Dredge Pumps and Slurry Transport

Vaclav Matousek
October 13, 2004
6. SPECIAL SLURRY FLOW CONDITIONS

INCLINED FLOWS

UNSTEADY SOLIDS FLOWS
INCLINED FLOWS

PRINCIPLES AND MODELING
Inclined Flows

Inclined flows are characterized by the pressure differential that occurs due to the gravitational force acting on the fluid. The pressure differential can be expressed as:

\[-dP = P_1 - P_2\]

where

- \(dP\) is the total pressure differential,
- \(P_1\) and \(P_2\) are the pressures at points 1 and 2, respectively.

Additionally, the manometric pressure differential can be calculated as:

\[-dP + dh \rho_f g\]

where

- \(dh\) is the change in height,
- \(\rho_f\) is the density of the fluid,
- \(g\) is the acceleration due to gravity.

The diagram illustrates a hose filled with fluid (water) and a manometer, which is a device used to measure pressure. The manometer shows the pressure differential due to the fluid's height change.
Inclined Flows

A. Physical background:

The total pressure gradient:

\[
\frac{(P_1 - P_2)}{dx} = -\frac{dP}{dx}
\]

over a pipe section of the length \(dx\) is composed of

the static pressure gradient: \(d(gh)/dx\), giving the potentially reversible effect of elevation change on the total pressure gradient in a slurry flow of the density gaining the height \(h\) and

the pressure gradient due to friction: \(-\frac{dP}{dx} - \frac{d(gh)}{dx}\) that is the irrecoverable energy loss due to friction in inclined slurry flow over the pipe length \(dx\).
Inclined Flows: Worster-Denny Model

B. Construction of the model for $I_m$:

- An inclined flow is a transitional flow between a horizontal flow and a vertical flow.
- The hydrostatic effect: all particles in a pipe contribute to the static slurry column; the manometric static head considered in the model = slurry column (in the pipe) − water column (in hoses of different pressure transmitter).
- The frictional effect: the pressure drop due to friction is lower in inclined pipe than in horizontal pipe. The solids effect for inclined flow

$$\frac{\text{solids effect in inclined pipe}}{\text{solids effect in horizon pipe}} = \frac{I_{m,\theta} - I_f}{I_m - I_f} = \cos \theta < 1$$
Inclined Flows: Woster-Denny Model

\[ i = i_w + \Delta i_h \cos \theta + c(s-1) \sin \theta \]

\[ i = i_w + \Delta i_h \]

Greek Symbols:
- \( \theta \) - inclination angle

Flow Types:
- Inclined flow
- Vertical flow
- Horizontal flow

Equation:
\[ i = i_w + \Delta i_h \cos \theta + c(s-1) \sin \theta \]

- \( i_w \) - initial flow
- \( \Delta i_h \) - change in flow
- \( c(s-1) \) - coefficient

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Inclined Flows: Woster-Denny Model

\[ I_m = I_f + (I_m - I_f) \cos \Theta + C_{vd}(S_s - 1) \sin \Theta \]

\[ i = i_w + \Delta i_h \cos \Theta + c(s-1) \sin \Theta \]
Inclined Flows: Worster-Denny Model

C. Discussion on the Worster-Denny model:

• The model predicts the same frictional pressure losses in the ascending and descending pipes of the same inclination angle \([\cos(\theta) = \cos(-\theta)]\). This means that the model expects the same solids distribution in both pipes. The assumption is correct only for non-stratified flows.

\[
\frac{\text{solids effect in inclined pipe}}{\text{solids effect in horizon pipe}} = \frac{I_{m,\theta} - I_f}{I_m - I_f} = \cos \theta < 1
\]
Inclined Flows: Lab Tests

Figure: Concentration distribution in inclined DN150 pipe (Vm=3.50 m/s, Angle in legend).

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Inclined Flows: Two-Layer Model

A. Physical background:
- For layered inclined flows the two-layer model is much better predictive tool than the empirical Worster-Denny model.
Inclined Flows: Coarse slurry d=1.8 mm

Delivered $C_v$: 21.77 [%]
Mean velocity: 5.51 [m/s]
Thickness $H_{sh}$: 41 [mm]

Incl Angle: 0 deg
Inclined Flows: Coarse slurry $d=1.8$ mm

Delivered $C_v$ : 21.58 \% 
Mean velocity : 5.5 \text{ m/s} 
Thickness $H_{sh}$ : 46 \text{ mm} 

**Incl Angle: 16 deg**
Inclined Flows: Coarse slurry d=1.8 mm

Delivered $C_v$ : 21.39 [%]
Mean velocity : 5.54 [m/s]
Thickness $H_{sh}$ : 48 [mm]

Incl Angle: 25 deg
Inclined Flows: Coarse slurry d=1.8 mm

Delivered $C_v$ : 21.27 [%]
Mean velocity : 5.48 [m/s]
Thickness $H_{sh}$ : 59 [mm]

**Incl Angle: 35 deg**

Diagram details:
- Vertical position $y/D [-]$
- Local concentration $c_v [-]$
- Top of the sliding bed
- Point of inflexion

Dredge Pumps and Slurry Transport
Inclined Flows: Coarse slurry d=1.8 mm

- Delivered $C_v$: 0.21 - 0.22 [-]
- Mean velocity: 5.48 - 5.54 [m/s]

Ascending pipe

Vertical position $y/D$ [-]

Local concentration $c_v$ [-]

0 0.1 0.2 0.3 0.4 0.5 0.6

0 0.2 0.4 0.6 0.8 1

0 deg
35 deg
25 deg
Inclined Flows: Coarse slurry d=1.8 mm

Descending pipe

Delivered $C_v$ : 0.21 - 0.22 [-]
Mean velocity : 5.48 - 5.54 [m/s]
Effect of inclination on the deposition limit velocity.
The empirical model based on visual observations in a small pipe. 

\[ V_{sm,0} = V_{sm} + \Delta_D \sqrt{2gD(S_s - 1)} \]

- Data from Tse.
- Data from Hashimoto et al.

\( V_{sm} \) is the velocity from the demi-McDonald’s diagram for horizontal flow.