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The heterogeneous to homogeneous transition for slurry flow in pipes

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ABSTRACT

Models for modeling slurry flow present difficulties on long lines with large pipe diameters and with broad graded sands or gravels. In order to get more insight into the slurry flow process, the Delft Head Loss & Limit Deposit Velocity Framework has been developed that integrates the 5 main flow regimes of slurry transport: fixed or stationary bed transport, sliding bed transport, heterogeneous transport, homogeneous transport and sliding flow transport. Additional models for; the limit deposit velocity, the holdup function, the bed height, the concentration distribution and graded sands and gravels, complement the Framework. The Framework is based on constant spatial volumetric concentration curves for uniform sands and gravels. The models for the flow regimes and the limit deposit velocity are based on energy considerations.

At line speeds near the transition of the heterogeneous and homogeneous flow regimes however, there is no sharp transition between the two flow regimes for medium sized particles. The limits of medium sized particles depend on the solid and liquid properties and on the pipe diameter. It is often observed that the hydraulic gradient lies in between the Equivalent Liquid Model (ELM) and the pure liquid Darcy Weisbach model at higher line speeds, resulting in the conclusion that at higher line speeds the pure liquid hydraulic gradient is approached. Based on energy considerations however, it is shown that the heterogeneous hydraulic gradient collapses due to turbulent near wall lift neutralizing the particle submerged weight and collisions with the pipe wall, while at higher line speeds the turbulent eddies integrate particles, resulting in a hydraulic gradient approaching a reduced ELM (RELM). For medium sized particles in large diameter pipes there is a gap between the moment the heterogeneous hydraulic gradient collapses and the homogeneous hydraulic gradient builds up, resulting in a hydraulic gradient approaching the RELM hydraulic gradient. The model for this transition is described and derived and experimental evidence is given.

1. Introduction

Although sophisticated 2 and 3 layer models exist for slurry flow (here the flow of sand/gravel water mixtures), the main Dutch and Belgian dredging companies still use modified Durand and Condolios (1952) and Fuhrboter (1961) models for heterogeneous transport, while the main companies in the USA use a modified Wilson et al. (2006) model, and the coal industry uses the Wasp (1977) model or the SRC (1991) model. The empirical models use one term for the excess head losses resulting from the solids (the solids effect). Most models are based on experiments in small diameter pipes. The use of these models does not give a satisfying result on projects with large diameter pipelines ($D_p > 0.75$ m), very long pipelines (up to 36 km) or broad particle size distributions (PSDs). This is the reason to study all existing models and develop a Framework that agrees with most existing models, but also solves the shortcomings. The result is the Delft Head Loss & Limit Deposit Velocity (DHLLDV) Framework. The DHLLDV Framework determines the resulting hydraulic gradient curve for spatial volumetric concentrations and uniform sands, consisting of parts of all flow regimes occurring for the pipe and particle diameter in question.

Since the slurry flow process in dredging is a non-stationary process, the PSD and concentration may be time and space dependent, resulting in time varying line speeds, density waves, moving dunes and so on, the modelling should be based on time averaged properties and parameters. In the Framework the flow regime models are based on energy considerations. Each flow regime has its own physical and mathematical model. Once the resulting hydraulic gradient curve and the Limit Deposit Velocity (LDV) are determined, a holdup function is used to construct the transport volumetric concentration curve and the bed height. The latest addition to the Framework is a method to determine the concentration distribution based on the LDV and the Wasp (1963) model. The LDV is defined here as the line speed above which there is no stationary or sliding bed.

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Nomenclature

$\mathbf{A_{cv}}$	coefficient RELM (default 3), dimensionless
$\mathbf{C_D}$	particle drag coefficient, dimensionless
$\mathbf{C_L}$	lift coefficient, dimensionless
$\mathbf{C_{vt}}$	delivered (transport) volumetric concentration, dimensionless
$\mathbf{C_{vs}}$	spatial volumetric concentration, dimensionless
$\mathbf{C_{vb}}$	spatial volumetric concentration bed (1-n), dimensionless
$\mathbf{C_{vB}}$	spatial concentration at the bottom of the pipe, dimensionless
$\mathbf{C_{vr}}$	relative spatial concentration, dimensionless
d	particle diameter, m
$\mathbf{D_p}$	pipe diameter, m
ELM	Equivalent Liquid Model, dimensionless
$\mathbf{E_k}$	kinetic energy loss, N m
$\mathbf{E_{rhg}}$	relative excess hydraulic gradient, dimensionless
$\mathbf{F_L}$	lift force on particle, dimensionless
$\mathbf{F_G}$	submerged weight of particle, N
$\mathbf{F_K}$	kinetic energy deceleration force, N
g	gravitational constant 9.81 m/s^2, m/s^2
$\mathbf{i_l}$	pure liquid hydraulic gradient, m/m
$\mathbf{i_m}$	mixture hydraulic gradient, m/m
LDV	Limit Deposit Velocity, m/s
LSDV	Limit of Stationary Deposit Velocity, m/s
$\mathbf{L_R}$	lift ratio, dimensionless
m	mobilized RELM factor, dimensionless
$\mathbf{m_p}$	mass particle, kg
RELM	Reduced Equivalent Liquid Model, dimensionless
$\mathbf{r,r_1,r_2}$	vertical distance in pipe, m
R	stratification ratio Wilson, dimensionless
$\mathbf{R_{sd}}$	relative submerged density, dimensionless
$\mathbf{S_{hr}}$	settling velocity hindered relative, dimensionless
$\mathbf{S_{rs}}$	slip velocity Relative Squared, dimensionless
$\mathbf{u_*}$	friction velocity, m/s
$\mathbf{u_{*,ldv}}$	friction velocity at LDV, m/s
$\mathbf{v_{ls}}$	line speed, m/s
$\mathbf{v_{sl}}$	slip velocity, m/s
$\mathbf{v_t}$	terminal settling velocity particle, m/s
$\mathbf{v_{th}}$	hindered terminal settling velocity particle, m/s
$\mathbf{v_{th,ldv}}$	hindered terminal settling velocity particle at LDV, m/s
$\mathbf{v_{\delta v}}$	velocity at viscous sub layer thickness, m/s
x	distance to decelerate particle, m
$\boldsymbol{\alpha}$	number of times thickness viscous sub layer, dimensionless
$\boldsymbol{\alpha_{sm}}$	coefficient concentration distribution, dimensionless
$\boldsymbol{\beta}$	Richardson & Zaki hindered settling power, dimensionless
$\boldsymbol{\beta_{sm}}$	diffusivity factor, dimensionless
$\boldsymbol{\delta_v}$	viscous sub layer thickness, m
$\boldsymbol{\kappa}$	Von Karman constant (about 0.4), dimensionless
$\boldsymbol{\kappa_C}$	concentration eccentricity factor, dimensionless
$\boldsymbol{\lambda_l}$	Darcy Weisbach friction factor liquid, dimensionless
$\boldsymbol{\mu_{sf}}$	sliding friction factor, dimensionless
$\boldsymbol{\rho_l}$	density liquid, ton/m^3
$\boldsymbol{\rho_m}$	density mixture, ton/m^3
$\boldsymbol{\rho_s}$	density solid, ton/m^3
$\boldsymbol{\nu_l}$	kinematic viscosity liquid, m^2/s
$\boldsymbol{\psi}$	shape factor, dimensionless
$\boldsymbol{\zeta}$	smoothing parameter lift ratio, dimensionless
$\boldsymbol{\theta}$	dimensionless lift ratio coefficient, dimensionless

For graded sands and gravels the curves are determined for each uniform grain fraction individually, and the resulting curves are then combined by superposition to form the overall hydraulic gradient curve, holdup function and bed height curve.

2. The DHLLDV framework

The Delft Head Loss & Limit Deposit Velocity Framework (DHLLDV) is a Framework based on constant spatial volumetric concentration curves and uniform sands or gravels for 5 flow regimes in a Newtonian fluid (Ramsdell and Miedema, 2013; Miedema and Ramsdell, 2014b). These 5 regimes are the stationary or fixed bed regime (Miedema and Matousek, 2014), the sliding bed regime (Miedema and Ramsdell, 2014a; Miedema, 2014b), the heterogeneous regime (Miedema and Ramsdell, 2013; Miedema, 2014a, in press), the homogeneous regime (Miedema, 2015a) and the sliding flow regime (Miedema and Ramsdell, 2014b). Crucial for the modelling is the determination of the Limit Deposit Velocity (LDV). The constant delivered volumetric concentration curves are determined based on the LDV ((Miedema and Ramsdell, 2015a)) and the holdup function (Miedema, 2015b). The bed height is determined based on the LDV and the holdup function. Curves for graded sands and gravels are determined by superposition of the curves of the fractions of the Particle Size Distribution (PSD). The Limit Deposit Velocity is defined here as the line speed above which there is no stationary bed or sliding bed, Thomas (1962). Below the LDV there may be either a stationary or fixed bed or a sliding bed.

The DHLLDV Framework is based on energy considerations. In each flow regime the main source of energy losses due to the solids is identified.

(1) The energy losses in the fixed or stationary flow regime are due to turbulence of the liquid above the bed.
(2) The energy losses in the sliding bed regime are due to sliding friction of the solids with the pipe wall.
(3) The energy losses in the heterogeneous flow regime are due to potential energy (gravity) and kinetic energy (collisions of the solids with the pipe wall).
(4) The energy losses in the homogeneous flow regime are due to turbulence of the liquid carrying the solids. Large eddies are formed, with a size related to the pipe diameter and a circumferential velocity related to the line speed. The large eddies break up into smaller eddies which break up in even smaller eddies until the smallest eddies are formed that will dissipate into heat. So the energy dissipated starts with the rotational energy of the largest eddies, which is proportional to the density of the rotating mass, the mixture density. This philosophy is the basis of the Equivalent Liquid Model (ELM). If the dissipated energy is proportional to the mixture density, then the liquid density can be replaced by the mixture density in the well-known Darcy Weisbach equation. Because of lift, due to the velocity gradient near the pipe wall, directed to the center of the pipe, particles are forced away from the viscous sub layer resulting in an almost particle free viscous sub layer. This effect reduces the Darcy Weisbach friction factor and results in pressure losses lower than the ELM (Miedema, 2015a). Wilson and Sellgren (2003) also identified this as the near wall lift effect.