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Head Losses Ratio Prediction for Hydraulic Sludge Transport in horizontal pipes for Different Concentrations and pipeline sizes

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Abstract

Sludge pumps in wastewater treatment plants are often oversized due to uncertainty in calculation of head losses. This issue increases costs for industry to purchase and operate the oversized pumps. Pumping sewage sludge of various types and concentrations through pipelines, both within treatment works and over longer distances between works and disposal areas, is a well-established practice. The design of these pipelines has been based mainly on the hydraulic laws of water but with the deduced coefficient of friction corresponding to the sludge concentration. This paper investigated the hydraulic transport characteristics of sludge-water mixtures in pipelines by changing the Reynolds number and volumetric delivered concentrations through analysis of results obtained from wastewater treatment plant. The analysis of these results was conducted in the light of pervious works. It was found that, the hydraulic head losses ratio increases with the Reynolds number and decreases with the pipe diameter. Equations were developed for prediction of head losses ratio for hydraulic sludge transport in horizontal pipes for different sludge concentrations and pipe sizes. Also, the results were represented in a form of curves used for the same purpose.

Key words: Sludge flow; Hydraulic transport; Head losses ratio; Sludge concentrations; bed friction; Deposit-limit velocity

INTRODUCTION

Although flow behavior of most liquids has been mathematically described and empirically verified, similar knowledge about solid-liquid mixtures is not available. Because of the complex nature of solid-liquid mixtures, postulations about their flow dynamics are presently beyond the reach of the most sophisticated computer programs. It has thus become necessary to gain this knowledge through empiricisms. Even though a substantial amount of data is beginning to accumulate, there exist wide variations among the results of different investigators, more as a consequence of the complexity of the phenomena rather than errors in investigation. The hydraulic transport of sludge in pipelines has been widely used in wastewater treatment plant. Head losses ratio is the main part, which was required for hydraulically transporting huge amounts of sludge in the treatment processes. Thus, the main concern of this paper is to focus on the head losses ratio prediction for hydraulic sludge transport in horizontal pipes for different sludge concentrations and pipe sizes. The predicted head losses are mainly required for pumping power.

Effect of pipe inclination on the pipe flow head losses for different sand concentrations and hydraulic gradient of sand-water mixture flow for different sands and pipes were studied and general equations and curves were developed to estimate the hydraulic gradient of the slurry flow through the pipelines with different size, type, inclination, and the sand concentrations, (Mahmoud A.Refaey Eltoukhy 2013).

Optimization of pumping systems can significantly reduce the energy consumption by wastewater treatment plants since pumps are among the highest energy consumers in wastewater treatment processes. Rheological characterization of sludge is important since it provides the essential information used in the design and optimization of pumping systems (Eshtiaghi et al. 2013, Slatter 1997).

Many predictive models exist in the case of suspensions, that is to say when the particle diameter is small compared to the flow length scales and the velocity of the carrier fluid is high compared to the settling velocity of a particle, (P.E. Baha Abulnaga 2002), (K. C. Wilson et al 2006, V. Matousek 2009).

The pipe flow theory for sludge is well developed (Slatter 2003, Slatter 2008) but the wide variability of the reported rheological model parameters hinders application of the theory to practical engineering design (e.g. the variability in Herschel-Bulkley (HB) model parameters used to describe sludge flow behavior). This variability is more than an order of magnitude for some of the parameters (Anderson et al. 2008, Water Environment 2008). The reason for the variability in sludge rheological data is unknown, but there are several possible reasons for this: One is that due to the difference in sludge sourcing and its treatment method, the sludge characteristics vary between sites (Jin et al. 2003). The second possibility is temporal variability in sludge characteristics at a single site. This temporal variability may be a result of the temporal change in sludge composition which occurs with the change of season (Mahmoud et al. 2004, Water Environment 2008) or time of sampling. Another possibility is the reliability of the method used for the analysis of sludge rheological data (i.e. nonlinear regression) (Ratkovich et al. 2013). This is more important where a three-parameter model such as HB fits the sludge flow curve. This inconsistency has resulted in proposing different relationships for the variation of HB model parameters with sludge concentration (Dabak and Yucel 1987, Farno et al. 2015, Lotito et al. 1997, Mori et al. 2006). As of other biological systems (He 2014, Zi 2011), not only sludge composition naturally contains variation but also sludge rheological data and model parameters introduce random errors (Dochain and Vanrolleghem 2001). Regardless of the source of errors, such non-deterministic features in every realistic engineering design contribute to stochasticity in the outcome (Dochain and Vanrolleghem 2001).

For transport of sludge in horizontal, and a fortiori in geometries in S-shape, there are few models (P. Doron 1987) and the effects of specific mass and more specifically of very large particle size have not been systematically explored. One major difficulty in the case of transport of large particles and high specific mass comes from the various flow regimes that may be observed (V. Matousek 2002, H. Yamaguchi et al 2011).

Engineers face two problems in the design of pumping systems for sewage sludge. One is the variability in the pressure drop as a result of the variability in the nature of sewage sludge. Second is the non-Newtonian behavior of sewage sludge which requires accurate rheological data and not relying on the rule-of-thumb approaches (Anderson et al. 2008, Slatter 2001). The design of these systems requires a reliable means of estimating pressure drop at various flow rates. This is a complicated task because the description of the complex behavior of sludge (i.e. flow behavior) typically requires two or three rheological parameters rather than the more traditional use of a single viscosity' value for simpler fluids (Malkin et al. 2004, Slatter 2004)

Slatter P. and Nicky E. (2018), predicts the probability distribution of pressure drop calculation in typical sludge pipe line when the model parameters vary in the 95% confidence region. Different parameter estimation scenarios were compared together in terms of the range of variation (standard deviation) created in the calculation of pressure drop for a typical sludge pipe line. Also, sensitivity analysis is employed to identify which model parameters are mostly correlated with the output (i.e. pressure drop calculation for sludge pipeline) (Hamby 1994)

In this paper, head losses were collected and analyzed to present the obtained results in a general curves to estimate the head losses ratio by knowing Reynolds number, sludge concentration, and pipe diameter. Also, general equations were developed for the same purpose.

DATA COLLECTION AND METHODOLOGY

1. Data Collection:

The data of this paper were collected from wastewater treatment plant. Seven sludge concentrations were used with values of 0, 2, 4, 6, 8, 10, and 12 % (weight by weight). Five pipe diameters of 100, 150, 200, 250, and 300 mm were tested for all sludge concentrations. In this paper, critical head loss was calculated for a typical pipeline of sludge with 20 m length for the used diameter. Critical head loss was only chosen here for the sake of comparing different models and estimation techniques (ordinary least-squares / robust fitting). Note, once the critical head is known in a pipe line system, it is of interest to operate sludge pipe line above this critical head loss to be sure operating in the turbulent regime to prevent sludge settling (Farno et al. 2017).

2. Methodology:

The data were collected according the following steps;

1- For pipe with diameter 100 mm install two pressure gauges at two points 1 and 2 with 20 m apart.
2- Pump sludge water mixture discharge larger than the critical one which give the critical head loss.
3- Record the reading of the two gauges for different sludge water mixture discharges at sludge concentration of 2 %.
4- Repeat step 2 for sludge concentrations of 4, 6, 8, 10, and 12 %.
5- Repeat steps 2 and 3 for pipe diameters of 150, 200, 250, 300 mm.
6- Tabulate the collected data and develop dimensionless groups, using Buckinham's Theorem, which were used in developing general curves and equations.

In this paper the head losses ratio (i = head loss, h/ pipeline portion length, L) was be function of sludge concentration, (C) Reynolds number, R_e and pipe diameter, d as;

$$h = \frac{p_1 - p_2}{\gamma} \tag{1}$$

where P_1 and P_2 are the pressure gauges readings at points 1 and 2.

$$i = \frac{h}{L} = f\left\{\frac{4\,\rho\,Q}{\pi\,d\,\mu}, C, \frac{d}{L}\right\} = f\left\{R_e, C, \frac{d}{L}\right\} \tag{2}$$

RESULTS AND DISCUSSION

All data were analyzed to show the effect of flow discharge on the head losses ratio for different sludge concentrations.

1. Variation of pipeline corrected coefficient of friction with the sludge Reynolds number for different sludge concentrations:

Firstly, the sludge pumped at Mt Osborne Mine behaves as a settling sludge. Although classified as a high density thickened tailings disposal facility, the material has a low fines fraction and is not non – Newtonian. Sludge flow in pipelines is complex as it is affected by many variables in particular the properties of the sludge relative to water. Due to this complexity and the uncertainties associated with the theories and models of slurry flow, significant investigations have been conducted on sludge flow with different sludge concentrations. When we experience a case out of the normal where the general assumptions would not be adequate, the rheology parameters of the sludge have to be measured in order to estimate the correct head loss. Through the analysis of the collected data, it was found that the corrected pipe friction coefficient, f decreases with Reynolds number, for example; for sludge concentration of 8 % and pipe diameter of 200 mm, change Reynolds number from 222727 to 381818 results in decreasing in the corrected coefficient of friction from 0.064153 to 0.026726, i.e. increasing 71.5% in Reynolds number leads to decreasing 58.34%. On the other hand, the corrected pipeline friction coefficient, f increases as the sludge concentration increases, for example; for Reynolds number of 254545 and pipe diameter of 200 mm, change sludge concentration from 6 % to 10 % results in increasing in the corrected coefficient of friction from 0.043331 to 0.060663, i.e. increasing 40 % in the corrected coefficient of friction due to 66.67 % increasing in the sludge concentration, Figs (1 – 5). The pipeline coefficient of friction was calculated as follows;

$$f = \frac{i\,\pi^2\,g\,d^5}{8\,Q^2} \tag{3}$$

where:
Q is the sludge discharge (m^3/s)
G is the gravitational acceleration (m/s^2)
d is the pipe diameter (m)
i is the head loses ratio (m/m)

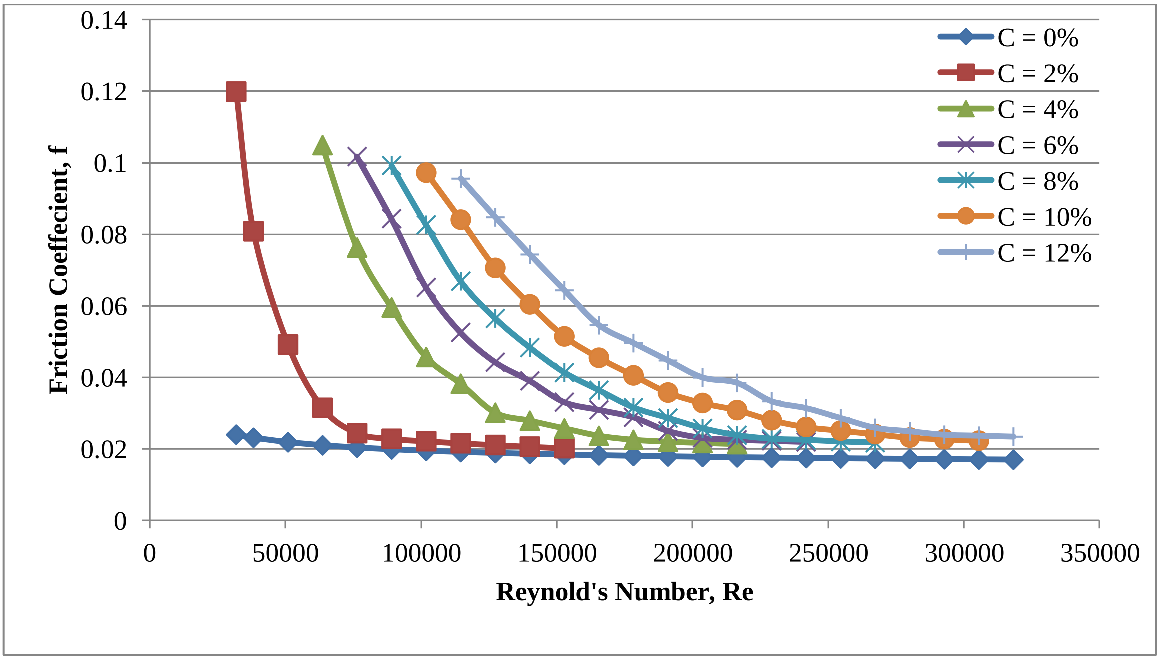

Fig 1 Friction coefficient for different sludge concentrations, for pipe diameter of 100 mm

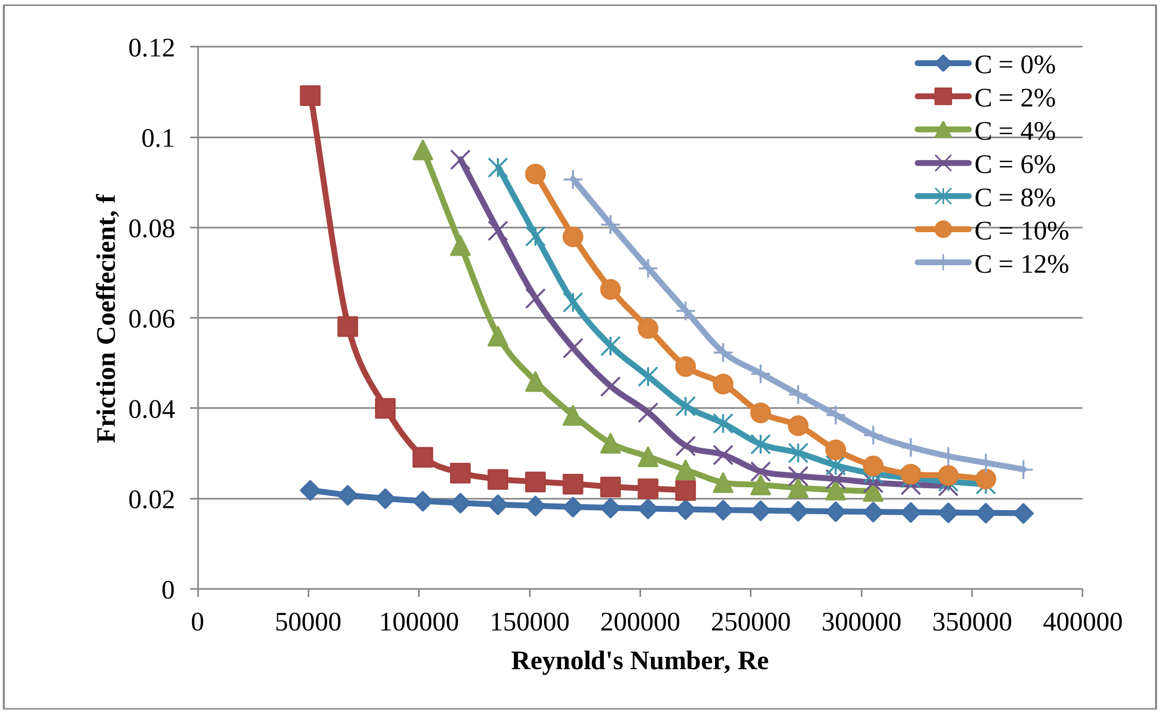

Fig 2 Friction coefficient for different sludge concentrations, for pipe diameter of 150 mm

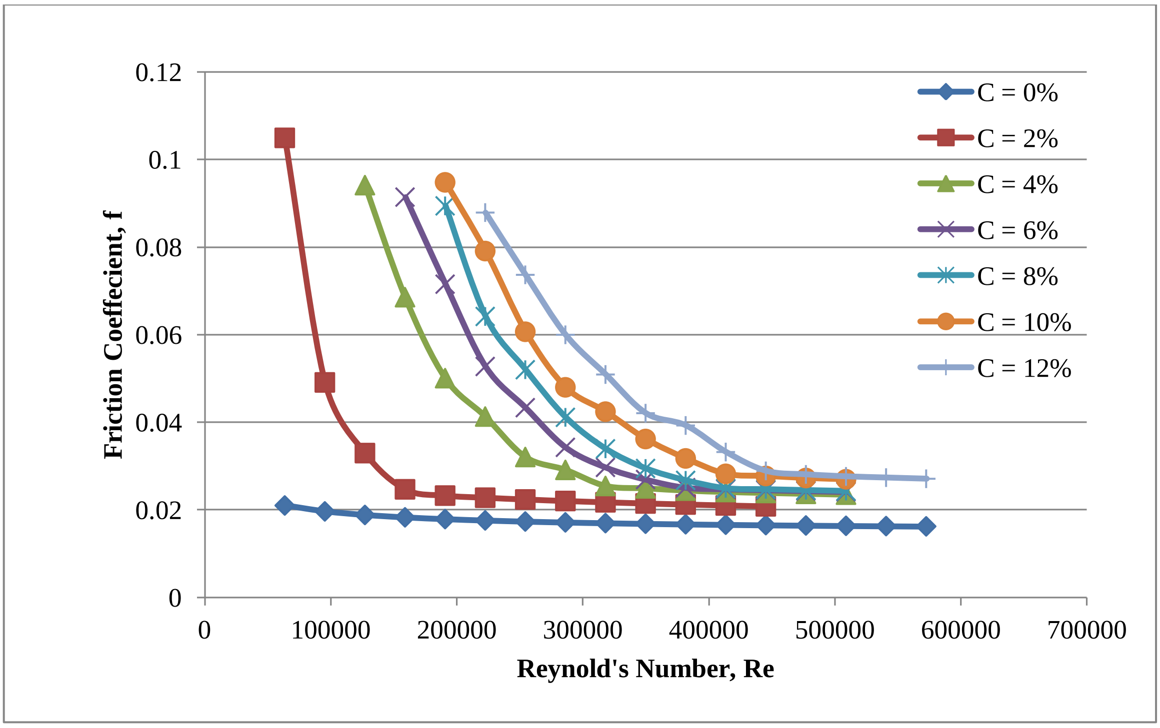

Fig 3 Friction coefficient for different sludge concentrations, for pipe diameter of 200 mm

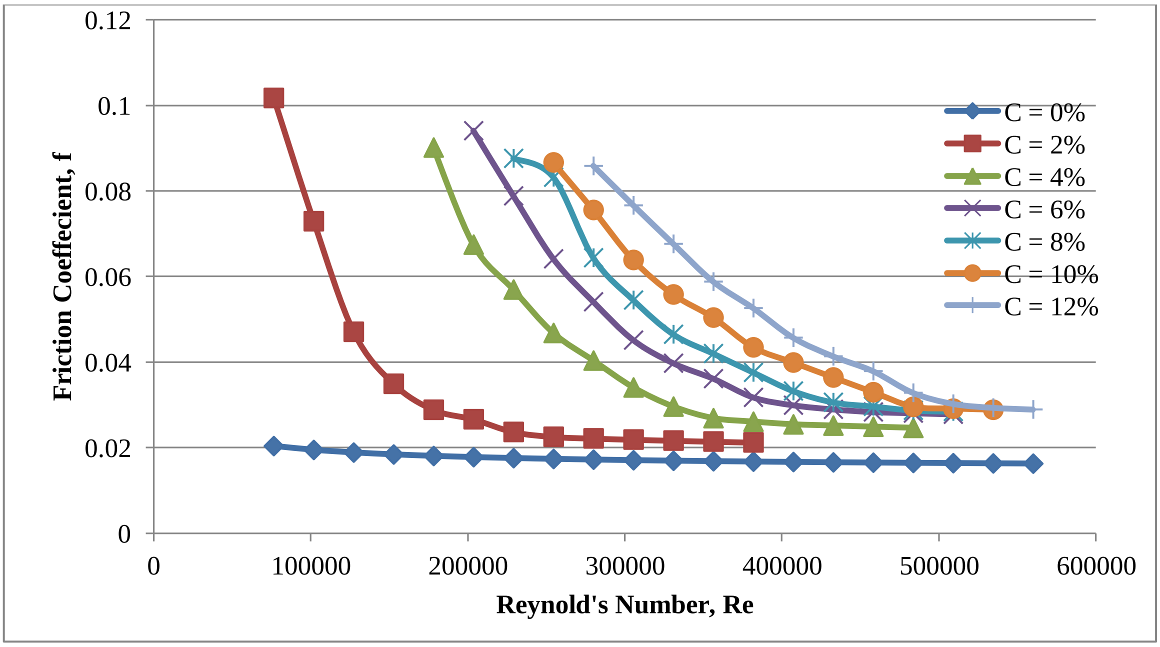

Fig 4 Friction coefficient for different sludge concentrations, for pipe diameter of 250 mm

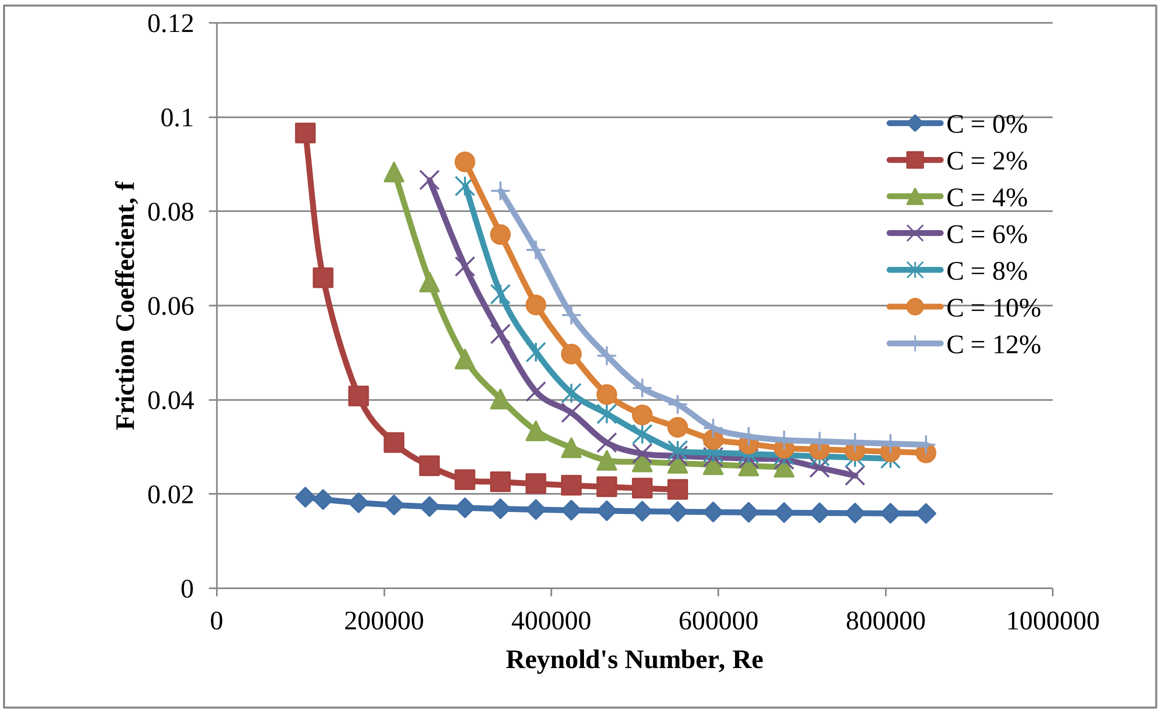

Fig 5 Friction coefficient for different sludge concentrations, for pipe diameter of 300 mm

2. Effect of the Reynolds number and sludge concentrations on the head losses ratio:

The head losses ratio, i was calculated from the collecting data for different sludge concentrations and pipeline diameter. Both critical head losses ratio and deposition-limit velocity are measured by changing the sludge concentrations (2%, 4%, 6%, 8%, 10%, and 12%). When the temperature of the water is high, the effect of the temperature should be considered. The effect of the temperature on the slurry flow characteristics is neglected in this paper. The head losses ratio has direct proportional relation with Reynolds number and the sludge concentration as shown in Figs (6 – 10). For example; for sludge concentration of 8 % and pipe diameter of 200 mm, change Reynolds number from 222727 to 381818 results in increasing in the head losses ratio from 0.020276 to 0.024824, i.e. increasing 71.5% in Reynolds number leads to increasing 22.43 %. On the other hand, for Reynolds number of

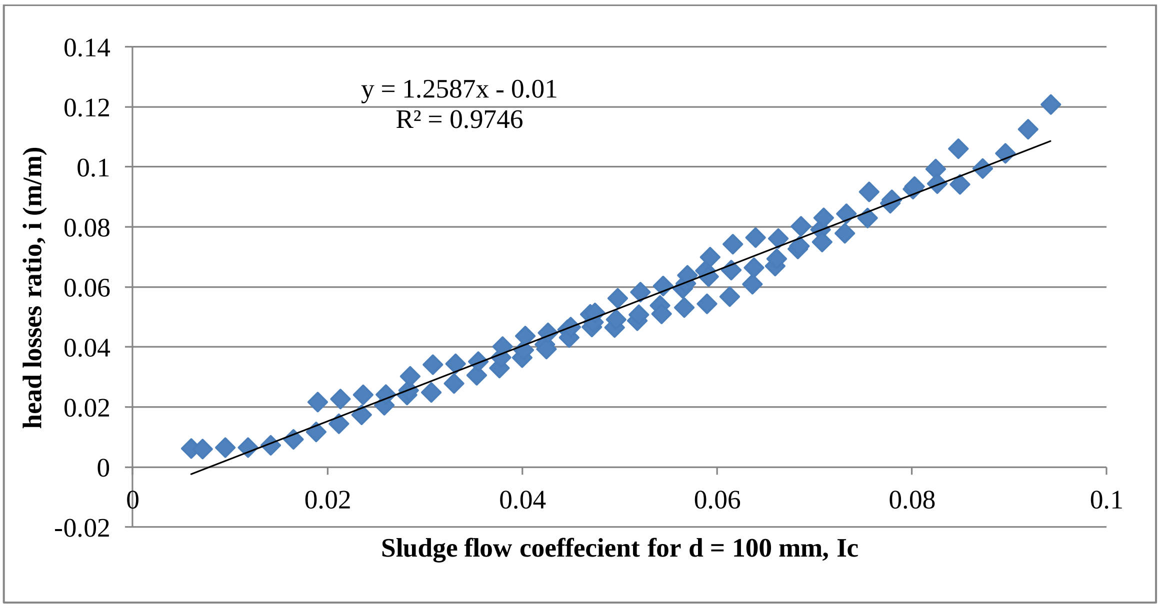

Fig 6 Head losses ratio for different flow velocities and sludge concentrations, for pipe diameter of 100 mm

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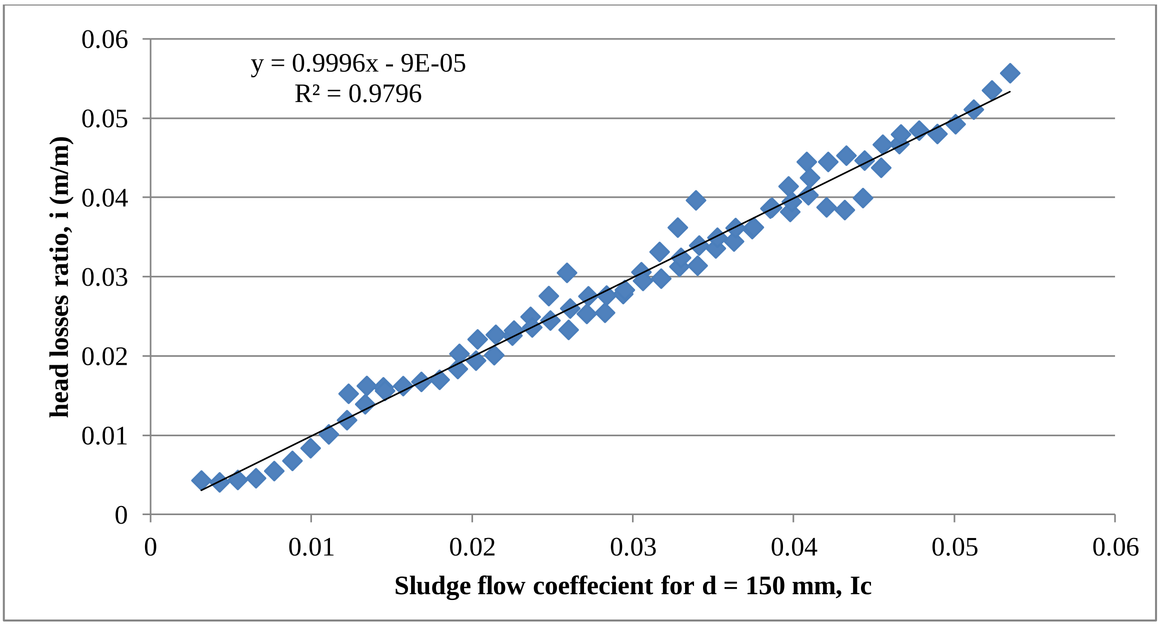

Fig 7 Head losses ratio for different flow velocities and sludge concentrations, for pipe diameter of 150 mm

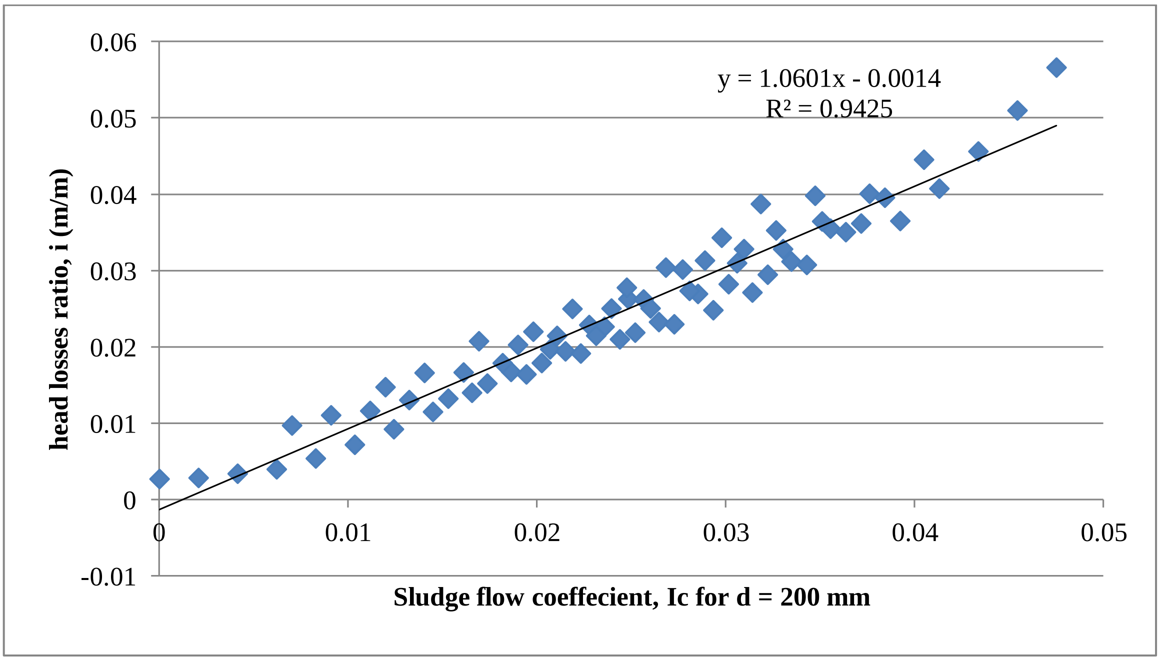

Fig 8 Head losses ratio for different flow velocities and sludge concentrations, for pipe diameter of 200 mm

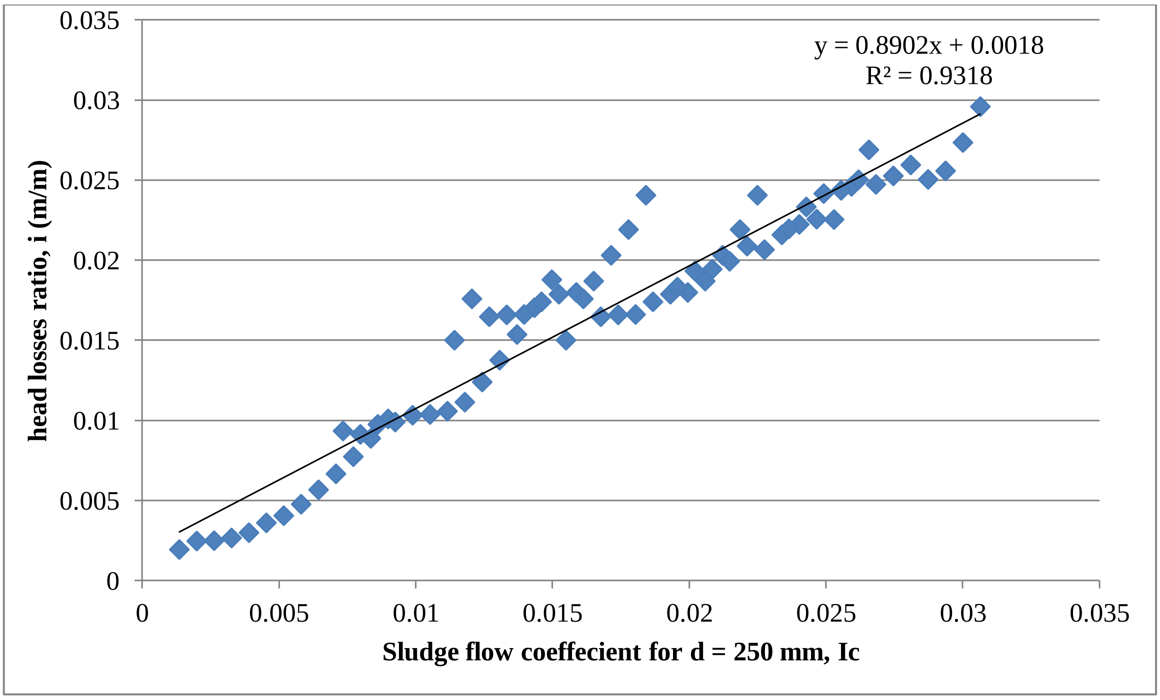

Fig 9 Head losses ratio for different flow velocities and sludge concentrations, for pipe diameter of 250 mm

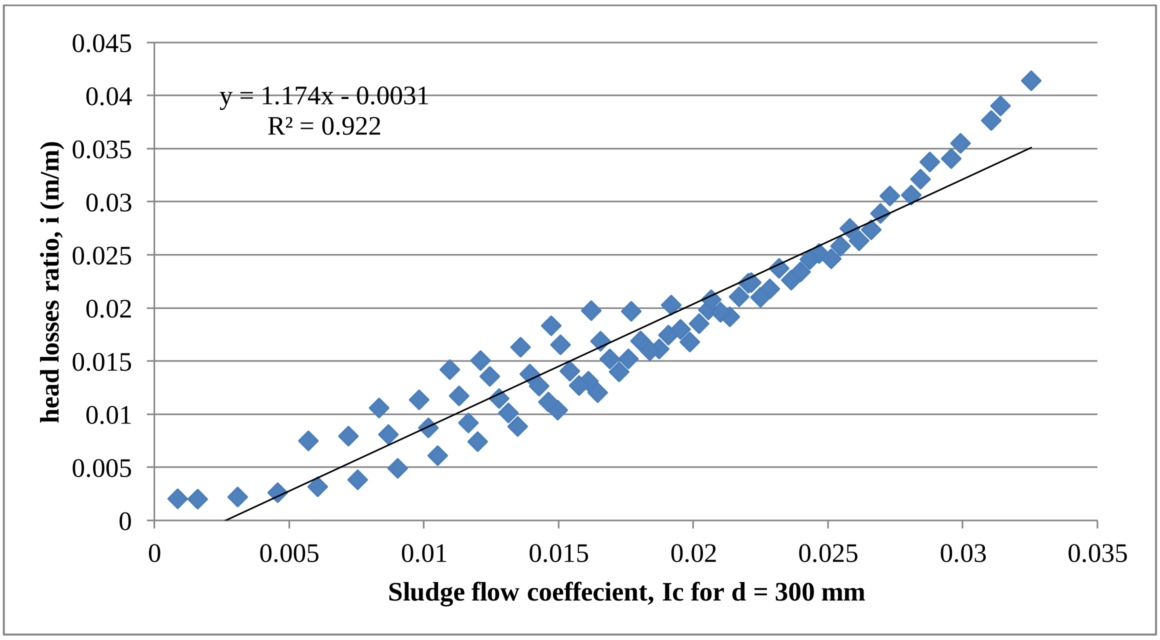

Fig 10 Head losses ratio for different flow velocities and sludge concentrations, for pipe diameter of 300 mm

254545 and pipe diameter of 200 mm, change sludge concentration from 6 % to 12 % results in increasing in the head losses ratio from 0.017887 to 0.030408, i.e. increasing 70 % in the head losses ratio due to 100 % increasing in the sludge concentration. The X- axis is a coefficient which can be calculated as;

$I_{C100} = 1.833\ x\ 10^{-7} R_e + 0.358$ C -0.007 for Fig (6) (4)
$I_{C150} = 6.67\ x\ 10^{-8} R_e + 0.288$ C -0.006 for Fig (7) (5)
$I_{C200} = 6.5\ x\ 10^{-8} R_e + 0.147$ C - 0.007 for Fig (8) (6)
$I_{C250} = 2\ x\ 10^{-8} R_e + 0.121$ C - 0.0035 for Fig (9) (7)
$I_{C300} = 3.5\ x\ 10^{-8} R_e + 0.057$ C -0.004 for Fig (6) (8)

By curve fitting for Figs (6 -10) the following equations will be developed;

$i = 2.306\ x\ 10^{-7} R_e + 0.4504$ C -0.01881 for pipeline diameter = 100 mm (9)
$i = 6.66\ x\ 10^{-8} R_e + 0.287$ C -0.0061 for pipeline diameter = 150 mm (10)
$i = 6.89\ x\ 10^{-8} R_e + 0.156$ C - 0.0084 for pipeline diameter = 200 mm (11)
$i = 2.5\ x\ 10^{-8} R_e + 0.172$ C - 0.001 for pipeline diameter = 250 mm (12)
$i = 4.095\ x\ 10^{-8} R_e + 0.0667$ C -0.0077 for pipeline diameter = 300 mm (13)

3. Effect of the pipeline diameter on the corrected pipeline coefficient of friction and the head losses ratio:

Also, through the data analysis, it was found that the corrected coefficient of friction of the pipeline with roughness, ε increases as the pipeline diameter increases as shown in Fig (11). The figure shows that all curves have the same trend that have steep decrease at smaller Reynolds number and have constant values for the corrected coefficient of friction for bigger Reynolds number.

But, increasing in the pipeline diameter results in decreasing the head losses ratio see Fig (12). Changing pipeline diameter from 150 to 250 mm leads to decrease in head losses ratio from 0.031375 to 0.017584. This means that, at Reynolds number of 254545 increasing 66.67 % in the pipeline diameter results in 44 % decreasing in the head losses ratio.

4. Estimating General Equation and Curve for the Head losses ratio:

By the analysis of all results and Bukingham's theorem general curve and equation were developed to calculate the head losses ratio for given sludge water mixture discharge (Reynolds number, R_e), sludge concentration, C, and the pipeline diameter, d. Fig (13) shows the general curve for this purpose in which the x-axis is the considered variables coefficient, I_{cv}which is;

$$I_{cv} = 8.641 \text{ x } 10^{-8} R_e + 0.2264\,C - 0.0084 \quad (14)$$

After curve feting and in Fig (13) and take the pipeline diameter the final equation will be:

$$i = 8.82\;x\;10^{-8}\,R_e + 0.2315\,C - 0.033\,\frac{\epsilon}{d} + 0.001 \quad (15)$$

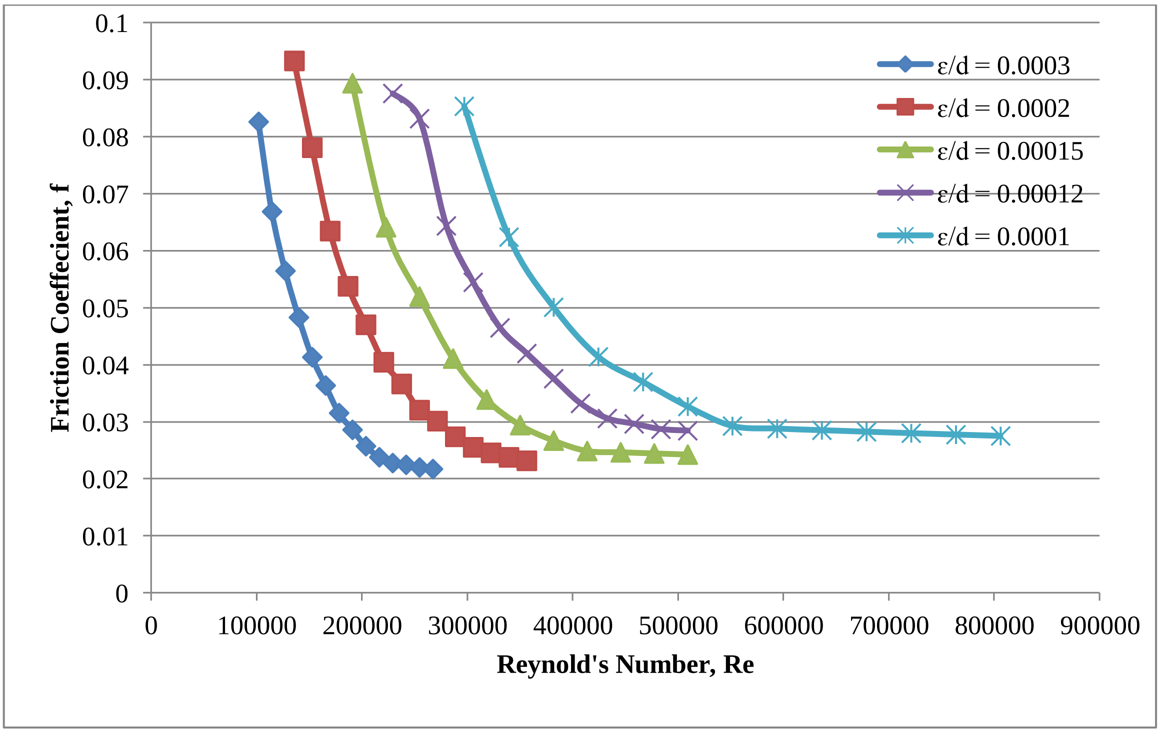

Fig 11 Effect of pipe diameter on the corrected coefficient of friction for sludge concentration of 8%

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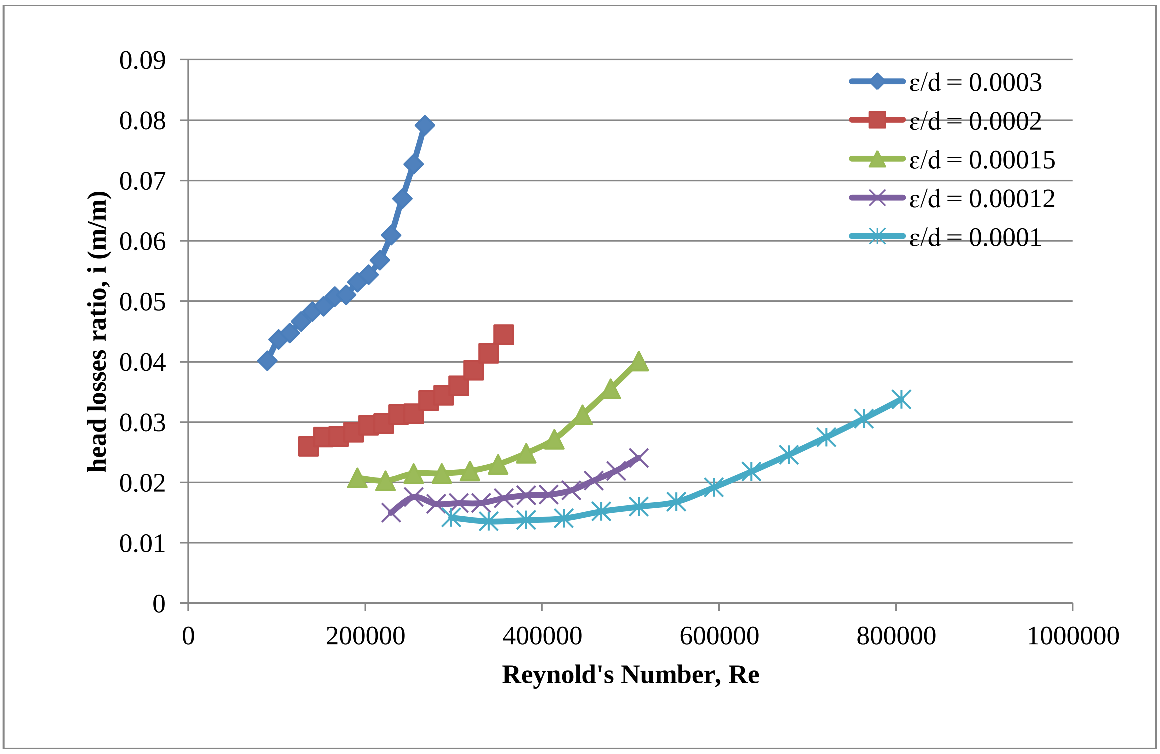

Fig 12 Head losses ratio for different pipe diameter and sludge concentration of 8 %

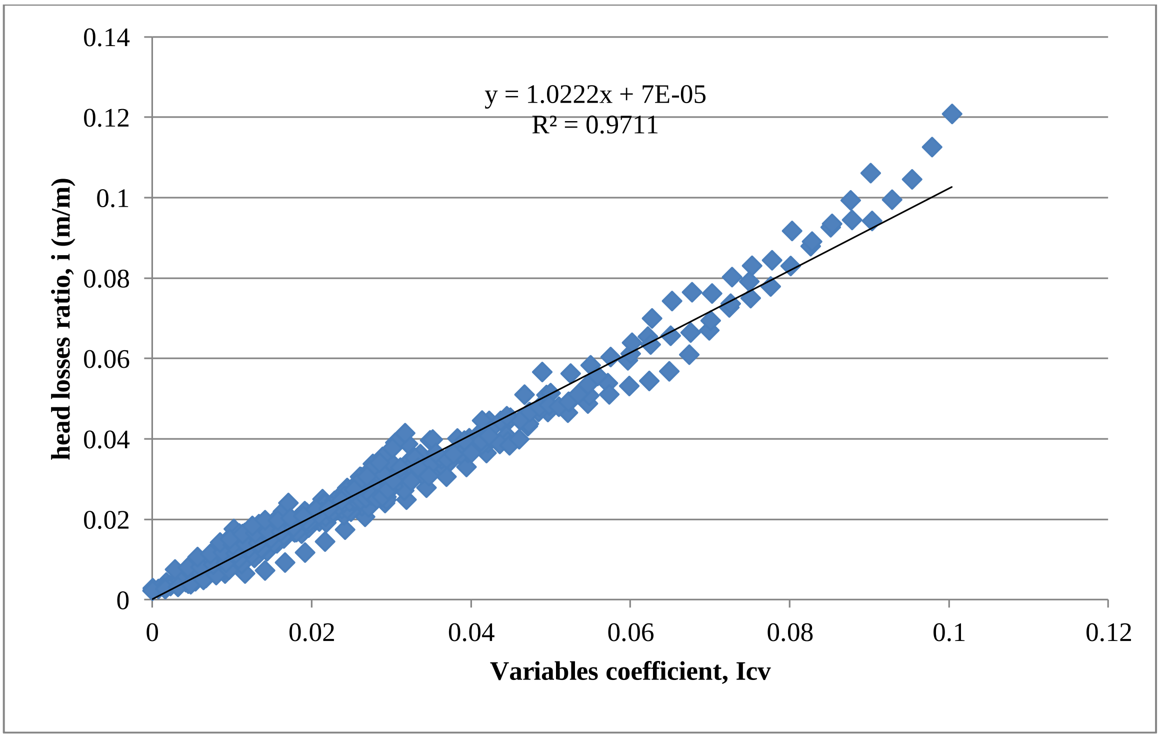

Fig 13 Head losses ratio for different pipeline diameter, sludge concentrations, and sludge discharge

CONCLUSIONS

The purposes of this paper, is to analyze the collected head losses for different sludge concentrations and pipe diameters. Based on the obtained results, fitted curves and equations, the following conclusions are reached:

1- The corrected pipeline coefficient of friction, increases as the sludge concentration, C increases
2- The head losses ratio, i has a directly proportional relationship with the sludge concentration, C.
3- Increasing in the pipeline diameter results in increasing in the corrected pipeline coefficient of friction,
4- The head losses ratio is inversely proportional with the pipeline diameter.
5- Equation (15) and Fig (13) may be used in calculating the head losses ratio for given sludge concentration, sludge discharge, and pipeline diameter.

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