Slurry Pipeline System: Simulation and Validation

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ABSTRACT

Multiple simulation techniques were used to simulate the operation of the Antamina pipeline system. For the storage tanks, the simulation was based on mass balance and the Monte Carlo simulation principle. The pipeline simulation was based on the method of characteristics. Field tests showed that with accurate estimation of the acoustic wave speed and friction factor, this method could simulate all hydraulic phenomena satisfactorily.

NOMENCLATURE

a	Acoustic wave speed in pipeline, m/s
C/C_A	Ratio of volumetric concentration of solids at 0.98*D* and 0.5*D* from bottom of pipe
C_D	Particle drag coefficient of solids
Cv	Volumetric concentration of slurry
D	Pipe diameter, m
E	Modulus of elasticity, GPa
e	Pipe wall thickness, m
f	Fanning friction factor
g	Gravitational acceleration, m/s²
H	Piezometric head, m
He	Hedstrom number, $He = \frac{D^2 \rho \tau_0}{\eta^2}$
i	Hydraulic gradient for slurry
i_w	Hydraulic gradient for water
K	bulk modulus of elasticity, GPa
s	Specific gravity of solids
Re	Reynolds number, $\mathrm{Re} = \frac{VD\rho}{\eta}$
t	time, s
$u*$	Friction velocity, m/s
V	Mean velocity of flow, instantaneous velocity, m/s
w	Fall velocity of solids, m/s
β	Ismail coefficient
ε	Pipe absolute roughness, m

κ_V	Von Karman constant
ρ	Density, kg/m³
τ_0	Yield stress of slurry, Pa
η	Plastic viscosity, Pa·S

1 INTRODUCTION

Numerous slurry transportation pipeline systems have been built in the past 10 years [1]. The Antamina copper and zinc 302-km cross-country slurry pipeline in Peru has often been referred to as one of the most challenging projects in terms of operating complexity and system configuration. The system was successfully commissioned in July 2001. All process design criteria were satisfied. Comprehensive computer simulation played an important role during the design and commissioning phases. The simulation methods were validated during the commissioning. This paper presents the pipeline system configuration, simulation methods and accuracy.

2 TASKS OF COMPUTER SIMULATION

Computer simulation is a technology to create a software representation of a system's operation. For the Antamina pipeline, a customized model called Pipeline Simulator™ was created. During the design phase of the pipeline, the simulator assisted in the following tasks:

- Optimizing the design parameters, such as the holding capacity of tanks, the pipeline diameter for each section, the wall thickness distribution, the number of valve stations and the pressure class of station piping components.
- Predicting system performance under normal and upset conditions and testing the worst transient scenario.
- Optimizing the pipeline shutdown and restart sequence.
- Testing adjusting ability of choke stations.
- Testing the pressure relief devices of pumps, pump stations and valve stations.
- Demonstrating why certain phenomena occur in operations, such as pressure fluctuations when a water batch is moving through a valley or a valve is closed.
- Gaining insight about which variables are most important to performance and how these variables interact.

During the commissioning phase, the simulator was used to guide some special operations, such as pipeline fill and pigging. The simulator also proved an ideal tool for training the pipeline operators (Figure 1). Since the computer interface and the simulated hydraulic phenomena are similar to the actual system, the new operators were confident controlling the real pipeline. They had gained experience by operating the model pipeline hundreds times in classroom.

Figure 1 Operators operated the virtual pipeline, Pipeline Simulator™, in classroom

3 SLURRY SYSTEM OPERATION SIMULATION

3.1 Tank Operation Simulation

The Antamina pipeline was designed for the transport of three different products, zinc, low bismuth copper, and high bismuth copper. These products would be stored in separate tanks and be pumped by separating the products with a minimum of 1-hour water slug to minimize product cross-contamination.

The tanks were expected to switch frequently to avoid overflow. The mill output for each product was expected to vary widely. It was found that the required capacity of the holding tanks would be very large if the design were based on the worst case scenario. Tank operation simulation, therefore, was specifically required during the pipeline design phase to determine the tank capacity with a reasonable balance between cost and risk.

The following steps were taken to size the tanks using simulation approach.

1) Mill production simulation. Many factors could affect the mill production. The mining plan, ore grade and hardness, production campaigns, mill availability and metal demand in the market are among them. Each factor would vary randomly within a defined range. The Monte Carlo method was used to simulate the fluctuations in production.
2) Pipeline operation simulation. The pipeline could operate in the defined operating range. The pipeline could be shut down any time with a probability of 1%. Pipeline flow rates were generated based on these assumptions.
3) Application of operation constraints.
   - Slurry batch duration should not be less than 10 hours.
   - Water batch duration should be between 1 and 4 hours or longer than 8 hours to avoid significant pressure fluctuation when the water batch flows through a valley.

Different numbers and sizes of tanks were tested with the simulation. Figure 2 is the summary of the simulation results. It shows the probability that a random eight-hour pipeline shutdown would force a concentrator shutdown. It can be seen that the probability would be less than 0.05 when the storage capacity of each tank is greater than 4500 m^3. Five 18 x 18 meter tanks (two for zinc, one for low bismuth copper, one for high bismuth copper and one as a swing tank for other types of product such as bornite ore concentrate) were finally selected. Figure 3 shows the simplified logic that was used to size the tanks.

3.2 Pipeline Operation Simulation

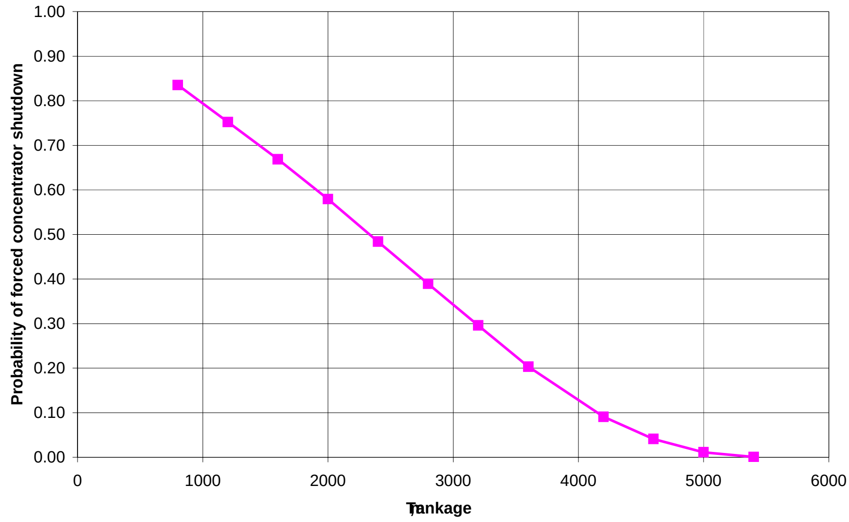

Figure 2 Relation between tank size and probability of forced concentrator shutdown

Operation of the Antamina long distance slurry pipeline consists of the following activities:

- Pipeline start-up, manually or automatically
- Flow rate control based on tank level and trend
- Pressure monitoring and control by choke adjustment, pump speed adjustment or both
- Batch operation, inserting water batches between slurry batches
- Pipeline normal shutdown
- Pipeline emergency shutdown
- Pipeline drain
- Pipeline fill

These activities cause complex hydraulic responses in the pipeline. The method of characteristics was used to simulate the responses. The following sections review the basics of applying this method to a slurry system. Further details of this method can be found in Reference [2].

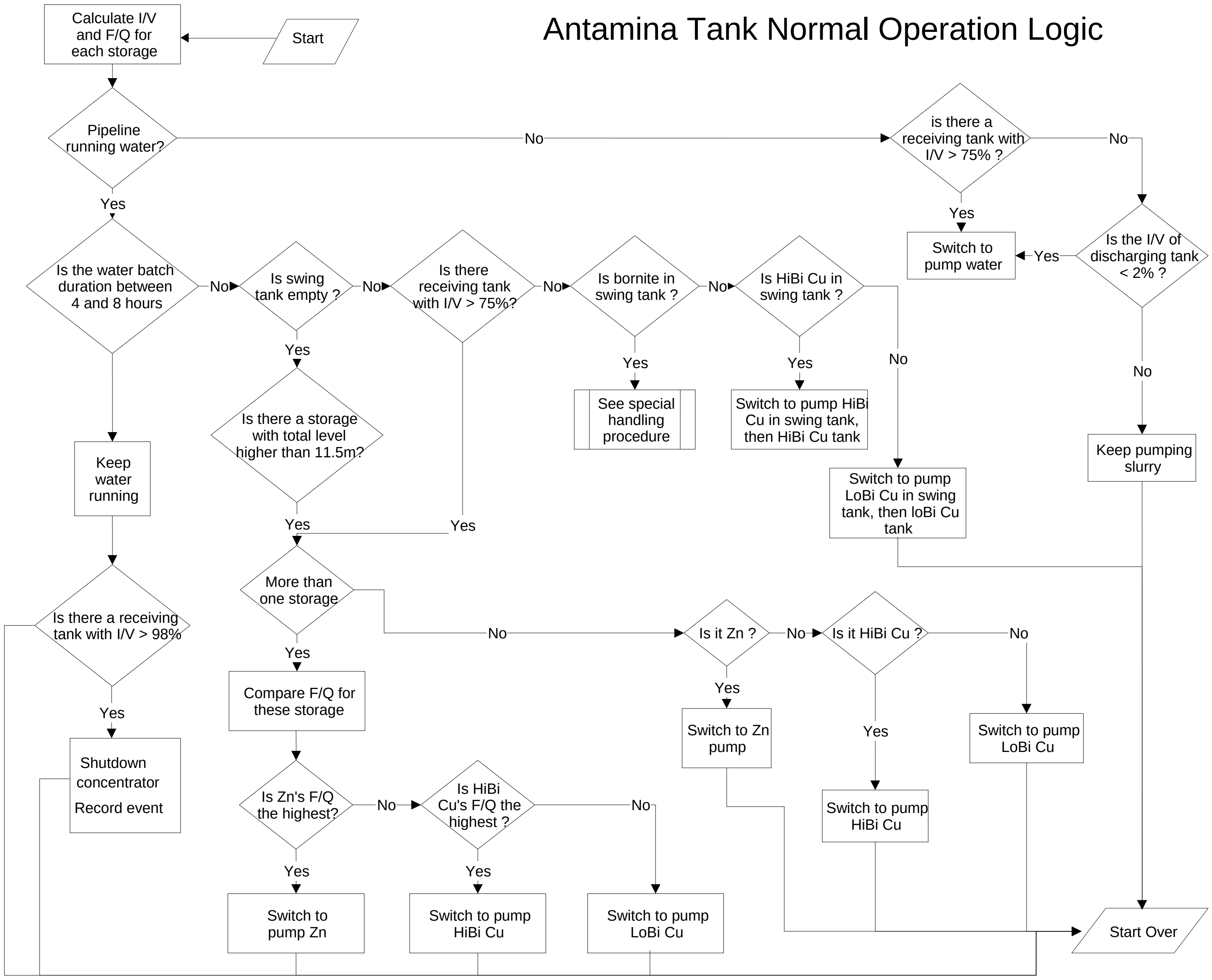

Figure 3 Antamina tank operation simulation logic (for tank sizing)

3.2.1 *Equation of Motion*

The equation of motion, Equation (1), can be derived by applying Newton's second law of motion to a free body shown in Figure 4.

$$g\frac{\partial H}{\partial x}+\frac{4fV|V|}{2D}+\frac{V\partial V}{\partial x}+\frac{\partial V}{\partial t}=0 \qquad \text{(1)}$$

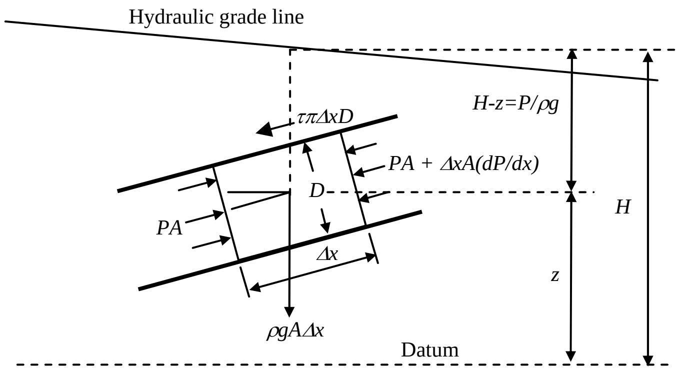

Figure 4 Free-body diagram for equation of motion

3.2.2 *Equation of Continuity*

The equation of continuity, Equation (2), can be derived by applying the law of conservation of mass to a control volume shown in Figure 5.

$$\frac{dH}{dx}+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \qquad \text{(2)}$$

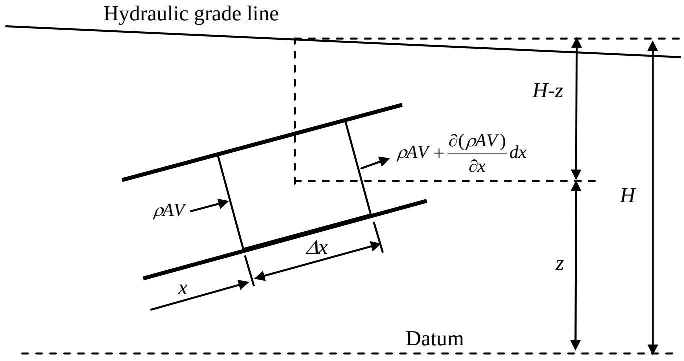

Figure 5 Control volume for continuity equation

3.2.3 *Method of Characteristics*

To simulate a slurry system dynamically, Equations (1) and (2) must be solved together. The technique used to transform the partial differential equations into total differentials is the method of characteristics. The detailed assumptions and derivation can be found in Reference [2]. The results are the compatibility equations, Equations (3) and (4). With help of a computer, these equations can be conveniently solved using finite differences.

$$C^+ : \begin{cases} \dfrac{g}{a}\dfrac{dH}{dt} + \dfrac{dV}{dt} + \dfrac{4fV\,|V\,|}{2D} = 0 \\ \dfrac{dx}{dt} = +a \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$C^- : \begin{cases} -\dfrac{g}{a}\dfrac{dH}{dt} + \dfrac{dV}{dt} + \dfrac{4fV\,|V\,|}{2D} = 0 \\ \dfrac{dx}{dt} = -a \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

The knowledge of the friction factor, *f*, and acoustic speed, *a*, for slurry is critical for accurate simulation. There are many published methods for estimating *f* and *a*. Different methods are associated with different application conditions. The following methods were used for the Antamina slurry with fine solids and high concentrations.

3.2.3.1 Friction Factor Calculation

Slurry can be categorized as either a homogeneous flow or a heterogeneous flow. Homogeneous flow does not exhibit a significant concentration gradient of solids along the vertical axis of the pipe. C/C_A is used to quantify the separation point between homogeneous and heterogeneous. C is the volume concentration at $0.98D$ from pipe bottom. C_A is the volume concentration at pipe axis. $C/C_A = 1$ represents a truly homogeneous flow. In practice, a flow is considered as homogeneous if C/C_A is 0.8 or greater.

The friction factor, *f*, of homogeneous flow can be computed based on its rheological characteristics. If it is Newtonian, the following Colebrook equation is widely used to predict *f*.

$$\frac{1}{\sqrt{f}} = 4\log(\frac{D}{2\varepsilon}) + 3.48 - 4\log(1 + \frac{9.35D}{2\varepsilon\,\mathrm{Re}\sqrt{f}}) \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

If the slurry is non-Newtonian, the charts provided by Hanks[3] are good tools for the estimation. Figure 6 is for Bingham plastic slurries. It is applicable to many types of slurry with fine particles and high concentration, such as the Antamina slurries.

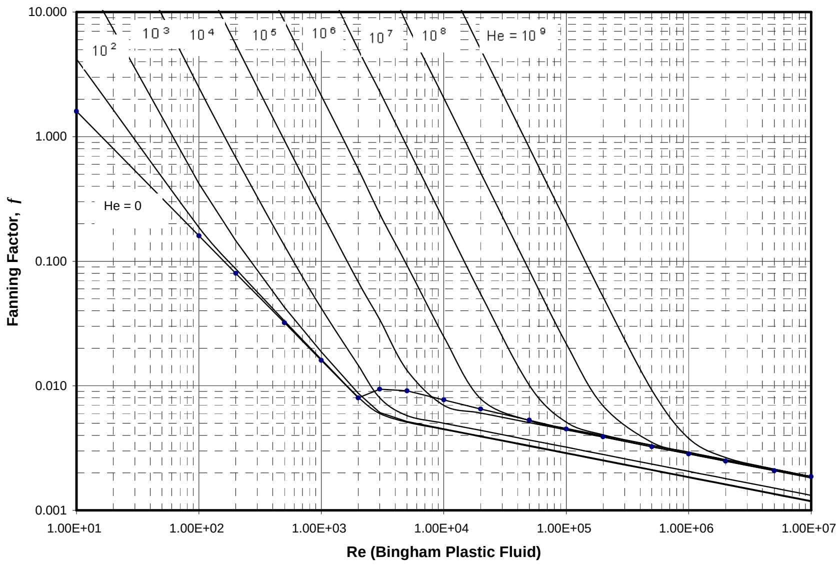

Figure 6 Friction factor, *f*, as a function of Reynolds number for Bingham plastic slurries

Once the friction factor is determined, the head loss of a homogeneous flow is given by the Darcy-Weisbach equation:

$$i = 4f\frac{V^2}{2gD} \qquad \text{(6)}$$

When the slurry is heterogeneous, additional head loss caused by solids must be considered. The Durand equation [4]is widely used for its prediction.

$$\frac{i - i_w}{i_w C_v} = 82\left(\frac{V^2\sqrt{C_D}}{(s-1)gD}\right)^{-1.5} \qquad \text{(7)}$$

However, the Durand equation was derived based on the tests of slurries with uniform particles. In most commercial applications, the particle size is not uniform. Fine particles form a homogeneous slurry while coarse particles are heterogeneously distributed. Equation (6) will underestimate head loss while Equation (7) will overestimate it. Wasp et al.[5] proposed to divide the slurry into a heterogeneous part (bed) and a homogeneous part (vehicle) using Equation (8).

$$\log\left(\frac{C}{C_A}\right) = -1.8\left(\frac{w}{\beta\kappa_V u^*}\right) \qquad \text{(8)}$$

They specified that the heterogeneous part be carried by the homogeneous part. It was assumed that for each size fraction, the portion of C/C_A is homogeneously distributed and the remainder (1- C/C_A) is heterogeneously distributed. Equation (6) was used for estimation of head loss of the homogeneous part and Equation (7) was used for the heterogeneous part. The sum of the two parts gives the prediction of the whole slurry head losses. The friction factor *f* needed in Equations (3) and (4) can be back calculated by Equation (6). It should be noted that the *f* for slurry is a function of pipe ID, roughness, slurry rheology and the particle size consist. When the slurry concentration, rheology or particle size distribution is changed, *f* must be recalculated for an accurate simulation. The detailed procedure cannot be presented in this paper due to the space limit. The interested readers can find the details in Chapter 7 of Reference [5].

3.2.3.2 Acoustic wave speed calculation

For single-phase liquid, Equation (9) is well accepted to predict the acoustic wave speed in the flow.

$$a = \sqrt{\frac{\frac{1}{\rho}}{\frac{1}{K} + \frac{D}{Ee}}} \qquad \text{(9)}$$

For slurry, there are two conflicting theories to account for the presence of solids. Wood & Kao[6] and Bechteler & Vogel[7] added a solids term into the equation of motion and concluded the following equation:

$$a = \sqrt{\frac{\frac{1-C_v}{\rho_l} + \frac{C_v}{\rho_s}}{\frac{1-C_v}{K_l} + \frac{C_v}{K_s} + \frac{D}{Ee}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

However, Thorley and Hwang[8] believed that Equation (11) should be used because $\rho_l(1 - C_v) + \rho_s C_v = \rho$

$$a = \sqrt{\frac{\frac{1}{\rho_l(1-C_v) + \rho_s C_v}}{\frac{1-C_v}{K_l} + \frac{C_v}{K_s} + \frac{D}{Ee}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

Both arguments are fundamentally sound. For $C_v = 0$ or $C_v = 1$, Equations (10) and (11) will give the same results. However, the volume fraction, C_v, for most commercial slurries is between 0.1 and 0.4. The acoustic wave speed calculated by Equations (10) and (11) is different in this range. Figure 7 shows the difference and some field-measured data (refer to Section 4.2.2). The different estimation of acoustic wave speed will result in a different estimation of the magnitude of the transient pressure and the time for a pressure wave to travel from one point to another. The travel time is critical for determining the startup and shutdown sequence of the complex pipeline system with a pump station and five valve stations.

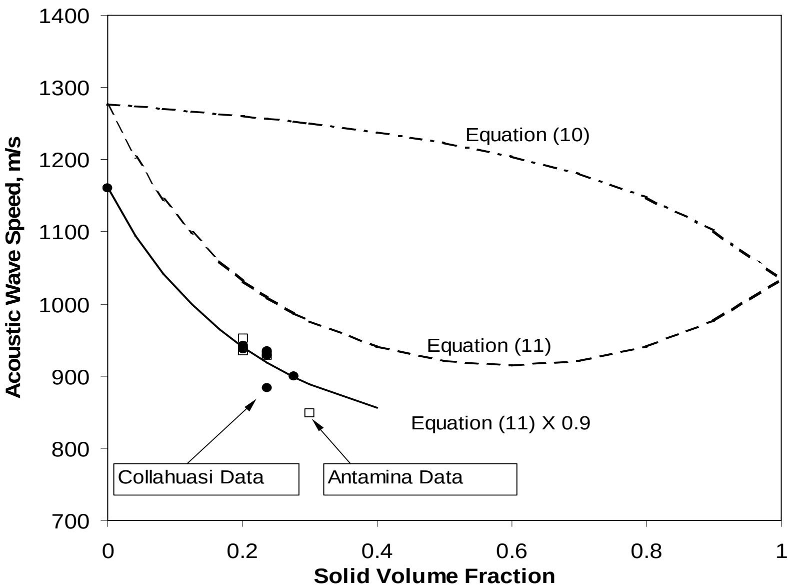

Figure 7 Acoustic wave speed comparison: calculated vs. measured

4 PIPELINE SIMULATION VALIDATION

4.1 Test Conditions

The Antamina pipeline ground profile and the system configuration are presented in Figure 8. The data acquisition system uses Wonderware FactorySuite™ and Modicon Modbus™ PLCs. The data communications are through a fiber optic network with 10M bps capacity. The pressure change history of each pressure transmitter was recorded and plotted by on-line monitoring software, Pipeline Advisor™.

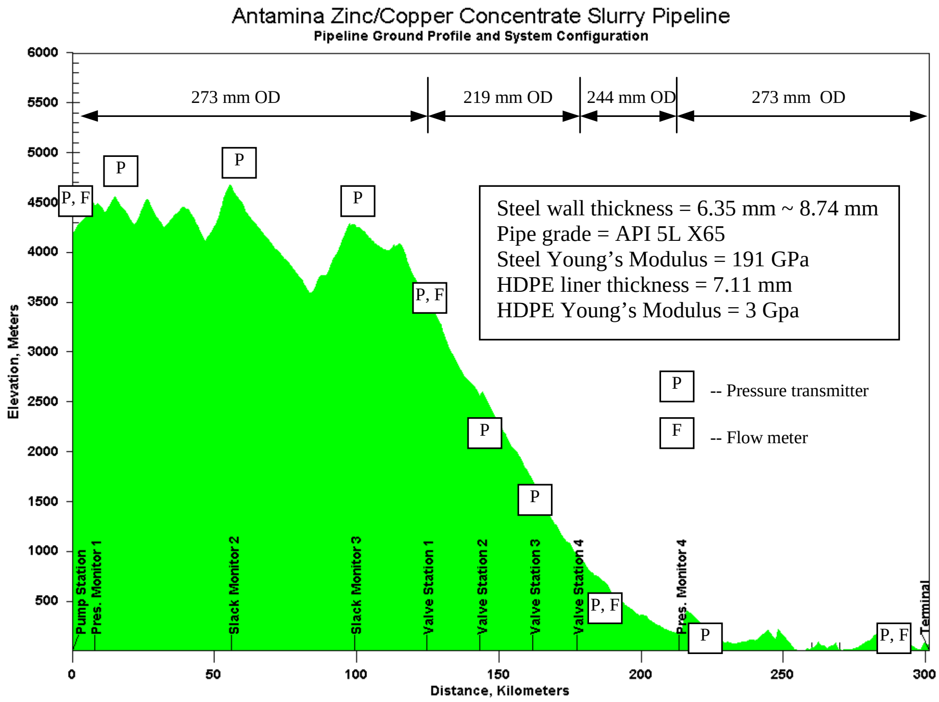

Figure 8 Antamina pipeline ground profile and system configuration

4.2 Test Results and Discussion

A series of tests were conducted to validate the above-mentioned procedures and to estimate friction factor, acoustic wave speed and, finally, the maximum transient pressure in the pipeline.

4.2.1 Pipe friction factor

The pipeline is divided into nine sections by the pressure monitoring stations. The particle size distribution, slurry concentration and rheology for each batch were measured before each batch was pumped into the pipeline. The batches were tracked by the Pipeline Advisor™. When the system reached a stable condition, a real time HGL plot was recorded (Figure 9). Based on the local concentration and pressure readings shown on the plot, the actual friction factor was back calculated. Table 1 shows the characteristics of tested slurry samples taken from the tanks. The slurries were slightly diluted by the seal water of the charge pumps. Table 2 shows a comparison of the Fanning friction factors between the simulated and the measured. As is seen, the simulation based on the procedure proposed by Wasp et al. predicts the friction factor satisfactorily.

Table 1 Characteristics of slurry batches

Batch	PSD, mesh			Solids	Viscosity	Yield Strs	pH	%	Temp.
N	-100	-200	-325	SG	cP	(dyn/cm?		solids	[illegible]
15	99.3	94.5	76.6	4.2	14.4	48.3	9.91	57.0	14
17	99.1	88.1	64.7	4.2	9.7	20.2	10.13	60.3	13
25	98.5	85.4	60.4	4.2	11.5	25.2	10.6	65.2	16

Table 2 Fanning friction factor comparison

Weight Concentration, %	V, m/s	Measured *f*	Simulated *f*	Error
56.50%	1.595	0.0044	0.0043	-2.8%
59.80%	1.595	0.0043	0.0042	-1.4%
59.80%	1.638	0.0041	0.0042	1.5%
56.50%	1.66	0.0041	0.0042	2.2%
64.80%	2.735	0.0043	0.0042	-2.9%
64.80%	2.697	0.0043	0.0042	-0.6%
63.60%	2.754	0.0041	0.0040	-0.3%
56.50%	2.760	0.0039	0.0041	4.2%
64.80%	2.742	0.0042	0.0043	1.8%
63.60%	2.760	0.0040	0.0040	0.3%
56.50%	2.060	0.0041	0.0042	3.3%
64.80%	2.047	0.0043	0.0042	-2.6%
56.50%	1.638	0.0040	0.0043	6.9%

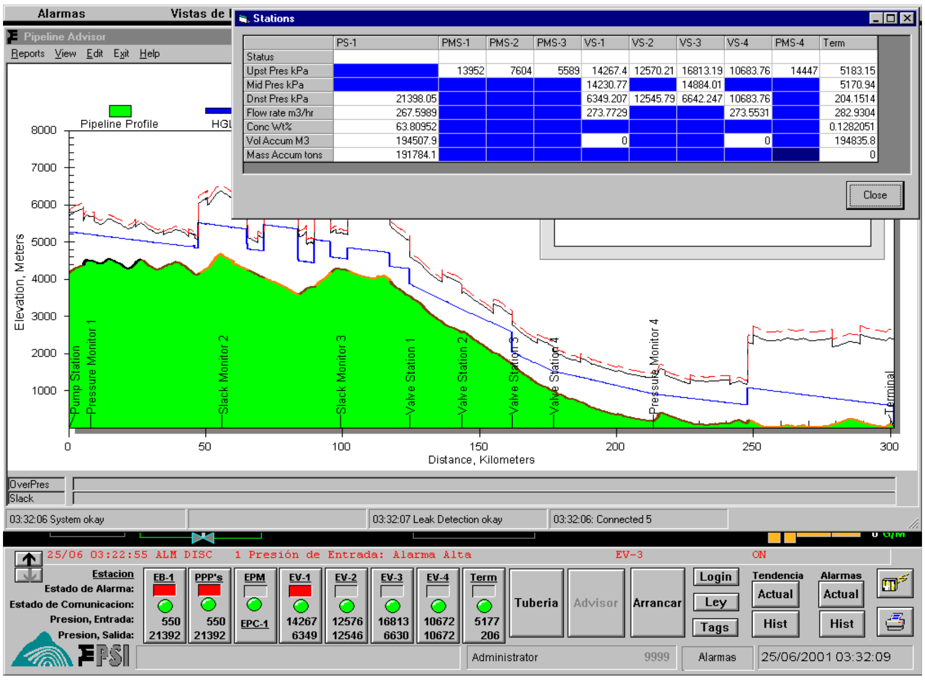

Figure 9 A graphical record from Pipeline Advisor™ for friction factor validation

4.2.2 Acoustic wave speed

The acoustic wave speed was measured by closing the station valve and creating a pressure spike at VS1, then measuring the pressure wave travel time from VS1 to the upstream pressure monitoring station, PMS3, refer to Figure 10. The measured acoustic wave speed for various conditions is plotted on Figure 7, along with the curves generated from Equations (10) and (11). It can be seen that the predicted values from both equations are higher than the measured values. Equation (11) gives a closer estimation. By multiplying by a correction factor of 0.9, Equation (11) matches the measured points well. Note that the correction factor is also needed when volume fraction equals 0 (pure water). It does not depend on solid concentration. Therefore, it is believed that the air trapped between the steel wall and the

HDPE liner causes the difference between Equation (11) and the measured data. The data collected from the Collahuasi pipeline[9] also support this conclusion.

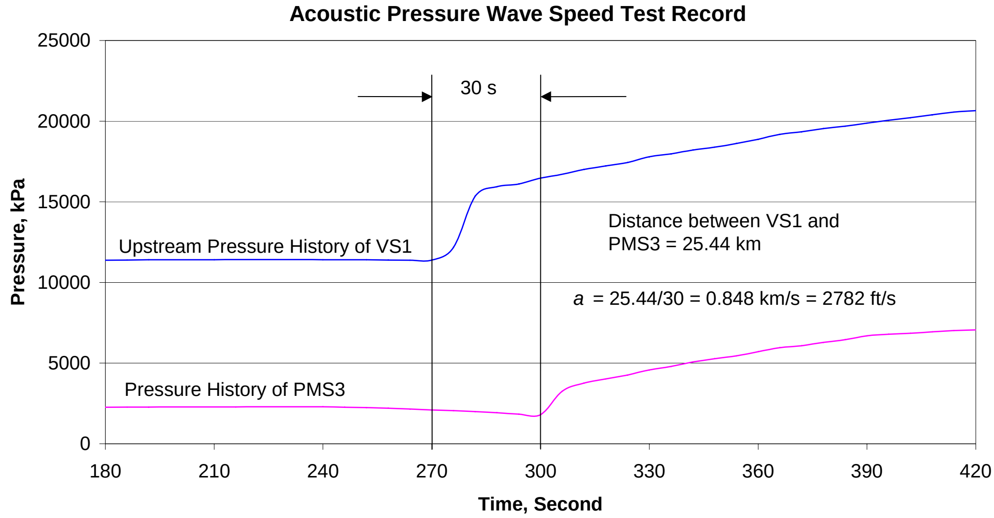

Figure 10 Acoustic wave speed calculation chart

4.2.3 Peak transient pressure

The peak transient pressure caused by valve closing was simulated and measured. Figure 11 shows a simulation of the pipeline shutdown. The field test was conducted by shutting down the pipeline using the same shutdown sequence as the simulation. The peak transient pressure at each station was recorded. Table 3 is a comparison between the simulated results and the measured data.

Table 3 Peak transient pressure, kPa

Stations	Simulated	Measured	Error
VS1	16218	16538	-1.93%
VS2	11980	12555	-4.58%
VS3	11153	10866	2.64%
VS4	13300	12500	6.40%
Terminal	12149	11935	1.79%

It can be seen that all simulated values are within a ±10% error range that can be covered by the design safety factor. It was also observed that simulation results were satisfactory for other operation scenarios, such as choke combination changes, batch interfaces moving through the choke stations and batches moving along the rugged terrain.

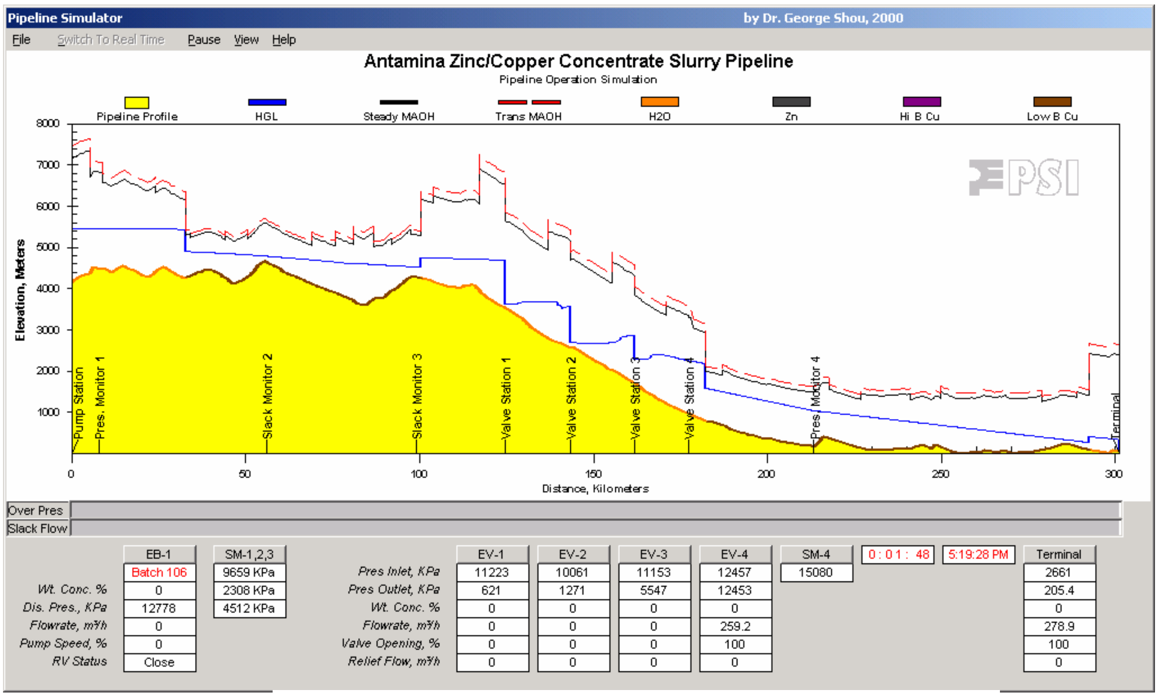

Figure 11 Pipeline shutdown simulation

5 CONCLUSIONS

1) Slurry pipeline system operation can be simulated accurately.
2) The procedure proposed by Wasp et al. predicts slurry friction factor satisfactorily.
3) The measured acoustic speed in slurry is lower than the available theoretical predictions. Thorley and Hwang's equation corrected by a factor of 0.9 gives a close estimation of the speed.
4) The method of characteristics is a practical tool to simulate hydraulic phenomena in a slurry pipeline. Pipeline operating sequences can be safely determined by the simulation.

6 ACKNOWLEDGMENT

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