Paste 2024 – AB Fourie & D Reid (eds)
© 2024 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-8-9
doi:10.36487/ACG_repo/2455_35

Effect of paste pump performance on the transient pressures and forces in an underground distribution system

LDC Correia *Paterson & Cooke, Canada*

J Jacobs *Paterson & Cooke, USA*

Abstract

One of the most important aspects of any paste backfill system is the transport of paste from the paste plant to the underground stopes, referred to as the underground distribution system (UDS). The reliability of the UDS can directly affect both the mining sequencing and the binder consumption; two aspects which heavily influence operating cost.

As an integral part of the UDS design, paste pumps are often required either due to the location of the paste plant relative to the orebody, or the geometry of the orebody. Most paste pumps are equipped with a dampening system for suppressing transient pressure surges caused by changes in the flow rate when switching from one piston stroke to the next. The pressure surges can be minimised by limiting the momentum change at the beginning and end of every pump stroke. However, not all dampening systems are created equal, and a poor dampening system design will negatively impact the operation of the UDS.

This paper discusses the fundamentals of transient analysis and how the paste pump selection affects both the design and operation of the UDS. The purpose of this paper is to provide the reader with key criteria to be considered before procurement of the paste pump and design of the underground paste pipeline system.

Keywords: *paste backfill, hydraulic piston pump, piston diaphragm pump, transient analysis, dampening system, underground distribution system, water hammer*

1 Introduction

Positive displacement (PD) pumps are often included in the design of a paste underground distribution system (UDS). Paste backfill operations that require this type of pump do not have sufficient gravity head to overcome pipeline friction losses to deliver paste to all parts of the mine. The PD pump provides the necessary energy to deliver paste to underground stopes at yield stresses between 200 and 450 Pa typically seen in paste backfill systems.

Hydraulic piston pumps (complete with poppet valves) or piston diaphragm pumps are primarily used for paste backfill applications. Typically, these pumps deliver between 50 to 150 m^3/h of cemented paste to the underground stopes at delivery pressures between 5,000 to 12,000 kPa. Recently implemented paste pumping systems are pushing boundaries with increased flow rates up to 200 m^3/h and pump pressures up to 15,000 kPa.

PD pumps create fluctuations in the discharge flow rate due to the reciprocating movement of the pump pistons. These flow fluctuations cause transient pressure surges within the UDS, potentially causing fluctuating loads and hydraulic hammering. The magnitude of these loads has direct bearing on the size and quantity of the pipe supports, the pipe wall thickness, and overall safety of the UDS.

Most PD pumps are equipped with a pulsation dampening system to reduce rapid pressure changes. Several papers have been published by various pump vendors describing their pump's unique dampening system including Balthazar et al. (2023), Hendriks & Jansen (2021), Karambalis (2013), Peschken & Hoevemeyer (2017), Peschken & Ludewig (2007), and Vlot & Keijers (2018). Depending upon how each specific dampening system works for a particular PD pump, the pump will produce a unique transient flow curve. It is the responsibility of the design engineer to consider the PD pump's flow characteristics in the design of the UDS.

This paper takes measured transient pressure data from several industry leading PD pump vendors and using commercial transient flow software, determines a representative transient flow curve for each pump. The flow curves are then used to determine the expected transient pressures and forces on a typical UDS. The lessons learned from this paper are also important for operations with PD pump dampening systems that are either ineffective or not functional.

2 Methodology

Paterson & Cooke engineers use a commercial software package to analyse transient pressures and forces in pipeline systems. This tool effectively models water, slurry or paste flows in complex pipeline systems, accurately predicting the transient pressures and forces during unsteady events such as pump trips, valve closures, and rupture disc releases (Jacobs et al. 2023). The software facilitates an in-depth assessment of a pipeline system's reaction to the unsteady flow caused by the normal cyclic operation of a PD pump.

2.1 Backfill pipeline profile and steady state hydraulic grade line

A typical backfill UDS pipeline profile was considered in this paper. Figure 1 provides the steady state hydraulic grade line (HGL) plot for this pipeline. The plot is shown in terms of elevation, or head in metres. The black line shows the pipeline profile (natural grade line), the red line displays the pipeline pressure rating in metres of paste along the line, and the blue line indicates a steady state HGL for a pump duty point of 100 m^3/h at 7,500 kPa pumping pressure. The gap between the HGL and the pipeline profile illustrates the pressure in the pipeline.

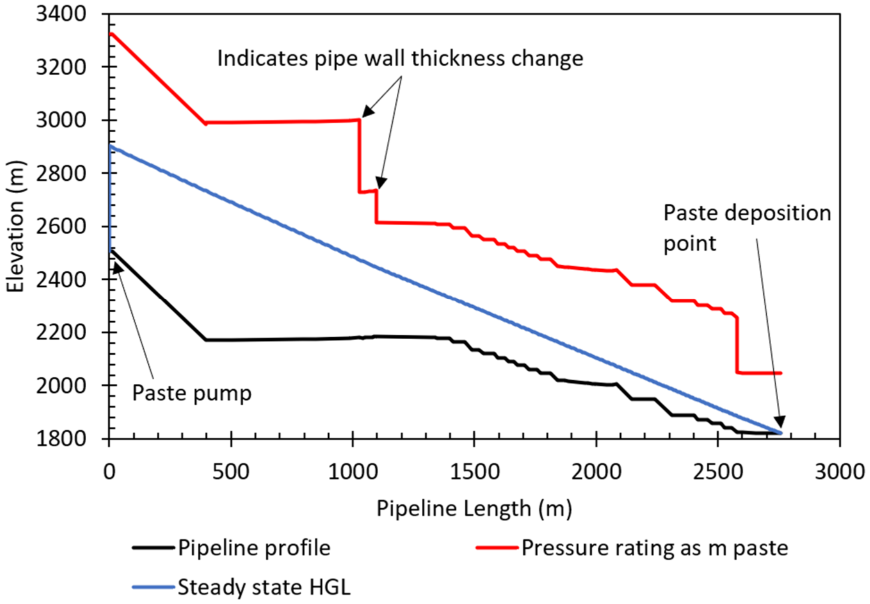


Figure 1 Typical steady state hydraulic grade line plot for a pumped backfill pipeline system

Paste is pumped directly into a borehole extending from the surface at 2,500 m elevation to an underground mine level at 2,170 m. The backfill pipeline crosses through this level before progressing through a network of boreholes and short levels, ultimately reaching the final paste deposition level at 1,820 m elevation. Four different pipe specifications are used over the 2.75 km length to provide sufficient pressure rating throughout this backfill pipeline.

This backfill pipeline system, based on an 8 inch (DN200) pipe size, was used as a basis to compare the predicted transient pressures and forces for the different PD pumps investigated. Transient pressure waves and forces in the pipeline result from rapid changes in flow. The magnitude of flow change directly impacts the scale of transient effects; larger flow changes lead to greater pressures and forces. Section 3 will investigate the predicted transient pressures and forces in this backfill pipeline system with the PD pump selection being the sole variable.

2.2 Paste recipe

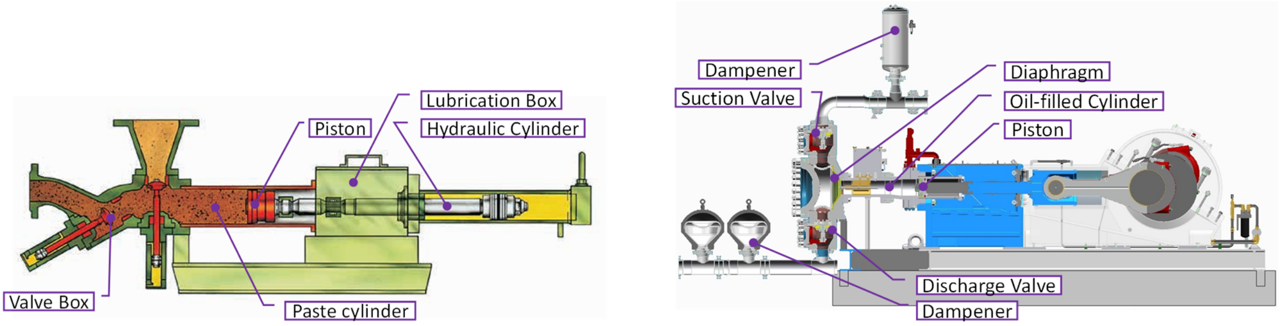
A paste recipe with a nominal mass concentration of 76%m (wt% solids) equating to a yield stress of 280 Pa was used as a basis for this study. The paste recipe incorporated a binder content of 2.8% (mass binder divided by total solids). A Boger slump of the paste is presented in Figure 2.

Figure 2 Photograph illustrating paste Boger slump at 76%m (2.8% binder; 280 Pa yield stress)

This paper does not present a sensitivity analysis with respect to different pipeline system geometries or paste recipes. This paper also assumes the paste pump valves are not worn. However, while these parameters do affect the specifics of the transient analysis results, they don't influence the conclusions of this study.

2.3 Types of positive displacement pumps investigated

This study investigates two types of PD pumps, namely hydraulic piston pumps and piston diaphragm pumps (Figure 3).



(a) (b)

Figure 3 Positive displacement pumps. (a) Hydraulic piston pump (complete with poppet valves) (Vlot & Keijers 2018); (b) Piston diaphragm pump (Abel Pump Technology)

2.3.1 Hydraulic piston pump

The hydraulic piston pump, most commonly used for backfill, is a two-cylinder, single acting PD pump (Figure 3a). The pump consists of a pump unit, hydraulic power pack and often a cooling unit. Two pistons, driven by the hydraulic power pack, operate in opposite directions or 180° out of phase. As one piston moves forward discharging paste from the cylinder into the paste pipeline, the second piston moves backwards, filling the cylinder space in front with paste.

A hydraulic piston pump employs sophisticated techniques to help smooth out the resulting paste flow rate. This is achieved by pre-charging the paste in the waiting cylinder such that it closely matches the pressure inside the pipeline prior to discharge. By pre-charging the material, the difference in pressure and flow during a piston switchover can be considerably reduced, thereby also decreasing the transient pressure and force magnitudes imparted to the pipeline system.

The generic characteristics of three hydraulic piston pumps from various vendors were considered in this paper, with these three pumps representing a range of possible operating modes. The flow curves used in the transient simulations are provided in Figure 4. Each flow curve was set up to provide a time averaged flow rate of 100 m³/h.

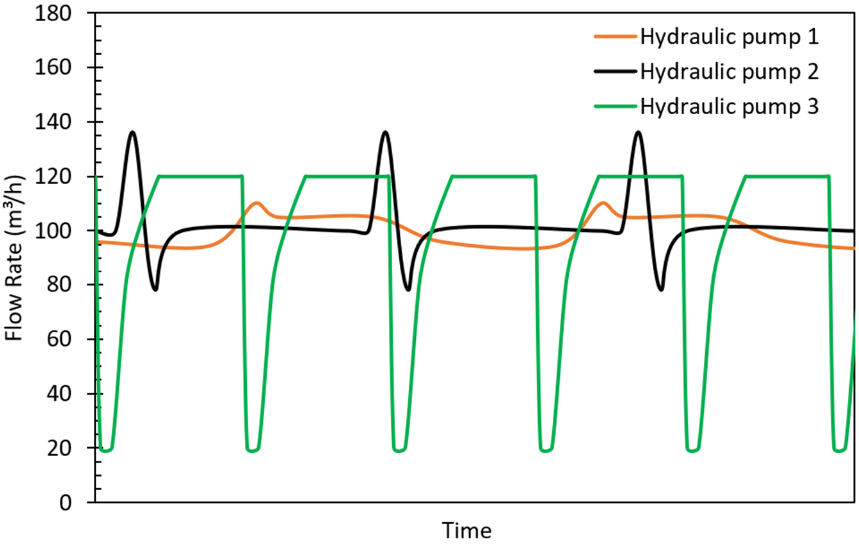


Figure 4 Flow curves of the investigated hydraulic piston pumps

2.3.2 Piston diaphragm pump

A piston diaphragm pump (Figure 3b) includes an electric motor connected to either an eccentric drive or crank mechanism. This drive is connected to several pistons via connecting rods and crossheads. Each piston pushes hydraulic oil into a housing fitted with a flexible diaphragm. The diaphragm isolates the hydraulic oil from the paste being pumped. As the piston moves forward, the diaphragm pushes paste out through a discharge non-return valve. As the piston then moves backwards, the diaphragm housing fills with paste via the suction non-return valve. Several pistons and diaphragms operate in a staggered out-of-phase sequence to produce the flow into a pipe. Piston diaphragm pumps are equipped with external discharge and/or suction conventional dampeners such as air vessels or bladder accumulators.

The generic characteristics of a piston diaphragm pump were analysed, both with (diaphragm pump 1) and without (diaphragm pump 2) a functioning discharge dampener. The flow curves used in the transient simulations for the piston diaphragm pump are provided in Figure 5. Diaphragm pump 1 has a pulsation magnitude of ±0.3% and diaphragm pump 2 has a pulsation magnitude of ±20%.

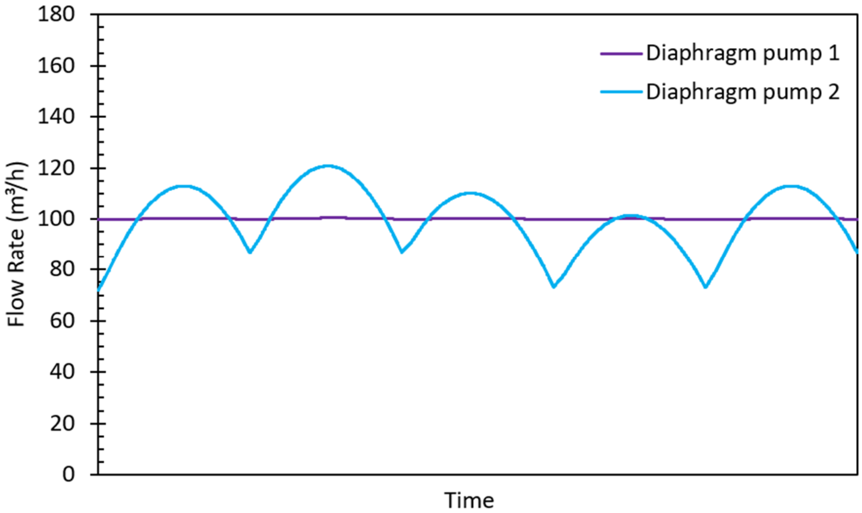


Figure 5 **Flow curves of the investigated piston diaphragm pump with (diaphragm pump 1) and without (diaphragm pump 2) a functioning dampener**

3 Analysis and discussion

3.1 Transient analysis considerations

Transient analysis of a pipeline is recommended if rapid changes in flow are expected in the system. These changes in flow could be caused by upset conditions such as a power failure, accidental valve closure, or a rupture disc event, or they could be caused by normal operations such as slurry batching, start-up and shutdown, or flow variations from a PD pump.

Without using commercial transient software, the Joukowsky Equation is a fundamental equation that can be used to approximate the transient pressure magnitude of a fluid in a pipeline. The Joukowsky Equation 1 is defined as follows (Tijsseling et al. 2007):

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

where:

ΔP = magnitude of the pressure surge (Pa)

ρ = density of the fluid (kg/m^3)

c = transient wave speed (m/s)

ΔV = 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. The pipeline period for the backfill system used in this study is four seconds.

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. The entire pipeline system needs to be modelled such that the transient pressures and forces can be accurately determined. The transient model components used in this study are presented in Figure 6.

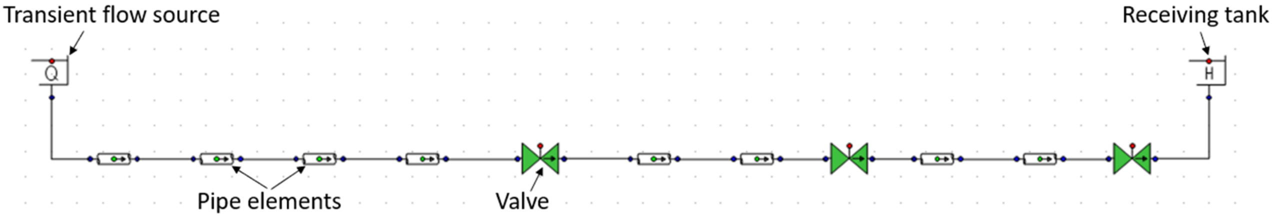
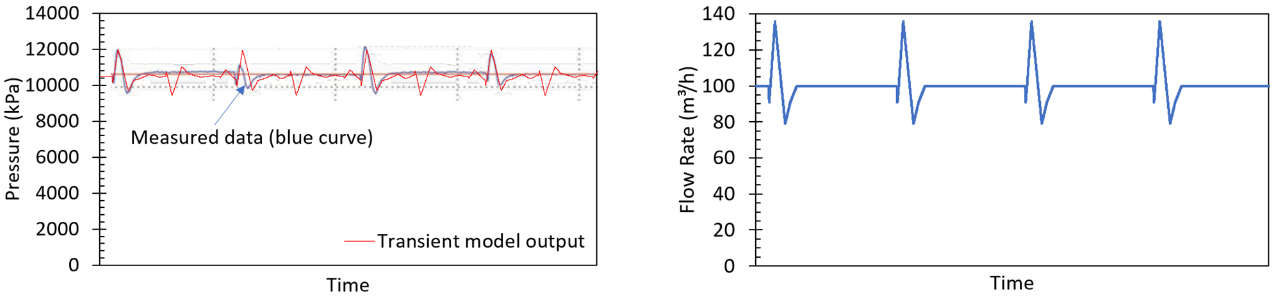


Figure 6 Transient model components

3.2 Transient model inputs

Ideally, PD pump flow rates should be directly measured and used as the pump input to the transient model. However, due to difficulties with accurately measuring the flow rate, pressure data was used to create the flow curves required for the transient analysis simulations. Transient simulations were iteratively run and the PD pump flow curve was varied until the pressure output of the simulation provided reasonable agreement with the frequency and magnitude of the measured PD pump pressure data.

As an example, Figure 7 a presents the transient model pressure output for one of the PD pumps considered as compared to the measured PD pump pressure data. It's worth noting that the pressure output of a PD pump is system dependent, therefore subtle differences between the transient simulation results and the measured pressure data are expected. The negative pressure spikes observed in the transient simulation data are system dependent and are caused by transient wave reflections in the 2,750 m long backfill pipeline system. Transient pressure wave reflections occur at all pressure boundaries in a pipeline system, including at the open discharge of a pipeline. The transient pressure waves are propelled to the speed of sound by the compressibility and elasticity of a combination of the fluid and pipe wall. At an open-ended discharge, the wave reflection results in a negative pressure wave with a similar pressure magnitude wave travelling back through the system.



(a) (b)

Figure 7 (a) The PD pump pressure output in the transient model compared to the measured PD pump pressure data; (b) The PD pump flow input in the transient model required to match the measured pressure data

It is possible that the vendor measured pressure data is from a relatively short pipeline, in which case the negative transient pressure wave reflections were not observed. The flow data used as a model input to achieve the approximated pressure data is shown in Figure 7b.

PD pump discharge pressure data from field measurements need to be verified before being considered for use in a transient analysis simulation. Commonly, the instrumentation available on site can only monitor averaged pump pressures and the overall paste production rate. This data does not provide any information about the rapid flow rate changes occurring in the system, which is the main source of transient pressures and forces.

It is essential to use high-speed pressure transducers to measure transient pressure fluctuations in the pipeline. Data acquisition dampening should be set to zero with a data acquisition rate faster than or equal to 1 kHz. Similarly, the PD pump discharge flow rate should be obtained either from monitoring the linear position of the pistons or from an external flow meter, with the more comprehensive data being from a flow meter. The dampening factor on the flow meter should also be set to zero. Data obtained using unsuitable instrumentation and data acquisition equipment will not accurately show the full system response and will lead to incorrect conclusions regarding the performance of the PD pump's dampening system.

3.3 Transient results

Using the flow curves presented in Figures 4 and 5, transient simulations were completed for each of the PD pumps using the backfill pipeline system shown in Figure 1.

Figure 8 shows the maximum estimated transient head along the pipeline for each pump type during normal operation compared to the quasi-steady state HGL. The quasi-steady state HGL represents the time averaged or mean head along the pipeline and thus is shared by all the PD pumps. Hydraulic pump 3, which exhibits the largest change in flow rate, experiences the highest transient pressures along the pipeline. For a pump such as hydraulic pump 3, approximately 180 m of extra head would need to be allocated for the pipe pressure rating to withstand normal operating transient pressures, thereby severely limiting the paste yield stress range that could reach each stope.

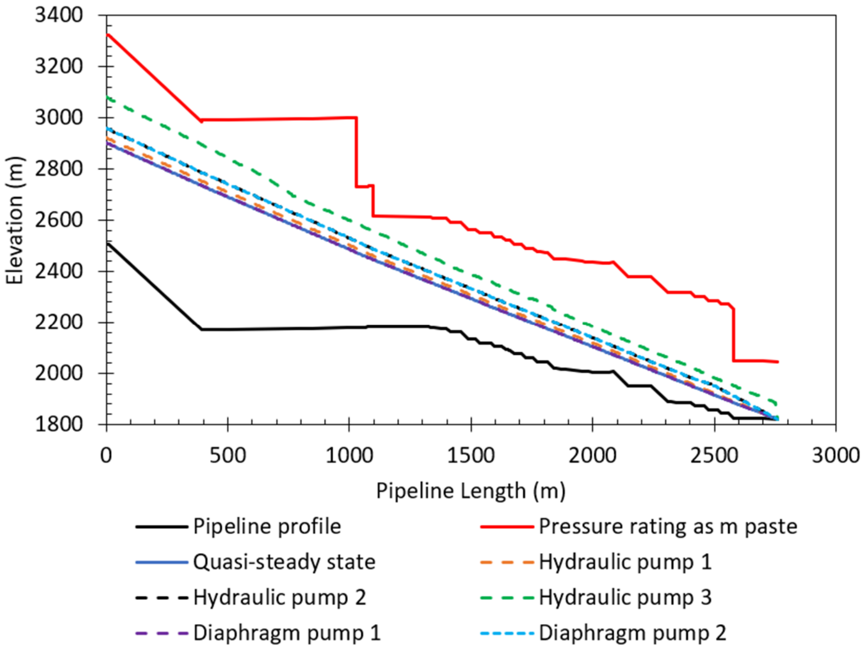


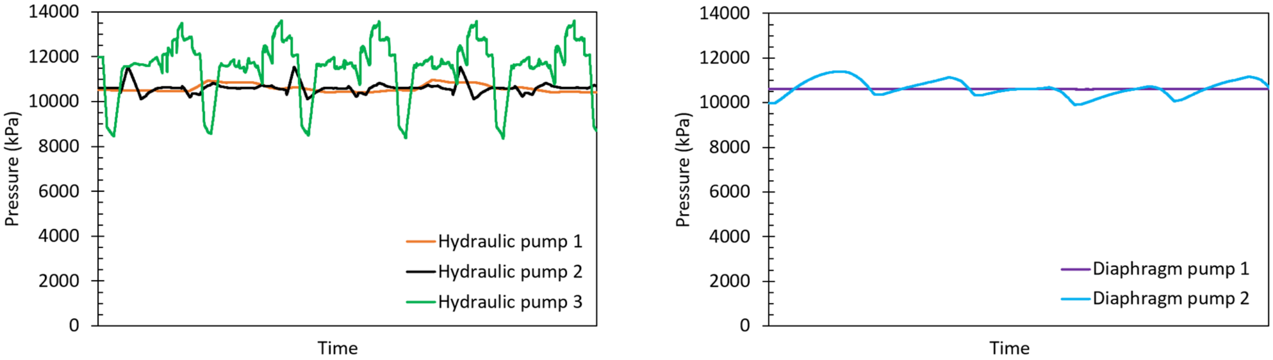
Figure 8 Maximum simulated transient heads for each pump type

From an operational viewpoint, this could have significant consequences for the mine in terms of safety of personnel if this aspect is not considered, as the pressure rating of the pipe could be exceeded. It will also affect the quality and operating cost of the paste backfill. To cater for the additional margin of head, the paste backfill would need to be diluted to operate at a lower yield stress, thereby reducing the friction gradient of the HGL. The cement content of the paste backfill would then need to be increased to maintain the same water to cement ratio to achieve the target backfill strengths.

Another critical consideration for a UDS is if the pipeline profile has relative high points where the pipeline pressures can transiently drop below vapour pressure (such as at a borehole collar). If vapour cavity formation and collapse occur, this will lead to additional transient pressure waves and forces in the pipeline.

In a paste backfill UDS, the base of the main surface borehole commonly experiences the highest operating pressures in the system. Figure 9 provides the estimated transient pressures at the base of the main surface borehole for each PD pump option. Most hydraulic piston pumps are equipped with a suitable dampening system and experience transient pressure less than ±15% of the quasi-steady state pressure. The maximum estimated transient pressure for hydraulic pump 3 at the base of the borehole reaches 13,650 kPa.

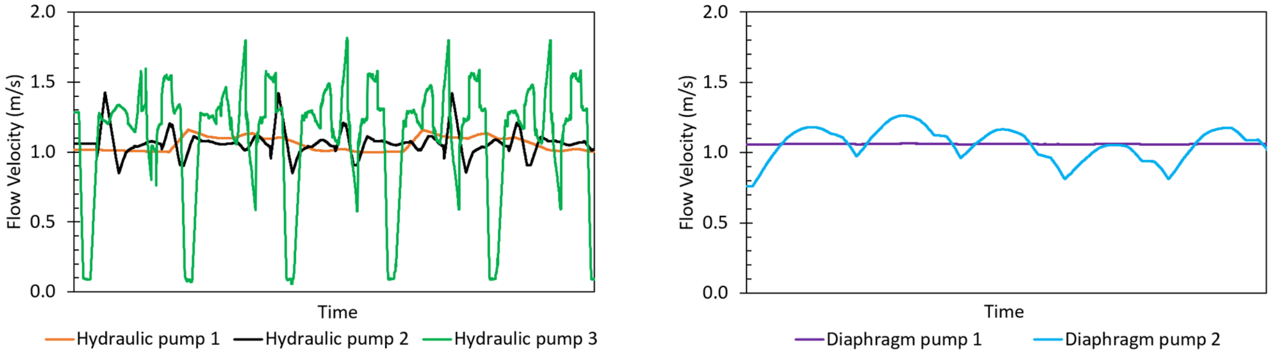
The PD pump is often a long lead item and is usually one of the first items to be procured once a project moves into implementation. Detailed transient analysis usually only happens later in the project cycle once the certified PD pump information has been received. At the time of procurement, a nominal 15% safety factor is added to the quasi-steady state friction gradient to allow for unknown transient pressures. Procurement of a PD pump, such as hydraulic pump 3, would potentially require an increase in project capital cost to account for thicker pipe walls and stronger pipe supports that can handle the higher transient pressures and forces. Alternatively, an inferior paste recipe with increased binder content may need to be accepted to operate the system at a lower paste mass concentration and associated lower yield stress.



(a) (b)

Figure 9 **Transient pressures at the base of the borehole (400 m downstream of the pump). (a) For the hydraulic piston pumps; (b) For the piston diaphragm pumps**

As discussed in Section 3.1, rapidly changing flow velocities in the system are ultimately what causes large transient pressures and forces in a pipeline system. The resulting transient flow velocities at the base of the borehole for this system are presented in Figure 10 and the resulting maximum transient forces for each of the pump types are presented in Figure 11. The reported transient forces include a dynamic load factor of 2, which is commonly used for impulse loads such as these.



(a) (b)

Figure 10 **Transient flow velocities at the base of the borehole (400 m downstream of the pump). (a) For the hydraulic piston pumps; (b) For the piston diaphragm pumps**

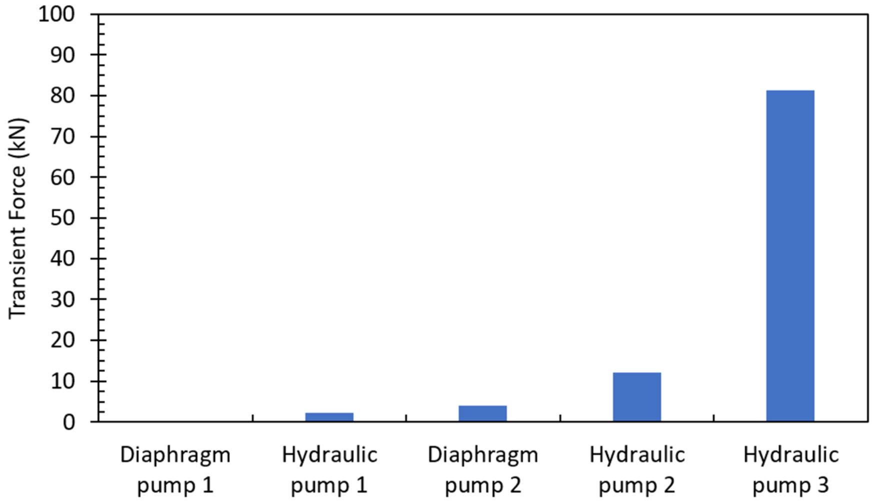


Figure 11 **Maximum predicted transient forces in the pipeline system**

Although diaphragm pump 2 and hydraulic pump 2 exhibit similar flow velocity magnitude changes (~0.6 m/s), there is a 300% difference in the expected maximum transient force (diaphragm pump 2 leads to 4 kN, hydraulic pump 2 leads to 12 kN). This suggests that a piston diaphragm pump will produce similar or lower transient forces as compared to a hydraulic piston pump, even considering a piston diaphragm pump without a functioning dampener. The velocity changes for diaphragm pump 2 occur over a duration that is longer than the pipeline period, whereas velocity changes for hydraulic pump 2 occur over a duration that is much shorter than the pipeline period. This is ultimately the cause of the 300% difference in transient force magnitudes.

A similar comparison can be made with an opportunity to reduce the UDS capital cost and/or operate with a better quality paste by selecting hydraulic pump 1 rather than hydraulic pump 2.

Although many backfill pipelines have anchors and supports adequately designed to handle transient forces higher than 80 kN, this would normally only be included in the design for occasional events such as a rupture disc pressure release or a pump power trip event, rather than for recurring cyclic loads. An important consideration that is often not considered for transient loads is fatigue failure caused by cyclical loading. The expected cyclical loads on the pump anchor for each of the PD pumps are presented in Figure 12.

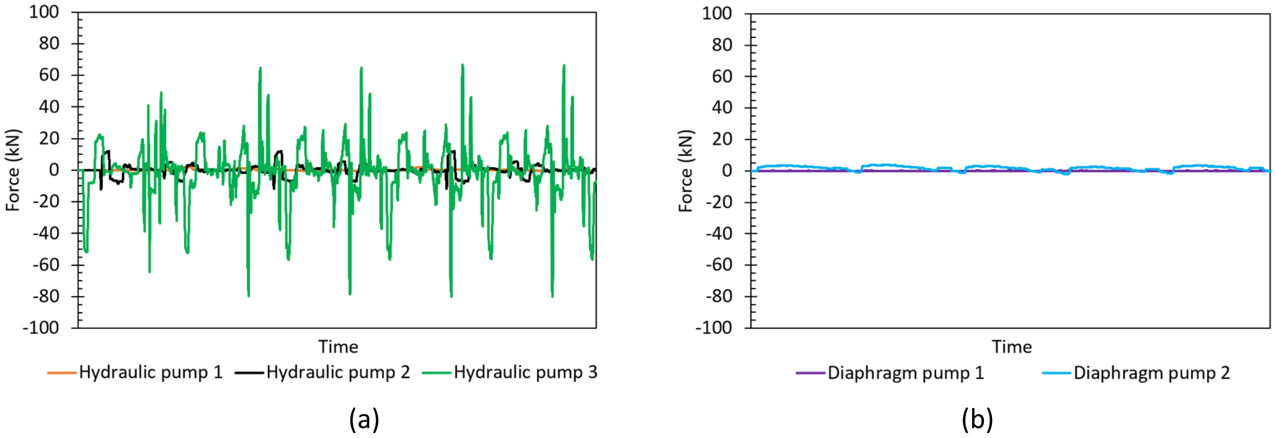


Figure 12 **Cyclical transient loads on the pump anchor. (a) For the hydraulic piston pumps; (b) For the piston diaphragm pumps**

Because the transient pressure waves travel through the entire length of the pipeline, these cyclical loads will affect anchors along the entire pipeline, and not just the anchors near the pump discharge. Significant cyclical loading of the UDS will eventually lead to fatigue failure of the pipeline, the supports, and the couplings. Figure 13 presents an example of a backfill pipeline coupling failure from fatigue loading caused by undampened cyclical pump pressure fluctuations.

Figure 13 Backfill pipeline coupling failure from fatigue loading

4 Conclusion

Flow curves of several industry leading PD pumps were analysed to determine the expected transient pressures and forces in a typical UDS. As demonstrated in this study, the unsteady flow from normal cyclic operation of a PD pump can cause large transient pressures and forces in the UDS.

Three hydraulic piston pumps and a single piston diaphragm pump (with and without a functioning dampener), representing a range of possible operating modes, were investigated. The analysis showed that although each of the PD pumps was specified to deliver 100 m^3/h of paste at 7,500 kPa, the maximum transient forces produced by the PD pumps varied greatly. Procurement of a PD pump that produces significant transient pressures would either require a sturdier UDS and associated pipe supports or would necessitate operating with an inferior paste recipe with increased binder content. Both outcomes would negatively impact a project both in terms of cost and operability. Although the UDS can be designed to handle relatively high transient forces, the additional complication of fatigue failure caused by cyclical loading from the PD pump also needs to be considered. Significant cyclical loading of the UDS will eventually lead to fatigue failure of the pipeline, the supports, and the couplings.

PD pump pressure measurements must be completed with high-speed pressure transducers. If the data acquisition equipment used is unable to accurately measure the rapidly changing pressure in the system, this will lead to false conclusions regarding the performance of the PD pump’s dampening system. The transducers used to measure transient pressures should be capable of a data acquisition rate faster than or equal to 1 kHz.

The lessons laid out in this paper are applicable for projects moving into implementation, or brownfield operations with PD pump dampening systems that are either ineffective or not functional.

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