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Technical Note

Should maximum pressures in ore pipelines be computed out of system startups or power outages?

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ABSTRACT

A key aspect of the design of long distance ore concentrate pipelines is the need to properly predict maximum pressures. This is traditionally done by means of transient analysis, thus predicting the possible impact of slurry hammers, which may occur during operation in a potentially uncontrolled manner in case of power outages. In this technical note, it is shown for typical ore slurry and pipeline characteristics, that in long distance systems with routes having inclined sections, the plug formation mechanism may become a dominant factor in system overpressures. A dimensionless number expressed as the ratio of the Joukowski and the plug overpressure value, suggests that a scale for the critical plug length above which maximum pressures are controlled by the plug mechanism rather than the transient flow is between about 150 m and 500 m, or a few percent points of the overall pipeline length in common long distance systems. A critical dependence on the solids initial concentration and the product of the static friction factor and the solids settled concentration is addressed.

1. Introduction

Long distance ore and tailings pipelines have the inherent complexity of dealing with shutdown and startup operations. In the former situation, the sedimentation of the solid matter occurs not only on the plane normal to the pipeline axis, but also parallel to it, with the potential implication of the formation of pipeline obstructions at low points (Abulnaga, 2002; Matoušek, 2005; Wilson et al., 2006). To remove the latter at system startup, additional energy is required to move an initially solid-like dense slurry. On the other hand, it is well known that such kind of facilities are prone to overpressures caused by water hammers (Wylie and Streeter, 1978). Despite operational guidelines often require a smooth increase and/or decrease of velocities during startup and shutdown operations, uncontrolled events such as power outages may cause potentially harmful pressure surges. On the other hand, the effect of solids segregation are a much less documented issue affecting starting-up of facilities and, in particular, causing pressure surges that may occur trying to unplug already settled solid matter. In this technical note, it is suggested that the relative importance of a slurry hammer and the additional friction caused by a plug at a pipeline low point depends on several factors and may deem either of both the dominant one depending on the slurry properties, the pipeline topology and material characteristics.

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2. Slurry hammer or pipeline plug?

A comprehensive description of the water hammer phenomenon may be achieved using standard approaches to solve the equations of continuity and momentum. Common numerical techniques to reproduce operational details include the method of characteristics or finite difference schemes of the governing equations (Wylie and Streeter, 1978; Bergant et al., 2008). Beside the slurry properties, the details of the pipeline in terms of topology, materials, dimensions, and operational issues including opening and closing cycles, the presence of valve stations, pressure relief devices, etc., need to be taken into account. Nonetheless, the simplest way to get a reasonable idea of the implications of a slurry hammer is by means of the Joukowski equation, which states that for an instantaneous valve closure, the maximum magnitude of the corresponding pressure surge, for a pipeline section of internal diameter D and thickness e, is given by

$$\Delta p_J = \rho_m c \Delta V, \tag{1}$$

with ρ_m the density of the fluid (or mixture) where the pressure wave propagates, c the pressure wave celerity and ΔV the instantaneous change on the mean flow velocity. ρ_m may be simply expressed in terms of the liquid density, ρ_l, and the specific gravity of solids, S, as $\rho_m = \rho_l[1 + \phi_0(S - 1)]$, with ϕ_0 the bulk solids fraction by volume of the slurry. The wave celerity term differs between the slurry and the water as it needs to take into account the liquid–solid interactions and the impact of the pressure increase in both the liquid and the solid phase, and thus becomes a function of the solids fraction, ϕ_0. It is also a function of the conduit mechanical properties. In particular, it is commonly expressed in the form:

$$c = \sqrt{\frac{k_\rho}{\rho_m K}}, \tag{2}$$

where $K = \frac{\phi_0}{K_s} + \frac{1-\phi_0}{K_f} + \frac{Dc_1}{Ee}$, with K_s and K_f denoting the bulk modulus of the solid matter and the fluid in the slurry, respectively, E is the Young modulus of the pipeline, and c_1 a constant representing the pipe constraint condition (Wylie and Streeter, 1978). The dimensionless constant k_ρ depends on the slurry composition and concentration. In particular, for a pressure wave propagating on a pure liquid ($\phi_0 = 0$), $\rho_m = \rho_l$ and $k_\rho = 1$ (Wylie and Streeter, 1978). In a slurry, Wood and Kao (1966) proposed $k_\rho = \frac{1}{S}[1 + \phi_0(S-1)][S - \phi_0(S-1)]$, whereas Thorley and Hwang (1979) suggest $k_\rho = 1$ (see also Han et al., 1998, for a discussion Han et al. (1998)). A generalization of the effect of solids for ellipsoidal particles from assumptions out of the continuity and momentum equations has been studied by Liou (1984), who obtained $k_\rho = 1 + \frac{m\phi_0(S-1)}{S+m}$, where m is the coefficient of virtual inertia of ellipsoids. They found good matching of experimental results using sands slurries with $m = 1$.

The overpressure caused by a plug in a horizontal line, or a segment symmetrical to the bottom point (e.g. a U-shaped one with inclined sections) may be related to the static friction between the solid matter trapped on it and the inner surface of the pipe. For a complete plug into the pipeline, Wilson et al. (2006) show that the normal force per unit length acting on the wall of the pipe due to the plug is given by $F_N = \frac{\pi D^2}{2} g \rho_l (S-1)\phi_m$, where g is the magnitude of the gravity acceleration vector and ϕ_m is the solids volume fraction in the plug, close to the loose packing concentration value—two examples yielding concentrations slightly below 0.5 are the measured values for sand reported by Matoušek (2005) and the fitted concentration proposed by Ihle (2013) from rheological measurements of concentrates—. Given the total frictional force per unit length is given by $\mu_s F_N$, where μ_s is a static friction factor, then the static shear stress required to keep a dense slurry plug from moving relative to the pipe wall is

$$\tau_s = \frac{D}{2}\mu_s g \rho_l (S-1)\phi_m. \tag{3}$$

The corresponding pressure to move the plug (Δp_p) is that which satisfies $\frac{\pi D^2}{4}\Delta p_p = \pi D L_p \tau_s$, where L_p is the corresponding plug length. Thus (Wilson et al., 2006),

$$\Delta p_p = 2 L_p \mu_s g \rho_l (S-1)\phi_m. \tag{4}$$

This expression has been tested experimentally with successful results using sands (Matoušek, 2002, and references therein, Matoušek, 2005, Wilson et al., 2006).

The conditions represented in a simplified manner by (1) and (4) become mandatory at design stage depending on the pipeline route: if no plugs exist whatsoever, and there is the possibility to start the system by smoothly resuspending the solids from top to bottom exerting an effective shear stress at the top of the bed, then the slurry hammer mechanism becomes dominant in the definition of the overpressure capacity of the system. In general, no plug will exist if the pipeline angle dips below both the angle of slide and the angle of repose of the slurry. The former corresponds to the critical angle that keeps static the solids layer in contact with the pipeline inner wall at system shutdown (see Shock et al., 1974, for a study of solids sliding in slurry pipelines) Shook et al. (1974) while the latter corresponds to the critical angle that keeps the solids static relative to each other (Jaeger et al., 1996). Defining, $\alpha^* = \max\{\alpha_s, \alpha_r\}$, where α_s and α_r are the angles of slide and repose, respectively, the plug length, L_p, may be roughly estimated from the length of the sections where $\alpha > \alpha_c$, defined herein as $L_{\alpha,c}$, by applying mass conservation, as $L_p\{\approx\}L_{\alpha,c}\phi_0/\phi_m$, where the equality depends on the particular boundary conditions relative to the interaction with neighboring points where $\alpha < \alpha_c$.

In most long distance pipelines, it is hardly possible to avoid zones with steep slopes in the route, and thus upon system shutdown it is most likely that there will exist a certain plug length. The relative impact of slurry hammer and pipeline plug may be assessed by estimating a certain allowable plug given a route and operational rationale. A critical condition would be that which equates (1) and (4), thus configuring the dimensionless ratio

$$\Pi = \frac{\Delta p_J}{\Delta p_p}, \tag{5}$$

which is, in particular, a function of the plug length L_p. A critical condition $\Pi = 1$ may therefore be cast in terms of a critical feasible plug length, $L_{p,c}$. In terms of the variables referred herein,

$$L_{p,c} \approx \frac{\rho_m c D \Delta V}{4\tau_s}, \tag{6}$$

where τ_s is given by (3). This relation may be alternatively expressed in terms of the critical pipeline length where $\alpha > \alpha_c$ as $L_{\alpha,c} \approx L_{p,c}\phi_m/\phi_0$, which becomes independent of ϕ_m. However, the

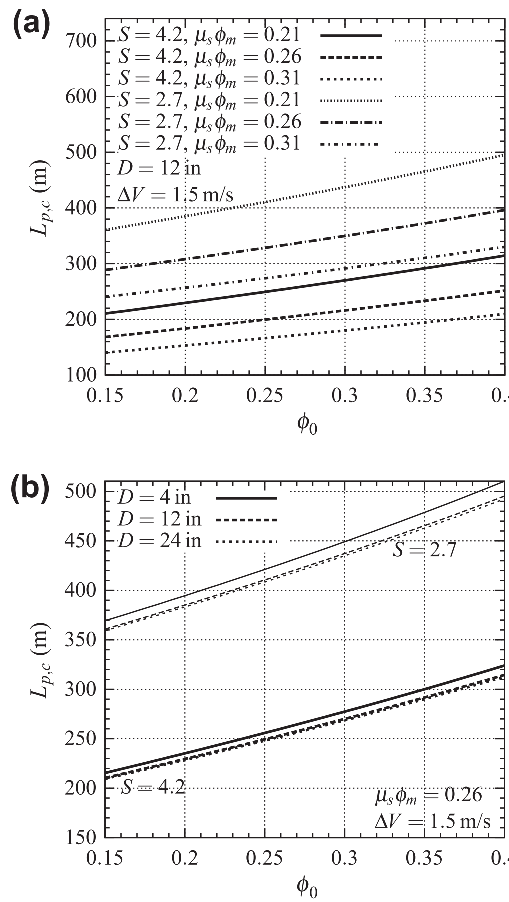

Fig. 1. Dependence of the critical plug length, $L_{p,c}$, with the bulk concentration, ϕ_0, for a 1.5 m/s step in velocity for the Joukowski equation with $k_\rho = 1 + \frac{m\phi_0(S-1)}{S+m}$ (Liou, 1984). (a) Different values of the specific gravity of solids and $\mu_s\phi_m$, with $S = 4.2$ and 2.7 resembling copper concentrate and tailings, respectively. (b) Different values of the pipeline internal diameter, $\mu_s = 0.55$ (Matoušek, 2002, assumed for sand in contact with steel) and $\phi_m = 0.47$ (Ihle, 2013, for copper and iron concentrates). In the present example, $E = 200$ GPa, $K_l = 2.09$ GPa, $K_s = 16$ GPa, corresponding to steel, water and sand, respectively. The pipe restriction coefficient, $c_1 = 0.8575$ is, in the present example, that corresponding to one valve closed and anchored (Wylie and Streeter, 1978). The coefficient of virtual inertia, $m = 1$ (Liou, 1984).

experimental results by Matoušek (2005) reveal that the friction factor μ_s is actually a function of ϕ_m. Therefore, both $L_{p,c}$ and $L_{\alpha,c}$ are indeed functions of the loose packing concentration, as intuitively expected. From this relation, when the pipeline route makes $L_p > L_{p,c}$, then the maximum overpressure that the system should withstand depends on the plug mechanism. Conversely, when $L_p \leqslant L_{p,c}$, then the slurry hammer controls the overpressure in the system. It is important to note that the exact form of (5)varies depending on the specific form to express the pressure wave speed and possible safety factors to be considered, according to particular pipeline construction codes.

Fig. 1 shows the dependence of $L_{p,c}$ with the bulk solids volume fraction, ϕ_0, for a steel pipe and different values of the dimensionless quantity $\mu_s\phi_m$, following the model by Liou (1984) for the pressure wave celerity. From the definition (5), Π is inversely proportional to the nondimensional quantity $\mu_s\phi_m$—or μ_s if $L_{\alpha,c}$ was considered instead of $L_{p,c}$— thus confirming that higher friction or solid packing concentrations will mean a smaller admissible plug length.

The critical plug length, $L_{p,c}$, tends to grow with the solids concentration. Although this might be a somewhat counterintuitive result, it is justified by the fact that the term Δp_J is strongly dependent on the concentration *via* the particle–fluid interaction. Despite that the overall effect of the presence of solids is to cause a decrease in c compared to a pure fluid, as may be seen from (2), increasing the concentration causes an effective increase on Δp_J—compared to a pure fluid—, proportional to $[1 + \phi_0(S - 1)]^{1/2}$, that is not counterbalanced whatsoever by the term Δp_p. This trend reverses with $L_{\alpha,c} = L_{p,c}\phi_m/\phi_0$ because for a constant plug length, higher bulk concentrations are related to shorter lengths where $\alpha > \alpha_c$. On the other hand, while the effect of the pipeline diameter is not important on the critical length (Fig. 1b), the specific gravity of solids has a significant impact on such variables. Given the same friction factor and settled solids concentration, the critical pipeline length is close to 60% larger in tailings than in ore concentrates.

3. Concluding remarks

The overall effect of the aforementioned variables, given a reasonable range slurry-like parameters, is the definition of a critical plug length, $L_{p,c}$, between about 150 m and 500 m for the slurry characteristics used. The impact of this restriction will depend significantly on the extent and route characteristics of the pipeline. Different topographic situations may derive into different needs and operational conditions. Two somewhat opposing examples are the realities of Chile and Brazil. While in the former country, concentrates—and, in some cases, tailings—are transported from the Andes mountains to coast level, in the latter slopes tend to be milder but concentrate lines may be longer. Nonetheless, higher distances make also likely that there will be several hundred meters, if not more than 1 km, of route sections exceeding the critical angle for significant axial solids migration to occur. For instance, in a 100 km copper concentrate pipeline operating at a volume fraction $\phi_0 = 0.3$, only 1% of the route exceeding the critical angle α^* might cause about a 600 m plug which, according to Fig. 1b, would require more than twice the estimated water hammer pressure using the Joukowski equation, to remove it.

Despite the present results are merely referential, they give an order of magnitude picture of the need to (a) effectively measure both the angles of slide and repose, where in the former case it is required to reproduce the real slurry-pipeline wall properties and (b) carefully choose the route to maximize operational robustness in terms of water/energy efficiency and/or operational variability requirements (Ihle and Tamburrino, 2012; Ihle et al., 2013). Overall, the answer to the original question is, as seen, a matter of engineering design and routing conditions that require a combined numerical and laboratory approach.

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