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Article *in* International Journal of the Society of Materials Engineering for Resources · October 2014

DOI: 10.5188/ijsmer.20.201

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Original
Received January 30, 2014
Accepted for Publication June 9, 2014

Slurry Pipeline Design of Multi-sized Solids : Application of Innovated Models

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The paper presents a design procedure for horizontal pipeline systems, such as those used in bulk solids handling/transportation in mining operations.
The mean velocity as well as pressure drop are important parameters in the design of the slurry pipeline. Accurate prediction of the parameters is needed for the selection of pipe diameter and the type of pump suitable for the slurry system. The objective of this paper was to provide a pipeline design procedure, especially for mixed-sized slurry flows typically found in the coal mining industry.
This study covered the evaluation methods for determining flow regimes, concentrations, and optimum pipe diameter. Critical velocity and transport velocity of flow were also discussed. The innovated models for mixed-sized slurry flows by Seitshiro et al. were applied for the prediction of the hydraulic gradients.
In conclusion, the design procedure proposed in this study was verified with field data.

Key Words : Pipeline Design, Multi-sized Slurry, Innovated Models.

1 INTRODUCTION

Pipeline transport of solids-in-liquid has been discussed in comparison to other conventional systems of trucks, railways, and conveyor belt transport. The practical slurry pipeline system was introduced in the 1950's to reduce the cost of rail transport of coal, with the construction of a 10-inch diameter Consolidation Coal Pipeline of length 108 miles, Ohio, USA. Subsequent to the considerable success of cost reduction, pipeline technology has made significant progress in the bulk solids handling, as well as tailings disposal and dredging applications.

For the sake of simplicity, pipeline designers have tended to apply the conventional procedures with Durand and Newitt correlations for estimating design parameters such as hydraulic gradient and flow velocity [1]. Nevertheless, the application of empirical or semi-theoretical equations of hydraulic gradient of slurry flow containing single size solids should be restricted to the range of the data. In addition, it is valid to evaluate the effect of fine portion of solids on the hydraulic gradient of multi-sized slurry flows in pipelines.

For these reasons, analytical models of slurry flow were developed by Seitshiro et al. [2] and confirmed with experimental data. The analytical results, which allow scale-up, were verified with the wide range of data covering practical transport conditions.

The object of this paper is to present a clear process for designing horizontal slurry pipeline systems. The study will cover the evaluation of the parameters of hydraulic gradient i and critical velocity V_{cd}, as well as practical flow velocity V_m. The value of V_{cd}, which depends on not only solids concentration but also solids distribution and solids density, could be estimated based on the relationship of hydraulic gradient against mean velocity. The effect of fines on the values of i and V_{cd} were also discussed.

The proposed design procedure was illustrated with field data, and it was concluded that the design flow velocity and pipe diameter approximately coincided with the values in operation.

2 DESIGN WITH KEY PARAMETERS

The determination of hydraulic gradient i, head loss per unit distance, is essential for designing slurry pipelines : in practice, flow velocity should be set over the critical velocity V_{cd}, the velocity at which solids begin to settle at the bottom of the pipe. In this section, the relationship between i and V_{cd} will be discussed based on the i-V_m curves with transport conditions.

2.1 Single size settling slurry

For single size slurry flow, the hydraulic gradient can be predicted with the settling slurry model proposed by Seitshiro et al. [3], as follows :

$$i = i_w + \frac{\overline{q}\,(\delta_s - 1)\,V_h}{V_m} + \frac{3}{16}\left[\alpha + \sqrt{\alpha^2 + \frac{4\sqrt{48}\alpha\beta}{\left\{\left(\frac{dV_m\rho}{\mu}\right)\frac{\overline{q}-C}{(1-\overline{q})\overline{q}}\right\}}}\,\right]^2$$

$$\cdot\frac{V_m^2}{gd}\left\{\frac{\overline{q}-C}{(1-\overline{q})\overline{q}}\right\}^2 \overline{q}\,(1-C) \quad \cdots\ (1)$$

Figure 1 shows representative analytical i-V_m relationship. If critical velocity V_{cd} could be approximately defined as the velocity at the minimum point of the curves [4], that is, $\partial_i/\partial V_m = 0$. The values of V_{cd} would be represented by the dotted line in Figure 1.

The Durand Froude number [5] with V_{cd},

$$F_L = \frac{V_{cd}}{\sqrt{2gD\,(\delta_s - 1)}} \quad \cdots\cdots\ (2)$$

was calculated and compared to Durand's results [6], as shown in Figures 2 and 3. According to this study, it is clear that the Froude number F_L is strongly dependent on the delivered concentration C.

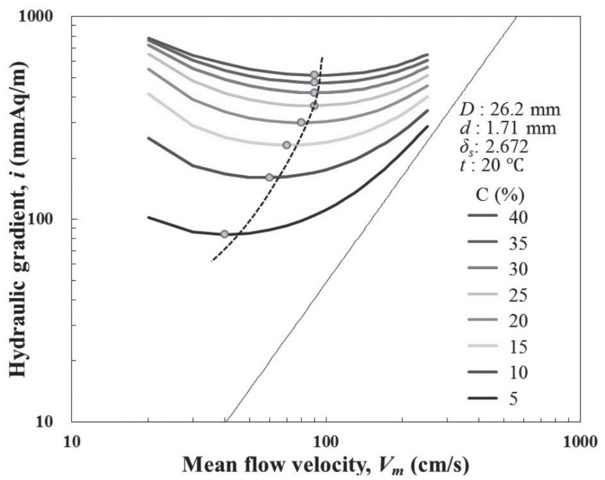

Figure 1 i-V_m relationships of single size slurries based on the laboratory data of fine solids

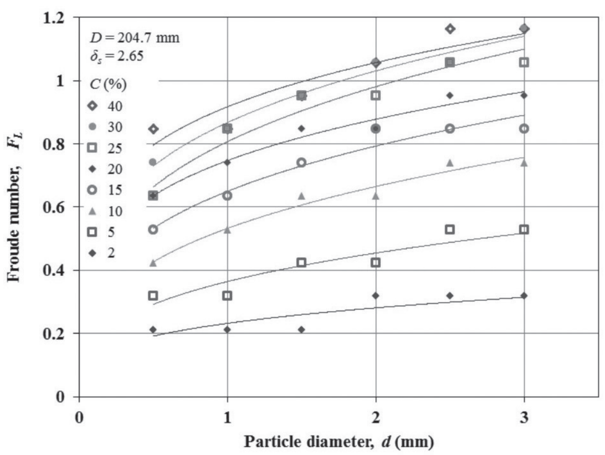

Figure 2 Predicted Froude numbers against particle diameter based on analytical models

2.2 Mixed-sized slurry

For slurries consisting of multi-sized solids, the innovated models developed by Seitshiro et al. [2], are recommended for the evaluation of hydraulic gradient: coarse-fine and coarse-coarse slurry models. For transporting fine and coarse solids in pipes, the coarse-fine model can be applied by a series of the following equations:

$$i = i_v + i_s \quad \cdots\cdots\ (3)$$

with:

$$i_v = \frac{\lambda_v \cdot V_m^{\,2} \cdot \delta_v}{2 \cdot g \cdot D} \quad \cdots\cdots\ (4)$$

$$i_s = \sum i_{si} \quad \cdots\cdots\ (5)$$

where i_{si} and i_s = contributed hydraulic gradient of each particle size d_i, and for all coarse solids calculated by the settling slurry model [3], while i_v is hydraulic gradient of modified form of vehicle. If the portion of fine solids in slurry increases, the value of not only i but also V_{cd} decrease, as shown in Figure 4.

If a slurry, however, consists only of coarse solids, the coarse-coarse model should be applied to estimate the hydraulic gradient i, which can be represented by:

$$i = i_w + \sum i_{si} \quad \cdots\cdots\ (6)$$

Figure 5 illustrates i-V_m relationships for mixed-sized slurries containing two different coarse particles of sand and Bakelite (Polyoxybenzyl methylene glycol anhydride). It is shown that, the effect of concentration on the hydraulic gradient of coarse-coarse slurry, tend to differ from that of coarse-fine slurry.

It has been recommended [6], [8], [9] that for safer system operation, the practical transport velocity could be evaluated by:

$$V_m = 1.2 \cdot V_{cd} \quad \cdots\cdots\ (7)$$

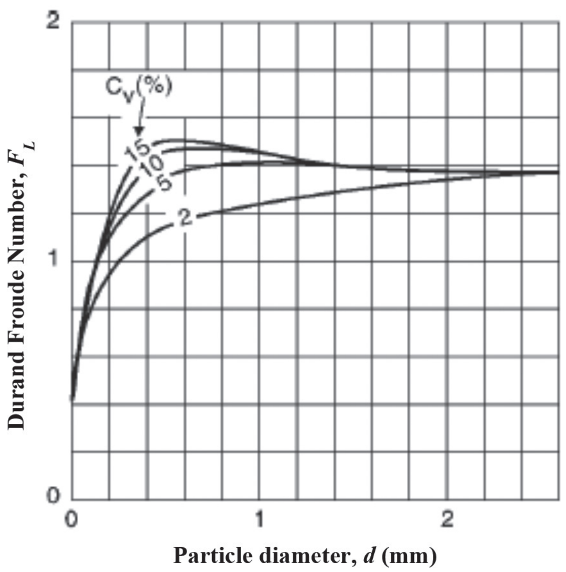

Figure 3 Variation of Durand Froude number with particle diameter [6]

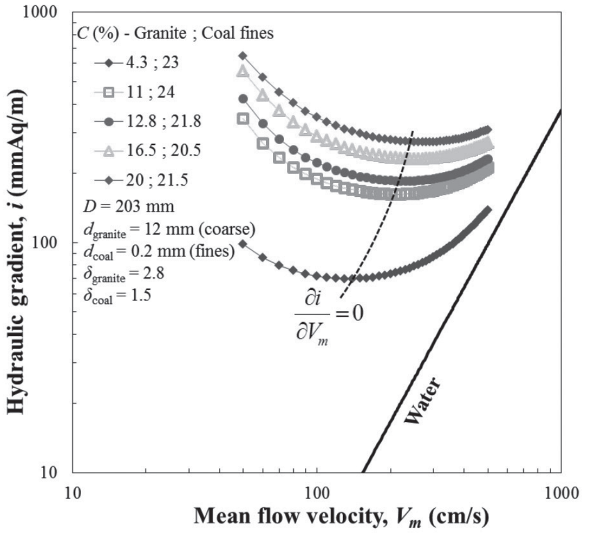

Figure 4 i-V_m relationships of coarse-fine mixed-sized slurries (containing granite and coal fines) based on the data of Boothroyde et al. [7]

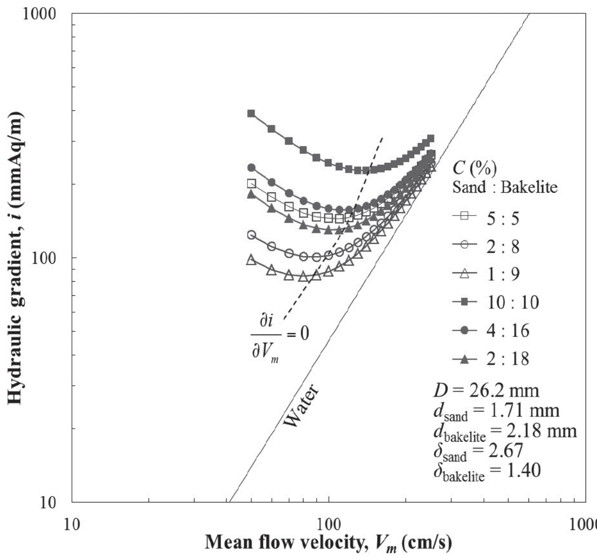

Figure 5 i-V_m relationships of coarse-coarse mixed-sized slurries based on the laboratory data

3 PIPELINE DESIGN

In this section, the processes for designing the pipeline are described. The design velocity based on the models of this study is compared with analytical result from the Durand correlation.

3.1 Calculation steps

The transport rate of solids G_a (in tonnes/year) for engineers should be related to solids quantity G_s (in kilograms/second) for analysis. If the operating rate could be assumed to be at 95% because of emergency stops, planned maintenance, and so on, the operating factor η equals 0.95 [10]. The transport rate can be expressed as:

$$G_a = \frac{G_s \cdot 3600 \cdot 24 \cdot 365 \cdot \eta}{1000} = 3.154 \times 10^4 \cdot \eta \cdot G_s \qquad (8)$$

Rearranging Eq. (8) for G_s, it yields:

$$G_s = \frac{G_a}{3.154 \times 10^4 \cdot \eta} \qquad (9)$$

From the fundamental relationship of solids flowrate,

$$Q_s = \frac{G_s}{\gamma_s} \qquad (10)$$

Substituting Eq. (9) into Eq. (10)

$$Q_s = \frac{G_a}{3.154 \times 10^4 \cdot \eta \cdot \gamma_s} \qquad (11)$$

With delivered concentration C, the slurry flowrate Q can be evaluated by:

$$Q = \frac{Q_s}{C} = \frac{G_a}{3.154 \times 10^4 \cdot \eta \cdot \gamma_s \cdot C} \qquad (12)$$

3.1.1 Design flow velocity:

a) Based on Durand correlation - According to the Durand method, which has widely been recommended for the estimation of the critical velocity [10], [11], the value of V_{cd} for the coarser solids of $d > 2$ mm can be evaluated by:

$$V_{cd} = 1.34 \sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)} \qquad (13)$$

Substituting Eq. (13) into Eq. (7), it yields the practical flow velocity of slurry:

$$V_m = 1.2 \times 1.34 \sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)} = 1.608 \sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)} \qquad (14)$$

b) Analytical results of V_{cd} - Based on analytical results of Froude number F_L at the illustrated conditions (d=2 mm, C=40%), as shown in Figure 2, the value of F_L can be determined as F_L=1.1. Following the previously-mentioned method, V_{cd} and V_m can be represented by:

$$V_{cd} = 1.1 \sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)} \qquad (15)$$

$$V_m = 1.32 \sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)} \qquad (16)$$

3.1.2 Pipe diameter of settling slurry: Pipe diameter should be restricted by the maximum size of solids and commonly designed with the following equation:

$$D > 3 \cdot d_{max} \qquad (17)$$

The design pipe diameter is also dependent on both the annual throughput of solids and flow velocity.

a) Design diameter based on Durand correlation - The slurry flowrate in a circular pipeline of inside diameter D flowing at mean velocity V_m can given by:

$$Q = \frac{\pi}{4} \cdot D^2 \cdot V_m \qquad (18)$$

Substituting Eq. (14) into Eq. (18),

$$Q=\frac{\pi}{4}\cdot D^2\cdot 1.608\sqrt{2\cdot g\cdot D\cdot(\delta_s-1)}$$

$$=5.593\cdot D^{5/2}\cdot\sqrt{(\delta_s-1)} \quad\cdots\cdots(19)$$

Equating the slurry flow rate of Eq. (11) with that of Eq. (19):

$$\frac{G_a}{3.154\times 10^4\cdot\eta\cdot\gamma_s\cdot C}=5.593\cdot D^{5/2}\sqrt{(\delta_s-1)}$$

Rearranging for D:

$$D^{5/2}=\frac{G_a}{3.154\times 10^4\cdot\eta\cdot\gamma_s\cdot C\cdot 5.593\cdot\sqrt{(\delta_s-1)}}$$

$$=\frac{G_a}{17.64\times 10^4\cdot\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}$$

$$\therefore\quad D=\left[\left(\frac{1}{17.64\times 10^4}\right)\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)\right]^{2/5}$$

$$=7.969\times 10^{-3}.\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4} \quad\cdots\cdots(20)$$

Converting the unit of specific weight from kg/m^3 to t/m^3; γ_s to γ_t,

$$D=5.028\times 10^{-4}.\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4} \quad\cdots\cdots(21)$$

b) Design diameter based on the analytical models - By using Eq. (16) based on the analytical models and Eq. (18), the slurry flowrate can be calculated by:

$$Q=4.591\cdot D^{5/2}\cdot\sqrt{(\delta_s-1)} \quad\cdots\cdots(22)$$

Similar to the derivation of Eq. (20), it can be written,

$$\frac{G_a}{3.154\times 10^4\cdot\eta\cdot\gamma_s\cdot C}=4.591\cdot D^{5/2}\cdot\sqrt{(\delta_s-1)}$$

$$D^{5/2}=\frac{G_a}{3.154\times 10^4\cdot\eta\cdot\gamma_s\cdot C\cdot 4.591\cdot\sqrt{(\delta_s-1)}}$$

$$=\frac{G_a}{14.48\times 10^4\cdot\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}$$

$$\therefore\quad D=\left[\left(\frac{1}{14.48\times 10^4}\right)\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)\right]^{2/5}$$

$$=8.624\times 10^{-3}.\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4}$$

Converting the unit of specific weight,

$$D=5.441\times 10^{-4}.\left(\frac{G_a}{\eta\cdot\gamma_s\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4} \quad\cdots\cdots(23)$$

3.2 Case study of pipeline design

The detailed data of the Consolidation Coal Pipeline in Ohio, USA [8], [12] - [15] is appropriate for illustrating pipeline design. The 108-miles-pipeline began operating in 1957 for the purpose of assessing transport costs against railway coal transport. After six-year-pipeline-operation, significant decrease of costs was confirmed. The pipeline system was mothballed in mid-1963. The summary of the transport conditions is shown in Table 1.

Table 1 Summarised transport conditions of Consolidation Coal Pipeline [8], [12] - [15]

Conveyed material…………	Coal
Production rate ………………	1.30 Mt/yr
Capacity range…………………	1.18-1.82 t/h
Flowrate……………………….	250 m^3/h
Pipe length…………………….	173.81 km
Pipe diameter………………….	254 mm
Particle mesh size…………….	–14 mesh
Maximum solids diameter…..	1.19 mm
Solids specific gravity……….	1.40
Weight concentration…………	50 %
Volume concentration………..	40 %
Mean velocity………………….	1.52 m/s

In this study, pipe diameter and mean flow velocity were estimated and compared with the field data

The following parameters were used in the design formulae;

G_a = 1.30 x 10^6 t/y
η = 0.95
C = 0.40
δ_s = 1.4
γ_t = 1.4 x 10^3 kg/m^3
g = 9.807 m/s^2

a) Durand correlation - According to the Durand correlation,

$$D=5.028\times 10^{-4}.\left(\frac{G_a}{\eta\cdot\gamma_t\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4}$$

Substituting the values of the parameters,

$$D=5.028\times 10^{-4}.\left(\frac{1.30\times 10^6}{0.95\cdot 1.4\cdot 0.40\sqrt{(1.4-1)}}\right)^{0.4}$$

D = 0.2169 m
$\therefore\quad D$ = 216.9 mm

On the other hand, the mean velocity of the pipe is estimated as:

$$V_m=1.608\sqrt{2\cdot g\cdot D\cdot(\delta_s-1)}$$

$$V_m=1.608\sqrt{2\cdot 9.807\cdot 0.2169\cdot(1.4-1)}$$

$$\therefore\quad V_m=2.098\text{ m/s}$$

b) Analytical correlation - Evaluating pipe diameter based on Eq. (23) for the field data;

$$D=5.441\times 10^{-4}\cdot\left(\frac{G_a}{\eta\cdot\gamma_t\cdot C\cdot\sqrt{(\delta_s-1)}}\right)^{0.4}$$

$$D=5.441\times 10^{-4}\cdot\left(\frac{1.30\times 10^6}{0.95\cdot 1.4\cdot 0.40\sqrt{(1.4-1)}}\right)^{0.4}$$

$\therefore\quad D$ = 234.68 mm

Table 2 Dimensions for Plain-end Steel Line Pipe*

Pipe size D (in)	Inside diameter, D_I (mm)	Outside diameter, D_O (mm)	Wall thickness, T (mm)
6	164.1	168.3	2.1
	154.1	168.3	7.1
	123.9	168.3	22.1
8	212.7	219.1	3.2
	201.7	219.1	8.7
	168.3	219.1	25.4
10	265.1	273.1	4.0
	250.9	273.1	11.1
	209.5	273.1	31.8
12	315.1	323.9	4.4
	298.5	323.9	12.7
	260.3	323.9	31.8
14	346.0	355.6	4.8
	331.8	355.6	11.9
	292.0	355.6	31.8
16	396.8	406.4	4.8
	381.0	406.4	12.7
	342.8	406.4	31.8
18	447.4	457.0	4.8
	428.4	457.0	14.3
	393.4	457.0	31.8

*** Rearranged based on API Specifications 5L for Line Pipe 43rd Edition-2004 [16]**

Calculating the mean velocity,

$$V_m = 1.32\sqrt{2 \cdot g \cdot D \cdot (\delta_s - 1)}$$

$$V_m = 1.32\sqrt{2 \cdot 9.81 \cdot 0.2347 \cdot (1.4 - 1)}$$

$$\therefore \quad V_m = 1.791 \text{ m/s}$$

The flow velocity in the field data in Table 1 was 1.52 m/s. It is clear that, if the Durand correlation could be applied, the velocity would be more overestimated than the analytical result.

Referring to the estimated value of pipe diameter, the appropriate pipe size can be selected from Table 2, which was rearranged based on the American Petroleum Institute Standards [16]. After selecting the pipe with inside diameter of 265.1 mm and arbitrarily selected wall thickness of 4.0 mm from the table, the calculation should be repeated as follows:

$$V_{cd} = 1.1\sqrt{2 \cdot 9.807 \cdot 0.2651 \cdot (1.4 - 1)}$$

$$\therefore \quad V_{cd} = 1.59 \text{ m/s}$$

$$V_m = 1.32\sqrt{2 \cdot 9.807 \cdot 0.2651 \cdot (1.4 - 1)}$$

$$\therefore \quad V_m = 1.90 \text{ m/s}$$

Thereafter, hydraulic gradient i, or headloss per unit distance, could be evaluated with the calculated values of D and V_m for the selection of the system equipments: the pipe material, pump and valves, and so on.

It should be noted that, the values of pressure drop for the Consolidation Coal Pipeline have not yet been published. As a result, the hydraulic gradient based on the innovated models of mixed-sized slurry, which have been explained in detail elsewhere [2], was not estimated for the comparison in this study.

3.3 The design procedure

The recommended design procedure can be summarised as:

① Consider the solids material for transport and carrier fluid.
② Plan the solids throughput and particle size range.
③ Determine the slurry flowrate.
④ Calculate the optimum pipe diameter.
⑤ Estimate the critical velocity as well as the optimum transport velocity.
⑥ Evaluate the pressure drop per unit distance, hydraulic gradient.
⑦ Select the system equipments.

4 CONCLUSIONS

An innovative procedure for designing a slurry pipeline system was derived. The main conclusions in this study are:

(a) The minimum points of the i-V_m curves could reasonably provide critical deposit velocities.
(b) The calculation of V_{cd} with the Durand correlation of F_L leads to overestimation, resulting in higher flow velocities.
(c) The design method offers justifiable prediction of pipe diameter and flow velocity for transport conditions.
(d) The applicability of the proposed method could be confirmed with field data of coal pipeline.

ACKNOWLEDGEMENTS – Authors' sincere gratitude to Professor Fumio Sugimoto, Professor Takaho Otomo, and Professor Masahide Nakamura, of Akita University, for their advise on this paper. This work was also supported by fellow students of the Slurry Transport Technology Laboratory, Akita University. We wish to thank their dedicated aide in this study.

SYMBOLS

C	Delivered concentration	(−)
d	Particle diameter	(m)
D	Pipe diameter	(m)
F_L	Durand Froude number corresponding to onset of solids deposition	(−)
g	Gravitational constant	(m/s^2)
i	Hydraulic gradient of slurry	(mAq/m)
i_s	Hydraulic gradient of solids	(mAq/m)
i_v	Hydraulic gradient of vehicle	(mAq/m)
i_w	Hydraulic gradient of water flowing alone at the same velocity as slurry	(mAq/m)
$\bar{q}$	Mean value of in-situ concentration for whole cross-sectional area of pipe	(−)
Q	Slurry flow rate	(m^3/s)
Q_s	Solids flow rate	(m^3/s)
t	Temperature of vehicle	(°C)
V_{cd}	Critical velocity	(m/s)
V_h	Hindered settling velocity of solids	(m/s)
V_m	Mean velocity of slurry flow	(m/s)
α, β	Swanson's shape factors	(−)
δ	Specific gravity of water	(−)
δ_s	Specific gravity of solids	(−)
δ_v	Specific gravity of vehicle	(−)

ρ	Density of fluid	(kg/m^3)
μ	Viscosity of fluid	(Pa·s)
λ_v	Coefficient of friction of vehicle	(−)
γ	Specific weight of water	(N/m^3)
γ_s	Specific weight of solids	(N/m^3)

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