TRANSIENT SIMULATION OF LONG-DISTANCE TAILINGS AND CONCENTRATE PIPELINES FOR OPERATOR TRAINING

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Abstract

A real-time transient pipeline simulation was used to model the operational pressure response in the concentrate and tailings pipelines of the Minera Los Pelambres copper mine in Chile. A high-fidelity simulator was needed to train the operators on safe operation of the pipeline for different scenarios. A simulator that solves the transient equations was used to dynamically predict the pressure and flow throughout the pipeline to provide real-time responses to operational changes such as opening or closing a choke valve, or sending a water batch. Slurry rheological properties were incorporated into the model. This paper presents the technical background of the pipeline simulation model and the study of slurry properties. The paper shows the results of the transient simulation for different operating scenarios such as start-up, shutdown and leakage, by presenting the hydraulic gradient curves for each case. Finally, the paper briefly presents how the simulator was connected to an emulated control system and used to train the operator, it demonstrates the most effective tool available to learn to resolve undesirable conditions.

Key words: Simulation, Pipeline, Slurry, Operator Training, Transient Flow, Pipe leakage.

Background

Minera Los Pelambres (MLP), located in the Illapel valley in Chile, runs a 120-km copper concentrate pipeline from the Andes mountains to the harbor. In parallel, there are two 50-km tailings pipelines: one 28" and a second 36" in diameter. The pipelines have been in operation for a couple of years. The mountainous terrain creates challenging pipeline operating scenarios resulting from pressure drop changes associated with high elevation drops and rises.

In 2011, the concentrate pipe was upgraded with a new booster pump station. The total drop for the concentrate pipe is 1500 meters and is rubber-lined. The first valve station along the pipeline is at Km 22; a second valve station is located by the booster station at Km 80, where a second mountain rise starts. The pipe ends at a dissipation station with four loops provided with ceramic orifice plates; the first and the smaller ring is used when running with water; the other three loops are used with concentrate depending on the flow requirements to get the appropriate pressure.

Only the 36" tailings pipe has a dissipation station. Both pipelines have a total head of 400 meters from the copper refinery to the tailings pond. These pipes are made of steel but do not have a lining. Also, both can be operated either by gravity or with head pumps running.

MLP has a high operational quality requirements and wanted to train the operators with the state-of-the-art technology. Andritz Automation has two decades of experience in building OTS (Operator Training System) and developing its simulation software - IDEAS. Together MLP and Andritz worked on making an OTS for all three pipelines, a task which was truly one of a kind for a concentrate or tailings pipelines.

Methodology

Transient Pipeline Simulation

For this project, the Transient Pipeline product on the IDEAS simulator was used. The IDEAS process simulator is an object-based graphical environment, where the user builds a model by retrieving icon-based "objects" from various libraries and assembling them on a P&ID-like worksheet. These objects generally have a one-to-one correspondence with actual process equipment, i.e., pumps, valves, tanks, transmitters, controllers, etc. The simulator is used for steady-state and dynamic process simulations in the mineral, chemical and oil sands industries [cite Parthasarathi et al., ref 1].

1

The pipe object solves the transient form of the Navier-Stokes equations using the 'method of characteristics.' Only a brief overview of the equations being solved is presented here as detailed derivations are available in literature [cite Roberson et al., ref 2; Shou, ref 3].

Equations

The transient equations are formulated by deriving the momentum and mass balance equations by assuming that the fluid in the pipeline is slightly compressible.
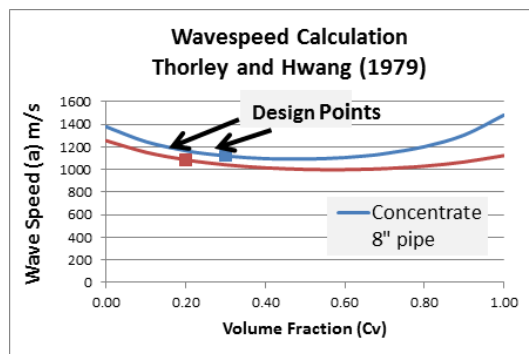
$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + R|Q|Q = 0 \qquad [1]$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad [2]$$

The sound wave speed can be estimated by using Thorley and Hwang equation [cite Thorley et al., ref 4]:

$$a = \sqrt{\frac{1}{\dfrac{\rho l(1-Cv) + \rho sCv}{\dfrac{1-Cv}{Kl} + \dfrac{Cv}{Ks} + \dfrac{D}{eE}}}} \qquad [3]$$

The wave speed "a" is a function of fluid and the particles and will vary with the process dynamics. Using the Thorley and Hwang equation [3] for the actual project data, the following graph was obtained.

Figure 1. Wave speed evaluated using Thorley and Hwang equation.

By analyzing these results, the wave speed was considered to be a constant. It was taken as

1100 m/s for pure water, for concentrate, and for tailings. This would mean that the simulation response time would have an error of up to 20% while running with water and less than 5% while running with slurry. However, water flow happens during start-ups and shut-downs a couple of times every year and also inside the water batches which separate different qualities of minerals. This typically would last for half an hour twice a day. This also implies that that the elasticity module K is assumed to be the same for pure water and for slurry mixture, which proved to be a good empirical approximation.

The two partial differential equations are transformed into a pair of ordinary differential equations using method of characteristics. Equations 4 and 5 are valid along their characteristic lines:

$$\text{If } \frac{dx}{dt} = a \ , \quad \frac{dQ}{dt} + \frac{gA}{a}\frac{dH}{dt} + R|Q|Q = 0 \qquad [4]$$

$$\text{If } \frac{dx}{dt} = -a \ , \quad \frac{dQ}{dt} - \frac{gA}{a}\frac{dH}{dt} + R|Q|Q = 0 \qquad [5]$$

Where,

$$R \qquad = f/2DA \qquad [6]$$

Equations 4 and 5 are integrated along their characteristic lines using finite difference scheme. Each Transient Pipe object is discretized into zones such that the volumetric flow rate (Q) and head (H) are calculated in each zone, therefore, there is a variation in pressure, flow and properties of the fluid throughout the pipe. The number of zones is set so that the length of each zone satisfies the stability criterion of the Transient equations:

$$\Delta x = a\Delta t \qquad [7]$$

In each zone, for each pipe, the mass and energy balance calculations as well as property estimation to determine properties such as density and viscosity are performed. The friction factor is calculated using the Colebrook equation [cite Roberson et al. ref 2]. Roughness used for the lined concentrate pipe was 1.50e-06 and for the steel tailings pipe was 6.10e-05 m. Additionally, an artificial correction factor was added over the overall pressure drop which

varies from 0.75 to 0.90 to adjust the result with the actual field measurements.

The viscosity was assumed to follow Newton's law of viscosity and varied with slurry concentration. Water viscosity was obtain through tables at the desired temperature and a project estimated viscosity was obtained from lab data. Interpolation and extrapolation of viscosity was done by rule of mixture. The results did not fit the curve outside the operational range, but it is very uncommon to run the tailings and concentrate pipelines out of the design range, even during washing.

Viscosity variations with particle size are consistent, for example, tailings at 57% is 8.8 cP +/-20%; trying to better predict it will not decrease the error, and the impact on pressure drop is negligible. In the concentrate pipeline, the variations are less due to quality control of the product's solid percentage and particle size. Therefore, the viscosity prediction is better in concentrate than in the tailings. The simulator is capable of tracking particle size distribution (PSD); however, we did not correlate viscosity with it due to the low impact and the lack of data available. To get more data was considered not worth the effort but could be considered in future models.

In addition to the pressure drop calculation, the J curve impact due to non-fluidized slurry was calculated. The extra pressure drop occurs when speeds inside the pipe drop and particles start to settle. Empirical data was gathered to correlate dP as a function of slurry speed and solids concentration.
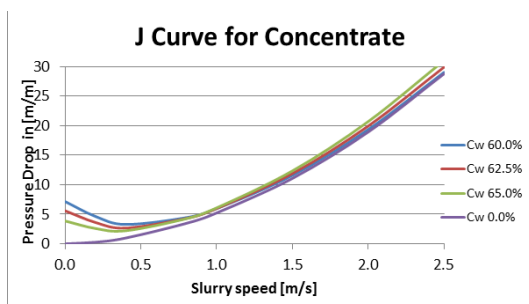

Figure 2. J curve for concentrate obtained from empirical data.

Fj factor was found from the empirical data as shown in Figure 8. This was done by adjusting the data to a polynomial (Eq.8) by calculating all four coefficients. The pressure drop increases when speeds inside the pipe drop substantially:

$$Fj = L*Cw*((a10+a11*Cw)+(a21+a22*Cw)*v) \qquad [8]$$

Note that the sedimentation process happens with certain dynamics which was not modeled on first principle. A simple time ramp was added to the model to slowly modify Fj; the time was obtained from operational experience. It takes about 2 hours to see the total effect inside the tailings pipelines and more than 8 hours inside the concentrate pipeline; this is due to the difference in PSD.
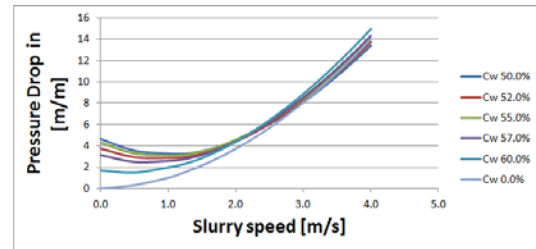

Figure 3. J curve for tailings obtained from empirical data.

Transient Modeling Approach

In the simulation program, the model that represents a pipeline is developed by connecting several Transient Pipe objects together. The pipes have a 'node' object placed between them. The flow through the pipe is calculated based on pressures at the ends of the pipes, while the node objects adjust their pressure to achieve a flow rate balance.

The amount of transient objects and the number of zones in each object was carefully selected considering the terrain profile, critical points, system singularities and the actual installed instrumentation.

The example below (figure 4) shows the curve obtained when the pipeline is balanced and running full of water; each of the dots represents one pressure probe. On the model, each dot represents a node in between each Transient Pipe object.
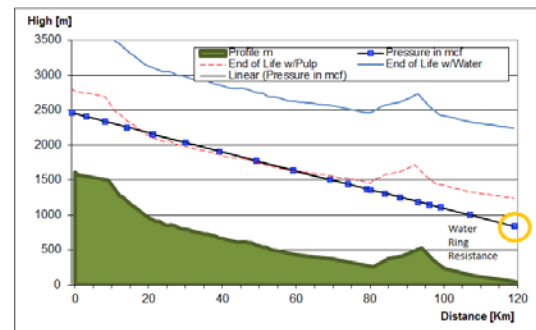

**Figure 4.** Concentrate Pipe profile started with water

3

Water Hammer Phenomenon

The Water Hammer Phenomenon is illustrated below using the Transient simulator. Below is an example of a downhill pipeline that is 4" diameter, 2.5 km long on a 1.5-degree incline, and is transporting slurry with specific gravity (SG) of 1.4. In Figure 5, the pressure response (at the end of the pipeline) to valve closure is shown. When the downstream valve is closed, there is an increase in the pressure at the valve. This pressure increase causes a pressure wave that travels back and forth between the ends of the pipe until dissipating due to friction losses. This surge in pressure can rupture the pipeline if it exceeds the maximum allowable operating pressure (MAOP) of the pipeline, also known as end of life.
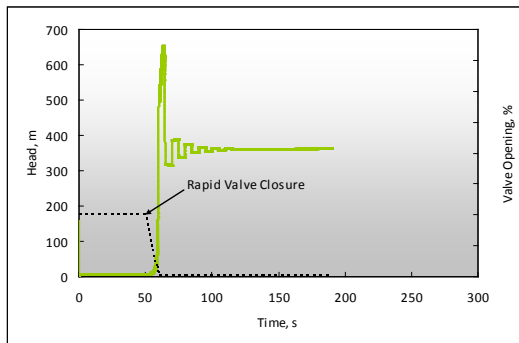
Figure 5. Pressure Response to Valve Closure of Downhill Pipeline

In Figure 6, the same pipeline experiences a different pressure response due to a ramped closure of the valve. In this case, valve closure is ramped down over 100s and the resulting pressure surge is lower (500 m head vs. 650 m head) and the response is also delayed.
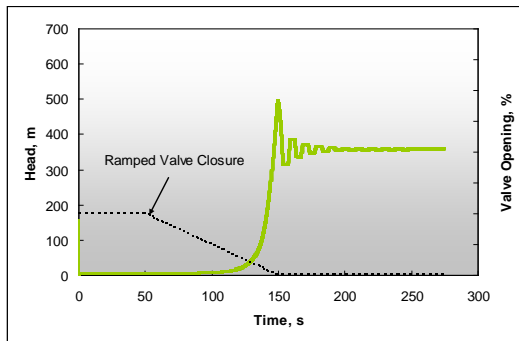

Figure 6. Pressure Response to Ramped Valve Closure of Downhill Pipeline

Operator Training System (OTS)

As it happened with the aerospace industry several decades ago, the use of process simulation tools was established as one of the best practices over the last decade in the process industry for:

- Design validation
- Control check-out
- Operator training

In the present case, the customer's interest was mainly to improve operators' capabilities; it also facilitated testing of a new booster station which will help revamp the production.

To this end, Andritz Automation constructed a training room containing an OTS which would connect the actual facility control logic (same software) to a pipeline model which would run at real-time and replace the physical process; by using the same HMI as in the field, the operator will be controlling a system similar to the one used in real life. It was improved by adding: a) the historical data b) the leak detection tools used at the facility.
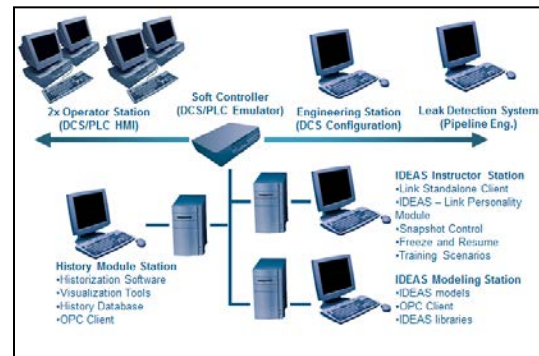

Figure 7. Concentrate Pipe profile started with water.

The OTS architecture also includes an engineering station which allows access to the control logic. This was used to adapt, repair and modify portions of the logic, especially the new sections. The role of an OTS is to add an Instructor station which helps control the OTS training process and trigger/simulate different operational scenarios. The communication between the different machines was obtained by OPC technology.

Typically, the training process involves evaluating the operators' abilities and knowledge during standard operating procedures and during abnormal conditions (fault scenarios). Prior to exposing the operators to the simulator, they had to undergo training on the basic theory and operational manuals. After this they go through

4

hands-on training on the simulator. Only employees with proven competence are selected for the tasks that their positions require.
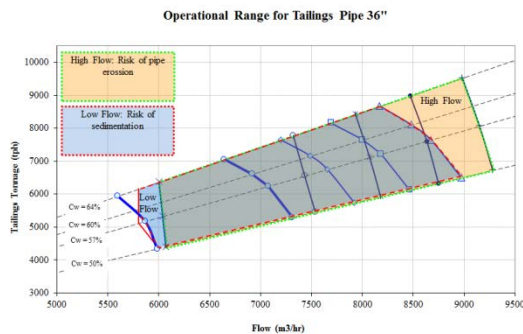
Figure 8. Operational Range for Tailings Pipe 36".

When operating a mineral pipeline it is important to:

1. Maintain the operation inside the volumetric flow vs. Mass flow window (ref. Figure 8).
2. Be able to start and stop relatively fast but assuring that the transients will generate the smoothest shock wave possible.

There are also certain constrains to the specific pipe case considering the following:

- Gravitational flow vs. forced flow; forced flow tends to make it easier to maintain the minimum flow.
- Tailings vs. Concentrate: Concentrates tend to avoid settling due to a smaller PSD and homogeneity; coarser material like tailings tend to settle faster.
- The possibility to operate a dissipation station with orifice plates and different CVs. This was mainly the case of the concentrate pipe at MLP.
- Replacing slurry with water or vice versa. The MLP tailings pipes have to be fully replaced to avoid plugging when stopped for more than 2 hours. MLP Concentrate pipe takes around 22 hours to flow from the peak to the harbor, and it typically contains several water batches inside the pipe.
- When the slurry pushes water, the higher weight tends to accelerate the flow and vice versa when water is behind the slurry. On the MLP concentrate pipeline, there is a second mountain chain that the pipe has to

climb and hence there are more acceleration/deceleration phenomena.

- This is not a full list but a short summary of the issues which the operator will have to manage during a normal operation.
- The operators were exposed to different scenarios like the following:
  o Changes of slurry quality imply changes in rheology rheology, PSD, Cw, etc.
  o Changes on production requirements.
  o Forced shut downs, some coordinated some as fast as a black-out.
  o Finally, leaks were also simulated in diverse locations, some large and wide opening and some small and slowly growing.

SIMULATOR RESULTS

The OTS was fully connected and the actual control logic allowed 100% of the IOs to interact at a scan rate of 1 second, and for some selected signals, even faster, which was enough to make the responses realistic, such that the operator could believe he/she was operating a real pipeline. Since the simulation is mainly based on first principles, it was possible to start an empty pipe and going through the whole start-up procedure until arriving at a steady state; also, when confronted with any abnormal situation, the responses were natural and the dynamic was almost identical when compared with actual operation.
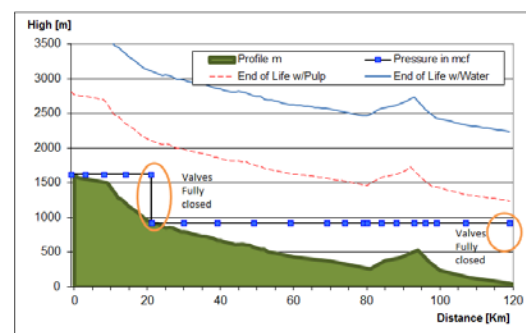

**Figure 9.** Concentrate Pipe profile stopped with Slurry.

5
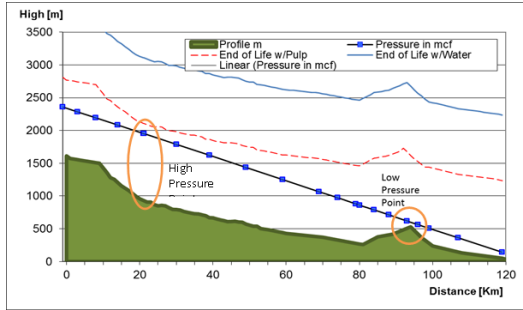
Figure 10. Concentrate Pipe profile full production with Slurry.

Figure 11 was also selected to show the visualization of the Slurry/Water Interface. We can observe a dynamic situation when starting slurry flow (already at Km 30) and at the same time the booster station running and the water dissipation ring in service. This example shows the complexity of the situation; on one side there is the need to dissipate high pressure at the booster station; on the other hand, the feed was maintained at the lowest possible pressure, almost gravitational, but which starts generating vacuum at Km 8 (High Point).
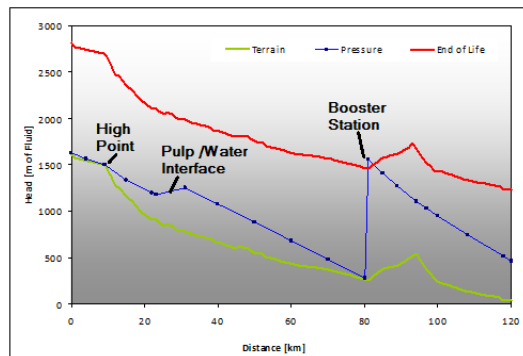
Figure 11. Concentrate replacing Water and booster pumps running.

In order to have a realistic operation at the OTS control room, historical data was added its trends were displayed on a wide screen and also a leak detection system was included. Data from an actual mill were obtained. The pressure transmitter's noise results varied (3 sigma) from 2.5 to 7.5 psi, depending on the probe location. The noise was included into the simulation and was forced to the leak detector to filter it like on the real control.
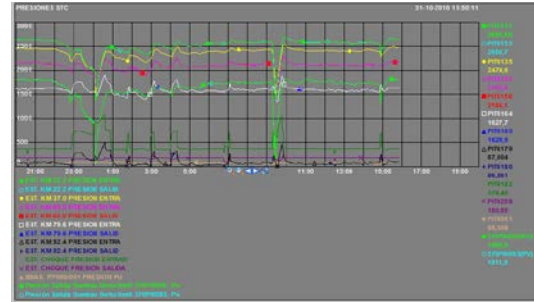
Figure 12. Concentrate Pipe Pressure trends, example of Historization.

On scenarios, the operator ability was tested on the following type of abnormal situations:

1. Failure of a pump
2. Solid sedimentation in a section
3. Rupture of disk brake
4. Loss of a pressure transmitter
5. Small leakage
6. Large leakage
7. Load Shedding

All consultants, supervisors and operators, agreed upon how realistic the responses become in all tested cases. Operators were asked to give a test before training and at the end of it. On an average, the start competencies were at the level of 35% and after 2 weeks of hands-on training, the test results showed it as above 80%.

One of the most relevant experiences was related to leakages. Once the operator was confronted with a large leak, the leak detector alarm was activated, and he/she was required to evaluate the situation, make an estimate of the leak location, and act accordingly. After training, all operators were able to react immediately, and in less than 10 minutes start the shut-down procedure. When the small leak scenarios were started (the scenario represented a pitting which starts from nil until it reached a full 2" hole in 50 minutes). This scenario would not trigger the leak detector alarm as the changes in dP are smaller than the filter on pressure transmitters. In the first test, it takes up to 8 hours for the operator to conclude there was a leak. After training, it took them one to two hours to arrive at the same result. We concluded that only a well-trained operator is prepared to find out a small leak situation and that there is no technology available to replace his experience.

6

NOMENCLATURE

a	wave speed in m/s
aii	correlation factors
A	pipe cross-section area in m2
Cv	Solids volumetric percent
Cw	Solids mass percent
D	pipe diameter in m
dP	Pressure drop in mcl
e	Wall thickness in mm
E	Modulus of elasticity of pipe material
f	Friction factor adimensional
g	Gravity acceleration: 9.81 m/s^2
H	Piezometric head in mcl
Kl	Bulk modulus of elasticity of liquid in Kg/m s2
Ks	Bulk modulus of elasticity of solid in Kg/m s2
L	Pipe Length in m
Q	Volumetric flow rate in m3/s
R	coefficient = f/2DA in 1/m3
ρ	density in kg/m3
t	Time in seconds
μ	viscosity in Pa s
v	Fluid speed in m/s

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