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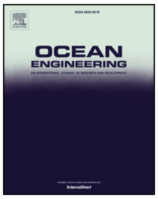

Pressure drop model of high-concentration graded particle transport in pipelines

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ABSTRACT

The existing formulas for calculating the pipeline transport resistances of granular materials are mostly based on the experimental data for single-sized or regularly graded particles. Consequently, it is necessary to simplify the in-situ distribution using an equivalent size, such as the median particle size (d50), arithmetic mean size (dm), or harmonic average size (dk), in the sediment transport resistance calculations. This simplification completely ignores the effect of particle gradation on the pressure drop, particularly in the case of multi-size, high-concentration particle transport. Therefore, the mechanism and degree of influence of the particle size variation in different flow conditions on the pipeline resistance was investigated in this study. The interaction between the differently sized particles in the graded slurry was also examined. Furthermore, a new model called the Shanghai Jiao Tong University high-concentration multi-sized slurry pressure drop (SJTU-HMSPD), which is based on the particle size distribution and multi-regime slurry resistance in pipeline transport throughout the flow velocity range, was developed and is presented in this paper. The SJTU-HMSPD is more suitable for calculating the pipeline transport resistances of complex graded slurries, and the calculation results agree well with the experimental data. All the input data are available in practice making the model very convenient.

1. Introduction

Pipeline transportation is favourable owing to its abilities to save energy, protect the environment, and facilitate control optimization, among other advantages. Consequently, this method is widely used in numerous industries, including the energy, food, and mineral industries. In addition, pipeline transportation is considered ideal for use in deep-sea mining.

Pipeline transportation has been rapidly developed in the dredging industry since the appearance of centrifugal pumps in the 19th century. According to statistics, dredging of up to billions of cubic meters has been completed by the annual global cutter suction and hopper dredgers (both using pipeline transportation) in recent years, and billions of dollars of economic benefits have been obtained.

The sediment transportation system is the main source of energy consumption in a dredger. Taking a cutter suction dredger as an example, the energy consumption of the sediment pipeline transportation system is more than 80% of the total energy consumed by the entire dredger. Similarly, the sediment transport system of a modern large cutter suction dredger accounts for more than 85% of the total energy consumption. A mere 1% increase in efficiency would provide significant energy savings and could be achieved by learning the characteristics of sediment pipeline transportation system, design optimization, and intelligent control.

Most of the existing formulas for slurry transport pipelines are based on the experimental data for single-sized or regularly graded particles. Therefore, parameters such as the median particle size (d_{50}), arithmetic mean size (d_m), and harmonic average size (d_k) are used instead of the in-situ particle distributions in sediment transport resistance calculations. This simplification completely ignores the effect of the particle gradation on the pipeline resistance, and the optimal calculation, system modelling, and dredging requirements of high-concentration transport are not met in complex in situ scenarios, especially in high-concentration situations.

In this study, we investigated the pipeline transport of differently sized particles in various flow conditions and the mechanism and degree of influence of these differences on the pipeline resistance. The interactions between the differently sized particles in a graded slurry were also researched. A new slurry pressure drop model called SJTU-HMSPD, which is based on particle gradation and multi-regime slurry

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resistance calculations throughout the flow velocity range, is presented in this paper, following a brief review of the previous related work.

2. Previous work

In recent decades, research on pipeline transportation systems has been ongoing. Continuous improvements and corrections of sediment pipeline transportation resistance calculations have been conducted by numerous researchers, such as Durand and Condolios, 1952), Newitt et al. (1955), Gibert (1960), Wasp et al. (1977), Jufin and Lopatin (1966), Zandi and Govatos (1967), Charles (1970), Bain and Bonnington (1970), Kazanskij (1978), Shook et al. (1986), Shook and Roco (1991), Kaushal and Tomita (2002, 2003), Matousek (2009, 2011), Wilson et al. (1965, 1980, 1982, 1987, 1989, 1990, 1997, 2002, 2003, 2006), Doron et al. (1987, 1993, 1995, 1996, 1997), Talmon (2013), Thomas (2014), Miedema and Ramsdell (2015, 2017), and Miedema (2015, 2016a, 2016b).

Among the calculation methods proposed, some typical widely used formulas are the following: The Durand and Condolios, 1952 formula, which is favoured in the European dredging industry, is based on a substantial amount of experimental data. Meanwhile, the Wilson (1965) formula is widely used in the American dredging industry. The distribution of particles in a pipeline is taken into consideration in the two-phase carrier fluid flow model of Wasp et al. (1977). The Turian and Yuan (1977) formula was obtained by using different dimensionless parameters, collecting experimental data from the literature, and performing dimensionless analysis. Lahiri and Ghanta (2008) obtained their formula by fitting experimental data using artificial intelligence. The formula developed by Doron and Barnea (1993) is based on a theoretical model of mechanical equilibrium. Meanwhile, the Miedema and Ramsdell (2017) framework is based on theoretical analysis, previous research results, and consideration of the applicability of the formulas (using only easily obtainable parameters).

The pipe Froude number, particle Froude number, and additional resistance loss are defined by Durand and Condolios, 1952. The resistance formula was obtained by fitting the relationship between these quantities. This formula was verified for slurries with pipe diameters of 40–580 mm, average particle sizes of 0.2–25 mm, particle weights of 1.5–3.95, and particle concentrations of 2%–22%. Following revision and expansion by Worster and Denny (1955), Gibert (1960), and Wasp et al. (1977), this formula has continued to be used and remains the most popular calculation method in the dredging industry. However, by using terms, such as particle arithmetic mean size (d_m), and particle Froude number ($Fr_p = v_t/\sqrt{g\,d}$), to simplify the in-situ distribution in the formula results in significant calculation bias if the gradation is wide, especially in high-concentration slurry transport.

The resistance growth mechanisms in different scenarios, such as the sliding bed, heterogeneous, and homogeneous regimes, and the effects of the particle size distribution on the resistance were researched by Wilson et al. (2006). The impact of large particles on the resistance in a pipeline was considered for a heterogeneous situation in the formula, and the particle size distribution was described using d_{85} and d_{50}. For a broadly graded slurry, the particles can be divided into four categories according to size. The first category includes particles with diameters less than 0.04 mm and corresponds to the homogeneous regime. The second category includes particles with diameters greater than 0.04 mm and less than 0.15 mm and corresponds to the pseudo-homogeneous regime. The third category corresponds to the heterogeneous regime and consists of particles ranging in size from 0.15 mm to 0.018 times the pipeline diameter. The fourth category includes particles with diameters more than 0.018 times the pipeline diameter and corresponds to the sliding bed regime. Obviously, the particle size ranges defining the different categories are not fixed in varying flow conditions, such as when the flow rate and particle concentration increase in actual practice.

For uniformly sized particles, detailed division and research has been performed for different slurry regimes with varying flow rates, and pipe resistance formulas for the fixed bed, sliding bed, heterogeneous, and homogeneous regimes were derived by Miedema and Ramsdell (2017) based on different theories, such as two-layer flow and energy theory. Miedema and Ramsdell (2017) divided graded slurries into two components. The first component is in the carrier phase with a Stokes number (S_{tk}) of less than 0.03 at the limit deposit velocity, and the carrier density and viscosity are corrected according to the volume concentration of this component. The component particles do not participate in the remainder of the resistance calculations. The remaining particles comprise the second component, in which flow regime depends on the particle size and flow velocity. The contributions of Durand and Condolios, 1952 and Wilson et al. (2006) were incorporated by Miedema and Ramsdell (2017), and the experimental diameter was expanded to 1 m. However, the Miedema and Ramsdell (2017) model only incorporates the effects of fine particles (carriers) on the effective slurry viscosity and pipe resistance, without considering the effect of the in-situ gradation uniformity on the pipe resistance, which is significant particularly when the particle concentration is high.

3. SJTU-HMSPD

In multi-sized slurry transport via pipelines, the flow regimes of differently sized particles may change with the flow rate and mixture concentration over time. When the flow rate and concentration are low, the shear stress on the fixed bed is low and insufficient to make the particles move; thus, the particles remain in the stationary bed regime at the bottom of the pipe. As the flow rate and solid concentration increase, the shear stress increases, and the particles begin to slip, jump, and become suspended, and forming a sliding bed, or heterogeneous, pseudo-homogeneous, or even homogeneous flow.

In the spatial dimension, differently sized particles in the pipe will be in different regimes in most situations. In certain flow rate conditions, the smallest particles are evenly distributed in the slurry, their slip velocities are close to zero, and liquid characteristics are observable; these particles comprise the homogeneous part, in which the size of the largest particles is called the non-settling particle size. Some particles, which are slightly larger than those in the homogeneous regime, although their velocity distribution is similar to that of the liquid part and their resistance characteristics are also similar to those of the homogeneous part, have a non-uniform vertical distribution in the pipeline owing to gravity and are called the pseudo-homogeneous component. The larger particles, although suspended owing to the lift force, are distributed more unevenly. They are mainly situated in the lower half of the pipe, a large slip velocity is generated, and the resistance characteristics are different. These particles are in the heterogeneous regime flow. The largest particles can no longer be suspended by the lift force and move by sliding along the bottom of the pipe; this part is known as the sliding bed part. If the flow velocity and concentration are low, the larger particles may also be deposited at the bottom of the pipeline and not move, forming a fixed bed.

Figs. 1 and 2 present the results of a simulation of the solid volume distribution profiles of differently sized particles (different phases) in a multi-sized slurry using computational fluid dynamics and their mixture concentration given by Kaushal et al. (2005). Fig. 1 shows the trend of the solid distribution with increasing slurry velocity at a solid concentration of 30%, and Fig. 2 shows the trend with increasing solid concentration at a velocity of 2 m/s. According to the slurry flow regime result obtained by Wasp et al. (1977), if the relative solid volume concentration ratio in the vertical centreline of the pipe $0.1 < C_{V,y' = 0.92}/C_{V,y' = 0.5}$, where $C_{V,y' = a}$ is the specific local (the dimensionless position along the vertical axis of the pipe $y' = \mathrm{a}$, defined as $y' = y/D_p$, where y is the distance from the pipe bottom, and D_p is the pipe diameter) is solid volume concentration. The slurry is in the heterogeneous regime, and the regime of each phase (containing differently sized particles) is clearly observable in the figures. A more complete study of