Research on numerical simulation and protection of transient process in long-distance slurry transportation pipelines

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Abstract: The calculation of water-hammer pressure phenomenon of single-phase liquid is already more mature for a pipeline of uniform characteristics, but less research has addressed the calculation of slurry water hammer pressure in complex pipelines with slurry flows carrying solid particles. In this paper, based on the developments of slurry pipelines at home and abroad, the fundamental principle and method of numerical simulation of transient processes are presented, and several boundary conditions are given. Through the numerical simulation and analysis of transient processes of a practical engineering of long-distance slurry transportation pipeline system, effective protection measures and operating suggestions are presented. A model for calculating the water impact of solid and fluid phases is established based on a practical engineering of long-distance slurry pipeline transportation system. After performing a numerical simulation of the transient process, analyzing and comparing the results, effective protection measures and operating advice are recommended, which has guiding significance to the design and operating management of practical engineering of long-distance slurry pipeline transportation system.

1. Introduction

The previous two-phase flow in the transient process has been conducted a lot of research so far, but most studies have focused on wave speed, friction loss and direct water hammer. In 1960s, in the design of coal pipeline system Wasp put forward to calculate the so-called complex slurry pipe resistance method. The point is that the entire method of solid particle suspension is divided into homogeneous suspension part and the bottom part of non-homogeneous, that is the carrier and the transportation material. The resistance of the two parts were calculated, and then added together, and that is the total pipe resistance of certain velocity and concentration. Since slurry pipeline particle distribution is continuous, Wasp also specifically proposed a formula as the distinction between the carrier and the seabed. In 1984, C.P.Liou assumed that two-phase flow in the steady state the velocity of solid particles and water flow is the same, only in the transient process when there is relative movement, as pressure wave arrived, particle velocity density will lag behind the fluid, and the greater the density, the greater the lag, and accordingly he put forward a formula to calculate the wave speed of the slurry that containing heavy particles. In 1994, Fei in its published works, after exploring and comparing various research results presented industrial slurry pipeline friction loss calculation model. This method has been verified by some practical examples. With the development of computer technology, and now pipeline water hammer calculations with computer simulations.
discrete model mainly includes the characteristic line method, finite volume method and the finite element method, the characteristic line method is the most widely used and it is relatively mature.

2. Mathematical model and calculation method of water hammer

2.1. Mathematical model of pseudo-homogeneous flow

The basic equations of pseudo-homogeneous solid-liquid two-phase unsteady flow can be expressed as follows:

The continuity equation:

\[ J_2 = \frac{c^2}{g} \frac{\partial v}{\partial x} + \frac{\partial H}{\partial t} + v \frac{\partial H}{\partial x} + v \sin \alpha = 0 \]  

(1)

Where \( H \) is water head, \( x \) represents the spatial coordinate, \( t \) represents time, \( v \) is the sectional average velocity, \( c \) is the wave speed, \( g \) is the acceleration of gravity, \( \alpha \) is the angle between the tube axis and the horizontal.

The motion equation:

\[ J_1 = \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + g \frac{\partial H}{\partial x} + \frac{\lambda}{2D} v |v| + \frac{F_s}{v_0} sign(v) = 0 \]  

(2)

Where \( F_s = KC_v \frac{\rho_s - \rho_m}{\rho_m} g \mu_c \bar{\omega} \), \( K \) is a comprehensive coefficient, \( C_v \) is the volume concentration of solids in the slurry, \( \rho_s \) is the density of the particles, \( \rho_m \) is the density of the slurry, \( \mu_c \) is the friction coefficient between the bottom particles and the pipe, \( \bar{\omega} \) is the particle settling velocity, \( \lambda \) is the drag coefficient of the liquid phase, \( D \) is the pipe diameter.

The wave speed equation:

\[ c = \sqrt{\frac{1}{1 - C_v} \left( \frac{1}{K_L} + \frac{\rho_m}{K_s} + \frac{c_1 D}{eE} \right)} \]  

(3)

Where \( K_l \) is the liquid bulk modulus, \( K_s \) is solid bulk modulus, \( e \) is the wall thickness, \( E \) is the elastic modulus of the pipe, \( c_1 \) is the coefficient of supporting.

2.2. Numerical solution method

According to the theory of partial differential equations, hyperbolic partial differential equations with two different real family feature line along the characteristic line can be reduced-order into ordinary differential equations, which is called characteristic equations, and then the ordinary differential equation can be solved. The method which is called the characteristic line method is convenient to solve more complex partial differential equation. \( J_2 \) multiplied by undetermined coefficients \( \lambda_1 \), then plus \( J_1 \) we have:

\[ J = \left[ \frac{\partial v}{\partial t} + \left( v + \lambda_1 \frac{c^2}{g} \right) \frac{\partial v}{\partial x} \right] + \left[ \frac{\partial H}{\partial t} + \left( \frac{g}{\lambda_1} + v \right) \frac{\partial H}{\partial x} \right] \lambda_1 + \lambda_1 v \sin \alpha + \frac{\lambda}{2D} |v| + \frac{F_s}{v_0} sign(v) = 0 \]  

(4)

When \( \lambda_1 = \pm \frac{g}{c} \), the above equation can be turned into ordinary differential equations. Taking \( v \ll c \) into account, the resulting ordinary differential equations are as follows:
2.3. Boundary conditions for valve and accumulator

Valve characteristics can be defined in terms of the flow coefficient. The pressure drop across an open valve can be given by:

\[ P_1 - P_2 = \rho_m Q \frac{Q}{\rho_0 C_v} \]  \hspace{1cm} (7)

where: \( C_v \) is the flow coefficient value. \( \rho_m \) is the density of the slurry. \( \rho_0 \) is the density of water at standard conditions (1000 kg/m\(^3\)). Combine this boundary conditions with the compatibility equation of water hammer as below:

\[
\begin{align*}
H_{PL,NS} &= C_{P1} - BQ_{PL,NS} \\
H_{P2,1} &= C_{M2} + BQ_{P2,1} \\
Q_{PL,NS} &= Q_{P2,1} \\
\rho_m g (H_{P2,1} - H_{PL,NS}) &= \rho_m Q_{PL,NS} |Q_{PL,NS}| \\
C_{P1} &= H_{1,NS-1} + Q_{1,NS-1} \left( \frac{1}{B - C - R_1 [Q_{1,NS-1}]} - R_2 \frac{g}{Q_{1,NS-1}} \right)/Q_0 \\
C_{M2} &= H_{2,2} - Q_{2,2} \left( \frac{1}{B + C - R_2 [Q_{2,2}]} + R_2 \frac{g}{Q_{2,2}} \right)/Q_0 \\
\end{align*}
\]  \hspace{1cm} (8)

The accumulator is a pressure damper filled with a certain amount of compressed gas. Gas volume in accumulators:

\[ P_c V_c^r = \text{const} \]  \hspace{1cm} (9)

Pressure head:

\[ P - P_c = \rho_m g Z + \frac{Z P_c dQ}{A \, dt} + \frac{\lambda \rho_m Z}{2DA^2} Q |Q| \]  \hspace{1cm} (10)

Rate of change of fluid height:

\[ A \frac{dZ}{dt} = Q \]  \hspace{1cm} (11)

Where \( A \) is the cross-sectional area at the fluid surface, \( Z \) is the height of the fluid surface from the bottom of the accumulator. \( P_c \) is the gas pressure, \( V_c \) is the gas volume of the accumulator, \( Q \) is the inlet flow rate, \( \gamma \) is the gas heat capacity ratio.

Combine this boundary conditions with the compatibility equation of water hammer as below:

\[
\begin{align*}
H_{PL,NS} &= C_{P1} - BQ_{PL,NS} \\
H_{P2,1} &= C_{M2} + BQ_{P2,1} \\
Q_{PL,NS} &= Q_{P2,1} + Q_{P3} \\
V_{cp} - V_c &= -0.5 (Q_{P3} + Q_s) \Delta t \\
P_{cp} V_{cp}^r &= P_c V_c^r \\
H_{PL,NS} &= H_{P2,1} \\
g(A[H_{P3} - H_{PL,NS}] - \frac{\lambda Z_p}{2DA^2} Q_{P3} |Q_{P3}|) &= -Z_p Q_{P3} - \frac{Q_{P3} - Q_s}{\Delta t} \\
V_{cp} &= A[H - Z_p] \\
C_{P1} &= H_{1,NS-1} + Q_{1,NS-1} \left( \frac{1}{B - C - R_1 [Q_{1,NS-1}]} - R_2 \frac{g}{Q_{1,NS-1}} \right)/Q_0 \\
C_{M2} &= H_{2,2} - Q_{2,2} \left( \frac{1}{B + C - R_2 [Q_{2,2}]} + R_2 \frac{g}{Q_{2,2}} \right)/Q_0 \\
\end{align*}
\]  \hspace{1cm} (12)
### 3. Calculation of transient process

According to the basic design information, the system is 139.6 km long, and the diameter of the pipe is 590 mm with the material of steel. There is a valve at the end of the pipeline. The altitude of the pump station is 686 m, the altitude of the slurry storage tank at the end of the pipeline is 363 m. There are two local high points on the pipeline, the altitude of the first local high point is 901 m, and the altitude of the second local high point is 869 m, so the first local high point is 32 m higher than the second local high point. The design discharge of the system is 1800 m$^3$/h, the fluid used for transporting solids is water, the solid concentration of slurry is 50%, with the slurry density of 1147 kg/m$^3$, the viscosity of 0.05 Pa·s. The pump station equipped with six piston-diaphragm pumps, the design pressure of imports is 0.5 MPa, the design pressure of the slurry storage tank is 2.0 MPa. According to the design standard, the minimum pressure in the transient process should not be less than 0.023625 MPa, and the maximum pressure should not be higher than the bearing capacity of the pipeline. Based on all the information and requirements, the model of the system is built and the transient process is calculated.

#### 3.1. Calculation of transient process caused by pumping accident

Six pumps accidentally shut down, two seconds later the flow rate of the pumps drops to 0. The tail valve does not close. As seen in the Figure 1, the minimum pressure of the first and the second local high point reaches the vapor pressure.

![Figure 1. Pressure envelopes along the main pipeline.](image)

#### 3.2. Calculation of transient process with an accumulator and valves closed

As seen in section 3.1, the minimum pressure of the first and the second local high point reaches the vapor pressure. In order to prevent this from happening, an accumulator is set at the second local high point. Accumulator is placed in systems in order to prevent pressure surges. They consist of a sealed cylindrical vessel connected to the network at one point. The trapped gas in the accumulator provides a cushioning effect which reduces any pressure surges or pressure dips. The accumulator is usually a cost effective way of reducing a pressure surge and pressure dip as they are reliable and easy to maintain. Because the pipeline is exceptionally long, one accumulator can not prevent the both high point from vaporizing, and the accumulator is not cheap, so and we set a valve 10.5 km downstream the first high point, which is called valve 1. The tail valve is called valve 2. 10 seconds after the pumping accident, valve 1 takes 90 seconds to close, and valve 2 takes 60 seconds to close. Figure 2 shows the pressure envelopes along the main pipeline under this condition.

As seen in Figure 2, the minimum pressure of the first and the second local high point does not reach the vapor pressure. Pipeline is without vaporization.

As seen in figure 3, the outlet flowrate of the piston-diaphragm pumps rapidly drops to 0 after the pumping accident, and the pressure drops quickly. Figure 4 shows the inlet and outlet pressure and flowrate variation of valve 1 with time. As valve 1 quickly closed after the accident, the pressure of the first high point does not drop to the vapour pressure at a minimum pressure of 0.417 MPa. The minimum pressure of the outlet of valve is 0.192 MPa, which is higher than the vapor pressure.
As seen in figure 5, when the pressure of the second drops, the trapped gas in the accumulator expands rapidly, providing a cushioning effect which reduces the pressure dip. Because of the presence of the accumulator, pressure in the pipeline from outlet of valve 1 to valve 2 keeps above the vapor pressure. As promptly closed the valve 2, the accumulator keeps a larger slurry volume.
4. Conclusion and recommendation
In this paper, we present the fundamental principle and method of numerical simulation of transient process and give boundary conditions of valve and accumulator. A model for calculating the water impact of solid-fluid phases is established based on a practical engineering of long-distance slurry pipeline transportation system. In long-distance slurry pipelines, when pumping accidents happen, the pressure of the high points of the pipeline might be drop to vapor pressure rapidly, it may cause more serious accidents unless we take proper protective measures. Here we present a slurry system with two local high points, we set two valves (one 10.5 km downstream the first high point, the other at the end of the pipeline) and a accumulator, which is at the second high point. Through the simulation, the valves and accumulator work well when pumping accident happens. It is an effective protection measure, which has guiding significance to the design and operating management of practical engineering of long-distance slurry pipeline transportation system.

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