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# Numerical investigation of pipeline transport characteristics of slurry shield under gravel stratum

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A R T I C L E I N F O

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A B S T R A C T

In order to grasp the pipeline transport characteristics of slurry shield under gravel stratum, with a cross-river tunnel construction of Lanzhou metro as the research background, the numerical simulation method is adopted, and a slurry-stone two-phase flow model is established based on multiphase flow theory by considering the rheological properties of slurry. Besides, corresponding simulation models validated by experiment are established using CFD and DEM softwares, and the impacts of inlet slurry velocity, stone volumetric concentration and pipe inclination angle on pressure drop and transport capacity of the pipeline are investigated. The results show that stones are mainly distributed at the bottom of the pipeline for horizontal straight pipes. The pressure drop and transport capacity increase exponentially with the increase of inlet slurry velocity and stone volumetric concentration. For inclined straight pipes, the pressure drop of the pipeline increases slowly with the pipe inclination angle increasing from 0° to 60°, but increases rapidly when the pipe inclination angle increases from 60° to 90°; the transport capacity reduces slowly at first and then increases rapidly with the increase of pipe inclination angle, and the lowest value appears at 45–60°.

## 1. Introduction

Slurry shield machine is a kind of large-scale tunnel boring machine which integrates functions such as digging and cutting soil, conveying soil, lining and oriented correction. It injects pressurized slurry into the cutter compartment to balance the water and earth pressure of the excavated surface, which can effectively maintain the pressure balance of the excavation surface and control the ground subsidence. For this reason, it is widely used in various kinds of cross-river and cross-sea tunnel projects. When the slurry shield is excavating in gravel stratum, a large number of gravels generated by cutters cutting and crushers crushing will need to be transported from the excavation chamber to the outside of the tunnel through the slurry pipeline. Therefore, grasping the pipeline transport characteristics of the slurry shield is the key to ensuring the efficiency and safety of tunnel constructions.

At present, a number of scholars have used experimental method to studied the pipeline transport characteristics. With water as the carrying fluid, Ravelet et al. (2013) and Vlasak et al. (2014a) experimentally investigated the pressure drop of horizontal and inclined pipes of inner diameter D = 100 mm. The hydraulic gradient under different mixing velocities was obtained and the frictional pressure drops in the horizontal pipe were found to be markedly higher than those in the vertical pipe. Edelin et al. (2015) experimentally investigated the transport of fluids composed of water and polypropylene particles (341–756 μm). The best operating conditions for energy optimum are obtained close to the limit deposition velocity, when the fully suspended pattern is reached. Wu et al. (2015a, 2015b) investigated the pipeline transportation of the cemented coal gangue-fly ash backfill (CGFB) mixtures using a test loop system and found the solid contents and the mix proportions of the coal gangue, fly ash and cement have a significant impact on the transportability and pressure drop of the CGFB slurry in the pipe loop. Matousek (2011) established sand (0.22–1.38 mm) transport formula based on experiments in the laboratory circuit with a pipe of inner diameter of 100 mm. Using PIV (particle image velocimetry) and EIT (electrical impedance tomography) technologies, Vlasak et al. (2014b), Pinto et al. (2014) and Hashemi et al. (2014) observed the motion of particles (< 8 mm) in pipes under different fluid velocities, and determined the critical velocities for different flow regimes. Nevertheless, these experimental studies mostly focus on small diameter pipes transport with water as the carrying fluid, which is different from slurry shield pipeline transport.

With the development of computer, the numerical simulation

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method is increasingly applied to the research of pipeline transportation, which can significantly shorten research cycle, cut research cost and improve research quality. Kaushal et al. (2012) numerically simulated the pipeline slurry flow of mono-dispersed fine particles at high concentration using Mixture and Eulerian two-phase models, and their results show that the Eulerian model gives more accurate predictions for both the pressure drop and concentration profiles at high concentration. Capecelatro and Desjardins (2013) and Arolla and Desjardins (2015) used Euler–Lagrange large eddy simulation methodology to predict the physics of turbulent liquid–solid slurry flow through a horizontal periodic pipe. The simulation results suggest that this computational strategy is capable of predicting critical deposition velocity. Based on the kinetic theory of granular flow, Chen et al. (2009) and Gopaliya and Kaushal (2016) simulated the flow of coal-water slurry (CWS) and sand-water slurry (SWS) in horizontal pipelines using an Eulerian multiphase approach, and the pressure drop, velocity distribution as well as concentration distribution of CWS and SWS were obtained. Using the computational fluid dynamics (CFD) model, Eesa and Barigou (2009) investigated the pipe transport of coarse solids (2–9 mm) in laminar power law fluids, and found the maximum particle velocity is always significantly less than twice the mean flow velocity for shear thinning fluids, but it can exceed this value in shear thickening fluids. Tian et al. (2014) established the ice slurry flow model and investigated the influences of ice packing fractions, ice particle size, additive concentrations and pipe size on transportation safety. Liu et al. (2015) used a simplified CFD-based procedure consisting of flow modeling, particle tracking, and penetration calculation to calculate the penetration rates in elbows for annular flow. By comparing with experimental data, the new method is proved to be reasonable in simplifying the simulation of annular flow field and shows good accuracy in erosion prediction.

Conceivably, numerical simulation has been widely used to study the characteristics of pipeline transportation and desirable results have been achieved. In this paper, with a cross-river tunnel construction of Lanzhou metro as the research background, a three-dimensional fluid-particle two-phase flow model is established based on multiphase flow theory by considering the rheological properties of the fluid. Subsequently, pipeline transport characteristics of slurry shield under gravel stratum are investigated through numerical simulation based on CFD-DEM technology.

## 2. Mathematical model

The stones broken by slurry shield cutters and crushers are carried into the slurry pipeline with the slurry flow, and finally pumped to the outside of the tunnel by multi-stage slurry pumps. The flow process is complicated due to the strong interaction between slurry and stones. In the present work, the rheological property model of slurry is obtained by experiment, and the three-dimensional slurry flow model, the stone motion model and other related models regarding flow characteristics are established by employing multi-phase flow theory.

### 2.1. Fluid phase

The fluid flow and heat transfer processes follow mass conservation law, momentum conservation law and energy conservation law, with their corresponding mathematical models being the continuity equation, Navier-Stokes equation and energy conservation equation, as follows:

$$\frac{\partial \alpha_f \rho_f}{\partial t} + \nabla\cdot(\alpha_f \rho_f \boldsymbol{U}_f) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f \boldsymbol{U}_f) + \nabla\cdot(\alpha_f \rho_f \boldsymbol{U}_f \boldsymbol{U}_f) = -\nabla p_f + \nabla\cdot\alpha_f \boldsymbol{\tau} + \alpha_f \rho_f \boldsymbol{g} + \boldsymbol{F}_{pf} \tag{2}$$

$$\frac{\partial}{\partial t}(\alpha_f \rho_f T) + \nabla\cdot(\alpha_f \rho_f \boldsymbol{U}_f T) = \nabla\cdot\left(\frac{k_T}{c_P}\nabla T\right) + s_T \tag{3}$$

where $\alpha_f$, $\rho_f$, $\boldsymbol{U}_f$ and $p_f$ are the fluid volume fraction, density, velocity vector and pressure respectively, $\boldsymbol{\tau}$ is the viscous stress tensor, $\boldsymbol{g}$ is the gravitational acceleration, $\boldsymbol{F}_{pf}$ is the force exerted by all particles on fluid, $T$ is the temperature, $k_T$ and $c_P$ are the heat transfer coefficient and the fluid specific heat ratio, respectively, and $s_T$ is the viscous dissipation phase.

Due to the large diameter of pipe and high flow velocity, the slurry flow in the slurry shield pipeline is a typical turbulent flow. In this paper, the two-equation $k-\varepsilon$ turbulence model (Launder and Spalding, 1974), which has been widely used in studies of turbulent flow (Grewal et al., 2013; Zhao et al., 2014; Wadnerkar et al., 2012; Torano et al., 2011; Wang et al., 2011), is adopted to simulate the turbulence.

The slurry used in the cross-river tunnel construction of Lanzhou metro is a mixture of water, bentonite, red clay and pulping agent. The pulping agent, which is mainly made of polyacrylic acid salts, cellulose salts and anti-calcium agent modified soil, can effectively increase the adsorption between particles. Therefore, the shear viscosity of slurry is improved and the amount of slurry leaked into stratum is reduced, which makes a great contribution to keeping the excavation surface stable. With the slurry on the construction site as the sample, the rheological curve is obtained using a six-speed rotary rheometer, as shown in Fig. 1. It can be observed from Fig. 1 that the shear rate of shield slurry is linear with the shear stress (determination coefficient $R^2 = 0.9914$), which can be described by Bingham fluid rheological equation:

$$\tau = \tau_d + \mu_p \dot{\gamma} \tag{4}$$

where $\tau$ is shear stress, $\tau_d$ is yield stress, $\mu_p$ is plastic viscosity, and $\dot{\gamma}$ is shear rate.

In addition, when $\tau_d = 0$, Bingham fluid rheological equation can be used to describe Newtonian fluid, such as water.

### 2.2. Particle phase

In the pipeline transportation process, the stone is forced by other stones, slurry and pipe wall, which can be described by Newton's second law of motion using the discrete element method originally proposed by Cundall and Strack (1979), as follows:

$$m_i \frac{d\boldsymbol{U}_{p,i}}{dt} = m_i \boldsymbol{g} + \sum_{j=1}^{n} (\boldsymbol{F}_{c,ij} + \boldsymbol{F}_{d,ij}) + (\boldsymbol{F}_{c,iw} + \boldsymbol{F}_{d,iw}) + \boldsymbol{F}_{f,i} \tag{5}$$

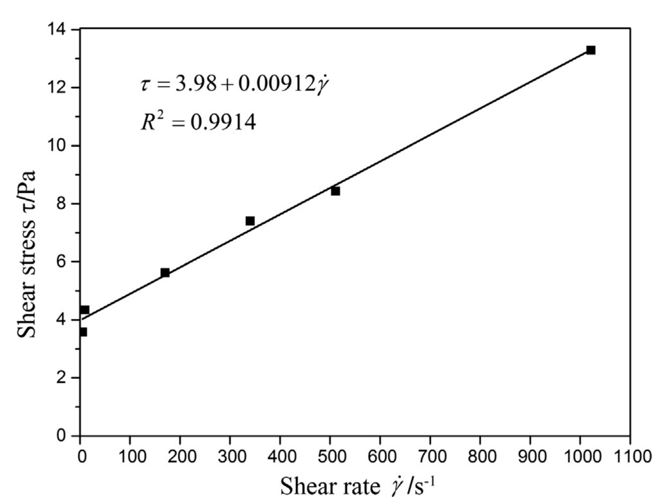

**Fig. 1.** The rheological curve of slurry.