HYDRAULIC EVALUATION OF TAILINGS TRANSPORT SYSTEMS IN MOUNTAINOUS TERRAIN: DENSITY WAVE ANALYSIS

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ABSTRACT

This paper presents a hydraulic evaluation of a tailings transport pipeline system extended over mountainous terrain, focusing on transient pressure behavior during flushing, water batching, and slurry restart operations. The primary subject of analysis is the propagation of the water/slurry and slurry/water density interface during transitional phases and the resulting implications on pipeline selection, pump system adequacy, and long-term operability. The study is based on a project where the original tailings pump station was reassessed and partially modified to service a deposition site nearly five times farther than the original design. The study builds on prior foundational work by Hallbom (Hallbom DJ, 2006), especially in the context of hydraulic grade line discontinuities, U-tube effects, and slack flow phenomena.

Keywords: tailings transport, slurry pipeline, hydraulic transients, density wave, slack flow, U-tube effect, choke station, pressure surge, mountainous terrain, pipeline design

INTRODUCTION

Long-distance tailings pipelines traversing mountainous terrain are subjected not only to steady-state hydraulic challenges but also to significant dynamic behaviors during transitional operations such as flushing, water batching, and system restarts. These phases often introduce pressure fluctuations due to transient density changes, referred to herein as density wave propagation, as slurry and water displace one another within the system. U-shaped sections (U-tubes) within the pipeline alignment are critical, as they can significantly distort the hydraulic grade line (HGL), creating localized overpressures or slack flow regions. This paper investigates these phenomena and highlights their implications for pump selection, pipeline material rating, and operational controls.

Figure 1 – Aerial view of the evaluated pipeline

METHODOLOGY

The case study involves a system where the initial tailings transport design serviced a tailings storage facility (TSF) located approximately 2 km from the pump station. The system was later modified to discharge into a second TSF situated approximately 9 km away, introducing considerable elevation changes and increasing overall frictional head loss. Although the original pump station design included capacity contingencies for future expansions, the extended alignment necessitated a thorough re-evaluation of both hydraulic and operational conditions. The system upgrade included the following:

- Increasing steel pipeline size from NPS 6 to NPS 8 steel,
- Reducing slurry concentration and adjusting rheological parameters,
- Maintaining two parallel pipelines (2 × 100% redundancy),
- Retaining the original pumping infrastructure with limited hardware upgrades.

These adjustments reduced the system's hydraulic gradient, validating operational feasibility under steady-state conditions (Giner et al., 2025). However, further assessment was necessary to confirm system adequacy under transient flushing and startup scenarios. Density wave analysis must account for the specific density and hydraulic gradient (i.e., friction losses) at each section of the pipeline, depending on whether water or slurry is being conveyed. Friction losses for water are estimated using the Hazen-Williams model, while for the two-phase slurry friction losses are determined using the methodology and the models adopted for the steady-state analysis (Giner et al., 2025)

RESULTS AND DISCUSSION

Knight Piésold analyzed and simulated the propagation of the density change interface along the pipeline during flushing and slurry restart on a pipeline full of water operations. This analysis aimed to assess the required pumping head and pressure and verify whether the available pump capacity was sufficient, particularly during the most demanding transient phases. This flushing scenario is analogous to long-distance water batching operations, as discussed in (Hallbom DJ, 2006), where transitions between fluids of differing densities can generate pressure surges due to inertia and momentum shifts. When fluids of different densities are in the same pipeline, there will be discontinuity in the hydraulic grade line (HGL) at the interface, though not in the actual pressure. This occurs because the head is expressed in meters of slurry on one side and meters of water on the other. Figures 1 shows the study case profile and Figures 2 and 3 summarize the impact of these transitions on pumping pressure, depending on where along the pipeline they take place. Key analysis considerations included:

- Interface travel time along the pipeline (~1hr),
- Localized incremental pressure calculation along the complete pipeline, with variable density change interface,
- Impact on pump discharge pressure and pipeline pressure rating,
- Transient overpressure risk assessment depending on interface location within undulating terrain.

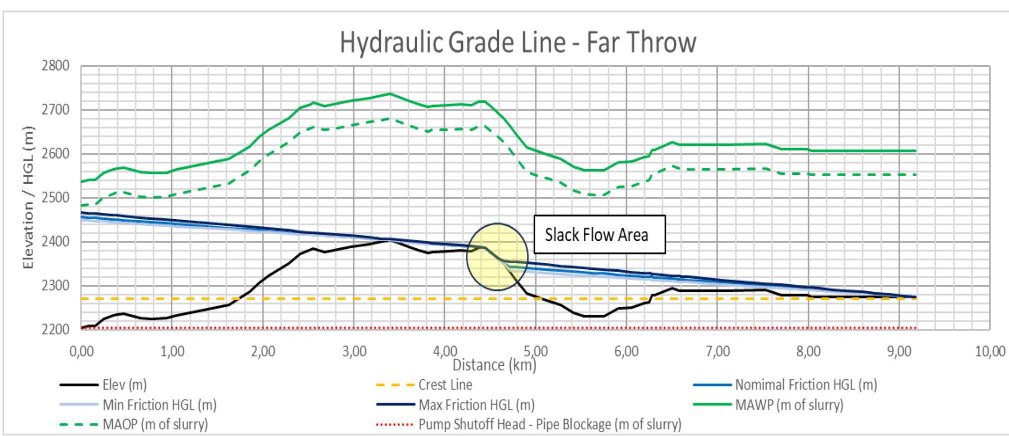

Figure 1 – Steady-State HGL of base case operating with slurry

The results and interpretations described below are based on the evaluation of the base case scenario, which reflects the current pipeline alignment and hydraulic configuration implemented in the project. This base case represents the primary condition used to assess both steady-state and transient performance.

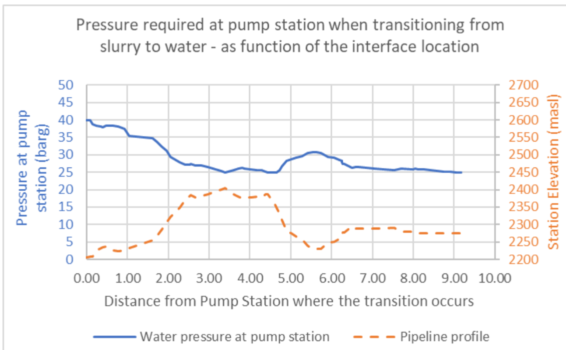

Figure 2 – Expected pressure fluctuations in transition from water to slurry

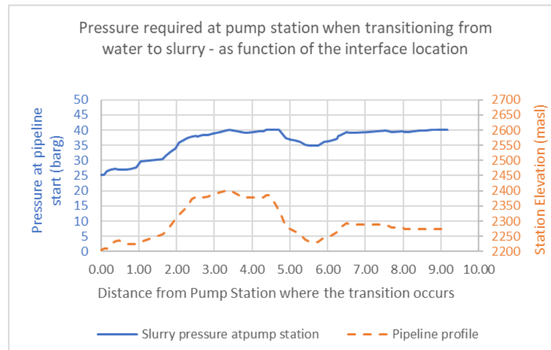

Figure 3 – Expected pressure fluctuations in transition from slurry to water

The additional profiles illustrated in Figures 4, 5, 6, and 7 are presented for comparative purposes only, to illustrate how more severe terrain configurations or downstream shifts in the governing elevation point may intensify pressure transients and overall system pressure requirements.

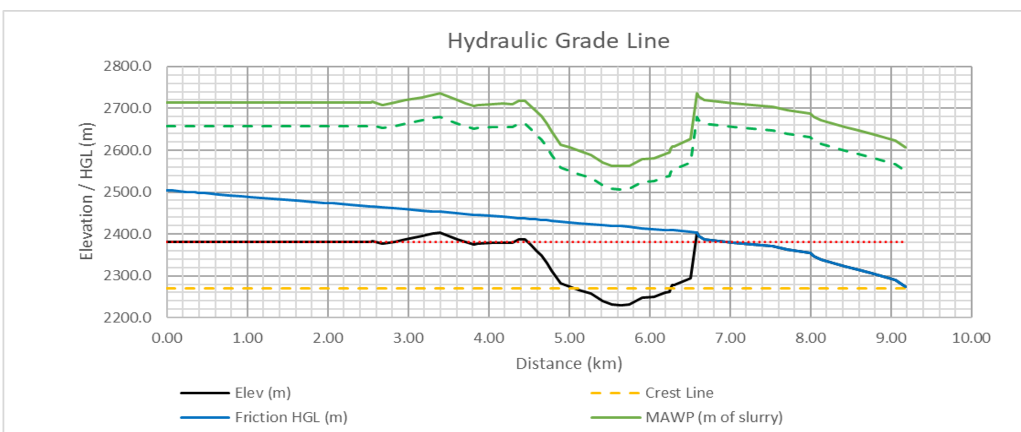

Figure 4 – Steady-State HGL of alternative profile with governing high point located downstream of U-tube

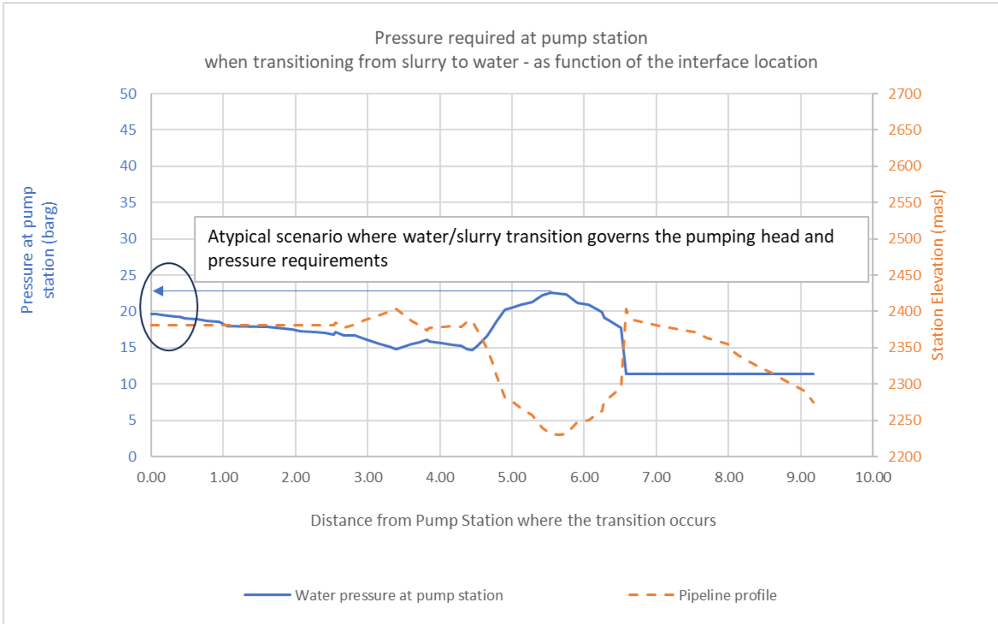

Figure 5 – Expected pressure fluctuations during water-to-slurry transition for figure 4 profile.

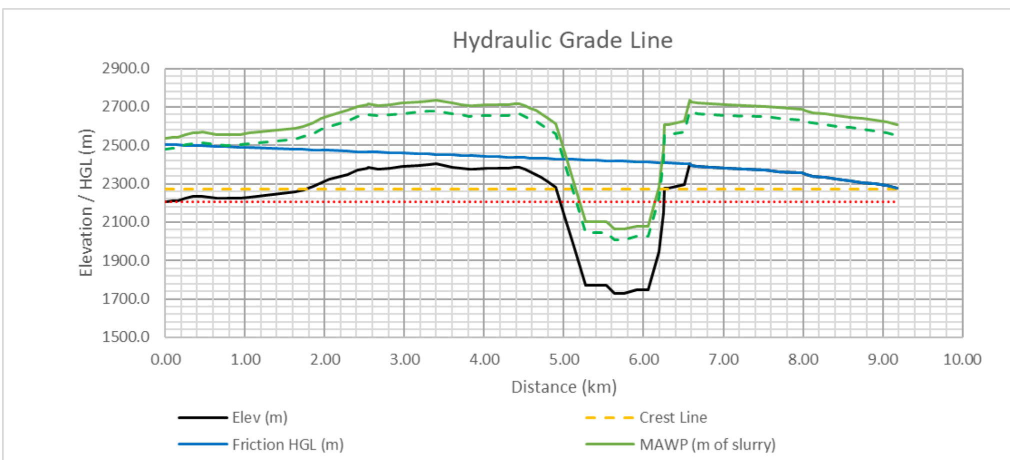

Figure 6 – Steady-State HGL for alignment with significant U-tube section intensity.

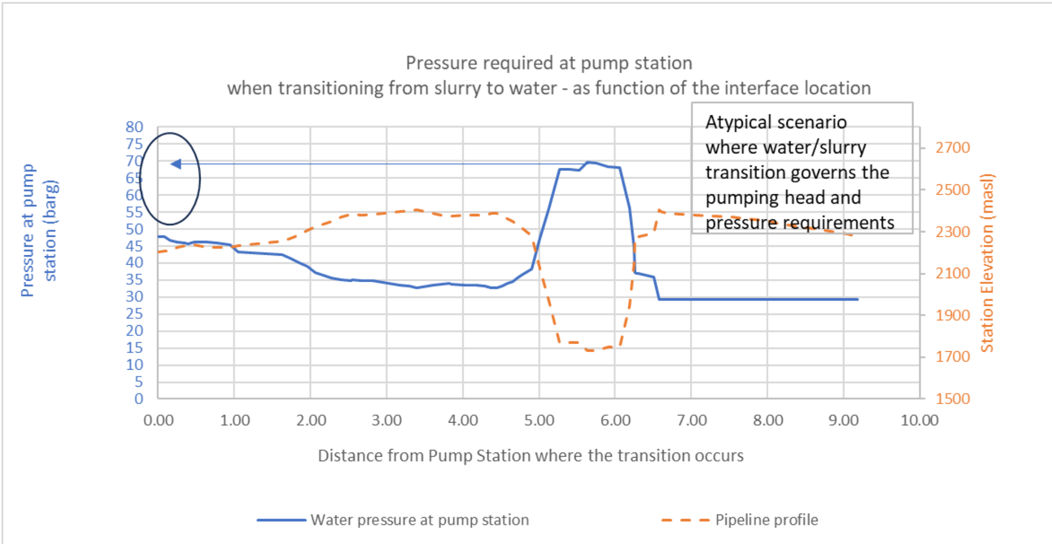

Figure 7 – Expected pressure fluctuations during water-to-slurry transition for figure 6 profile.

Hydraulic analysis of the base case scenario also identified the risk of slack flow in certain sections, visible in Figure 1, particularly after the crest of a high elevation point where the downhill slope exceeded frictional energy losses. In such cases, the hydraulic grade line dips below the pipeline elevation, potentially leading to vaporization and open-channel flow (slack flow), followed by hydraulic jumps and local wear. The initial design evaluated the implementation of a choke station to manage this condition. However, further analysis (Hallbom DJ, 2006), concluded that:

- The choke station could not be reliably bypassed during flushing operations,
- Improper choke use during density transitions could introduce overpressures due to the difference in head drop between slurry and water,
- Fixed chokes would risk under- or over-regulating pressure during flushing and pipeline restart (similar with batch cycling in other applications).

Given the operational life of the system and construction limitations, it was determined that a choke station would not be a viable solution. Instead, the following mitigation strategies were adopted:

- Leveraging pipeline redundancy by alternating flow between two lines,
- Establishing routine inspection and maintenance intervals,
- Accepting localized wear at slack flow regions based on expected slurry hardness and flow conditions.

CONCLUSION AND RECOMMENDATIONS

The analysis confirmed that even with the increased pipeline length and complex terrain profile, the system could function safely without pump upgrades, provided the transient operational phases were explicitly evaluated and controlled.

Key design recommendations include:

- Transient analysis of flushing and startup scenarios is essential in systems with significant terrain variation or U-sections,
- Density interface analysis and modeling must accompany steady-state HGL design to ensure pressure and power adequacy,
- Avoid reliance on fixed infrastructure such as choke stations where operational strategies and built-in redundancy offer more flexible and robust alternatives,
- When considering choke stations, evaluate only variable choke loop designs capable of managing both slurry and water interface pressures without inducing over pressurization,
- Use digital control and simulation tools for operator training and to automate valve and choke operations (Hallbom DJ, 2006).

Ultimately, the study demonstrates that while the steady-state design may appear sufficient, unmodeled transients, particularly those involving fluid density changes and slack flow, can pose significant risks to both pipeline integrity and operational reliability.

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