An Overview of Flow Regimes Describing Slurry Transport

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Safety Moment
Problem Definition

• There are many models, empirical and fundamental for the various phases of flow.
• The models are often based on lab tests, and often in small pipe relative to current dredging practice.
• There is still no generic fundamental model for slurry transport, particularly in large diameter pipelines, connecting the different flow regimes.
Regimes History

I. Homogeneous

II. Heterogeneous with full suspension

III. Heterogeneous with rolling, saltation

IV. Sliding bed

V. Fixed bed

- $v$ m/s
- $C_vS\%$
- $C_vT\%$
- Mixture velocity
- Volume concentration
- Transport concentration
Flow Regimes according to Newitt et al. (1955) & Durand & Condolios (1952)

- Flow a Stationary Bed
- Flow with a Moving Bed
- Flow as a Heterogeneous Suspension
- Flow as a Homogeneous Suspension

- Limit of Stationary Bed
  - $D_p = 1$ inch
- Limit of Moving Bed, All $D_p$
- Heterogeneous vs Homogeneous $D_p = 1$ inch
- Heterogeneous vs Homogeneous $D_p = 6$ inch
Comparison of Transport Models
Dp=0.762m, Vls = 5.5 m/sec

- Coarse Particle (Sliding Bed)
- Homogeneous (Non-settling)

Particle diameter (mm)
Abulnaga (2002)
9 Flow Regimes
Volume Concentrations

$C_v = \frac{\rho_m - \rho_{fl}}{\rho_s - \rho_{fl}}$: Volume concentration from density readings.

$C_{vt} = \frac{\dot{v}_s}{v_m}$: Transport (delivered) volume concentration.

$C_{vs} = \frac{Q_s}{Q_m}$: Spatial volume concentration. Generally fixed in a lab environment.
Regimes with No Bed

$C_{vs} \approx C_{vt}$

5. Heterogeneous Transport

6. Pseudo-Homogeneous Transport

7. Homogeneous Transport
Regimes with a Sliding Bed

8. Sheet Flow
   \( C_{vs} \approx C_{vt} \)

3. Sliding Bed with Suspension
   \( C_{vs} > C_{vt} \)

4. Sliding bed with Suspension
   \( C_{vs} > C_{vt} \)
Regimes with a Fixed Bed

1. Fixed Bed without Suspension
   Note $C_{vt} = 0!$

2. Fixed Bed with Suspension
   $C_{vs} \gg C_{vt}$

9. Fixed bed with Suspension
   $C_{vs} \gg C_{vt}$

Constant $C_{vs}$

Constant $C_{vt}$
$C_{vs} = 1.0$

$C_{vt} = 0.0$
Scenarios

R1 – R3: Real Life, constant $C_v$ (we hope)

L1 – L3: Laboratory Setting, constant $C_{vs}$
Scenario L1 & R1

\[ i = \frac{\Delta p}{p_{fl} \cdot g \cdot L} \]
Scenario L1 & R1 (S_{rs} vs i_m)

\[ F_{pg} = S_{rs} = \left( \frac{v_{sl}}{v_t} \right)^2 \approx \frac{i_m - i_{fl}}{R_d \cdot C_v} \]

\[ i_w = \frac{\Delta p w}{p_{fl} \cdot g \cdot L} \]
Scenario L2 & R2 ($S_{rs}$ vs $i_m$)
Scenario L3 & R3 ($S_{rs}$ vs $i_m$)
Verification/Validation

Experimental Data
Sliding Bed, Cvt=c.

Newitt et al. (1955) \( D_p = 0.025 \text{m}, d = 1.6-3.2 \text{mm} \)
Fixed Bed - Heterogeneous

Kazanskij (1980) $D_p=0.5m$, $d=1.5mm$, $C_{vs}$
Clift et al. (1982) $D_p=0.44m$, $d=0.68mm$, $C_v$. 

Heterogeneous
Wiedenroth (1967) \( D_p = 0.125 \text{m}, \; d = 2.2 \text{mm}, \; C_{vs} \)
Boothroyde (1979) \( D_p = 0.2 \text{m}, \ d = 4.3 \text{mm} \)
21 Different Models

Pressure Gradient, All

- Water
- Homogeneous
- Heterogeneous Cvs=c.
- Fixed Bed Cvs=c.
- Sliding Bed Cvs=c.
- Heterogeneous Cvt=c.
- Sheet Flow Cvt=c.
- LDV FB-H
- LDV H-H
- LDV SB-H
- LDV Current
- Turian & Yuan Regime 0
- Turian & Yuan Regime 1
- Turian & Yuan Regime 2
- Turian & Yuan Regime 3
- Durand & Condolios
- Newitt et al.
- Newitt et al. Bed
- Jufin & Lopatin
- Fuhrboter
- Wilson et al. - 1.0
- Wilson et al. - 1.7
- Wilson et al. Bed
- Zandi & Govatos
- Zandi & Govatos Hom.

Dp=0.3000 m, d=1.00 mm, Rd=1.65, Cv=0.300
Different Models for Dp=0.15 m, Cv=0.30
Different Models for $D_p=1.00 \, \text{m}$, $C_v=0.30$

Transition Heterogeneous - Homogeneous

Parameters:
- $D_p=1.0000 \, \text{m}$
- $R_d=1.65$
- $C_v=0.300$

Velocity $v_{\text{rel,th}}$ vs. Particle Diameter $d$

Models:
- Newitt et al.
- Fuhrbomer
- Durand & Condolios
- Jufin & Lopatin
- Wilson et al. - 1.0
- Wilson et al. - 1.7
- Turian & Yuan 1
- Turian & Yuan 2
- Zandi & Govatos
- Miedema

Max velocity $v_{\text{ls,hh, max}}=29 \, \text{m/sec}$
Energy Considerations

Energy Dissipation by:
- Viscous Friction & Turbulence (Darcy Weisbach)
- Potential Energy Losses ( Hindered Settling Velocity)
- Kinetic Energy Losses (Collisions)
- Sliding & Rolling Friction
- Magnus Lift Work (Viscous Sub-Layer, Low Speed)
- Turbulent Lift Work & Eddy Work (High Line Speed)
Heterogeneous Transport

- Energy Dissipation by:
  - Viscous Friction & Turbulence (Darcy Weisbach)
  - Potential Energy Losses (Hindered Settling Velocity)
  - Kinetic Energy Losses (Collisions)

\[
\Delta p_m = \Delta p_{\text{fl,visc}} + \Delta p_{s,\text{pot}} + \Delta p_{s,\text{kin}} = \Delta p_{\text{fl,visc}} \cdot \left( 1 + \frac{\Delta p_{s,\text{pot}}}{\Delta p_{\text{fl,visc}}} + \frac{\Delta p_{s,\text{kin}}}{\Delta p_{\text{fl,visc}}} \right)
\]

Details:
Sape A. Miedema, Robert C. Ramsdell (2013):
A HEAD LOSS MODEL FOR SLURRY TRANSPORT BASED ON ENERGY CONSIDERATIONS
WODCON XX. Brussels, Belgium.: WODA
Conclusions – Regimes and Results

• 9 Flow regimes can be distinguished. Not every flow regime is present for every combination of particles, pipe and concentration.
• It is crucial to distinguish between constant volumetric spatial and transport concentration in interpreting experimental results.
• With a good model for each flow regime, the scenarios can be constructed and the correct flow regime can be predicted.