WELCOME

Flow regime diagrams in slurry transport models

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Delft University of Technology
DHLLDV Framework
Flow Regimes
&
Scenarios

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Dredging A Way Of Life

Delft University of Technology – Offshore & Dredging Engineering
SLURRY TRANSPORT
Fundamentals, A Historical Overview & The Delft Head Loss & Limit Deposit Velocity Framework

By Sape A. Miedema
Edited by Robert C. Ramsdell
Introduction
Chapter 7.1
The Elephant of Wilson
Possibilities

1. Small versus large pipe diameter
2. Small versus large particle diameter
3. Low versus high concentration
4. Low versus high line speed
5. Spatial versus delivered concentration
6. Uniform versus graded sands/gravels

1. Carrier liquid properties
2. Solids properties

For sands/gravels in water 64 combinations possible
Data from Yagi et al., $C_{vs}$

Hydraulic gradient $i_m$, $i_l$ vs. Line speed $v_{ls}$

Dp=0.1552 m, d=0.91 mm, Rsd=1.59, Cv=0.150, μsf=0.800
DHLLDV Model, The Solids Effect, $C_{vs}$

Hydraulic gradient $i_m, i_l$ vs. Line speed $v_{ls}$

- **Fixed Bed $C_{vs}=c.$**
- **Sliding Bed $C_{vs}=c.$** Lower Limit
- **Sliding Bed $C_{vs}=c.$** Mean
- **Sliding Bed $C_{vs}=c.$** Upper Limit
- **Heterogeneous Flow $C_{vs}=c.$**
- **Equivalent Liquid Model**
- **Homogeneous Flow $C_{vs}=C_{vt}=c.$**
- **Resulting $i_m$ curve $C_{vs}=c.$**
- **Resulting $i_m$ curve $C_{vt}=c.$**
- **Limit Deposit Velocity $C_{vs}=c.$**
- **Limit Deposit Velocity $C_{vt}=c.$**
- **Limit Deposit Velocity**

Formula:

$$i_l = \frac{\Delta p_1}{\rho_1 \cdot g \cdot \Delta L} = \frac{\lambda_1 \cdot v_{ls}^2}{2 \cdot g \cdot D_p}$$

$$E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot C_v}$$

$D_p = 0.1524$ m, $d = 1.500$ mm, $R_{sd} = 1.585$, $C_v = 0.300$, $\mu = 0.420$
DHLLDV Model, The Solids Effect, $C_{vt}$

**Equation:**

$$i = \frac{\Delta p}{\rho \cdot g \cdot \Delta L} = \frac{\lambda \cdot v^2}{2 \cdot g \cdot D_p}$$

**Diagram:**

- Hydraulic gradient $i_m$, $i_l$ vs. Line speed $v_{ls}$
- Fixed Bed $C_{vs}=c.$
- Sliding Bed $C_{vs}=c.$ Lower Limit
- Sliding Bed $C_{vs}=c.$ Mean
- Sliding Bed $C_{vs}=c.$ Upper Limit
- Heterogeneous Flow $C_{vs}=c.$
- Equivalent Liquid Model
- Homogeneous Flow $C_{vs}=C_{vt}=c.$
- Resulting $i_m$ curve $C_{vs}=c.$
- Resulting $i_m$ curve $C_{vt}=c.$
- Limit Deposit Velocity $C_{vs}=c.$
- Limit Deposit Velocity $C_{vt}=c.$

**Equation:**

$$E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot C_v}$$

**Notes:**

- $D_p=0.1524 \text{ m}$, $d=1.500 \text{ mm}$, $R_{sd}=1.585$, $C_v=0.300$, $\mu=0.420$
Data from Yagi et al., $C_v$s

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $C_v$s=c.
- Sliding Bed $C_v$s=c.
- Mean
- Heterogeneous Flow $C_v$s=c.
- Homogeneous Flow $C_v$s=Cvt=c.
- Resulting $E_{rhg}$ curve $C_v$s=c.
- Limit Deposit Velocity

- Ratio Potential/Kinetic Energy
  - $C_v$s=0.225-0.275
  - $C_v$s=0.175-0.225
  - $C_v$s=0.125-0.175
  - $C_v$s=0.075-0.125
  - $C_v$s=0.025-0.075

Dp=0.1552 m, d=0.91 mm, Rsd=1.59, Cv=0.150, $\mu_{sf}$=0.800

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Regimes History

Chapter 1
Regimes History

I. Homogeneous

II. Heterogeneous with full suspension

III. Heterogeneous with rolling, saltation

IV. Sliding bed

V. Fixed bed

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Abulnaga (2002)

Pressure Gradient $i_m$ versus Line Speed $v_{ls}$

- Water
- Slurry

- $V1$: Start Fixed Bed With Suspension
- $V2$: Start Moving Bed/Saltating Bed
- $V3$: Start Heterogeneous Transport
- $V4$: Start (Pseudo) Homogeneous Transport
Flow Regimes according to Newitt et al. (1955) & Durand & Condolios (1952)

- Flow with a Stationary Bed
  - $D_p = 1$ inch
  - $D_p = 6$ inch
  - $D_p = 36$ inch

- Flow with a Moving Bed
  - $D_p = 1$ inch
  - $D_p = 6$ inch
  - $D_p = 36$ inch

- Flow as a Heterogeneous Suspension
- Flow as a Homogeneous Suspension

- Line Speed $v_L$ (m/sec)
- Particle Diameter $d$ (mm)
Flow Regimes

Chapter 7.2
Flow Regimes 1

1: Fixed bed without suspension or sheet flow, constant $C_{vs}$.

2: Fixed bed with suspension or sheet flow, constant $C_{vs}$.

3: Fixed bed with suspension or sliding bed with sheet flow, constant $C_{vs}$. 
Flow Regimes 2

5: Heterogeneous transport, $C_{v_t} \approx C_{v_s}$.

6: Homogeneous transport, $C_{v_t} \approx C_{v_s}$.

5/6: Pseudo homogeneous transport, $C_{v_t} \approx C_{v_s}$.

7: Sliding Flow if $d/D_p > 0.015$. 

5: Heterogeneous transport, $C_{v_t} \approx C_{v_s}$.

6: Homogeneous transport, $C_{v_t} \approx C_{v_s}$.

5/6: Pseudo homogeneous transport, $C_{v_t} \approx C_{v_s}$.

7: Sliding Flow if $d/D_p > 0.015$. 

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Flow Regimes 3

4: Fixed bed with suspension or sliding bed with sheet flow, constant $C_{vt}$.

8: Fixed bed with suspension or sliding bed with sheet flow, constant $C_{vt}$.

Distinguish $C_{vs}$ & $C_{vt}$

Scenario’s with L are with $C_{vs}$
Scenario’s with R are with $C_{vt}$
Scenarios
Chapter 7.2
Equations in Graphs

Hydraulic Gradient $i$

$$i_1 = \frac{\Delta p_1}{\rho_1 \cdot g \cdot L} \quad \text{or} \quad i_m = \frac{\Delta p_m}{\rho_1 \cdot g \cdot L}$$

for water as carrier fluid:

$$\frac{\Delta L}{D_p} \cdot \frac{1}{2} \cdot \rho_1 \cdot v_{ls}^2 = \frac{\lambda_1 \cdot v_{ls}^2}{2 \cdot g \cdot D_p}$$

Relative Submerged Density $R_{sd}$

$$R_{sd} = \frac{\rho_s - \rho_1}{\rho_1}$$

Relative Excess Hydraulic Gradient $E_{rhg}$

$$E_{rhg} = \frac{i_m - i_1}{R_{sd} \cdot C_{vs}} \quad \text{or} \quad E_{rhg} = \frac{i_m - i_1}{R_{sd} \cdot C_{vt}}$$
Spatial versus Transport Concentration & the Slip Velocity

Spatial Volumetric Concentration is volume based. Transport Volumetric Concentration is volume flow based.

\[
C_{vt} = \left(1 - \frac{v_{sl}}{v_{ls}}\right) \cdot C_{vs} \quad \Rightarrow \quad C_{vt} < C_{vs}
\]

\[
C_{vs} = \left(\frac{v_{ls}}{v_{ls} - v_{sl}}\right) \cdot C_{vt}
\]

Relative Excess Hydraulic Gradient \(E_{rhg}\), \(C_{vt} = \text{constant}\)

\[
E_{rhg} = \frac{i_{m} - i_{l}}{R_{sd} \cdot \left(1 - \frac{v_{sl}}{v_{ls}}\right) \cdot C_{vs}} = \left(\frac{v_{ls}}{v_{ls} - v_{sl}}\right) \cdot \frac{i_{m} - i_{l}}{R_{sd} \cdot C_{vs}}
\]
Scenario L1 & R1, $i_m - v_{ls}$

Hydraulic gradient $i_m, i_l$ vs. Line speed $v_{ls}$

- **Liquid $i_l$ curve**
- **Fixed Bed $C_{vs} = c$.**
- **Sliding Bed $C_{vs} = c$. Lower Limit**
- **Sliding Bed $C_{vs} = c$. Mean**
- **Sliding Bed $C_{vs} = c$. Upper Limit**
- **Heterogeneous Flow $C_{vs} = c$.**
- **Equivalent Liquid Model**
- **Homogeneous Flow $C_{vs} = C_{vt} = c$.**
- **Homogeneous Liquid Model**
- **Resulting $i_m$ curve $C_{vs} = c$.**
- **Resulting $i_m$ curve $C_{vt} = c$.**
- **Limit Deposit Velocity $C_{vs} = c$.**
- **Limit Deposit Velocity $C_{vt} = c$.**
- **Limit Deposit Velocity**

- **Dp = 0.1524 m, d = 0.200 mm, Rsd = 1.585, Cv = 0.300, μ = 0.416**

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Scenario L1 & R1, $E_{rhg}-i_l$

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $C_{vs}=c.$
- Sliding Bed $C_{vs}=c.$
- Lower Limit
- Sliding Bed $C_{vs}=c.$
- Mean
- Sliding Bed $C_{vs}=c.$
- Upper Limit
- Heterogeneous Flow $C_{vs}=c.$
- Equivalent Liquid Model
- Heterogeneous Flow $C_{vs}=c.$
- Resulting $E_{rhg}$ curve $C_{vs}=c.$
- Resulting $E_{rhg}$ curve $C_{vs}=c.$
- Limit Deposit Velocity $C_{vs}=c.$
- Limit Deposit Velocity $C_{vs}=c.$
- Limit Deposit Velocity $C_{vs}=c.$
- Ratio Potential/Kinetic Energy
- Fixed Bed $C_{vs}=c.$
- Sliding Bed $C_{vs}=c.$
- Lower Limit
- Sliding Bed $C_{vs}=c.$
- Mean
- Sliding Bed $C_{vs}=c.$
- Upper Limit

$D_p=0.1524$ m, $d=0.200$ mm, $R_{sd}=1.585$, $C_v=0.300$, $\mu=0.416$
Scenario L2A & R2A, $i_m - v_{ls}$

Hydraulic gradient $i_m$, $i_l$ vs. Line speed $v_{ls}$

- Liquid $i_l$ curve
- Fixed Bed $Cv_{s=c}$
- Sliding Bed $Cv_{s=c}$
- Lower Limit
- Sliding Bed $Cv_{s=c}$
- Mean
- Sliding Bed $Cv_{s=c}$
- Upper Limit
- Heterogeneous Flow $Cv_{s=c}$
- Equivalent Liquid Model
- Homogeneous Flow $Cv_{s=c}$
- Resulting $i_m$ curve $Cv_{s=c}$
- Resulting $i_m$ curve $Cv_{t=c}$
- Limit Deposit Velocity $Cv_{s=c}$
- Limit Deposit Velocity $Cv_{t=c}$
- Limit Deposit Velocity

Dp=0.1524 m, d=0.500 mm, Rsd=1.585, Cv=0.300, μ=0.416

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Scenario L2A & R2A, $E_{rhg} - i_l$

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $Cv = c.$
- Sliding Bed $Cv = c.$ Lower Limit
- Sliding Bed $Cv = c.$ Mean
- Sliding Bed $Cv = c.$ Upper Limit
- Heterogeneous Flow $Cv = Cvt = c.$
- Equivalent Liquid Model
- Homogeneous Flow $Cv = c.$
- Resulting $E_{rhg}$ curve $Cv = c.$
- Resulting $E_{rhg}$ curve $Cvt = c.$
- Limit Deposit Velocity $Cv = c.$
- Limit Deposit Velocity $Cvt = c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy

Dp=0.1524 m, d=0.500 mm, Rsd=1.585, Cv=0.300, μ=0.416
Scenario L2B & R2B, \(i_m-v_{ls}\)

Hydraulic gradient \(i_m, i_l\) vs. Line speed \(v_{ls}\)

- **Fixed Bed** \(C_{vs}=c_0\)
- **Sliding Bed** \(C_{vs}=c_0\) Lower Limit
- **Sliding Bed** \(C_{vs}=c_0\) Mean
- **Sliding Bed** \(C_{vs}=c_0\) Upper Limit
- **Heterogeneous Flow** \(C_{vs}=c_0\)
- **Equivalent Liquid Model**
- **Homogeneous Flow** \(C_{vs}=C_{vt}=c_0\)
- **Resulting \(i_m\) curve** \(C_{vs}=c_0\)
- **Resulting \(i_m\) curve** \(C_{vt}=c_0\)
- **Limit Deposit Velocity** \(C_{vs}=c_0\)
- **Limit Deposit Velocity** \(C_{vt}=c_0\)

Dp=0.1524 m, d=1.500 mm, Rsd=1.585, Cv=0.300, \(\mu=0.420\)
Scenario L2B & R2B, $E_{rhg} - i_l$

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

Fixed Bed $C_v = c.$
Sliding Bed $C_v = c.$
- Lower Limit
- Mean
- Upper Limit
Heterogeneous Flow $C_v = c.$
Equivalent Liquid Model
Homogeneous Flow $C_v = C_{vt} = c.$
Resulting $E_{rhg}$ curve $C_v = c.$
Resulting $E_{rhg}$ curve $C_v = C_{vt} = c.$
Limit Deposit Velocity $C_v = c.$
Limit Deposit Velocity $C_v = C_{vt} = c.$
Limit Deposit Velocity
Ratio Potential/Kinetic Energy

Dp=0.1524 m, d=1.500 mm, $R_{sd}=1.585$, $C_v=0.300$, $\mu=0.420$

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Scenario L3 & R3, $i_m - v_{ls}$

Hydraulic gradient $i_m, i_l$ vs. Line speed $v_{ls}$

- Fixed Bed $C_{vs} = c.$
- Sliding Bed $C_{vs} = c.$ Lower Limit
- Sliding Bed $C_{vs} = c.$ Mean
- Sliding Bed $C_{vs} = c.$ Upper Limit
- Heterogeneous Flow $C_{vs} = c.$
- Equivalent Liquid Model
- Homogeneous Flow $C_{vs} = C_{vt} = c.$
- Resulting $i_m$ curve $C_{vs} = c.$
- Resulting $i_m$ curve $C_{vt} = c.$
- Limit Deposit Velocity $C_{vs} = c.$
- Limit Deposit Velocity $C_{vt} = c.$
- Limit Deposit Velocity

Dp = 0.1524 m, d = 3.000 mm, Rs_d = 1.585, Cv = 0.300, \( \mu = 0.416 \)

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Scenario L3 & R3, $E_{rhg} - i_l$

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $Cvs = c.$
- Sliding Bed $Cvs = c.$
  - Lower Limit
  - Mean
  - Upper Limit
- Heterogeneous Flow $Cvs = Cvt = c.$
- Equivalent Liquid Model
- Homogeneous Flow $Cvs = Cvt = c.$
- Resulting $Erhg$ curve $Cvs = c.$
- Resulting $Erhg$ curve $Cvt = c.$
- Limit Deposit Velocity $Cvs = c.$
- Limit Deposit Velocity $Cvt = c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy

$Dp=0.1524$ m, $d=3.000$ mm, $Rsd=1.585$, $Cv=0.300$, $\mu=0.416$
Verification/Validation Experiments

Chapter 7.2
Fixed Bed – Heterogeneous

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $C_v=0.170$
- Sliding Bed $C_v=0.134$
- Heterogeneous Flow $C_v=0.076$
- Homogeneous Flow $C_v=0.036$
- Resulting $E_{rhg}$ curve $C_v=0.170$

Dp=0.5000 m, d=1.50 mm, Rsd=1.59, $C_v=0.170$, $\mu_{sf}=0.415$

Kazanskij (1980), $C_{vs}=c.$

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Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

Dp=0.4400 m, d=0.680 mm, Rsd=1.585, Cv=0.100, $\mu_{sf}$=0.416

Clift (1982), $C_{vt}$=c.
Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Sliding Bed $C_{vs}=c$
- Equivalent Liquid Model
- Homogeneous Flow $C_{vs}=C_{vt}=c$
- Uniform Sand $C_{vs}=c$
- Uniform Sand $C_{vt}=c$
- Limit Deposit Velocity
- Graded Sand $C_{vs}=c$
- Graded Sand $C_{vt}=c$

Clift (1982), $C_{vt}=c$, Broad Graded.

Dp=0.2032 m, d=0.681 mm, Rsd=1.585, Cv=0.110, μsf=0.416
Fixed Bed - Sliding Bed - Heterogeneous

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

Homogeneous Flow $C_v = C_t = c.$
Uniform Sand $C_v = c.$
Uniform Sand $C_t = c.$
Limit Deposit Velocity
Graded Sand $C_v = c.$
Graded Sand $C_t = c.$

Wiedenroth (1967), $C_v = c.$, Coarse Sand

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Fixed Bed - Sliding Bed - Heterogeneous

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

Wiedenroth (1967), $C_{vs}=c.$, Medium Sand

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Sliding Bed

Newitt et al. (1955), $C_{vt}=c.$, MnO2

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Sliding Bed, Sliding Flow

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $C_v=s=c.$
- Sliding Bed $C_v=s=c.$ Mean
- Heterogeneous Flow $C_v=s=c.$
- Homogeneous Flow $C_v=C_v=t=c.$
- Resulting $E_{rhg}$ curve $C_v=s=c.$
- Fixed Bed, Sliding Bed & Sliding Flow $C_v=t=c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy
  - $C_v=0.210$
  - $C_v=0.180$
  - $C_v=0.170$

Dp=0.0508 m, d=3.00 mm, Rsd=0.21, $C_v=0.187$, $\mu_{sf}=0.416$

Doron & Barnea (1993), $C_{vt}=c.$, Acetal

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Homogeneous

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $Cv_s=c.$
- Sliding Bed $Cv_s=c.$ Mean
- Heterogeneous Flow $Cv_s=c.$
- Homogeneous Flow $Cv_s=Cv_t=c.$
- Resulting $E_{rhg}$ curve $Cv_s=c.$
- Fixed Bed, Sliding Bed & Het. Flow $Cv_t=c.$
- Fixed Bed, Sliding Bed & Sliding Flow $Cv_t=c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy
- $Cv=0.100$
- $Cv=0.100$

Dp=0.0254 m, d=0.16 mm, Rsd=1.59, Cv=0.100, μsf=0.415

Babcock (1970)
Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_i$

- Fixed Bed $C_{vs}=c.$
- Sliding Bed $C_{vs}=c.$
- Mean
- Heterogeneous Flow $C_{vs}=c.$
- Homogeneous Flow $C_{vs}=C_{vt}=c.$
- Resulting $E_{rhg}$ curve $C_{vs}=c.$
- Fixed Bed, Sliding Bed & Het. Flow $C_{vt}=c.$
- Fixed Bed, Sliding Bed & Sliding Flow $C_{vt}=c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy
- $C_{v}=0.240$

Dp=0.1585 m, d=0.04 mm, Rsd=4.00, $C_{v}=0.240$, $\mu_{sf}=0.415$

Thomas (1976), Iron Ore

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Fixed Bed – Sliding Bed – Sliding Flow

Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

Dp=0.2000 m, d=4.30 mm, Rsd=1.49, Cv=0.128, μsf=0.470

Boothroyde (1979), $C_{vs}=c.$

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Relative excess hydraulic gradient $E_{rhg}$ vs. Hydraulic gradient $i_l$

- Fixed Bed $C_{vs}=c.$
- Sliding Bed $C_{vs}=c.$
- Mean
- Heterogeneous Flow $C_{vs}=c.$
- Homogeneous Flow $C_{vs}=C_{vt}=c.$
- Resulting $E_{rhg}$ curve $C_{vs}=c.$
- Fixed Bed, Sliding Bed & Het. Flow $C_{vt}=c.$
- Fixed Bed, Sliding Bed & Sliding Flow $C_{vt}=c.$
- Limit Deposit Velocity
- Ratio Potential/Kinetic Energy
  - $C_v=0.200$
  - $C_v=0.150$
  - $C_v=0.100$
  - $C_v=0.050$

Dp=0.1250 m, $d=4.45$ mm, $R_{sd}=1.59$, $C_v=0.200$, $\mu_{sf}=0.416$

Wiedenroth (1967), $C_{vs}=c.$, Gravel

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Transition Line Speed
Heterogeneous – Homogeneous
Chapter 9
The Transition Line Speed
Heterogeneous-Homogeneous

Problem definition:

For slurry transport in general and specifically in dredging, there are many models. But how to decide which model to use in which situation, or, when are specific models valid especially in the heterogeneous flow regime.

Solution:

The transition line speed of the heterogeneous flow regime with the homogeneous flow regime is a good indicator and limits the number of graphs.
Relative Transition Line Speed

\[ D_p = 0.1016 \text{ m}, \ C_{vs} = 0.05 \]

Transition Heterogeneous - Homogeneous

\[ \text{Particle diameter } d \text{ (mm)} \]

\[ \text{Relative line speed } v_{ls, hh} \]

\[ \text{Particle diameter } d \text{ (m)} \]

Transition Stokes=0.03

Transition \( d = 0.015 \cdot D_p \)

Upper Limit SB=ELM

Standard Deviation 12

Standard Deviation 3

\[ D_p = 0.1016 \text{ m}, \ Rsd = 1.585, \ C_{vs} = 0.050, \ \mu_{sf} = 0.416 \]

\[ v_{ls, hh, max} = 9.8 \text{ m/sec} \]

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Relative Transition Line Speed
\( D_p = 0.1016 \text{ m}, \ C_{vs} = 0.30 \)

Transition Heterogeneous - Homogeneous

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Relative Transition Line Speed

\[ D_p = 0.7620 \text{ m}, \ C_{vs} = 0.05 \]

**Transition Heterogeneous - Homogeneous**

- **Newitt et al.**
- **Fuhrboter**
- **Durand & Condolios**
- **Jufin & Lopatin**
- **Turian & Yuan 1**
- **Turian & Yuan 2**
- **Zandi & Govatos**
- **Wilson et al. - 1.0**
- **Wilson et al. - 1.7**
- **Wilson et al. NWL**
- **SRC**
- **DHLLDV**
- **DHLLDV LDV**

- **Transition Stokes=0.03**
- **Transition d=0.015·Dp**
- **Upper Limit SB=ELM**
- **Standard Deviation 12**
- **Standard Deviation 3**

\[ D_p = 0.7620 \text{ m}, \ Rsd = 1.585, \ C_{vs} = 0.050, \ \mu_{sf} = 0.416 \]

**v_{ls, hh, max} = 20.3 \text{ m/sec}**
Relative Transition Line Speed

\[ D_p = 0.7620 \text{ m}, \ C_{vs} = 0.30 \]

Transition Heterogeneous - Homogeneous

Particle diameter \( d \) (mm)

Relative line speed \( v_{ls, hh} \)

- Newitt et al.
- Fuhrborer
- Durand & Condolios
- Jufin & Lopatin
- Turian & Yuan 1
- Turian & Yuan 2
- Zandi & Govatos
- Wilson et al. - 1.0
- Wilson et al. - 1.7
- Wilson et al. NWL
- SRC
- DHLLDV
- DHLLDV LDV
- Transition Stokes=0.03
- Transition \( d=0.015 \cdot D_p \)
- Upper Limit SB=ELM
- Standard Deviation 12
- Standard Deviation 3

Dp=0.7620 m, Rsd=1.585, Cvs=0.300, \( \mu_{sf} = 0.416 \)

vls, hh, max=19.6 m/sec
Standard Deviation 12 Models

Standard Deviation at Transition He-Ho, 12 Models

- Homogeneous
- Heterogeneous
- Sliding Bed

Particle Diameter (m)

- Dp=0.0254 m
- Dp=0.0508 m
- Dp=0.1016 m
- Dp=0.1524 m
- Dp=0.2032 m
- Dp=0.2540 m
- Dp=0.3000 m
- Dp=0.4000 m
- Dp=0.5000 m
- Dp=0.6000 m
- Dp=0.8000 m
- Dp=1.0000 m
- Dp=1.2000 m

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Standard Deviation at Transition He-Ho, 4 Models

- Homogeneous
- Heterogeneous
- Sliding Bed

Dp=0.0254 m
Dp=0.0508 m
Dp=0.1016 m
Dp=0.1524 m
Dp=0.2032 m
Dp=0.2540 m
Dp=0.3000 m
Dp=0.4000 m
Dp=0.5000 m
Dp=0.6000 m
Dp=0.8000 m
Dp=1.0000 m
Dp=1.2000 m

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Flow Regime Diagrams
Chapter 7.8 & Appendix D
Small Pipe Diameter, $C_{vs}=0.175$

DHLLDV Flow Regime Diagram

- Homogeneous (Ho)
- Heterogeneous (He)
- Sliding Flow (SF)
- Sliding Bed (SB)
- Fixed/Stationary Bed (FB)
- Undefined

Viscous Effects

Durand Froude number $F_{d}$

Line speed (m/s)

Particle diameter (mm)

Dp=0.1524 m, Rsd=1.585, Cvs=0.175, $\mu_{sf}=0.416$
A Large Diameter Pipe, $C_{vs} = 0.175$

DHLLDV Flow Regime Diagram

- Homogeneous
- Heterogeneous
- Sliding Bed
- Stationary Bed
- Viscous Effects
- Undefined

Particle size (mm)

Durand Froude number $F_l$:

- $D_p = 0.7620 \text{ m}$, $Rsd = 1.585$, $C_{vs} = 0.175$, $\mu_{sf} = 0.416$

$Dp=0.7620 \text{ m}, Rsd=1.585, C_{vs}=0.175, \mu_{sf}=0.416$
A Large Diameter Pipe, $C_{vs} = 0.3$

DHLLDV Flow Regime Diagram

- Homogeneous
- Heterogeneous
- Sliding Bed
- Stationary Bed
- Viscous Effects
- Sliding Flow
- LDV
- LSDV
- Undefined

Particle diameter (mm)

Durand Froude number $F_d$ (t)

Line speed (m/s)

$Dp=0.7620$ m, $Rsd=1.585$, $C_{vs}=0.300$, $μsf=0.416$
Conclusions
The DHLLDV Framework
The Double Logarithmic Elephant: Leeghwater

- Constant Transport Concentration
- The Solids Effect
- LS
- LDV
- Sliding Bed
- Sliding Flow
- Constant Spatial Concentration
- Fixed Bed
- Sheet Flow
- Heterogeneous
- Homogeneous

Relative excess hydraulic gradient $E_{tg}$ (-)

Hydraulic gradient $i_i$ (-)

Delft University of Technology – Offshore & Dredging Engineering
SLURRY TRANSPORT
Fundamentals, A Historical Overview
& The Delft Head Loss & Limit
Deposit Velocity Framework

By
Sape A. Miedema
Edited by
Robert C. Ramsdell
The Elephant of Wilson is our best Friend

Questions?

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