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# Importance of transient analysis in successful design and operation of underground paste distribution systems

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## Abstract

*The initial design of a paste underground distribution system (UDS) traditionally relies on steady-state hydraulic analyses to specify the piping. While this approach offers a useful baseline, it often fails to capture the full range of operating conditions encountered in practice. Transient events, such as paste pump trips, pipeline filling, pipe blockages and ruptures, and poor operator control, will introduce pressure surges that may compromise system integrity, safety, and operability. This paper highlights the importance of incorporating transient analysis into the design phase of paste backfill distribution systems, particularly for complex networks with multiple discharge locations, elevation changes, or long pipe runs.*

*Using case studies and simulation results, the paper demonstrates how transient modelling identifies vulnerabilities in the design not apparent under steady-state conditions. Once potential flaws in a design have been identified, the analysis can guide the selection of mitigation strategies, including, but not limited to, appropriate pipe specification, adequately sized pipe supports, and ensuring operators run the paste UDS at the correct operating conditions. In addition to protecting the UDS, transient analysis supports robust commissioning planning and reduces the likelihood of costly downtime or system failure post-implementation.*

*The discussion is centred around the practical challenges and lessons learned from recent paste backfill projects, reinforcing that transient analysis should be regarded not as an optional consideration, but as a critical component of responsible UDS design.*

**Keywords:** *paste transport, underground distribution system, hydraulic modelling, transient analysis, safety*

## 1 Introduction

The success and safety of modern mining operations depend on the reliable delivery of paste backfill to underground stopes. Without the timely deposition of paste, planned mining sequences can be disrupted, especially as many current mine plans assume high extraction rates and require quick stope turnarounds.

Paste underground distribution systems (UDSs) are complex hydraulic networks that transport highly viscous material through long underground pipelines. As mines extend deeper and distribution networks become more intricate, understanding the full hydraulic behaviour of these systems becomes increasingly important.

There is a tendency to only rely on steady-state hydraulic analysis to determine baseline flow conditions, pipe sizing and pump selection for UDS design. While this approach is valuable as a starting point, it is limited in fully understanding the operational behaviour within a modern UDS. In practice, events such as pump trips, pipeline filling, variations in paste density, pipeline blockages or pipeline rupture can introduce transient pressures that result in significant surge events. If not properly understood, these pressure fluctuations may exceed design limits, compromise pipeline integrity and cause operational challenges.

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Transient analysis provides a means to predict and manage these effects by simulating the UDS time-dependent response to various operational scenarios. Integrating this into the design phase enables engineers to identify vulnerabilities not apparent under steady-state conditions and to develop robust design solutions. These may include refining pipe specifications, adjusting support designs, upgrading the pump dampener system and selecting suitable safety measures and operating protocols.

This paper discusses the importance of transient analysis in the design of a paste UDS. Through selected case studies, the paper demonstrates how transient modelling can identify vulnerabilities that steady-state analysis alone may overlook. The lessons presented emphasise that transient analysis should be regarded as a standard component of responsible paste backfill system design rather than an optional consideration.

# 2 Definitions and methodology

In steady flow, pressure and flow rate remain constant with time at any point in a pipeline system. In unsteady flow, these parameters vary with time. The 'term transient' flow describes unsteady flow in pipelines. A more familiar term for transient flow is 'water hammer', commonly known as the noise made from rattling pipes when rapidly opening or closing a household tap.

The assumption of steady flow conditions when designing a UDS is valid for most design considerations, where the change in flow rate and pressure is gradual. However, the greatest risk to any operating UDS is when a transient event occurs, where flow conditions change rapidly and pressure surges can exceed the system's pressure design limits.

A transient analysis should therefore follow the completion of a steady-state hydraulic design in the overall design process of a UDS. Specialist engineering, analysis and experience are needed to understand, mitigate and control the high risks that may occur due to transient events. The design of a reliable and safe pipeline system depends on understanding these transient pressures, the resulting transient forces, and overall loads that the UDS will experience in operation.

## 2.1 Causes of transient events

Transient pressures are generated by any event that causes a change in flow conditions over time. In general, the magnitude of the velocity change in the pipeline directly correlates to the magnitude of the transient pressure (further described in Section 2.2.1 – the rate at which this change occurs is only significant relative to the pipeline period).

In paste backfill systems, transient analysis is typically focused on transient events that cause the flow velocity to change, such as:

- flow fluctuations from positive displacement (PD) pump strokes
- PD pump trip
- emergency flush pump trip
- effectiveness of external hydraulic pulsation dampener (HPD)
- pipe blockage and rupture (including blasting tee or rupture device events)
- rapid valve actuation (e.g. diverter valve or emergency paste dump).

## 2.2 Basic principles

### *2.2.1 Joukowsky pressure equation*

A fundamental method that can be used to quantify transient pressures, and give an initial estimate, providing a rough approximation of the maximum transient pressures, is obtained using the Joukowsky pressure equation (Tijsseling & Anderson 2007), as shown in Equation(1).

$$\Delta P = \rho c \Delta V \tag{1}$$

where:

$\Delta P$ = magnitude of the pressure surge (Pa)

$\rho$ = density of the fluid (kg/m$^3$)

$c$ = transient wave speed (m/s)

$\Delta V$ = velocity change (m/s).

This equation states that the surge pressure resulting from a transient event is linearly proportional to the change in flow velocity. This equation is practical for estimating the maximum transient pressures in the system by assuming that the maximum flow velocity will be quickly stopped during an upset condition. To assess if the Joukowsky pressure estimation is valid, the duration of the event must also be considered. The pipeline period can be defined as the amount of time that it takes for a transient pressure wave to travel through a pipeline system and be reflected back to the point of origin, as shown in Equation 2.

$$T = 2L/c \tag{2}$$

where:

$T$ = pipeline period (s)

$L$ = pipeline length (m)

$c$ = transient wave speed (m/s).

To achieve the full transient pressure magnitude predicted by the Joukowsky equation, the transient event duration must be shorter than the pipeline period. If Equations 1 and 2 indicate that significant transient pressures are expected to occur, then completing a detailed transient analysis is crucial to designing a safe pipeline system.

However, this methodology does not account for interactions and the actual pipeline system characteristics. As a transient pressure propagates through a piping system, it will reflect off boundaries in the system such as the paste pump or a pipe blockage. Reflecting pressure waves can interreact with each other, resulting in additive waves that exceed the initial transient pressure. In addition, transiently occurring low pressure regions can result in vapour cavity formation and closure, leading to the creation of additional transient pressure waves, where the magnitude is caused by the velocity of the liquid during the vapour cavity closure. This is likely the worst case transient scenario and can be worse than the prediction provided by the Joukowsky equation (considering that the cavitation closure velocity could be larger than $\Delta V$ in Equation 1).

Equation 1 requires an estimate for $\Delta V$ and assumes an instantaneous change in velocity. Velocity change can be easily defined for inline changes in velocity due to pumping but can be more difficult when looking at branch flow due to rupture disc burst events or emergency dump valves opening.

Due to the complexity of UDS, the Joukowsky pressure equation can underpredict the maximum transient pressure expected. To fully understand and evaluate transient flow behaviour, the entire pipeline system needs to be modelled using commercial software such that the transient pressures and forces can be accurately determined.

### *2.2.2 Commercial software*

To fully understand transient behaviour, the entire UDS should be simulated using specialised commercial software. Such tools will consider many variables, including pipeline profile, transient event location, pipeline and paste fill properties, speed of transient events, and interactions of transient pressures in the pipeline system (Jacobs et al. 2023), providing a more-accurate analysis and increased confidence in simulation results. The transient model components of a typical analysis using commercial software are presented in Figure 1.

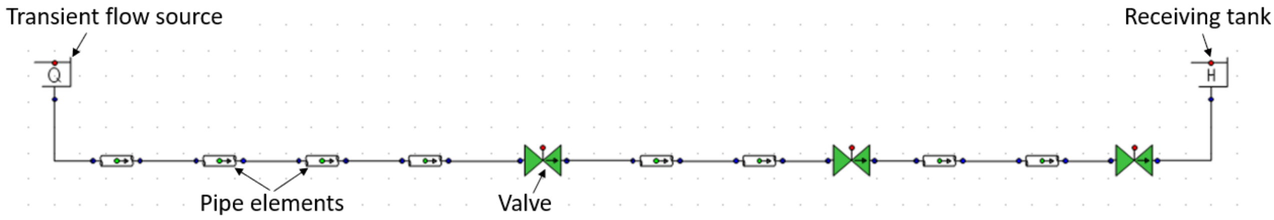


**Figure 1 Typical transient model components using commercial software (Correia & Jacobs 2024)**

# 3 Case studies

In some cases, transient pressures can significantly exceed pressures predicted by the steady-state analysis. If a transient analysis is not performed and these pressures are not accounted for in the piping design, pressures could exceed the design rating of piping or components in the UDS, presenting serious safety risks to people and damage to property. Several case studies are presented in this paper providing examples of actual operations where the outcomes of a steady-state analysis did not adequately understand the operational behaviour.

## 3.1 Case study 1: changing operating parameters

Éléonore mine, located in northern Quebec, Canada, has an operating paste UDS. The UDS has a short surface borehole followed by a ramp to 140 Level. After 140 Level, a series of internal boreholes distribute paste approximately 1,400 m down, with level piping branching off to the stopes.

Éléonore mine was experiencing significant transient forces in their paste UDS, which was causing significant damage to the pipeline supports. Figure 2 shows an example of a rockbolt used to secure a support for UDS piping sheared off due to transient forces.

**Figure 2 Rockbolt from underground distribution system support sheared by transient forces (McGuinness et al. 2021)**

A typical hydraulic grade line (HGL) plot of the UDS pouring paste to the middle of the orebody is presented in Figure 3. The plot indicates the pressure at any point in the pipeline as the gap between the steady-state line and the natural grade line (pipeline profile). The maximum and minimum transient pressures (shown as head max and head min) are also indicated.

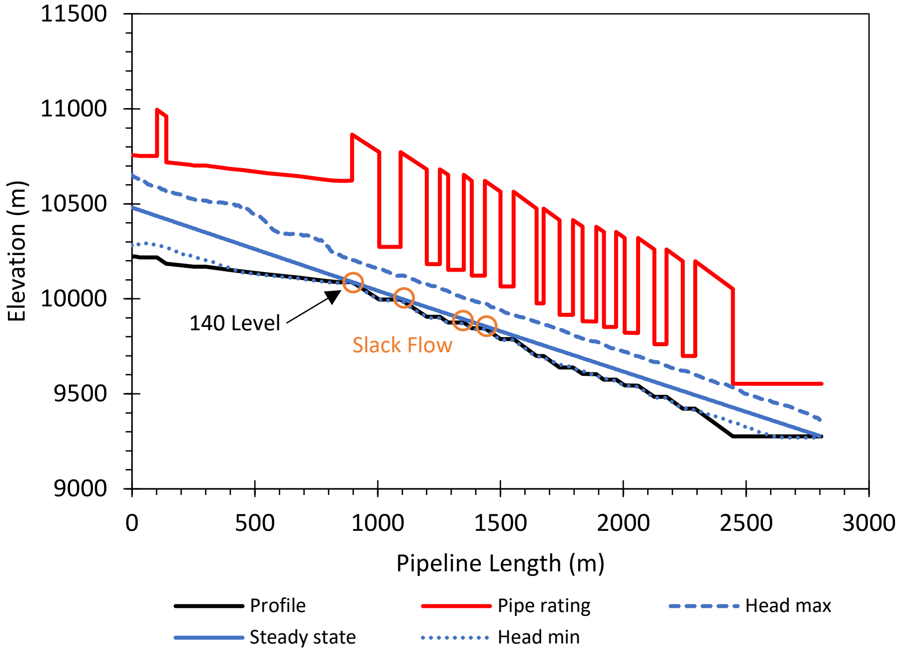


**Figure 3 Example of Éléonore mine paste underground distribution system hydraulic grade line plot (McGuinness et al. 2021)**

The system exhibited the potential for slack flow conditions as the steady-state line intercepts the natural grade line at several points – around 140 Level (elevation 10,140 m), in particular. Slack flow conditions can arise when the absolute pressure inside a pipeline falls below the liquid or slurry vapour pressure. Typically, this occurs downstream of a local high point along a pipeline route. In a slack flow condition, the slurry will flow with a free surface (i.e. open channel or launder flow). If the pipeline slope is steeper than the hydraulic gradient when the pipeline is flowing in slack flow, the slurry will accelerate until it reaches a velocity such that the friction losses equal the pipeline slope. This velocity may be significantly higher than the full flow rate, resulting in rapid erosion of the pipeline invert.

To examine the transients in the Éléonore mine paste UDS, McGuinness et al. (2021) collected pressure data underground using in situ high speed measurements and compared these against a model developed using commercial transient software. Pressures collected underground lined up closely with pressures predicted using commercial transient software, with amplitude of the pressure peaks and frequency aligning.

McGuinness et al. (2021) observed that when the UDS is operating in slack flow, the transients are focused on the upper section of the UDS and that the transient forces always exceed the 35 kN load rating of the normal (light) duty anchors and sometimes exceed the 150 kN load rating of the heavy duty anchors (Figure 4).

The authors observed that operating solids concentration and resulting yield stress had a large impact on the transient forces experienced in the UDS. In Figure 4, yield stress increases from 159 to 325 Pa. As yield stress increases, friction in the pipeline increases, resulting in a steeper HGL slope, representing higher pressures throughout the UDS. As pressures increase, areas of slack flow are eliminated.

The mine was typically operating at reduced yield stress, preventing transients from travelling to lower sections of the mine, due to the break in the pressurised pipeline at the slack flow section (Test 9.1 and 9.1B). However, the transients were shown to reduce significantly when operating with higher yield stress and in full flow conditions with a fully pressurised pipeline (Test 9.1D and 9.1F).

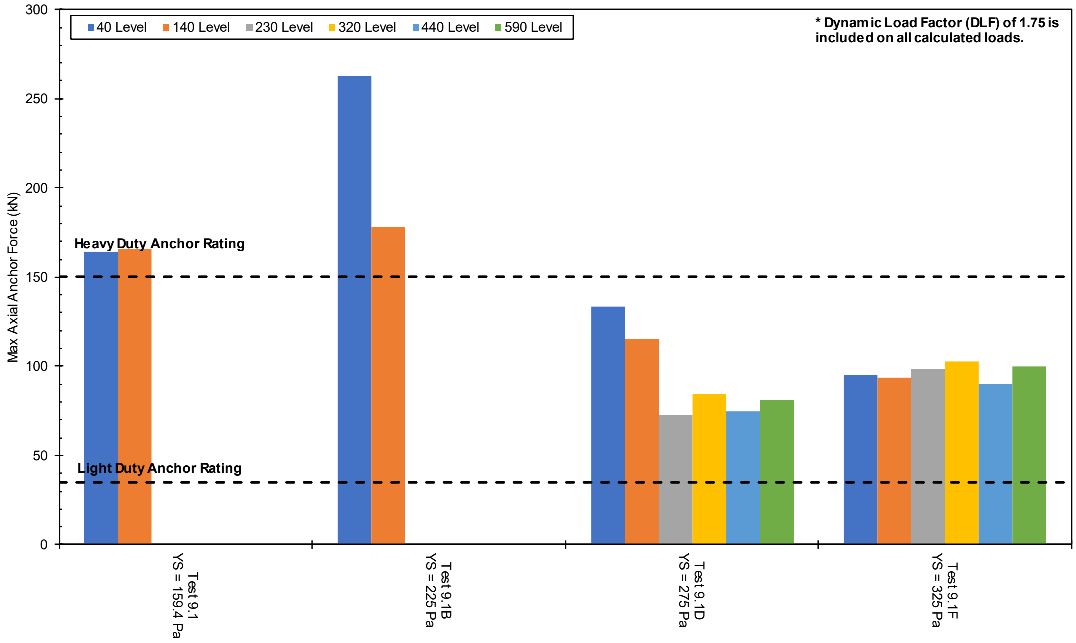


**Figure 4 Effect of yield stress on transient forces (McGuinness et al. 2021)**

## 3.2 Case study 2: flow fluctuations from positive displacement pump strokes

Manufacturers of hydraulically driven PD piston pumps, typically used for paste fill applications, recognise the importance of limiting transients from their pumps and have continuously been working to develop and improve technology that reduces the magnitude of changes in velocity in their pumps that used poppet valves. Technology to dampen pulsations in the pumps that use swing tubes also exists using an external HPD, but it will need further development to match the performance of poppet valve pumps or piston diaphragm pumps.

Correia & Jacobs (2024) used transient analysis to compare various paste pump technologies, demonstrating the downstream effects of pump selection on the overall UDS design. The main input used to compare different pumping technologies is the flow curve over time from the discharge of the paste pump.

Transient analysis can be used to compare a system with and without pulsation dampening technology, helping mine owners to make informed decisions when selecting a paste pump. The authors compared 3 hydraulic piston pumps and a single piston diaphragm pump (with and without a functioning dampener). The maximum transient force produced by each paste pump option varied greatly (Figure 5).

Investing more capital into paste pumps with pulsation dampening technology can reduce the overall cost of the system by allowing for a reduced pipe restraint system throughout the UDS.

Large forces and movement of underground piping will act directly on the piping and end connections. The industry standard for UDS end connections is to use mechanical couplings. While they are quick and easy to install, offering great operability, they do have reduced allowable end loading and bending moments, when compared to flanged piping. If transient pressures, transient forces, and the support system are not adequately understood and engineered, the mechanical end couplings can fail, leading to leaks that pose safety concerns and can interfere with mine operations.

Figure 6 shows an example of a mechanical end coupling that failed due to fatigue from cyclical transient forces in the UDS induced by the paste pump pressure fluctuations. To overcome this issue, the authors have observed some sites welding additional steel onto pipe ends and around the mechanical couplings, increasing rigidity and preventing failure (Figure 7). This is a time-consuming activity that also reduces the operational flexibility benefits of mechanical couplings.

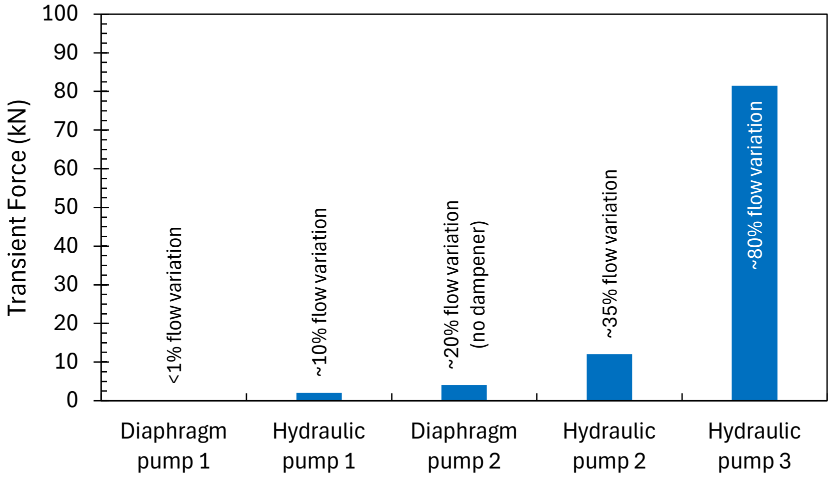


**Figure 5 Maximum predicted transient forces (Correia & Jacobs 2024)**

**Figure 6 Mechanical end joint coupling failure (Correia & Jacobs 2024)**

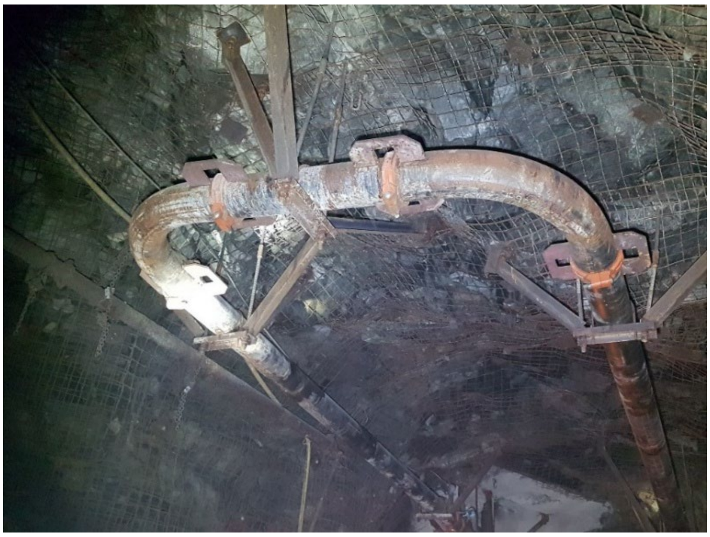

**Figure 7 Additional reinforcement added around mechanical couplings**

## 3.3 Case study 3: effectiveness of external hydraulic pulsation dampener

Unlike hydraulic piston pumps equipped with poppet valves, where dampening is controlled via a sophisticated hydraulic power pack, a swing tube pump relies on an external dampener to absorb pressure transients and smooth out flow. The HPD effectively functions as a third cylinder, installed on the paste pipeline immediately downstream of the pump's outlet flange. During operation, the HPD compensates for a loss in flow between pump piston strokes by gradually accumulating paste during a paste stroke and then discharging paste into the pipeline during the cylinder switch.

The HPD operation is synchronised with the pump cylinder positions. Proper timing is critical to minimise transients within the UDS. McGuinness et al. (2021) investigated the impact of HPD misalignment on UDS performance and showed that synchronisation between the pump and HPD strokes had a large influence on transient behaviour (Figure 8). Consistent and predicable HPD performance is key for reducing the transient forces in a UDS.

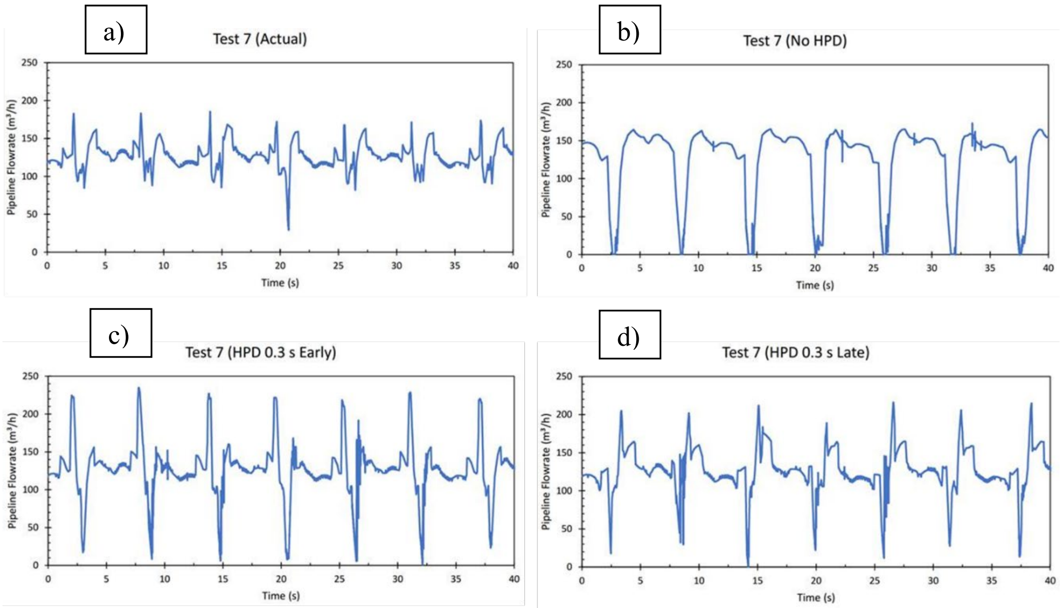


**Figure 8 Flow rate profile for various hydraulic pulsation dampener (HPD) scenarios (McGuinness et al. 2021). (a) HPD aligned with positive displacement pump strokes; (b) no HPD; (c) HPD starting early; (d) HPD starting late**

The authors showed the most severe transient events occurred when the HPD timing was out of phase with the pump cycle. If the HPD stroke initiates too early, the pipeline flow rate can momentarily double, generating higher transient forces compared to if no HPD were used. Conversely, if the HPD stroke begins too late, the flow rate may drop to zero during each cylinder switch, again producing abrupt flow changes and a corresponding increase in transient forces.

## 3.4 Case study 4: rupture disc burst event

Rupture discs are critical elements installed in the UDS that are designed to burst before pressures exceed the design pressure of the piping. They should not fail during normal operation and will typically only burst if the UDS piping becomes blocked.

Typical rupture discs used in the UDS are top-hat style (Figure 9) to reduce the dead leg lengths and reduce the chance for a cemented plug of paste to form in front of the rupture disc. The disc itself is a precisely machined and scored plate of steel designed to fail at its burst set pressure. When they burst, a rapid release of pressure occurs as paste fill discharges out of the piping system through the rupture disc. This rapid drop in pressure typically results in the highest transient forces that will occur in a UDS.

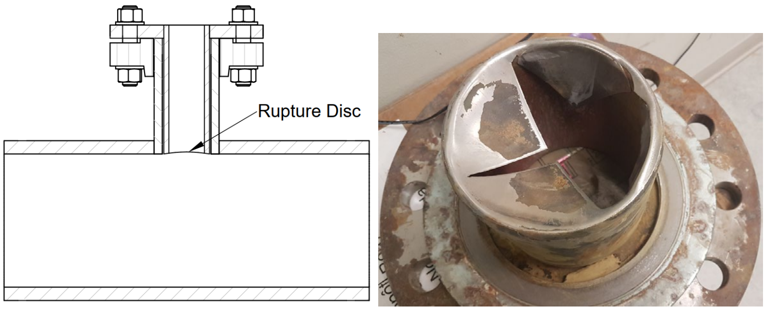


**Figure 9 Top-hat style rupture disc. (a) Typical rupture disc arrangement in piping; (b) Burst rupture disc**

### *3.4.1 Rupture disc sizing*

Rupture disc size refers to the diameter of the rupture disc, which must be sized and specified by the design engineer.

If a rupture disc is sized too small, the pressure-relieving capacity will be limited. This can cause pressures to continue to rise in the piping system after a rupture disc has burst, defeating its purpose to protect the pipeline system from excessive pressure. By modelling a rupture event with transient software, rupture discs can be sized with confidence so that they will have sufficient relieving capacity to protect the system from overpressure.

Sizing can also be optimised to reduce the transient force in a system generated from a rupture disc event. Limiting the size of a rupture disc reduces the instantaneous drop in pressure in the pipeline when the rupture disc bursts, which reduces the resulting transient force.

Figure 10 shows an analysis of various rupture disc sizes, and the pressure upstream of the rupture disc. The figure also lists the calculated axial transient forces for the various rupture disc sizes. Optimisation of the rupture disc diameter was completed, selecting 40 mm, which allows for sufficient pressure-relieving capacity, while also minimising the resulting axial transient force on the UDS.

Transient forces are a key component to be considered when designing the support system of a UDS. Modelling and defining transient pressures and transient forces from rupture disc events is critical to ensure the axial anchors in a system are large enough to restrain the maximum transient force events.

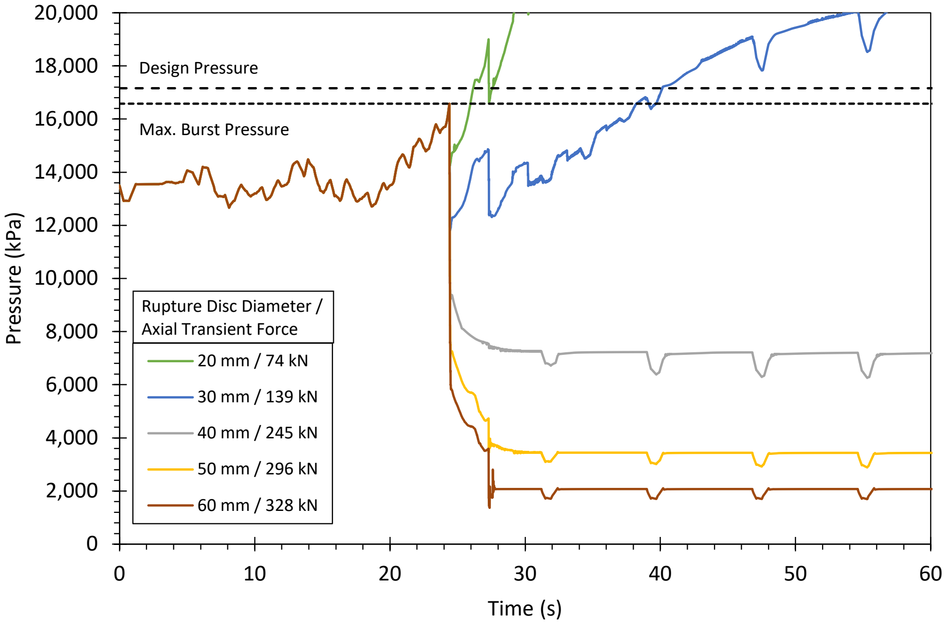


**Figure 10 Pressure upstream of rupture disc for various sizes**

### *3.4.2 Rupture disc transient pressure*

Transient pressures do not quickly attenuate and will travel throughout the entire UDS, provided the entire pipeline is pressurised and full of paste. Therefore, transient pressure events that happen underground, such as a rupture disc burst event or pipeline blockage, are not isolated to the underground and will travel back to the surface plant and its piping, valves, and pump.

Figure 11 shows an example of a transient model simulating a blockage at 2,100 m and rupture event at 1,725 m in the UDS. As the pipeline becomes blocked and flow reduces, pressures in the system begin to rise from the steady-state operating condition. The increase in pressure triggers a rupture disc to burst, creating a transient event (an additional transient event as increasing pressure from a blockage is already a transient event).

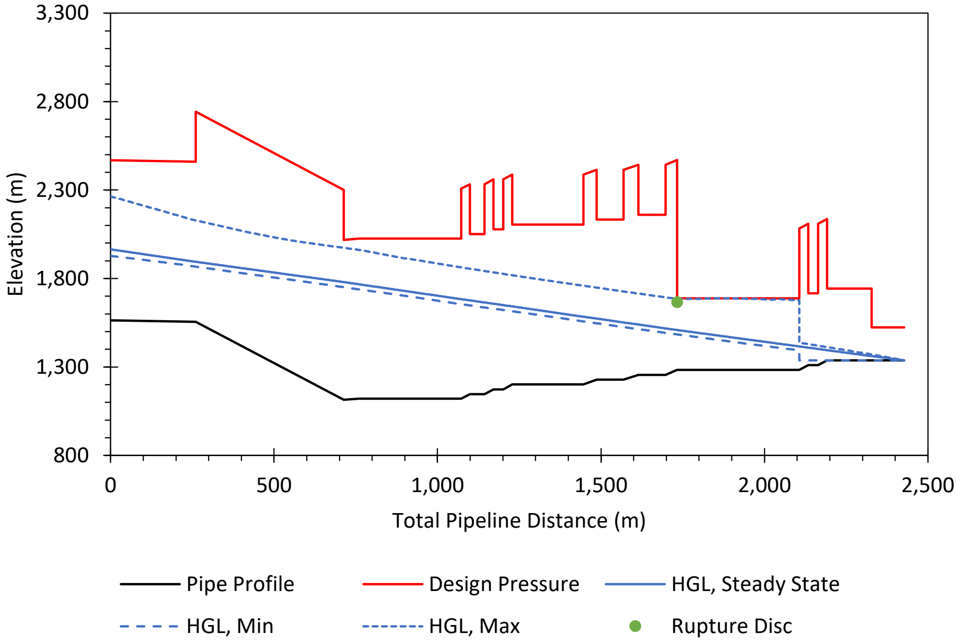


**Figure 11 Hydraulic grade line of transient simulation of blockage and rupture**

The static representation of this transient pressure wave is shown by plotting the maximum pressures at all points in the pipeline. As shown, the pump was operating a steady-state pressure of 75 bar; however, the transient pressure at the pump exceeded 130 bar. The pressure experienced at the paste pump was likely caused by the pipeline blockage and the maximum pressure was limited by the rupture disc event.

## 3.5 Case study 5: diverter and dump valve actuation

Automated diverter valves and automated dump valves are becoming increasingly commonplace in paste fill UDS design. Diverter valves allow for time savings in locations where frequent pipe changeovers are required to reroute the pipeline to different areas of the mine. If their configuration is reversed, they can also be used to quickly switch from the duty paste pump to the standby. Dump valves allow for controlled release of paste fill, typically used when a partial blockage of the UDS is identified by the paste plant operator.

While the design intent is to always actuate a diverter valve when the pipeline is empty, improper operation can create transient events in the system that can be modelled to ensure the pipeline design accommodates for operational mistakes.

Improper operation of a diverter valve used to join pipelines can fully block the operating pipeline, causing pressures to rise and trigger a rupture disc event (described in Section 3.4). Improper operation of a diverter valve used to divert flow will result in paste fill being sent through an unintended pipeline route. In this case, the characteristics of the valve can be used and included in the transient model. When switching from one discharge port to another discharge port, there will be a length of time over which the flow area is restricted, followed by a fully blocked line, and then a period of time when flow area increases and discharges into an empty line. The timing of these steps will depend on the valve actuation speed and geometry of the valve.

Dump valve actuation is typically completed with the system full of paste and pressurised. Transient modelling of this valve actuation can be completed to quantify the expected transient pressures and forces in the system. Additionally, if required, the dump valve actuation speed can be modelled and specified to limit the magnitude of the resultant transient forces.

# 4 Conclusion

Reliable operation of paste UDSs is essential to mining productivity and safety. This paper has shown that steady-state hydraulic analysis alone does not capture the dynamic behaviour of a modern UDS. Transient events in the UDS can produce large transient pressures that must be accounted for in the piping design, and the resulting transient forces that affect supporting requirements.

The case studies presented demonstrate that transient pressure can significantly exceed those predicted under steady-state conditions. Events such as pump trips, pipe blockages, rupture disc bursts and poor synchronisation of hydraulic pulsation dampeners can generate high transient forces capable of damaging pipelines and supports. Transient modelling enables engineers to quantify these risks, assess system resilience, optimise component sizing and implement effective mitigation strategies. It also assists in developing safe operating procedures and commissioning plans.

As underground paste distribution systems become longer and more complex, transient analysis should be regarded as a standard component of responsible design practice rather than a specialised or optional task.

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