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# Computational modeling for efficient long distance ore transport using pipelines

Christian F. Ihle [a,b,*,1], Aldo Tamburrino [b,c,1], Santiago Montserrat [b,1]

[a] Department of Mining Engineering, Universidad de Chile, Av. Tupper 2069, Santiago, Chile
[b] Advanced Mining Technology Center, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile
[c] Department of Civil Engineering, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile

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ABSTRACT

The term efficiency in hydraulic transport system design and operation has several possible interpretations. Whether it may stand for energy consumption, it may also aim to the minimization of the water or the carbon footprint. All these tentative means of efficiency should meet project and operational goals, including throughput constraints. The consideration of these aspects altogether, seeking for best project and operational conditions, represents a major optimization problem which, on the other hand, depends on the evolution of input variables for slurry transport along with environmental, energy and water consumption costs. In this paper, an example of a long distance ore pipeline with plant demand-dependent inputs is studied in the light of the implementation of an optimization problem. Results have been compared with those corresponding to typical transport modes, and show that common operational conditions differ from those optimized in terms of system utilization, flow rate and slurry concentration. In particular, the optimal computed parameters include lower fractions of the total available times, lower flow rates and higher concentrations than in typical systems, thus suggesting a different design and operational rationale.



## 1. Introduction

Long distance slurry pipelines are a widespread means of transport for iron and copper concentrates in South American locations including, Argentina, Chile, Brazil and Perú (Jacobs, 1991; Ihle, 2013a). They are traditionally designed according to specific hydraulic and site considerations inherited from the earliest designs, during the late sixties. Although such design rationale has been proven robust throughout the years, they do not directly deal with the increasingly challenging environmental scenarios, faced both in greenfield and brownfield projects. In particular, provided a set of representative economic and environmental indicators can be put together as cost indexes, even modern system designs lack of any consideration to this kind of element as an operational decision driver (Ihle, in press). Although long distance slurry pipelines are commonly commissioned and proven to work within a given operational range (Fig. 1), which allow for several different combination of throughputs (delivered dry solids), slurry concentrations and flow rates, there is not a special regard to which slurry concentration is best in terms of energy efficiency in combination with environmental metrics. Moreover, typical system operational ranges disregard the use of a variable system utilization fraction, defined as the part of the total time where the system will be effectively working. The simple exercise of drawing a horizontal line at a given throughput value, $\dot{m}$ (i.e. parallel to the flow rate axis in Fig. 1a), reveals not a single, but a collection of different solids volume fractions, $\phi$, and slurry flow rate ($Q$) combinations (Fig. 1b). Which one to choose is a question often left to the operators or their supervisors who, in the absence of additional information to decide, tend to stick to familiar concentrations and flow rates, defined after the system startup phase. A possible operational choice is the highest possible concentration within the operational range, thus minimizing the water volume and consequently the water footprint of the operation. However, this causes an increase on the energy consumption that may somewhat create a worse operational condition (Ihle and Tamburrino, 2012b). A natural question is then to elucidate, not only which are the best flow rate-concentration combinations given the slurry properties and the throughput characteristics, but also which are the best system utilization fractions ($\lambda$). In this paper, this problem is analyzed in the context of an optimization problem where the relative effect of energy and water use are included as weighting factors in the form of unit costs. Emphasis is placed herein in the effect of a variable system throughput demand, thus complementing a previous analysis centered on the effect of variable unit costs (Ihle, 2013a),

* Corresponding author at: Department of Mining Engineering, Universidad de Chile, Av. Tupper 2069, Santiago, Chile. Tel.: +56 2 29784503.
*E-mail address:* cihle@ing.uchile.cl (C.F. Ihle).
[1] Tel.: +56 2 29784991.

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**Nomenclature**

| | |
|---|---|
| $Ar$ | Archimedes number |
| $c$ | unit cost |
| $D$ | pipeline internal diameter |
| $E$ | energy consumption (Eq. (7)) |
| $f$ | Darcy friction factor |
| $Fr$ | Froude number |
| $g$ | magnitude of gravity acceleration vector |
| $k$ | design constant for minimum velocity |
| $L$ | pipeline length |
| $\dot{m}$ | dry solids flow (throughput) |
| $p$ | pressure |
| $Q$ | flow rate |
| $Re$ | Reynolds number |
| $S$ | specific gravity of solids |
| $T$ | time per period |
| $U$ | mean flow velocity |
| $W$ | water consumption (volume/period, Eq. (9)) |
| $x$ | route position along tube length |
| $z$ | route altitude measured from an arbitrary datum |

*Greek letters*

| | |
|---|---|
| $\alpha$ | prefactor |
| $\beta$ | exponent |
| $\epsilon$ | efficiency of pumping system |
| $\lambda$ | pipeline utilization fraction |
| $\mu$ | liquid dynamic viscosity |
| $\eta$ | Bingham plastic viscosity |
| $\phi$ | solids volume fraction |
| $\rho$ | slurry density, $\rho = \rho_W(S\phi + 1 - \phi)$ |
| $\tau$ | shear stress |
| $\hat{\tau}$ | yield stress prefactor |
| $\Omega$ | cost function (Eq. (9)) |

*Subscripts*

| | |
|---|---|
| 0 | general definition |
| 50 | median size |
| $*$ | optimal value |
| $c$ | critical condition |
| $d$ | solids deposition condition |
| $E$ | related to energy |
| $f$ | related to the friction factor |
| $J$ | related to the hydraulic gradient |
| max | maximum condition |
| min | minimum condition |
| $SS$ | loose packing (settled solids) condition |
| $t$ | laminar–turbulent transition condition |
| $v$ | vapor pressure condition |
| $W$ | related to water (e.g. $\rho_W$ is the slurry density) |
| $w$ | related to wall |
| $y$ | yield (applied to the concept of yield stress) |

additionally adding a terrain constraint in the example being analyzed.

## 2. Problem formulation

Consider an operating long distance slurry transport system with known internal diameter ($D$) where the throughput ($\dot{m}$), defined as the dry solids rate, along with route and slurry properties are known. The total energy and water cost may be expressed as:

$$\Omega = c_E E + c_W W, \tag{1}$$

where $c_E$ and $c_W$ represent the unit costs of energy and water, respectively. They not need to be economic costs only, but may also represent environmental and/or social costs bonded to local conditions. The variables $E$ and $W$ represent the amount of energy and water volume required to allow for the operation, respectively. This simple relation bears the inherent trade off relating energy and water use: whereas a high energy cost will imply the need to use additional water, this will cause the slurry flow rate to increase, given a fixed throughput goal. In particular, neglecting the importance of water will drive to the maximization of the energy efficiency and possibly the utilization fraction (Wu et al., 2010; Ihle and Tamburrino, 2012b), regardless the economic and/or environmental cost of water. On the other hand, if only water was the relevant element to save, then best operational scenarios, given the throughput, would be those with very high concentrations, and thus prohibitively high energy consumptions. In most locations, it is of uttermost importance to find a right balance between the use of energy and water in a conveniently defined way. However, such optimal values are not obvious and, in particular, depend on the unit costs of water and energy, $c_W$ and $c_E$, respectively.

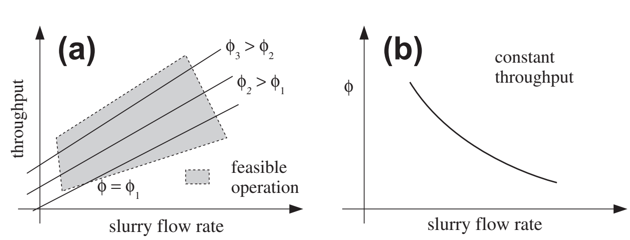


**Fig. 1.** Schematic representation of a typical operational guidelines, with $\phi$ representing the solids volume fraction. (a) Operational range, with the shaded region denoting the allowable operational points and (b) schematic representation of flow rate/volume fraction relation for a constant throughput value.

The components $E$ and $W$ may be expressed depending on the pipeline design approach. To assess the energy requirement, $E$, the hydraulics needs to be calculated and, in particular, the total energy consumption on a specific period. In pipeline flow, an energy balance between points 1 and 2 of a turbulent flow stream across the pipeline is given by Granger (1987):

$$\frac{p_1}{\rho g} + z_1 = \frac{p_2}{\rho g} + z_2 + JL_{12}, \tag{2}$$

with $J = \frac{f}{D}\frac{U^2}{2g}$ the hydraulic gradient. Here $p_i$ and $z_i = z(x = x_i)$ are the line pressure and altitude at the route point $x_i$, assuming the flow going from point $x_1$ to $x_2$, distant by a tube length $L_{12}$, and $g$ is the magnitude of the gravity acceleration vector. The last term of the right hand side of (2) represents the frictional pressure losses, which control the energy balance. There, the Darcy friction factor, $f$, is defined as $f = 8\tau_w/\rho U^2$, with $\tau_w$, $\rho$ and $U$ the wall shear stress, slurry density and mean flow velocity, respectively, with $D$ the pipeline internal diameter. It is customary for design purposes to slightly overestimate the energy consumption by incorporating a gradient factor, $\alpha_J > 1$, such that $J_{\text{design}} = \alpha_J J$. The unknown $\tau_w$ (or $f$), should be modeled considering the need to adequately represent the slurry segregation phenomena as well as the effect of the viscous characteristic of the slurries. Here, the Bingham model for the rheology is assumed (Chhabra and Richardson, 2008). There are several models to compute the frictional losses,