective method in identifying problems and developing solutions to ensure pipelines can be designed with resilience in mind and can extend the life of existing assets, saving considerable expenditure.

KEYWORDS

Surge Analysis, Water Hammer, Hytran Modelling, Transients

1 INTRODUCTION

Water hammer can occur in pressure pipelines when there is any change inflicted on the fluid being pumped. This can occur during pump start up, change in pump flows, or when pumping stops. Usually, the most severe water hammer can occur when power to a pumping station is switched off suddenly. The momentum of the pumped fluid can cause pressure waves to propagate back and forward along the pipeline. The result of which, are large spikes in positive and negative pressures experienced at particular locations along the rising main.

Hydraulic Transient Modelling is an effective method in highlighting potential problems with newly designed pipelines and can help identify the reasons why an existing pipeline may not be performing adequately. Although a large number of proprietary software packages are available on the market, projects discussed in this paper have been modelled using Hytran water hammer software from Hytran Solutions (NZ).

1.1 TECHNICAL ISSUES

1.1.1 POSITIVE PRESSURES

When modelling the surge performance of a pipeline, peak positive pressures are one of the key aspects to review. The rated pressure of a pipeline is a maximum pressure which the pipe can be subject to, as specified by the pipe manufacturer. As rising mains are subject to varying degrees of water hammer, it is common practice to design a pipeline so that the normal operating pressure is well below that of the rated pressure of the pipe material used. If specific water hammer modelling is not done, the hydraulic engineer cannot be certain of the magnitude of peak pressures within the pipeline.

Should the rated pressure be exceeded, the rising main's useful life could be reduced, leading to failure.

1.2 NEGATIVE PRESSURES

Negative pressures within a pipeline cause buckling of the pipeline and/or cavitation.

A pipeline can buckle if the negative pressures experienced within the line are greater than the structure of the pipe can tolerate, and the pipe will collapse in on itself. This usually only occurs with high negative pressure and relatively thin walled pipes. If surge modelling of a pipeline shows that significant negative pressures are likely, it is prudent to conduct a specific buckling calculation.

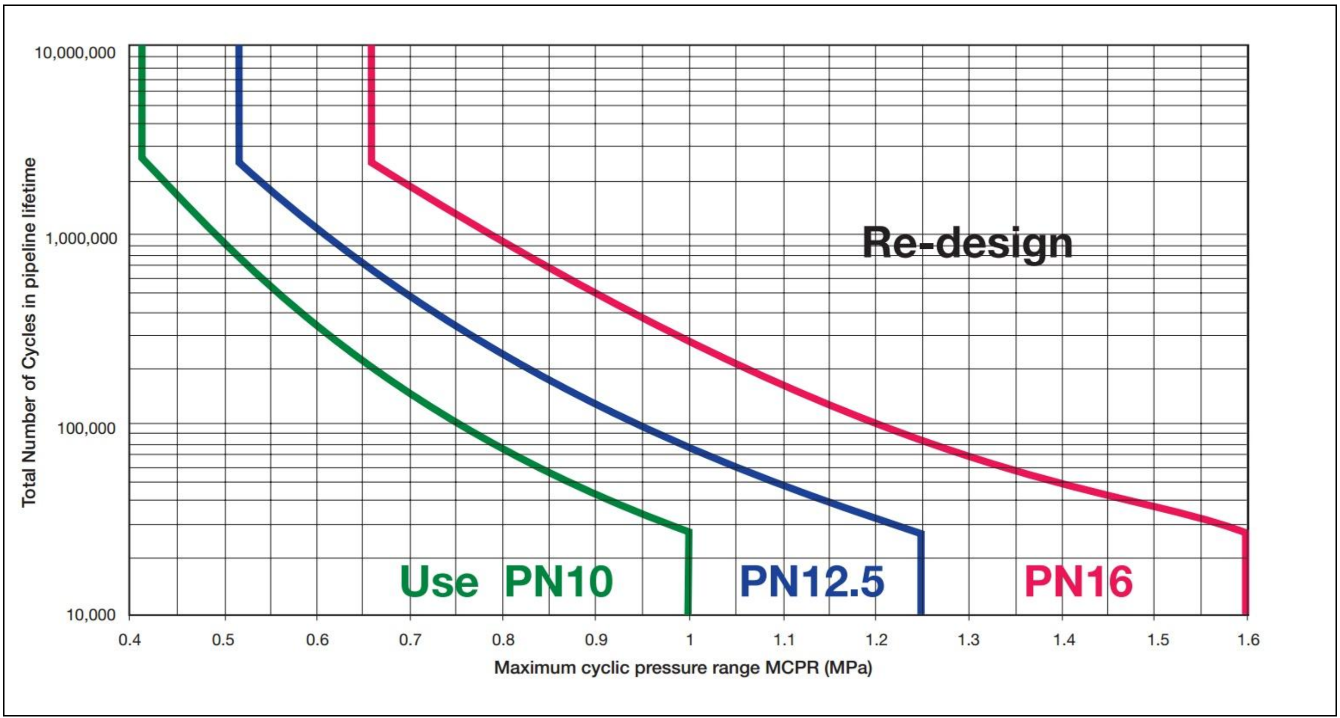
Cavitation occurs when the pressure within a pipeline approaches negative 10m head. It is very important that negative surge vacuums of this magnitude be avoided. If cavitation is left to occur often, the fluid can vaporise and condense very rapidly. This will lead to unnecessary degradation to the surrounding pipe and fittings. If cavitation does occur, excessively high positive pressure can be generated when the water columns re-join.

1.3 FATIGUE LOADING

When some pipe materials are subjected to repeated cyclic loading, which occurs with water hammer, the material can weaken due to fatigue. This type of failure should be checked for, during the design phase, when a large number and/or high amplitude of stress cycles are anticipated. The amplitude or pressure range considered when checking for fatigue loading is defined as the maximum pressure minus the minimum pressure, experienced within a pipeline, during its day to day operation.

For the purpose of pipeline design, if a large pressure range is observed during transient modelling and a pipe material susceptible to fatigue failure is being used, then a fatigue calculation should be done. An illustration of how cyclic loading affects PVC pipe can be seen below in Figure 1.

Figure 1: Re-rated Performance of PVC Piping under Cyclic Loading (Iplex)

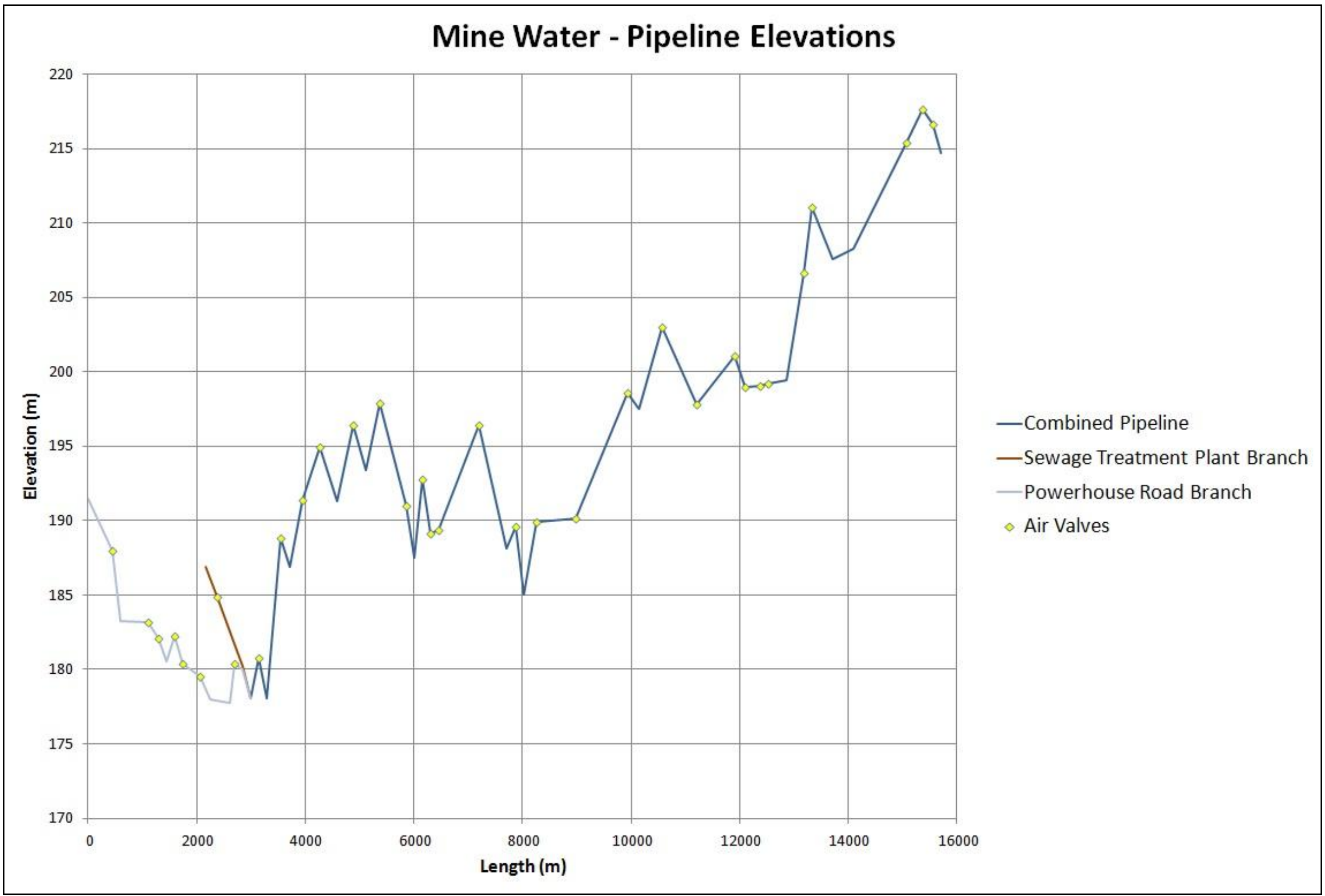


2 EXAMPLE PROJECTS

2.1 MINE PROCESS WATER SUPPLY – QUEENSLAND OUTBACK

The design of a 15.7 km rising main, laid mostly above ground, to service the non-potable water requirements of a Queensland mine, resulted in Harrison Grierson being engaged to conduct a hydraulic surge analysis of the project. Due to the semi-arid climate, the pipeline can draw water from two sources, potable water or treated sewage effluent. The layout of the pipeline is shown below in Figure 2.

Figure 2: Schematic Depiction of Rocklands Pumping System



The main source of water will be the Water Treatment Plant (WTP) pumping station, which takes from the same source as the town's water supply. The secondary source, which will be utilized during dry periods, will be the Sewage Treatment Plant. The specific characteristics of the pumping system are listed below:

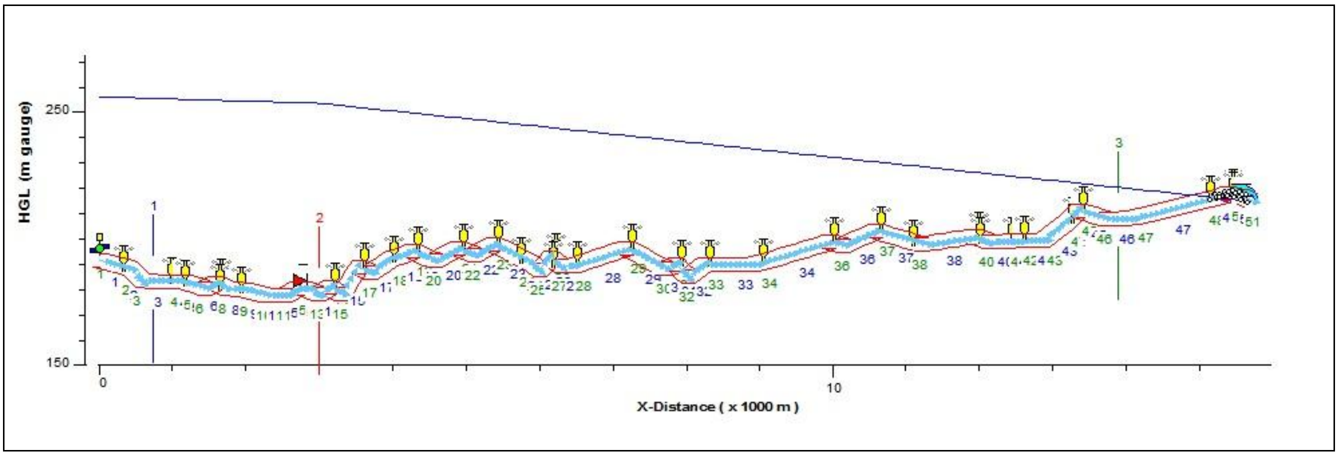
Combined Design Flow	=	23.0 l/s
Pipe Material	=	250 OD PE100 SDR 13.5
Length	=	15.7km

The nature of this investigation was to determine whether or not the pipe material, alignment, air valves specified, and air valve locations were all suitable and did not cause any undesirable affects to the pipeline during its everyday running and during sudden power failure.

2.1.1 MODELLING ANALYSIS

The rising main was modelled to determine the effects of a sudden power failure would have on the system. Figure 3, below, shows the steady state hydraulic grade line (HGL) for the scenario of when both pumping stations producing the combined flow of 23.0 l/s, shown from the WTP pumping station to the discharge point.

Figure 3: Mine Water Rising Main – Steady State Hydraulic Grade Line



When a water hammer model is run, there are two significant ways to view the output data. Firstly, a pressure envelope is produced which shows the maximum and minimum pressures experienced at every location along the pipeline, during a surge event of a specified time duration. The other way is to view the transient data with respect to time at key locations along the pipeline. The transient data locations for this model can be seen above in Figure 3 as the vertical lines labelled 1, 2, and 3. At these locations, the instantaneous pressure is plotted against time to show the analyser exactly when, and to what magnitude, pressure spikes are experienced. Figure 4 and Figure 5 show the Hydraulic Grade Line Envelope and the Transient plots for this model.

Figure 4: Mine Water Rising Main Power Failure – HGL Envelope

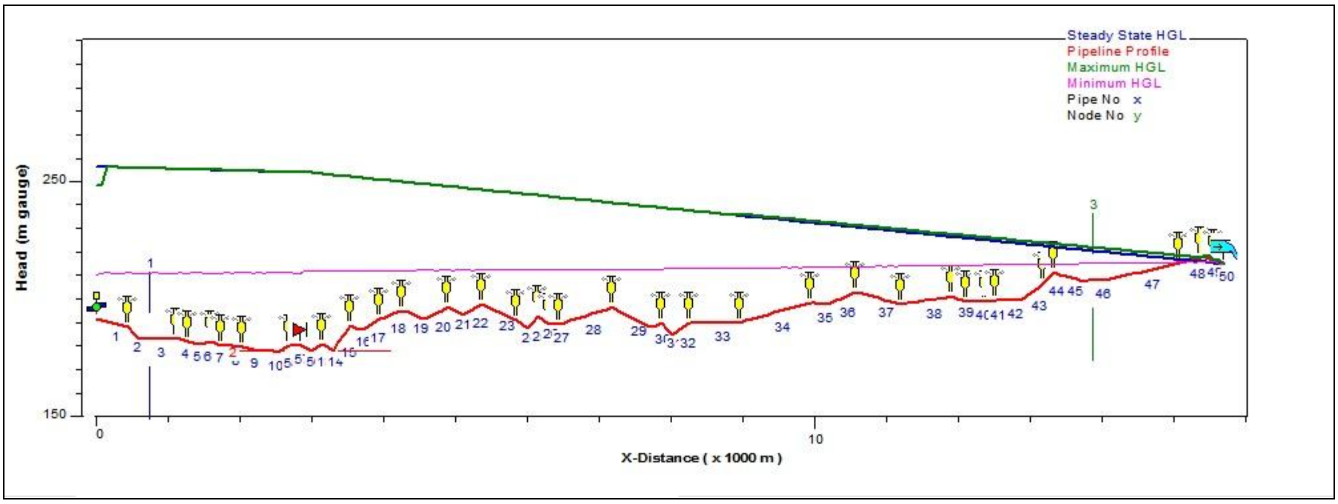
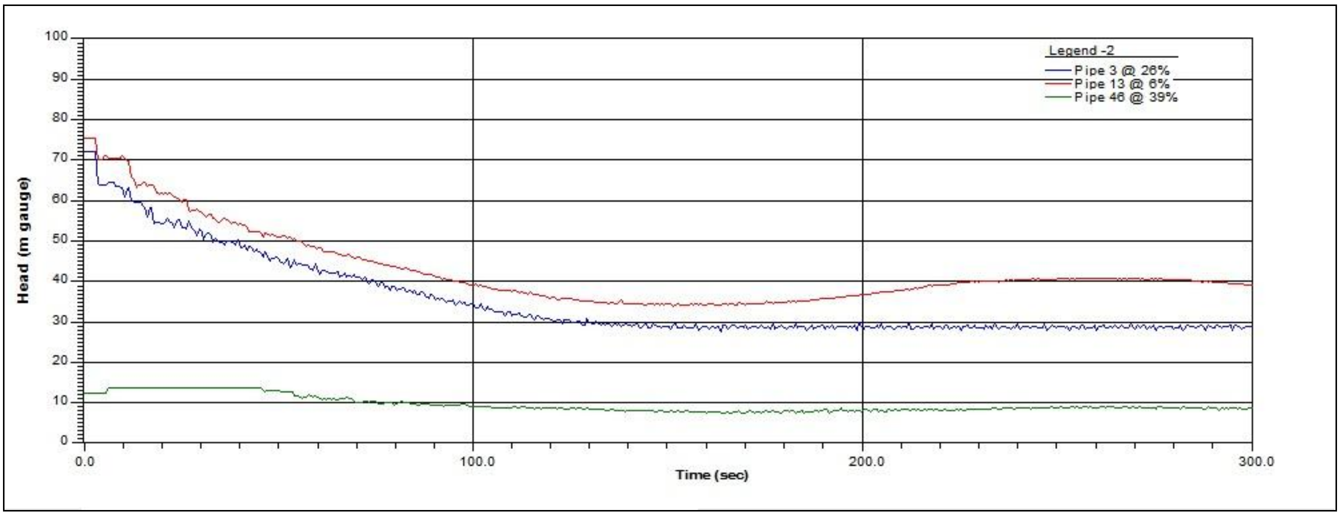


Figure 5: Mine Water Rising Main – Transients Plot



What can be observed from looking at the HGL envelope in Figure 4 is that nowhere along the rising main do significant pressure fluctuations appear to be present. The steady state HGL follows the profiles of the maximum HGL quite closely, with no clear spikes.

The transient plot locations were chosen as they are points where large fluctuations in pressure can commonly occur during a surge event. Some of the maximum pressures experienced in a pipeline during a sudden power failure will be at the pumping station itself.

In this case, the results show that upon power failure, there is a gradual fall in pressure at all three locations, with no significant pressure fluctuations observed. This is often the case in long rising mains with relatively low flows.

2.2 WASTEWATER RISING MAIN – NEW ZEALAND

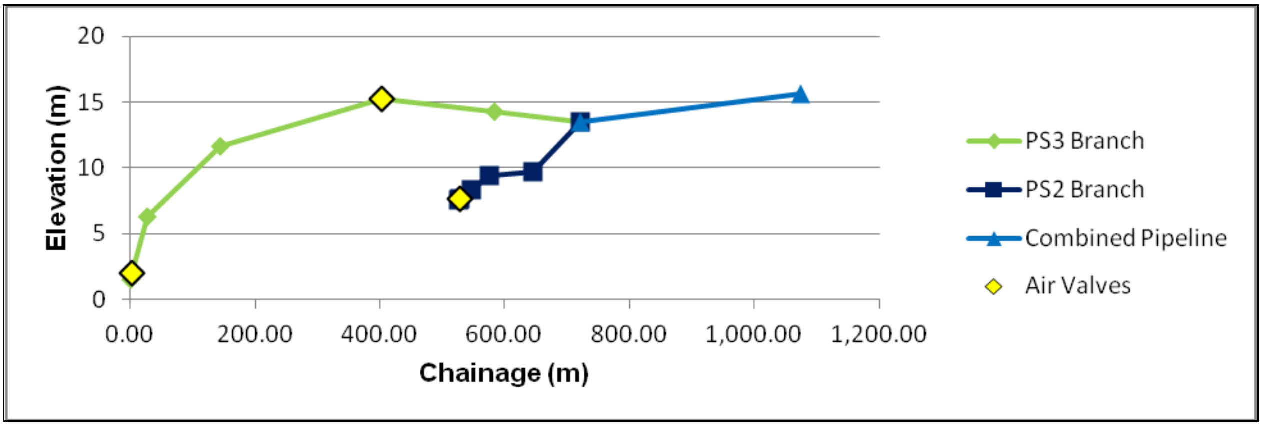
For this project it was necessary to investigate the expected surge within this wastewater rising main produced by two pumping stations, named PS2 and PS3. Both pumping stations will operate independently and therefore, could be pumping on their own or simultaneously. The intended pipe material for this project is polyethylene. The calculated flows expected can be seen below in Table 1.

Table 1: Pump Flows - PS2 and PS3

	PS2	**PS3**	**Combined Flow**
Calculated pump flow with pump running at PS2	39	0	39
Calculated pump flow with pump running at PS3	0	62	62
Calculated pump flow with pump running at PS2 and PS3	33	58	91

The layout of the rising main network is shown in Figure 6.

Figure 6: Schematic Depiction of PS2 and PS3 Rising Main



These pumping stations and pipelines had been designed but had not yet been constructed. It was anticipated that water hammer was going to be an issue with this pumping system as the flows are relatively high for such a short rising main.

This system was analysed using anti-slam air release valves located at each pumping station and at the intermediate high point. Non-return valves were proposed at each pumping station (on the pump discharge pipes) and also on each pipe at the junction, where the rising main from PS2 joins the larger rising main from PS3.

2.2.1 MODELLING ANALYSIS

The cases considered for water hammer modelling were;

a) PS2 operating, normal shut down by soft stop controller

b) PS3 operating, normal shut down by soft stop controller

c) Sudden power failure, PS2 operating

d) Sudden power failure, PS3 operating

e) Sudden power failure, both PS2 and PS3 operating simultaneously.

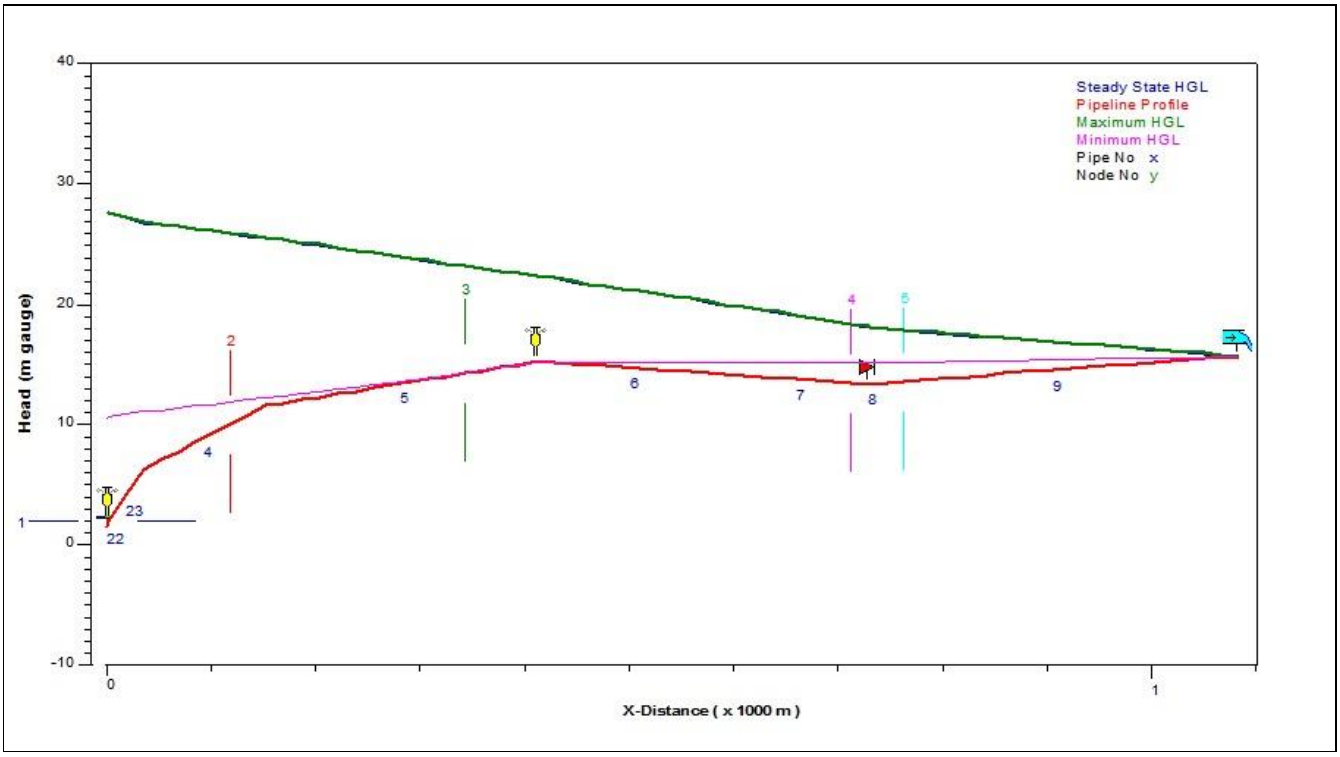
Cases a) and b) are likely to occur several times per day. It is important that these occur without putting undue stress and cyclic loading on the pipeline. As the flow through PS3 is larger than that of PS2, case b) was modelled to show the everyday stresses on the pipeline.

Cases c) and d) will occur relatively infrequently. Power failures to either pumping station may only occur once every year or so. Case e) is an unlikely “worst case” scenario, and would only be expected to happen once every 5 to 10 years. Though the stresses exerted on the pipeline for these three cases are expected to be of a higher magnitude than that of cases a) and b), the events will occur only seldom, and therefore this higher level of stress should be acceptable and not result in material fatigue over the life of the pipe. In all cases, the maximum working pressure of the pipe must not be exceeded, and the pipe must not collapse under a vacuum. Fatigue will not be an issue for cases c), d), and e) as the frequency levels are very low.

CASE B)

The soft stop for PS3 was set at 60 seconds. This was adequate to slow down the momentum of the pumped fluid sufficiently to reduce any severe spikes in pressure. Figure 7 shows the HGL envelope for this scenario. Here we can see that nowhere along the pipeline does the pressure spike to above that of the steady state HGL and that the minimum HGL never drops below the profile of the pipeline, which would indicate a vacuum.

Figure 7: PS3 Soft Stop – HGL Envelope



It should also be noted that the largest pressure range seen in this scenario occurs at the pumping station, measured by transient 1. The fluctuations in pressure deviate from 10m head up to 28m head. This cycle of 1.8bar is significantly low enough that this pipeline will not be affected by fatigue.

CASE E)

The worst case scenario of case e) was modelled to find the maximum stresses which are likely to occur within the pipeline. It is clearly shown in Figure 8 and Figure 9 that when there is a sudden power failure while both pumping stations are running, large down surges are produced in the rising main.

Figure 8: PS2 and PS3 Power Failure – HGL Envelope

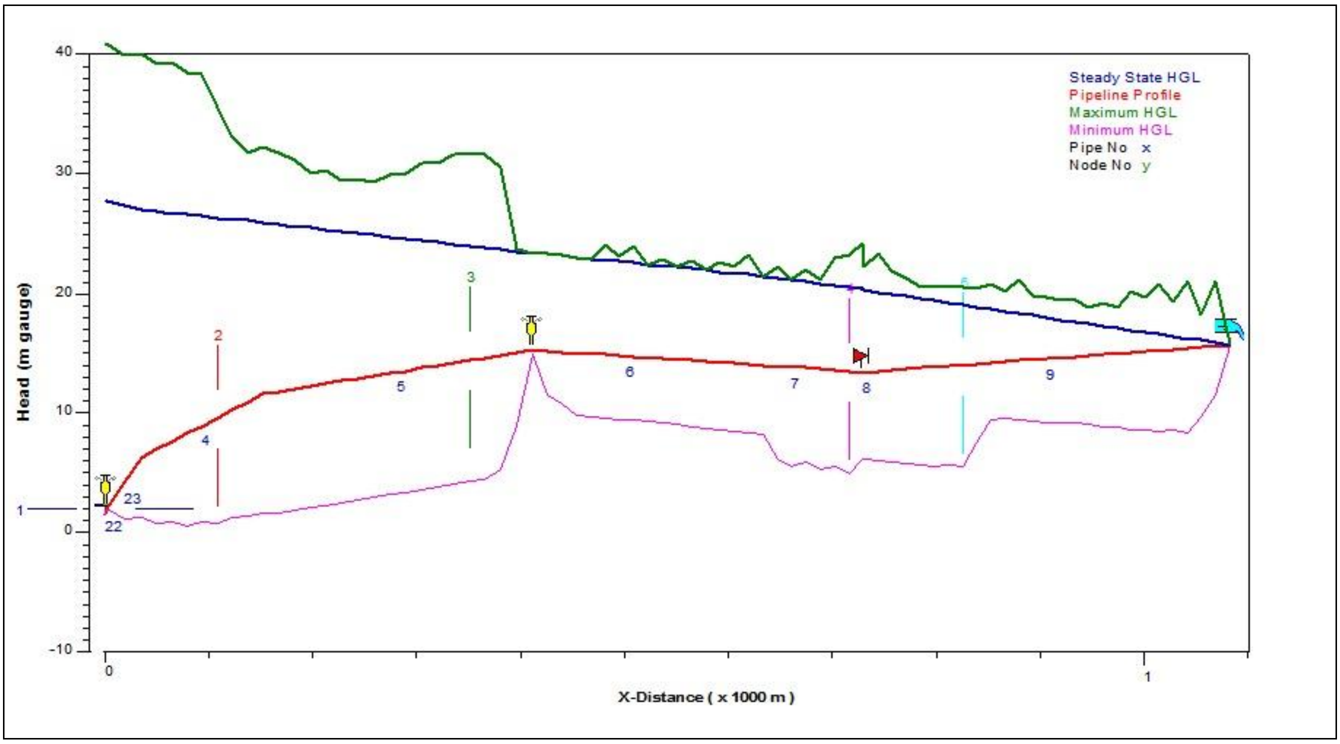
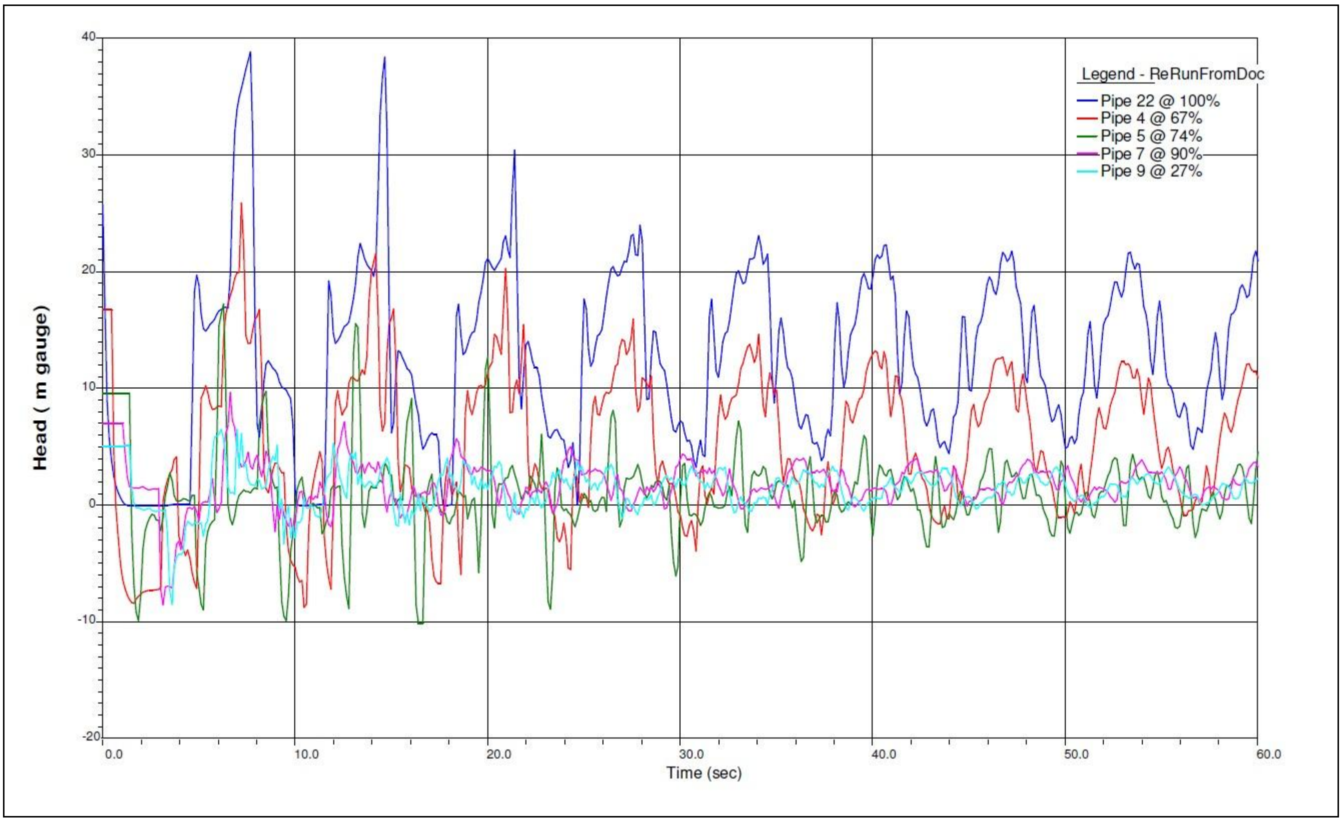


Figure 9: PS2 and PS3 Power Failure – Transient Plot



The model for case e) was run for 60 seconds. The surge which appears to reverberate in the pipeline has a maximum pressure observed of around 4 bar. The pipe materials being considered for this project all have a rating of at least 10 bar, therefore the maximum upsurge pressure is not a design constraint.

The maximum downsurge pressures, however, are a point of concern. Transient 3 shows pressure within the pipeline dropping, virtually to -10m head, almost a complete vacuum. This finding highlighted the need to check the pipe specification for buckling.

The pipe buckling calculation was conducted in accordance with AS/NZS 2566. It was found that PN10 pipe was theoretically non-compliant under the imposed vacuum of -10m, whereas PN12.5 pipe was compliant. Therefore, PN 12.5 polyethylene pipe was selected as the pipe material for this project as part of the detailed design.

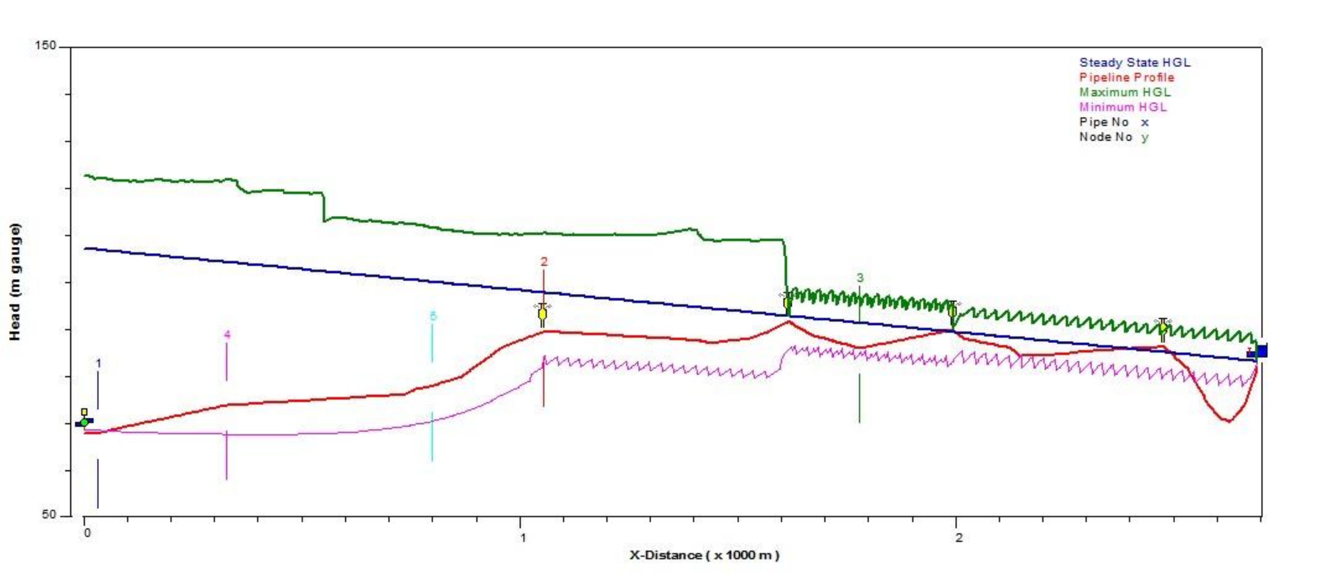
It is acknowledged that at negative pressure of -10m, cavitation could occur. However, due to the infrequent occurrence of this event, it is unlikely to result in damage or fatigue of the pipeline.

2.3 TREATED EFFLUENT PUMPING – NEW ZEALAND

Harrison Grierson was commissioned to prepare a report to identify concept design solutions for increasing an effluent pumping station capacity from 420 m^3/h, up to 700 m^3/h. The existing rising main is a 2.7km long, 375mm mPVC class C pipeline delivering effluent from the oxidation pond to a marine outfall.

It was found that the maximum pressure which could be expected upon power failure would be around 63m at the pumping station, decreasing rapidly along the line. As this pressure was marginally over the de-rated pressure rating of 6 bar for the pipe, it was recommended that the first 200 to 300m of the pipeline be replaced with 10 bar rated PE pipe. Figure 10, below, shows the system pumping at 700 m^3/h and reacting to a sudden power failure.

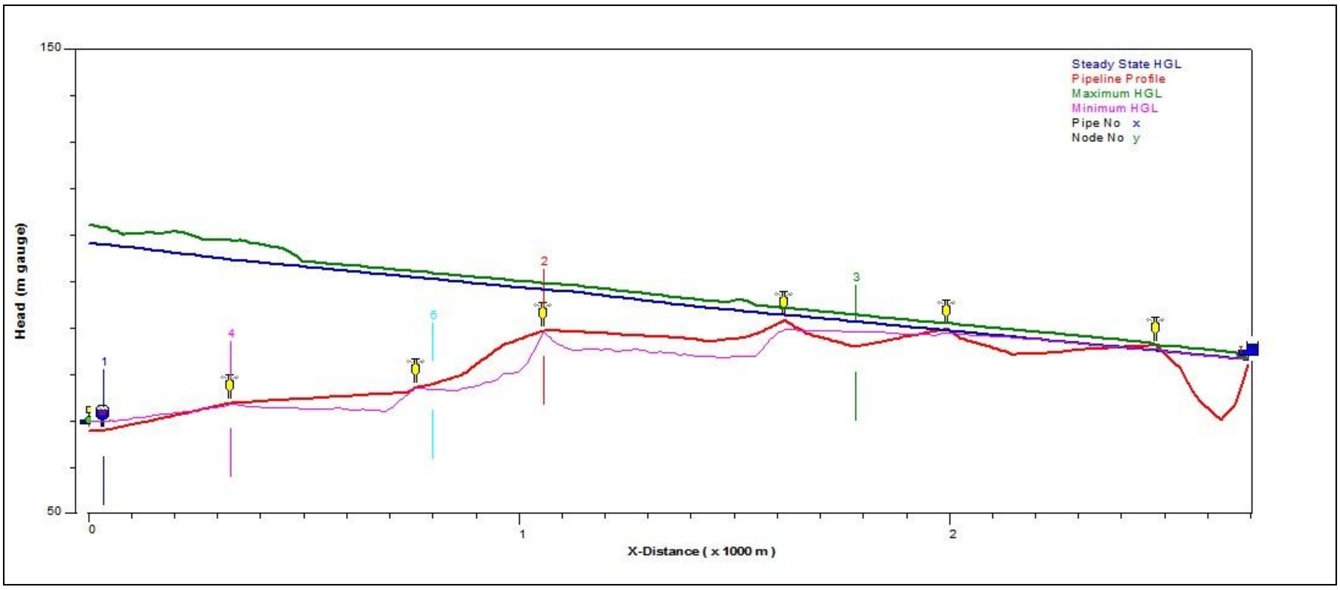
Figure 10: Effluent Pumping Power Failure – HGL Envelope



A range of pump upgrades were reviewed for this project. It was recommended that a pump with the ability to have the impellor upgraded at a later date would give the client the most flexibility with regards to increasing capacity of the pumping station in the future. Variable speed drive (VSD) units were proposed which would reduce surge effects during normal operation by slowly ramping up and down the pump performance. Under these conditions, maximum positive and negative pressures will be kept well within acceptable limits of the pipe material, and will also reduce fatigue. However, as Figure 10 shows, under the power failure scenario, there are negative pressures of up to -10m in places, which is excessive.

The proposed solution for this was the addition of two air valves situated within the first kilometre of the rising main, and a 2m^3 hydro-pneumatic tank installed immediately downstream of the pumping station. The results were extremely successful. Figure 11 shows how the maximum negative pressures were reduced considerably, as well as reducing the maximum positive surge spikes to only slightly above the steady state HGL.

Figure 11: Effluent Pumping Power Failure (with a Hydro-Pneumatic Tank Installed) – HGL Envelope



2.4 MEATWORKS EFFLUENT RISING MAIN – NEW ZEALAND

An aging 1.5 km DN 200 asbestos cement (AC) rising main had failed several times and both the council and company were concerned about maintaining operation of this pipe until a new pipeline could be built in about two years time. Harrison Grierson were asked to consider possible causes of the failure and to suggest temporary solutions.

Pressure testing of the pipeline was done during regular start up and shut down. The operating pressure at the pumping station was measured at 53m head. Field testing showed that surge spikes were observed 10 seconds after pump shut down, with pressure fluctuations ranging from 0m to 63m head.

As the budget for this project was limited, specific water hammer modelling was not an option and this field testing of the pipeline was what recommendations needed to be based on. It was assumed that the existing VSD was ramping down too quickly and the suggestion was made to repeat the field testing with the VSD speed ramp down set to a longer period. The results were that surge rebound reduced to 42m, which was less than the 53m of the operating pressure.

After these operational changes were made, no more pipeline failure occurred under normal operating conditions, and the pipeline was decommissioned a few years later. The changes suggested did not require any capital expenditure, an excellent result for both the company and the environment.

3 TECHNICAL COMPARISONS

The technical data associated with the projects discussed in this paper is given in brief below.

Table 2: Comparison of Pumping Systems

Project	Flow	Maximum Positive Head	Mitigated Maximum Positive Head	Maximum Negative Head	Mitigated Maximum Negative Head	Surge Mitigation Method	Rising Main Length	Pipe Material	Pipe Diameter	Flow Velocity
	L/s	m	m	m	m		m		mm	m/s
Mine Water Supply Pipeline							**15700**			
Water Treatment Plant to Junction	11.5	72	-	-	-		3000	PE100 SDR13.6	250 OD	0.33
Sewerage Treatment Plant to Junction	11.5	75	-	-	-	-	830	PE100 SDR13.6	250 OD	0.33
Junction to Discharge Point	23	76	-	-2	-		12700	PE100 SDR13.6	250 OD	0.65
Wastewater Rising Main							**1080**			
PS3 to Junction	58	40	26	-10	0		404	PE100 SDR17	280 OD	1.32
PS2 to Junction	33	24	17	-7	0	Soft Stop	199	PE100 SDR17	200 OD	1.56
Junction to Discharge Point	91	10	7	-8	0		676	PE100 SDR17	315 OD	1.60
Treated Effluent Pumping Rising Main							**2658**			
Pumping Station to 1000m	700	55	44	-10	-7	Hydro-Pneumatic Tank + 2 additional Air Valves	1000	mPVC	DN 375	1.80
1000m to Discharge Point	700	24	14	-10	-5		1658	mPVC	DN 375	1.80
Meatworks Effluent Rising Main										
Pumping Station to Gravity Wastewater Line	55	63	42	14	-	VSD Re-programmed	1510	AC	DN 200	1.77

4 CONCLUSIONS

Many problems can arise when one endeavours to design an efficient and resilient pipeline. A number of technical issues need to be carefully thought through in order for adequate longevity of a pipeline to be achieved. With forward thought at the design phase of a project, it is possible to see the potential problems which could present themselves, and save on costs in the long run.

This paper has shown that hydraulic transient modelling is an effective tool in predicting the behaviour of a pipeline under a range of conditions. It is evident that a lot more thought goes into fixing the water hammer problems of existing rising mains than what is needed at the design phase of a project.

Experienced designers will know when it is important to analyse pipelines for water hammer, fatigue, and buckling. Failure to perform the analysis of these factors can lead to premature and sometimes catastrophic pipeline failure, possibly with serious environmental consequences.

Effective modelling and analysis for water hammer, fatigue, and buckling can avoid costly errors and achieve economic solutions to mitigate serious problems.

ACKNOWLEDGEMENTS

Dr. Norman Lawgun – Hytran Solutions (NZ)

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