DHLLDV Framework An Overview Of Slurry Transport Models

Dr.ir. Sape A. Miedema
Head of Studies
MSc Offshore & Dredging Engineering
& Marine Technology
&
Associate Professor of
Dredging Engineering

Wednesday, September 27, 2023

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Delft University of Technology

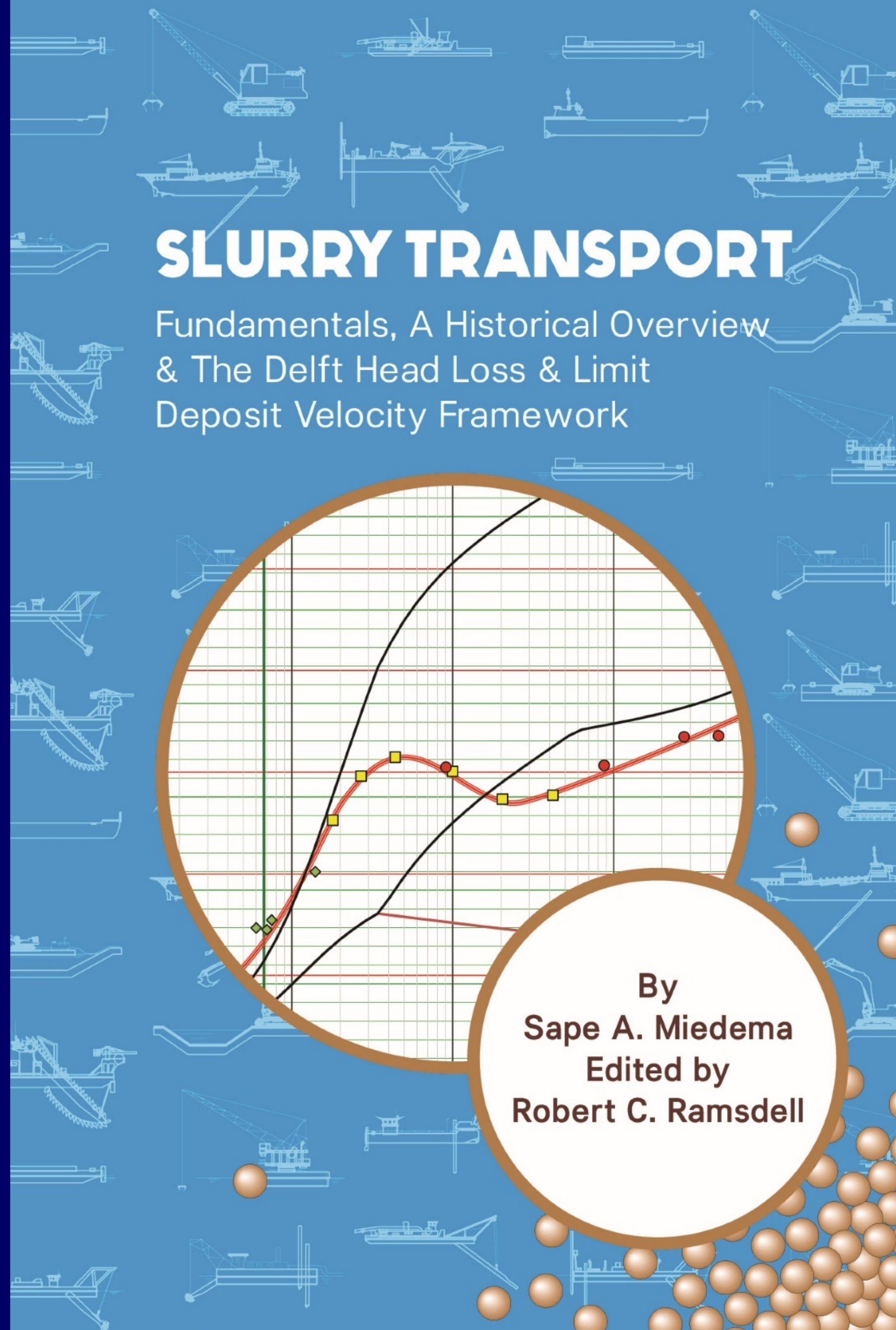
TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Dredging A Way Of Life

Delft University of Technology
Offshore & Dredging Engineering

Delft University of Technology – Offshore & Dredging Engineering

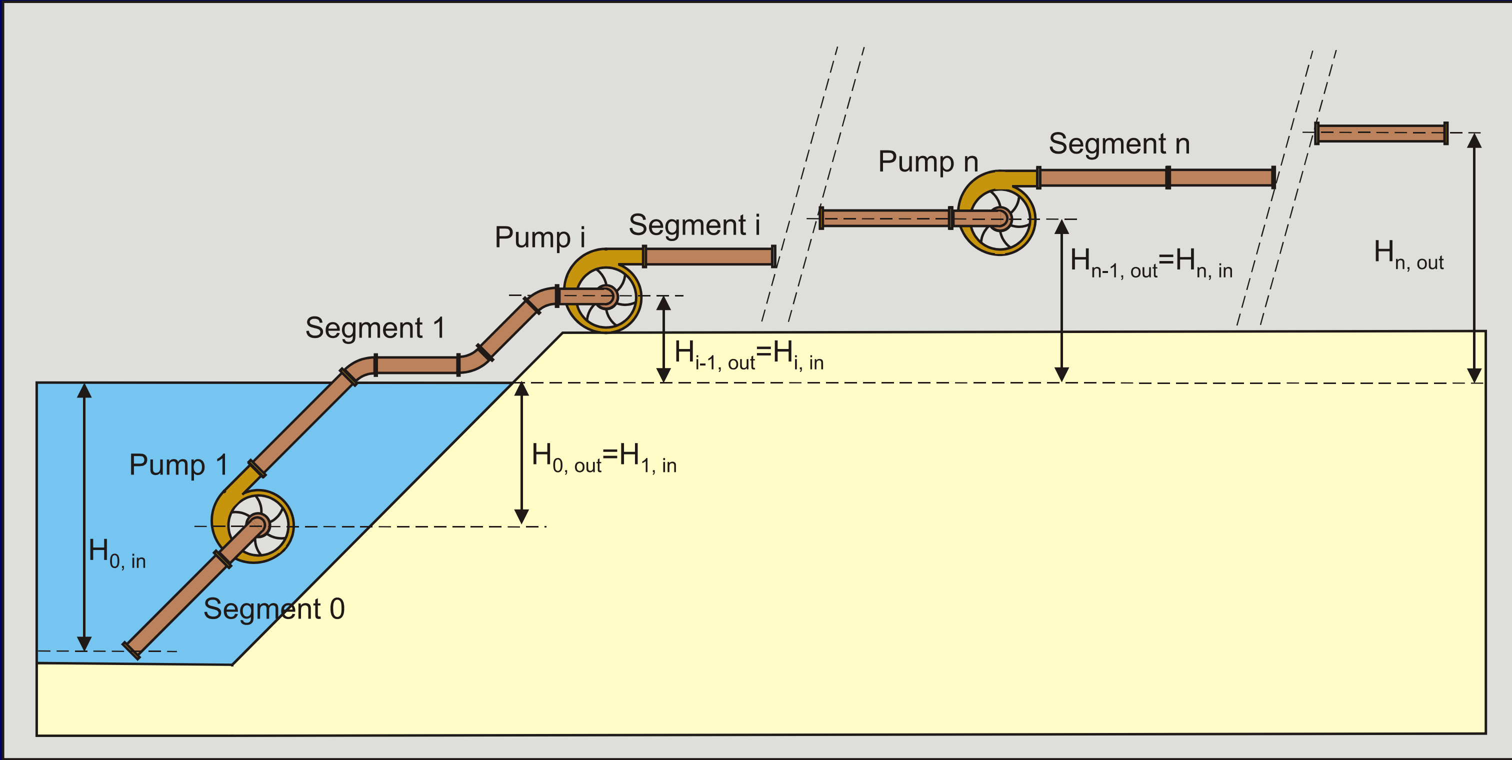
TU Delft
Delft University of Technology
Offshore & Dredging Engineering



Delft University of Technology
Offshore & Dredging Engineering

Goals & Targets

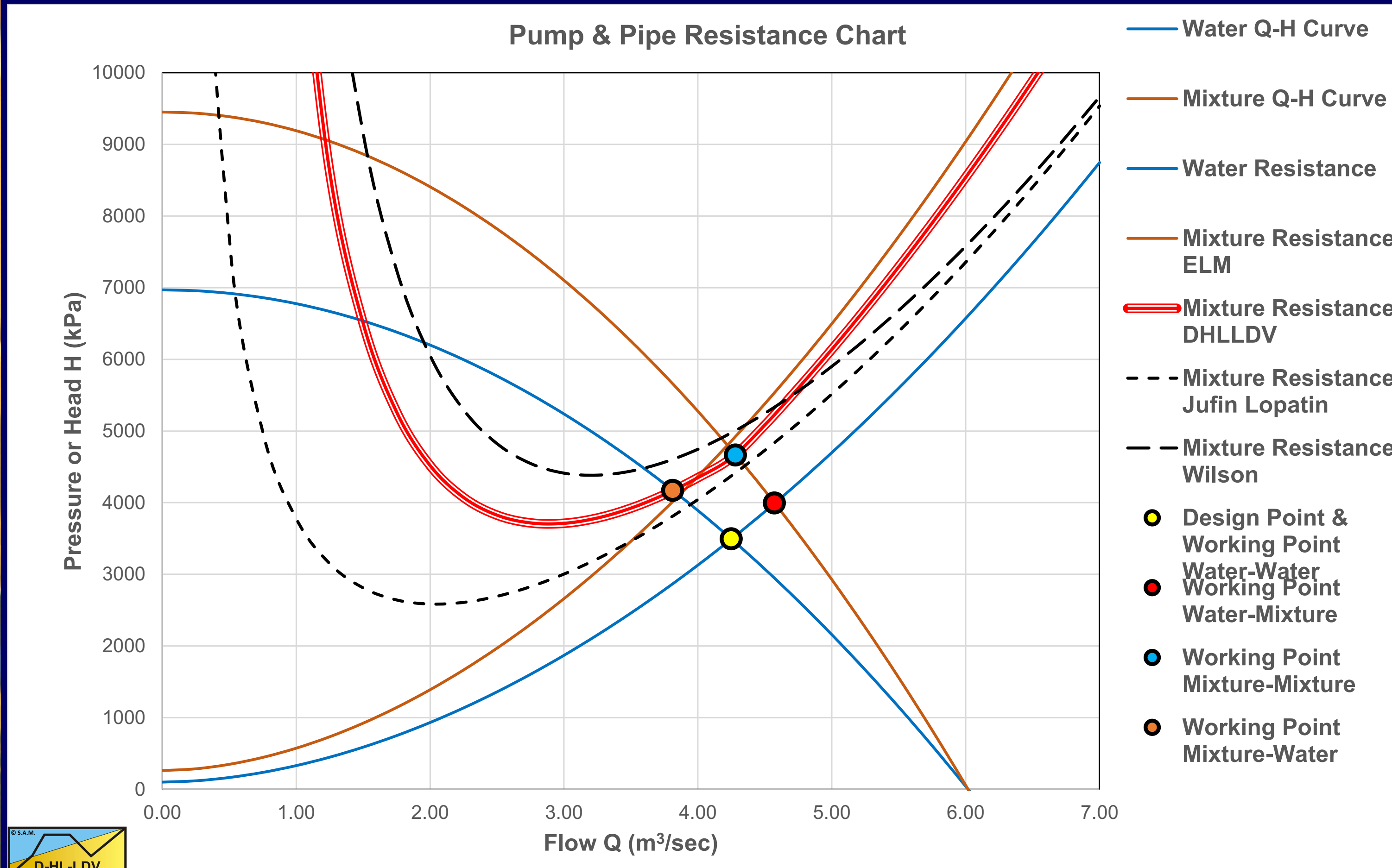
Pump/Pipeline System



- Total pressure/power required
- Limit (Stationary) Deposit Velocity
- Cavitation limit of each pump
- Deposition/plugging the pipeline

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Pressure/Flow Graph (Q-H Graph)



- Working points/working area in a stationary situation

Delft University of Technology
Offshore & Dredging Engineering

Goals & Targets

Determining Slurry Transport Behavior
Based On Known Parameters Like:
Liquid Properties,
Pipe Diameter,
Particle Diameter,
Volumetric Concentration

As A Function Of The Flow Or Line Speed

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

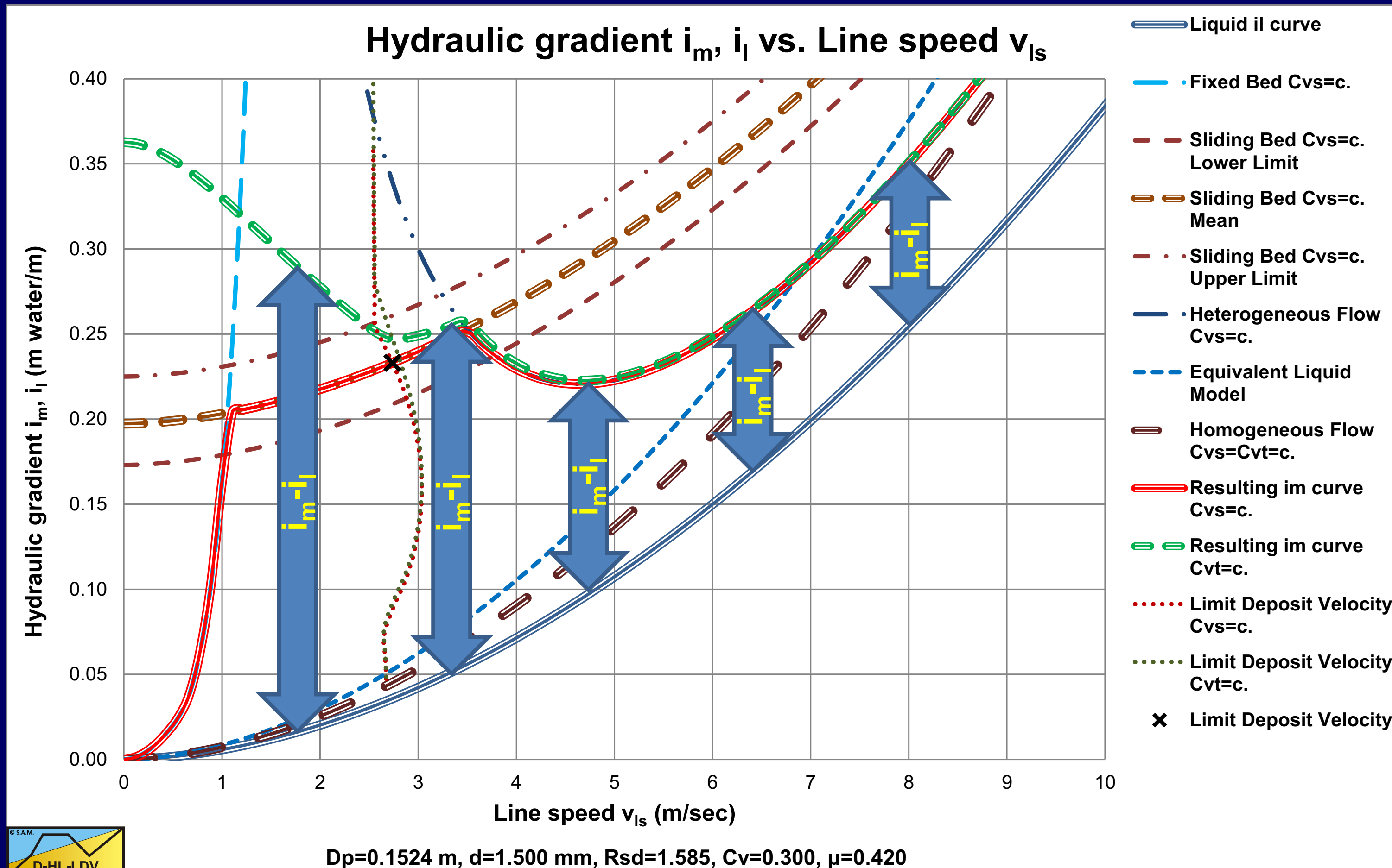
1. Carrier liquid properties
2. Solids properties

For sands/gravels in water 64 combinations possible

Delft University of Technology
Offshore & Dredging Engineering

The Solids Effect

Solids Effect



$$i_l = \frac{\Delta p_l}{\rho_l \cdot g \cdot \Delta L} = \frac{\lambda_l \cdot v_{ls}^2}{2 \cdot g \cdot D_p}$$

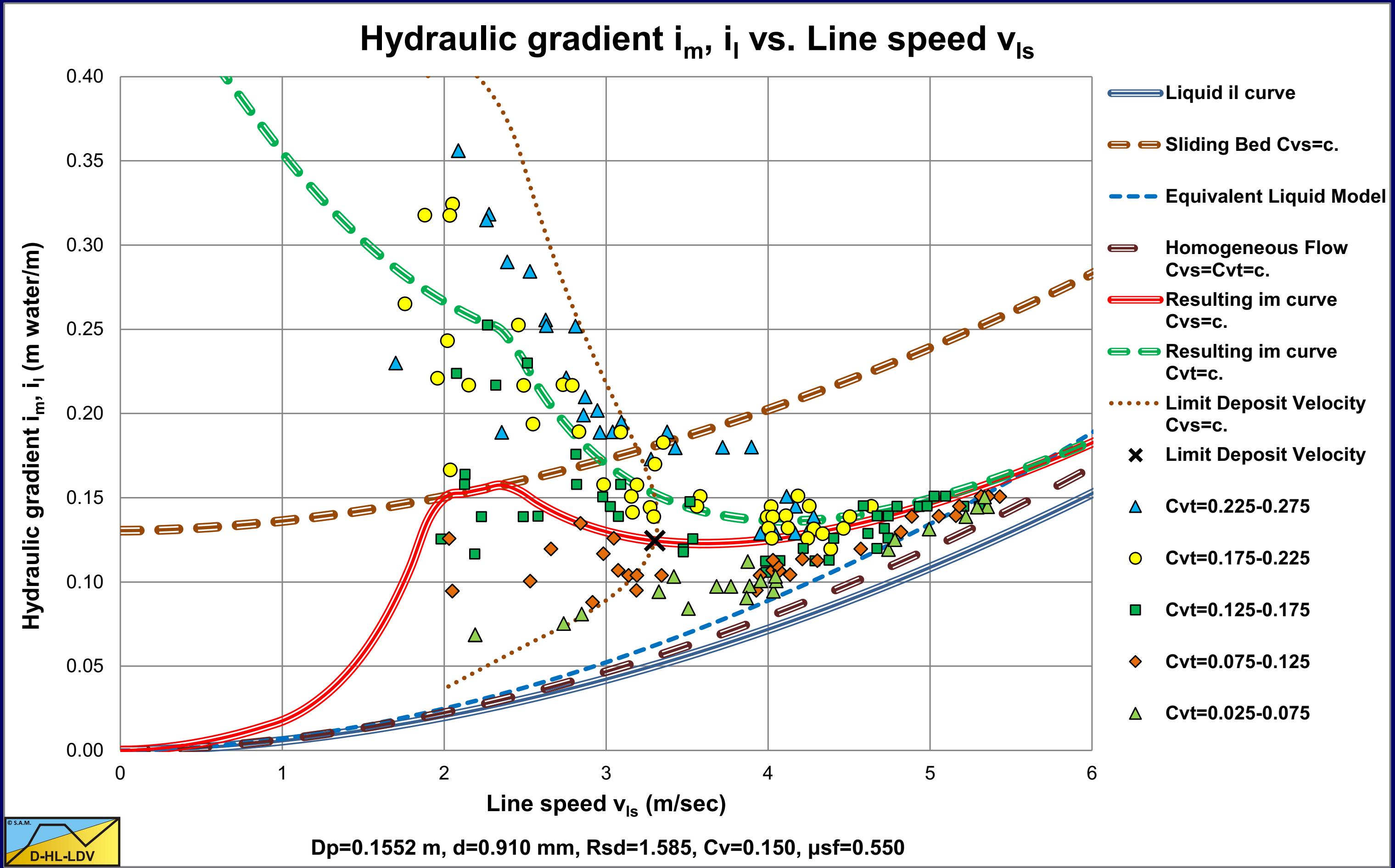
Hydraulic Gradient
Relative Excess H.G.

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

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

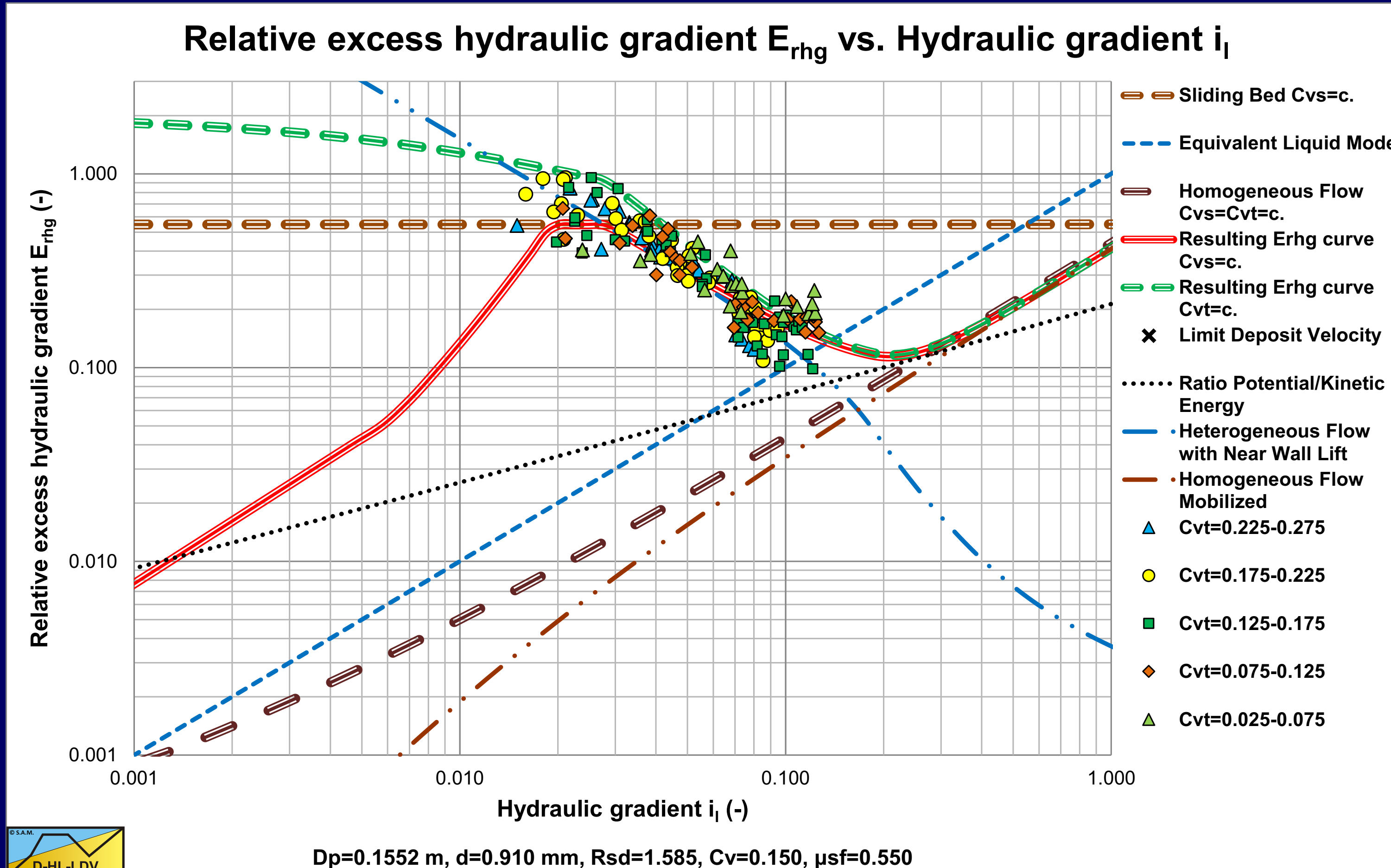
Delft University of Technology – Offshore & Dredging Engineering

Data from Yagi et al., i_m-v_{ls}



Data looks unorganized depending on the volumetric concentration of the solids.

Data from Yagi et al., E_{rhg}-i_l



Data looks more organized not depending on the volumetric concentration of the solids.

Delft University of Technology
Offshore & Dredging Engineering

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}=constant.

$$E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot \left(1 - \frac{v_{sl}}{v_{ls}}\right) \cdot C_{vs}} = \left(\frac{v_{ls}}{v_{ls} - v_{sl}}\right) \cdot \frac{i_m - i_l}{R_{sd} \cdot C_{vs}}$$

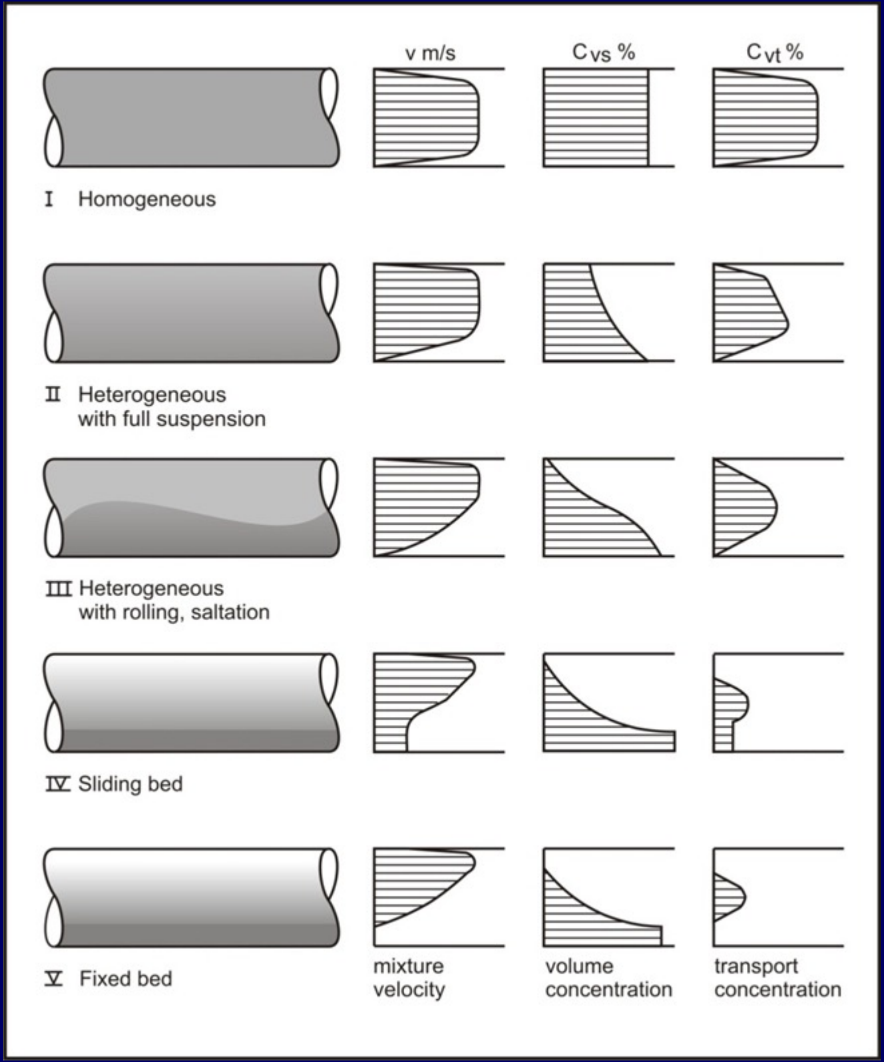
The slip velocity here is the velocity difference between the line speed and the particle velocity.

Flow Regimes History

Chapter 1

Delft University of Technology – Offshore & Dredging Engineering

Regimes History



The 5 Main Flow Regimes

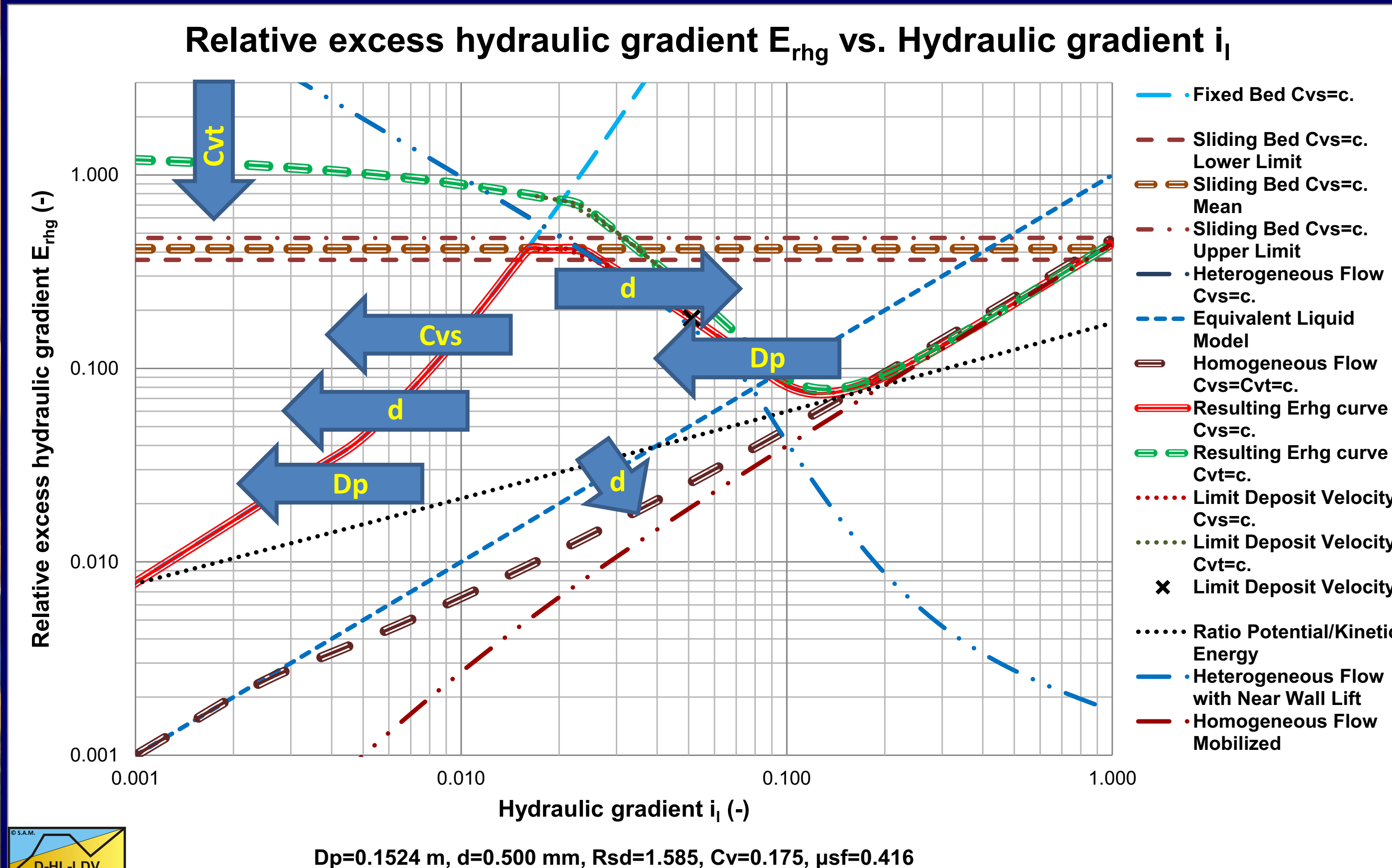
The 5 main flow regimes are identified based on their dominating behavior regarding energy dissipation.

1. The fixed bed regime is identified based on shear stresses at the liquid-fixed bed interface (sheet flow).
2. The sliding bed regime is identified based on sliding friction energy losses.
3. The heterogeneous flow regime is identified based on potential and kinetic energy losses.
4. The homogeneous flow regime is identified based on energy losses in turbulent eddies and viscous friction.
5. The sliding flow regime is identified based on sliding friction, potential and kinetic energy losses.

At flow regime transitions, a mix of two flow regimes will be present.

The Solids Effect Graph

How To Read The Graph? (D_p=6 inch)

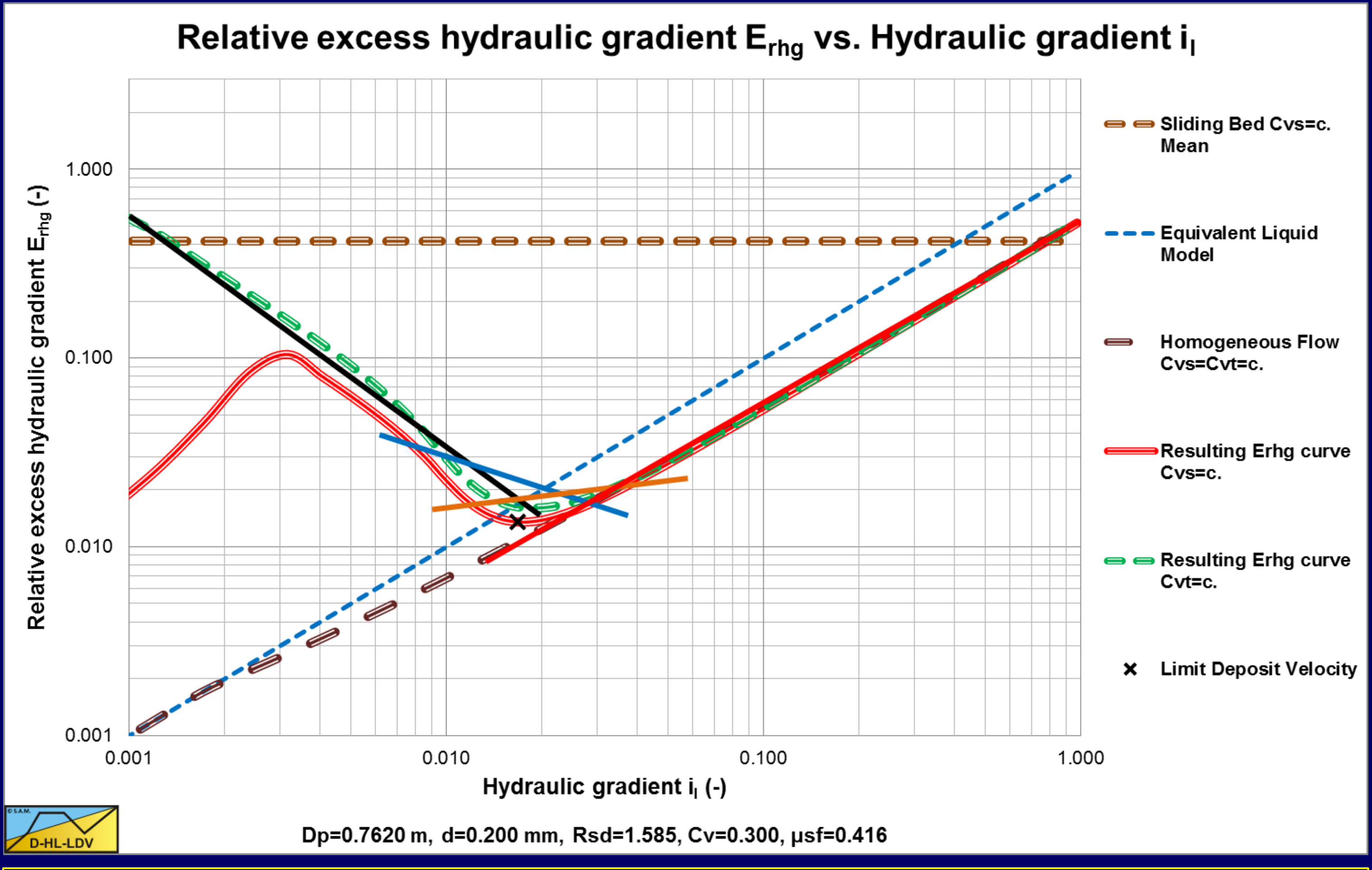


$$i_l = \frac{\Delta p_l}{\rho_l \cdot g \cdot \Delta L} = \frac{\lambda_l \cdot v_{ls}^2}{2 \cdot g \cdot D_p}$$

Hydraulic Gradient
Relative Excess H.G.

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

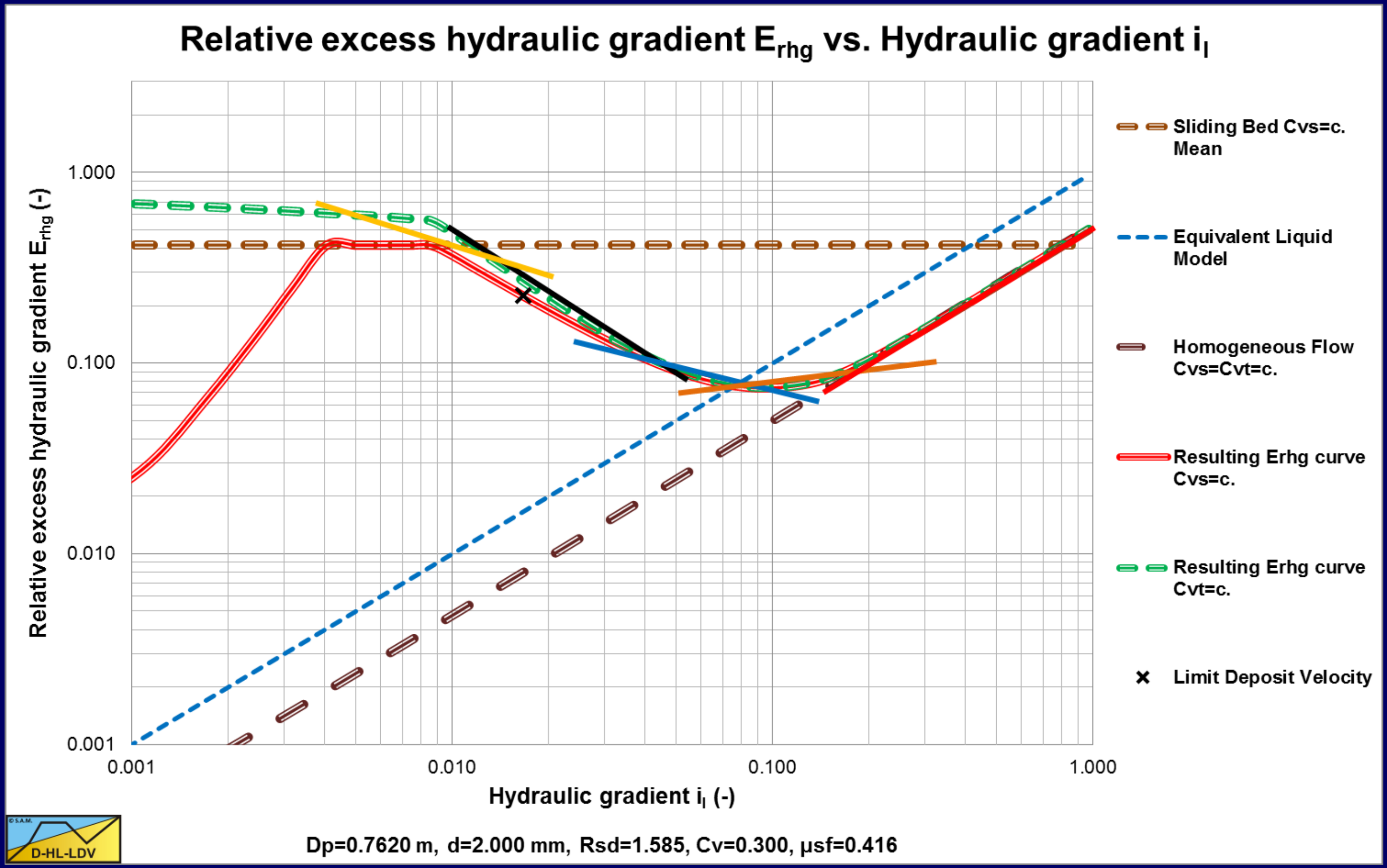
Different Models Fine Sand



4 possible models: Black heterogeneous, blue pseudo homogeneous, light brown pseudo homogeneous & red homogeneous.

Delft University of Technology
Offshore & Dredging Engineering

Different Models Coarse Sand & Gravel

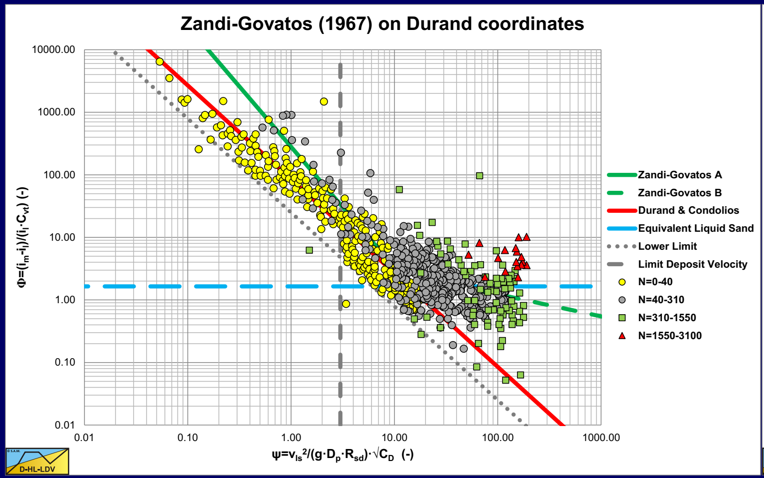


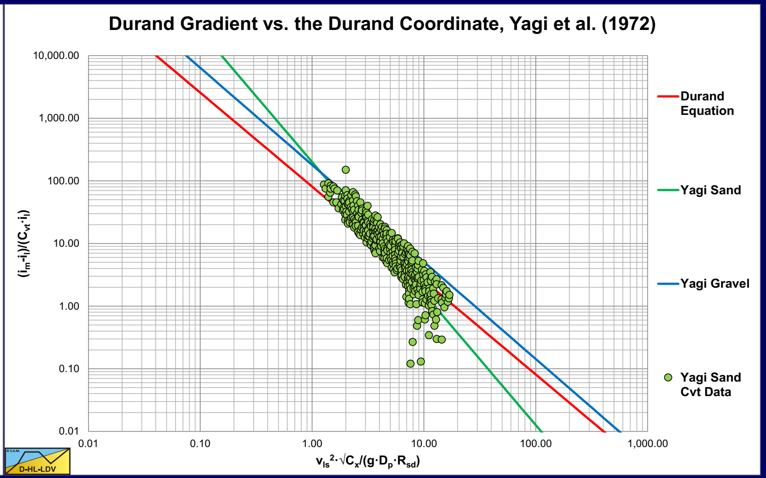
5 possible models: Orange SB/He, black He, blue pseudo Ho, light brown pseudo Ho & red Ho.

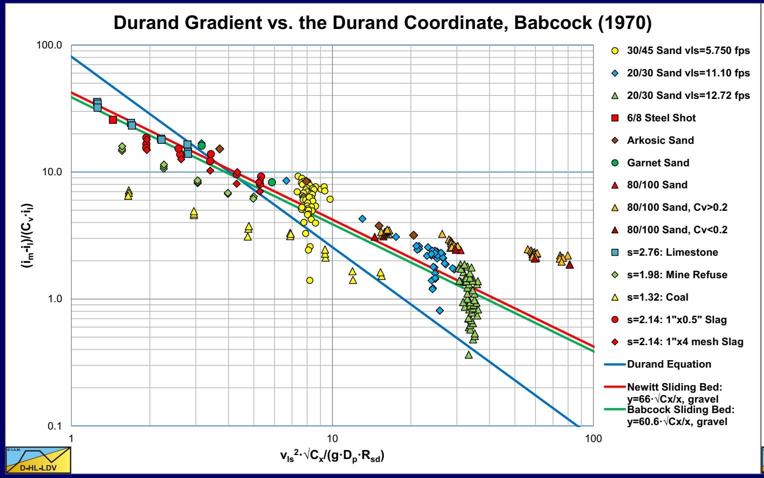
Existing Models

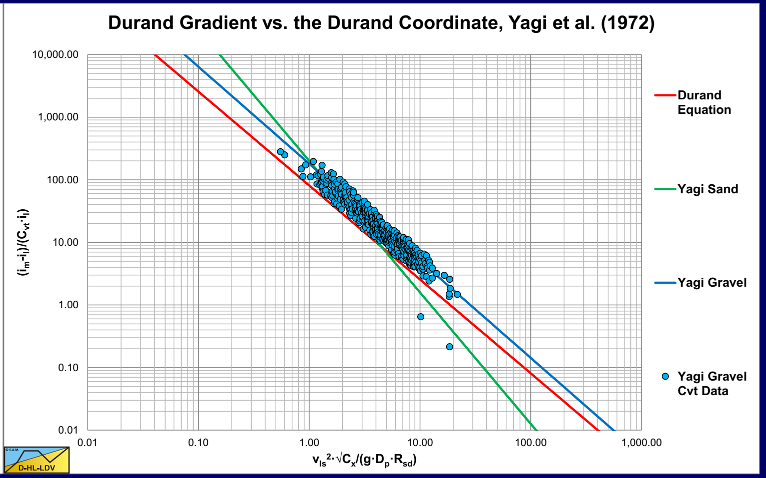
Chapter 6

Zandi & Govatos, Yagi et al. & Babcock





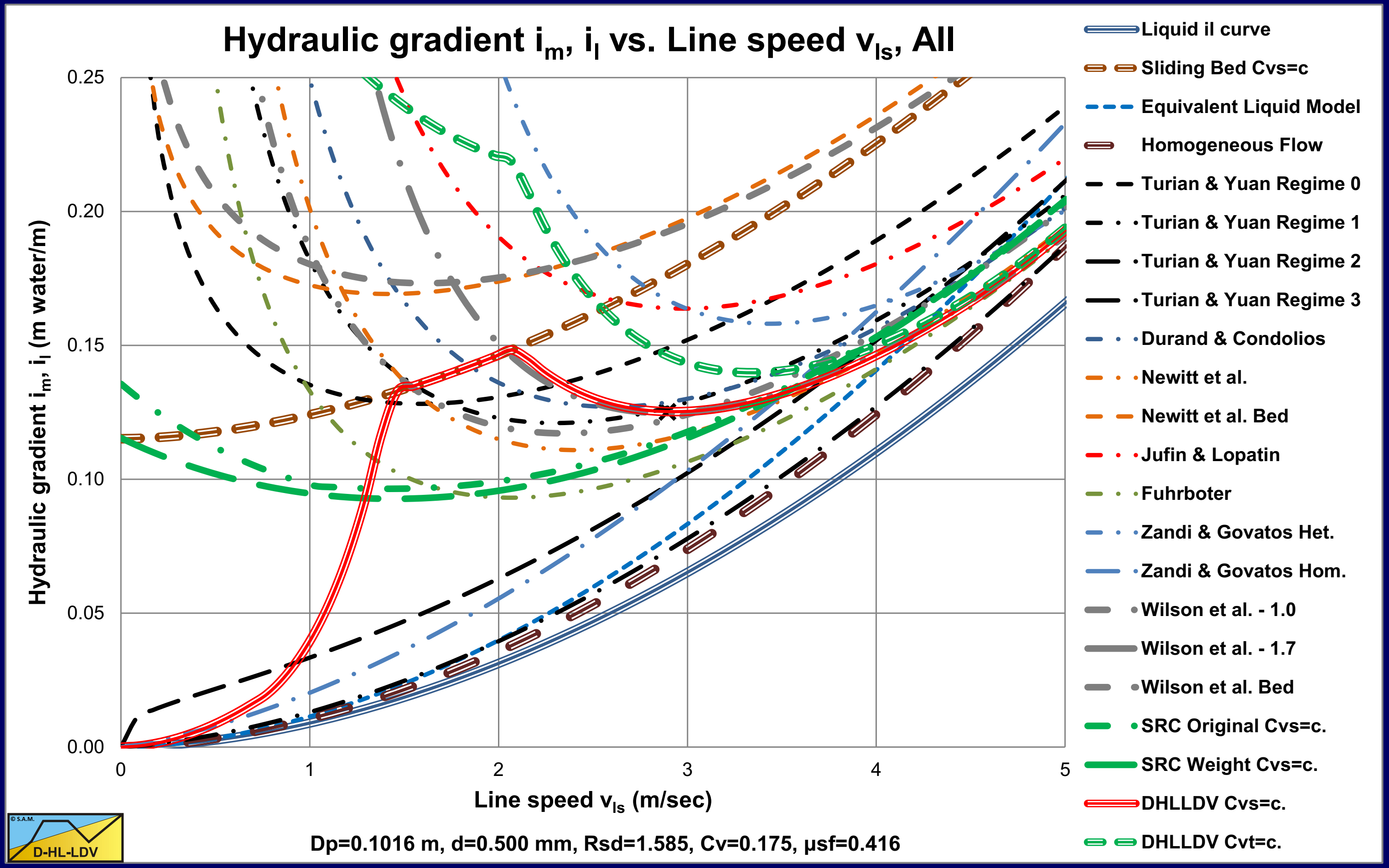




TU Delft
Delft University of Technology
Offshore & Dredging Engineering

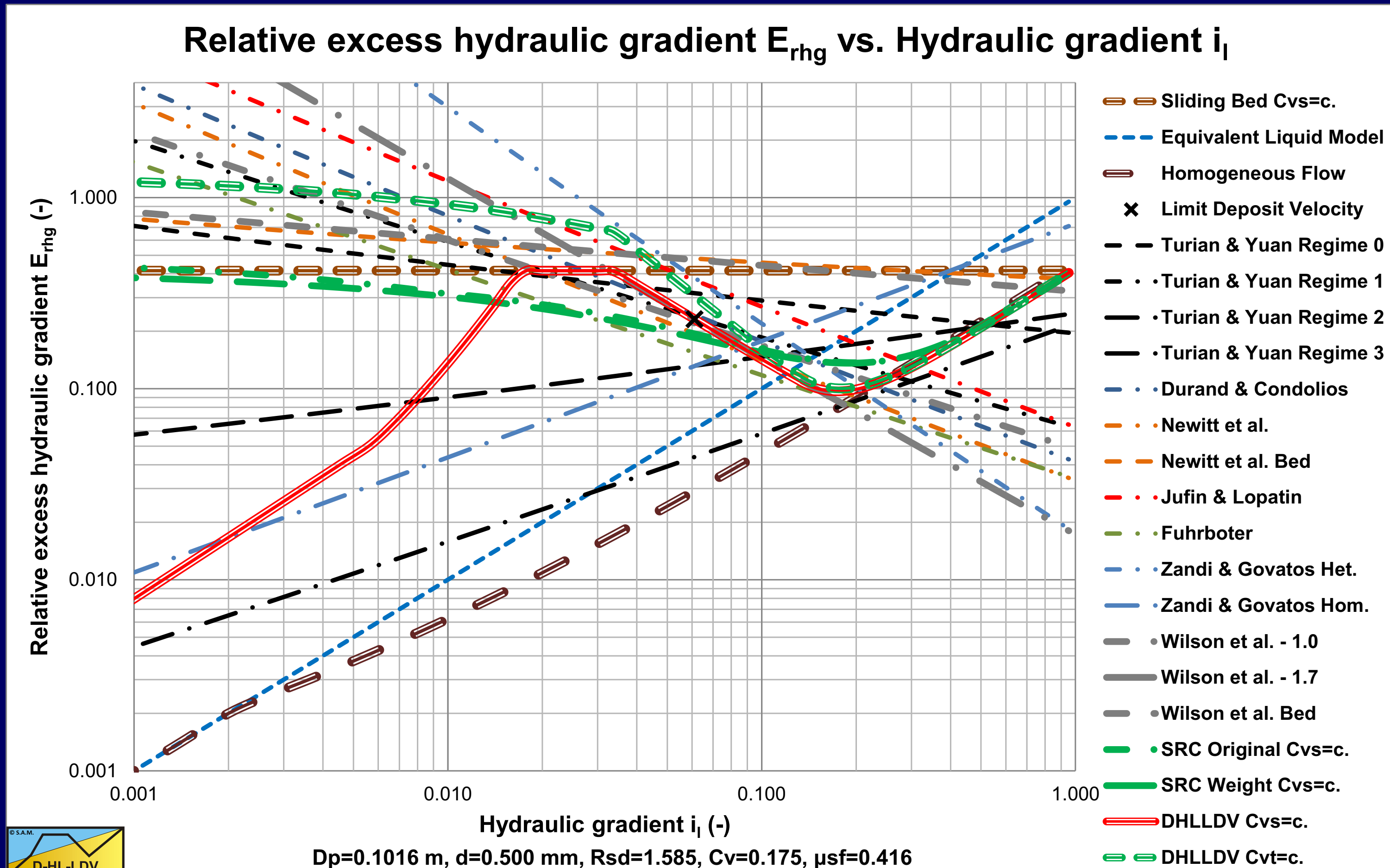
Delft University of Technology – Offshore & Dredging Engineering

22 Models i_m-v_{ls} graph



For small pipe diameters the models are still "close". For large diameter pipes the difference is much much more.

22 Models E_{rhg}-i_l graph



This graph organizes the models better, but there is still a lot of difference between the models.

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Types of Models

- There are many empirical models, mainly for heterogeneous flow, some for sliding bed and homogeneous flow.
- Most empirical models add one term to the Darcy-Weisbach equation, often based on Froude numbers.
- There is the equivalent liquid model (ELM) for homogeneous flow.
- There are some 2 layer and 3 layer models for transport with a stationary or sliding bed or sheet flow, Wilson, Doron & Barnea, SRC Model, Matousek.
- The 2 layer and 3 layer models are closed with empirical equations for the bed shear stress and the concentration distribution.

Stationary/Fixed Bed Regime

Chapter 7.3 & 8.3

Wilson et al.

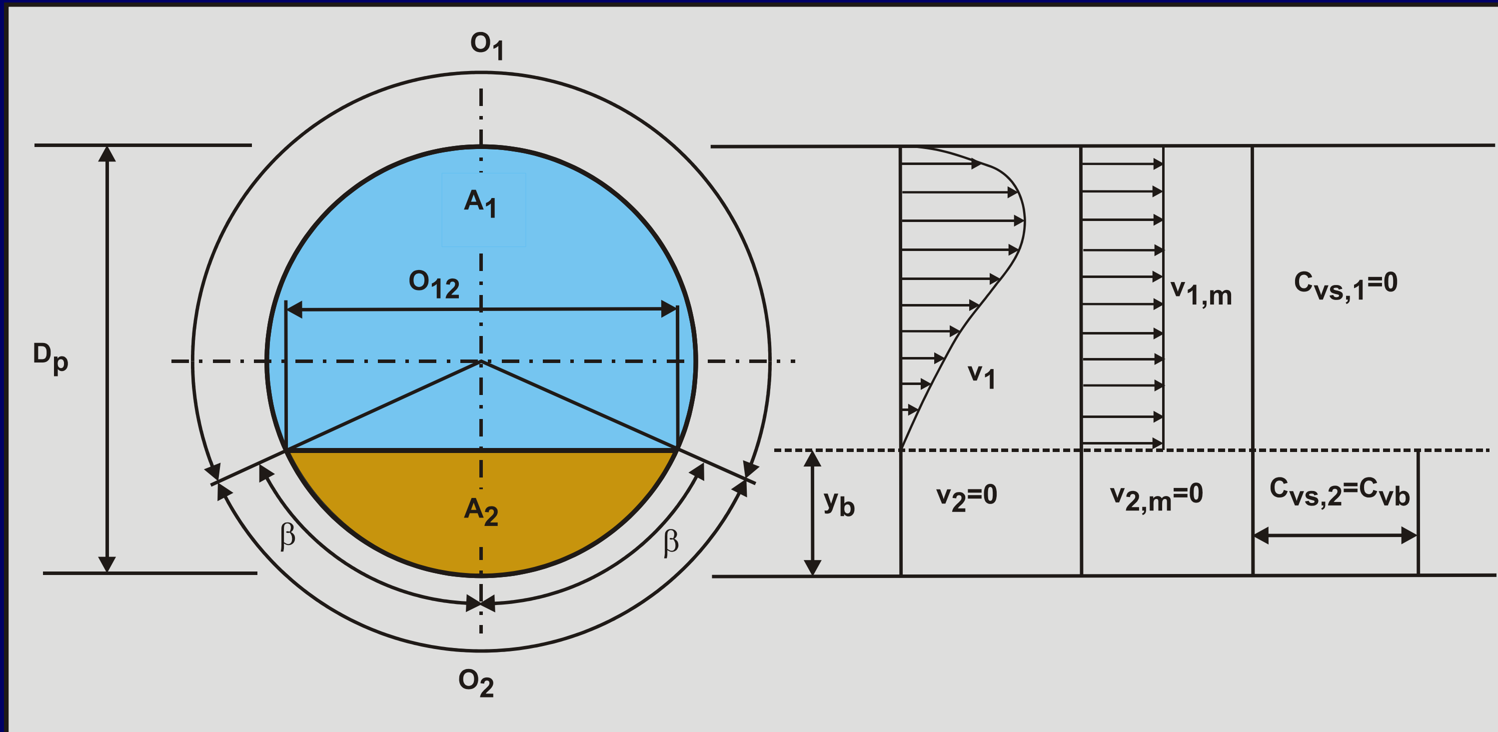
Doron & Barnea

SRC Model

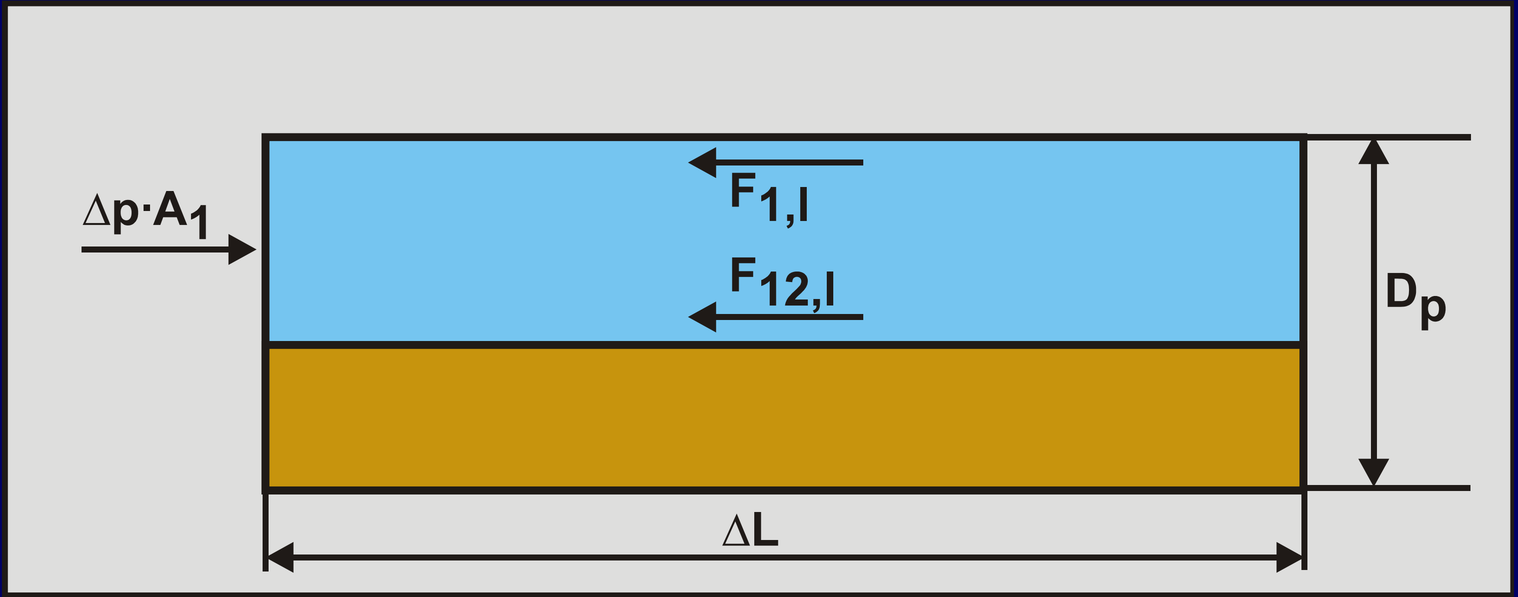
Matousek Model

DHLLDV Framework

Definitions

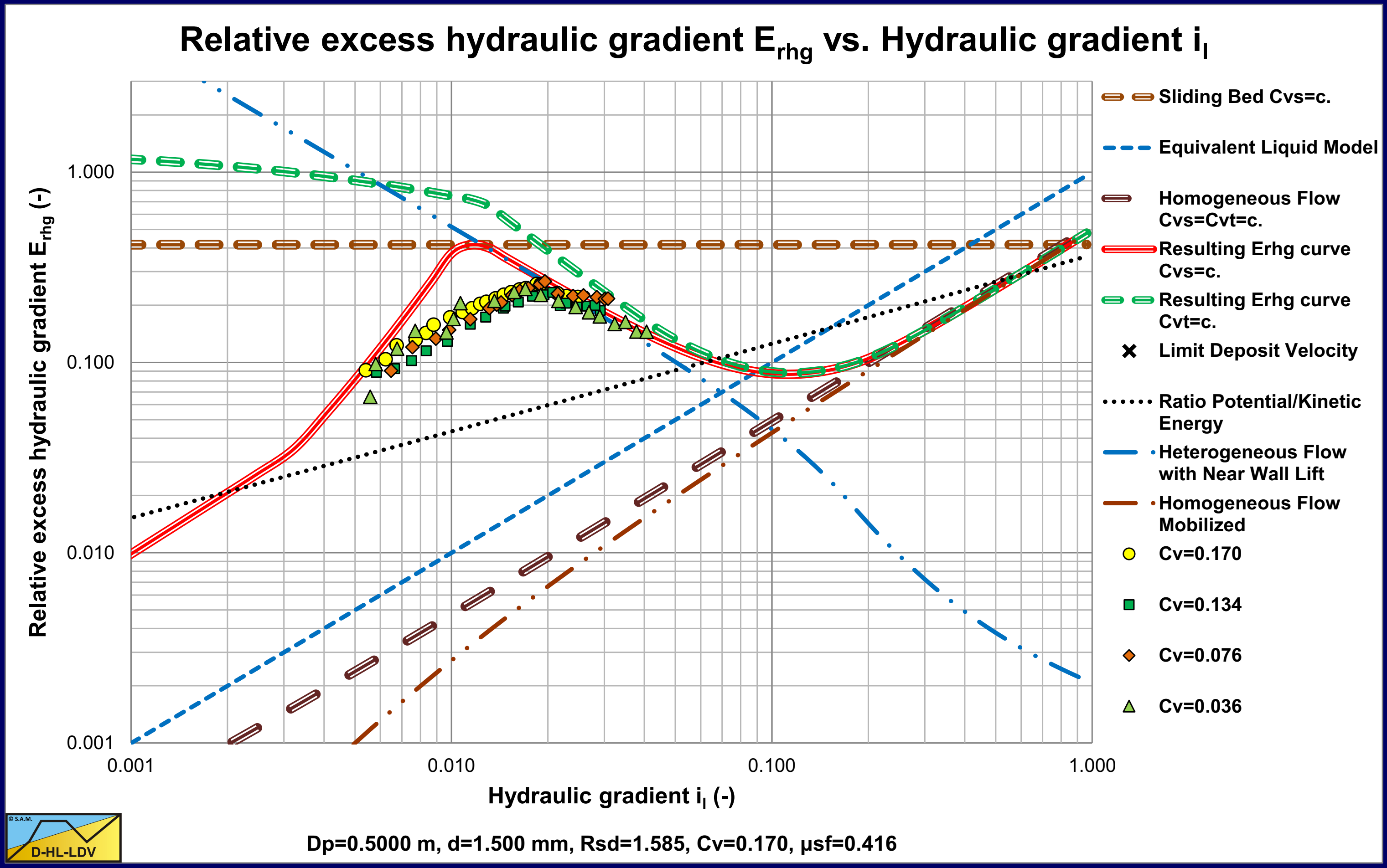


Equilibrium of Forces



$$\Delta p = \Delta p_2 = \Delta p_1 = \frac{\tau_{1,l} \cdot O_1 \cdot \Delta L + \tau_{12,l} \cdot O_{12} \cdot \Delta L}{A_1} = \frac{F_{1,l} + F_{12,l}}{A_1}$$

Kazanskij (1980), Cvs=0.17



TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Sliding Bed Regime

Chapter 7.4 & 8.4

Wilson et al.

Doron & Barnea

SRC Model

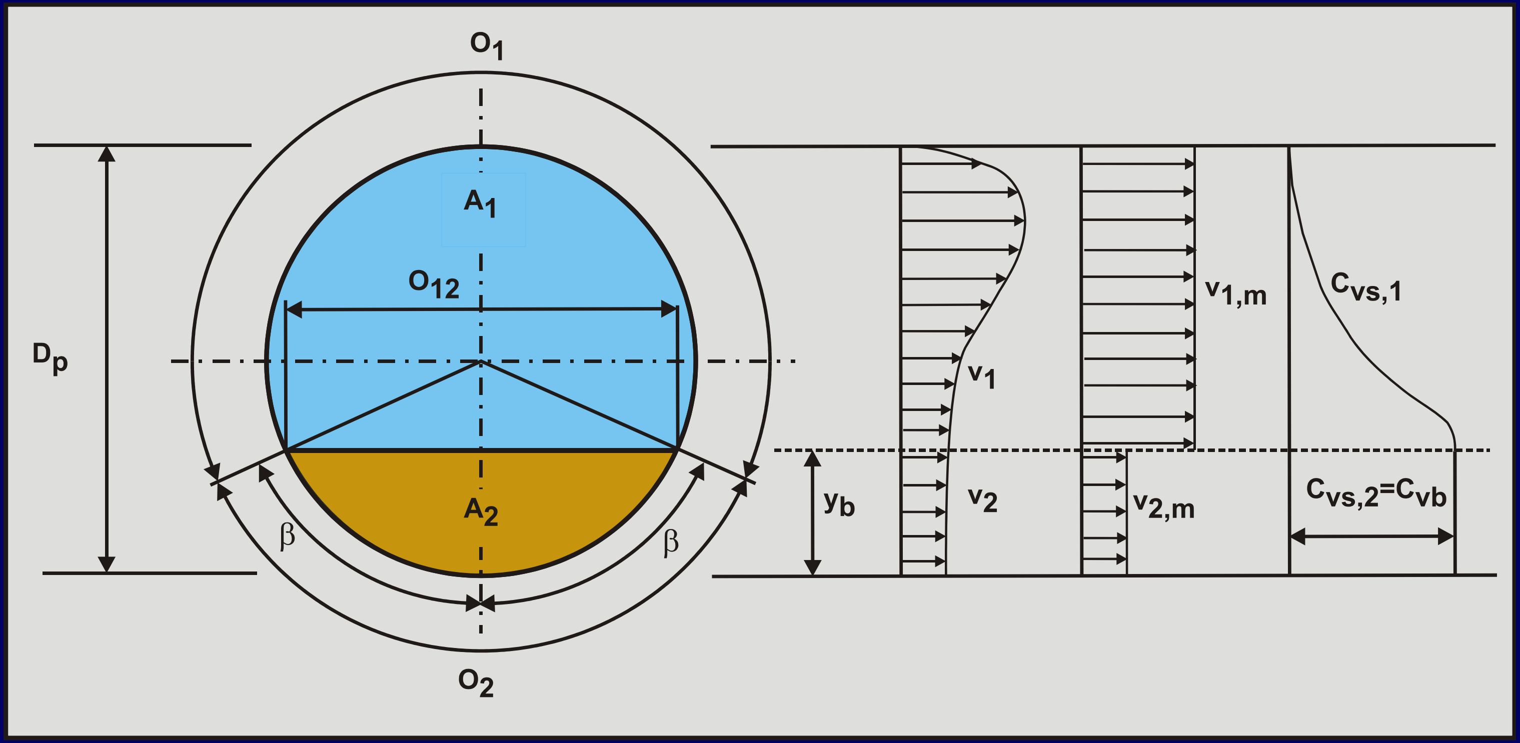
Matousek Model

DHLLDV Framework

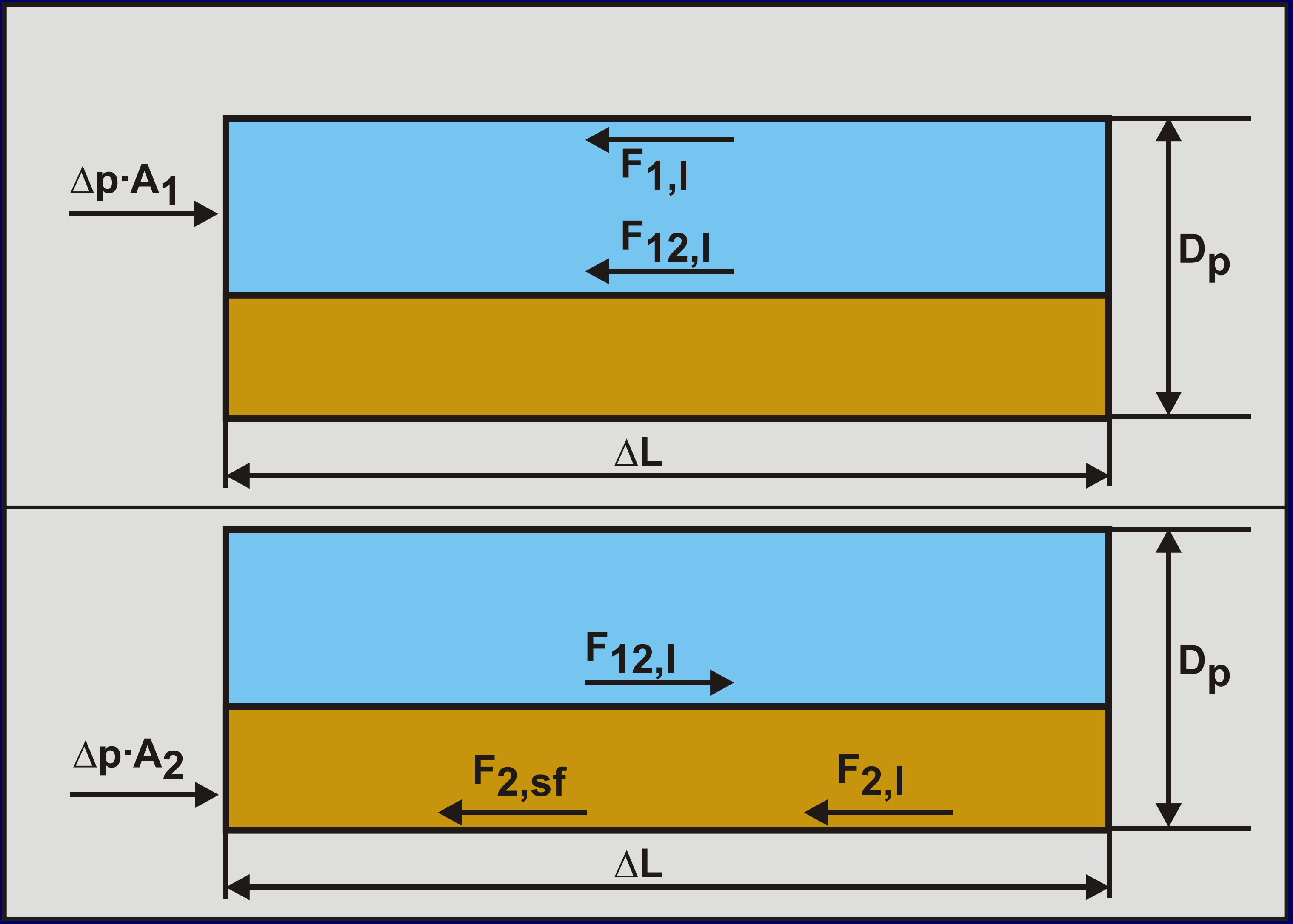
Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Definitions



Equilibrium of Forces



The Models 1

- For the wall friction the standard Darcy Weisbach friction coefficient is used (Moody diagram).
- The Newitt et al. Model is empirical and based on experimental data. Newitt et al. were the first to use the solids effect graph.
- The Wilson 2LM is based on a bed and water above. The bed friction is the Darcy Weisbach friction coefficient with the particle diameter as the roughness multiplied with a factor. Televantos found a factor 2, but Wilson also used different factors over the years like 2.6. For the normal stress between the bed and the wall Wilson uses a hydrostatic stress distribution, resulting in a higher friction force compared to the submerged weight times the sliding friction coefficient.

The Models 2

- The Wilson model is based on constant spatial concentration. Constant delivered concentration curves are constructed by interpolation.
- Doron & Barnea (2LM) basically use the Wilson model, but extended it with suspension above the bed, based on the standard advection diffusion equation. For the constant delivered concentration case this always results in a sliding bed, also at very low line speeds. So they extended their model to a 3LM giving it the possibility to have a fixed bed at very low line speeds.
- The SRC model is based on the Wilson model for constant spatial concentration, but with suspension above the bed. The fraction in suspension and the fraction in the bed are based on an exponential power.

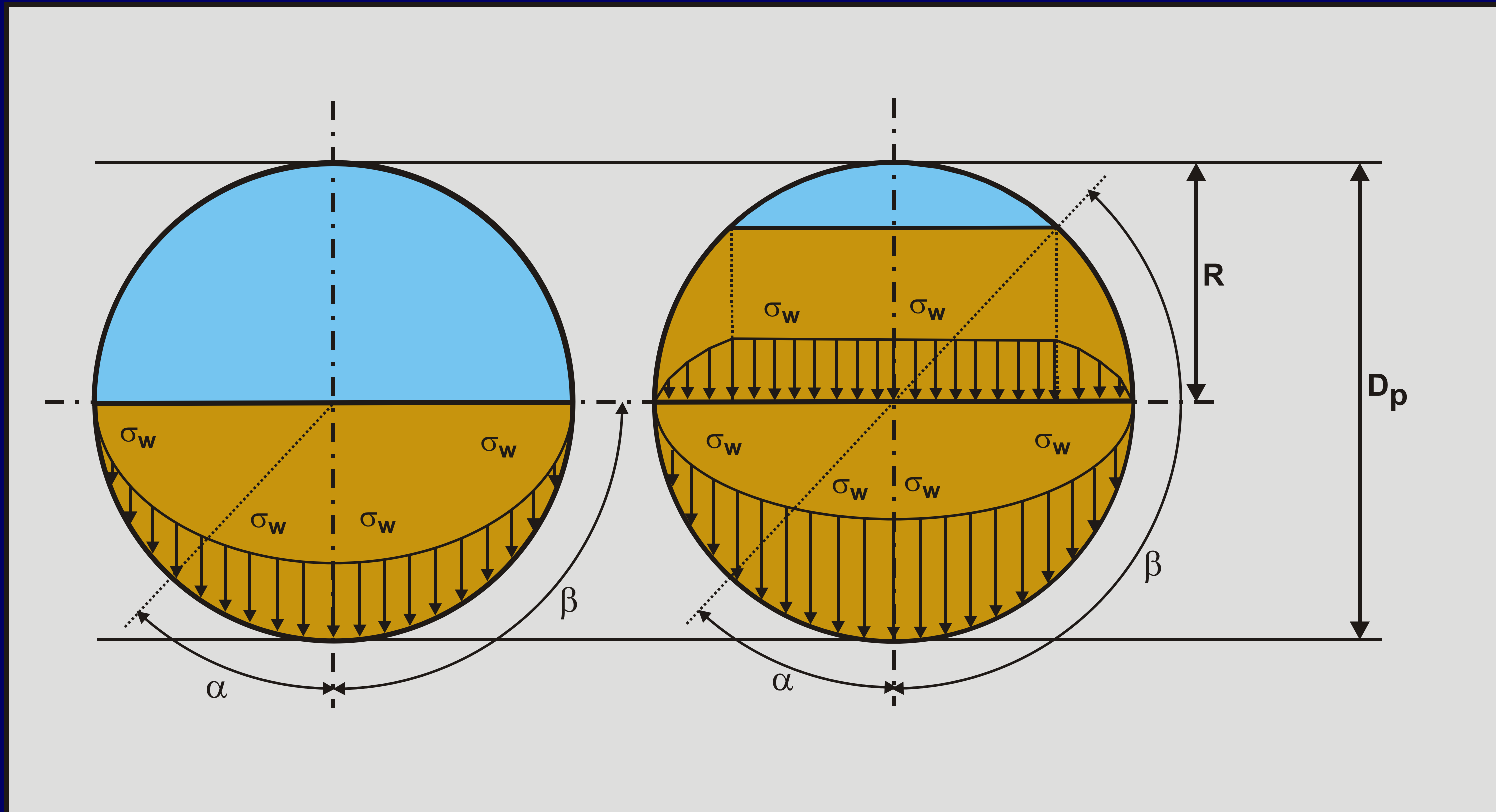
The Models 3

- This power contains the ratio of the terminal settling velocity to the line speed. The suspended fraction forms an adjusted carrier liquid, resulting in adjusted liquid properties and an adjusted submerged weight of the bed. This way there is a smooth transition of fully stratified flow to heterogeneous flow to homogeneous flow.
- Matousek uses a completely different method. Based on the delivered concentration, the Shields parameter is determined with the reversed Meyer Peter Muller equation. Once the Shields parameter is known, the bed friction coefficient can be determined from the equivalent bed roughness. The method is based on sheet flow as a transport mechanism.

The Models 4

- The DHLLDV Framework uses the Wilson approach, however with the weight approach for the sliding friction. So the sliding friction force equals the submerged weight times the sliding friction coefficient. Above the bed sheet flow is assumed according to Wilson & Pugh. The method is spatial concentration based. The delivered concentration follows from the transport in the sheet flow layer and the transport in the sliding bed. The method results in a solids effect almost equal to the sliding friction coefficient.

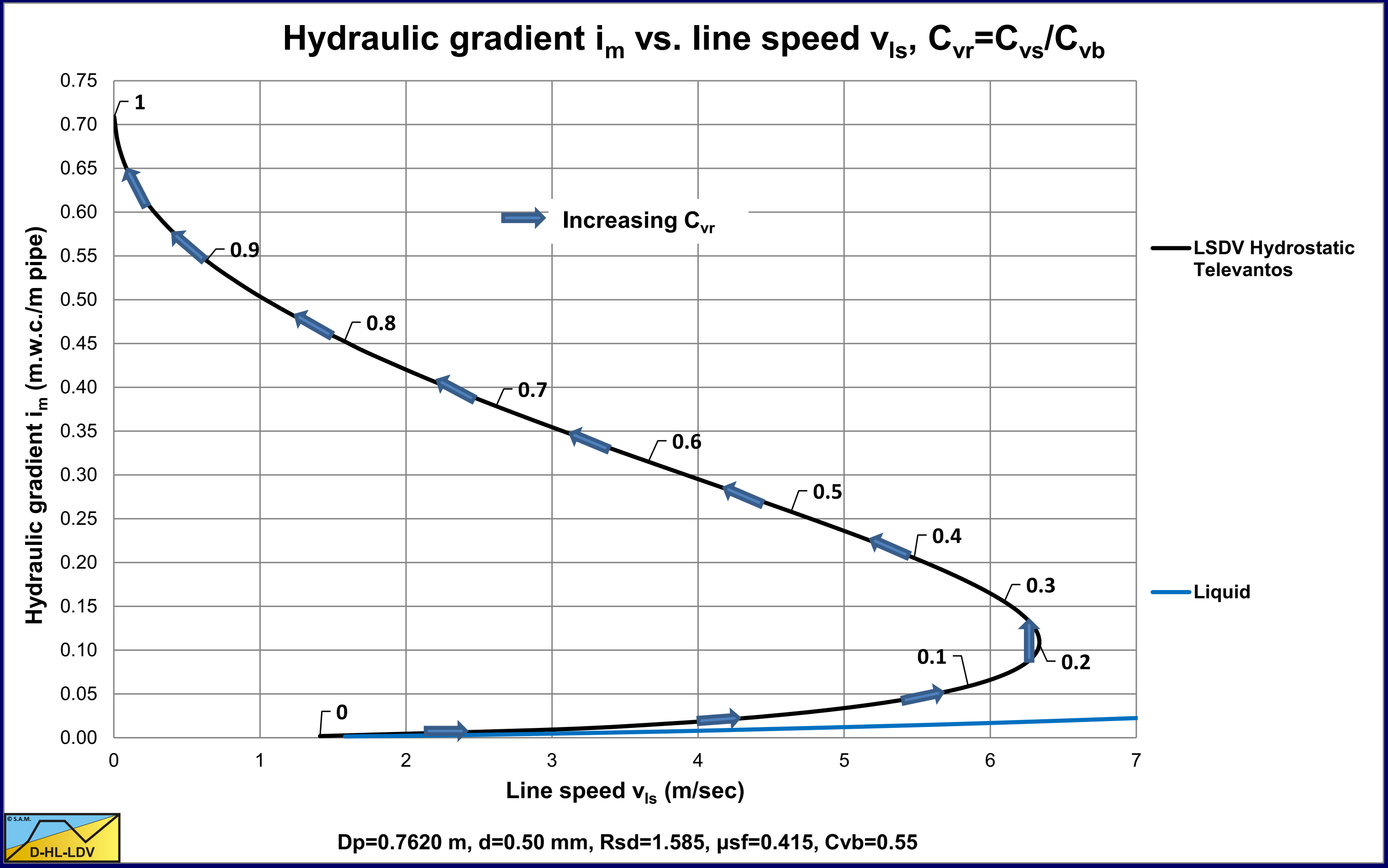
The Submerged Weight Approach



$$F_{sf} = \mu_{sf} \cdot \rho_l \cdot g \cdot \Delta L \cdot R_{sd} \cdot C_{vb} \cdot \frac{\left(\beta - \sin(\beta) \cdot \cos(\beta)\right)}{\pi} \cdot A_p$$

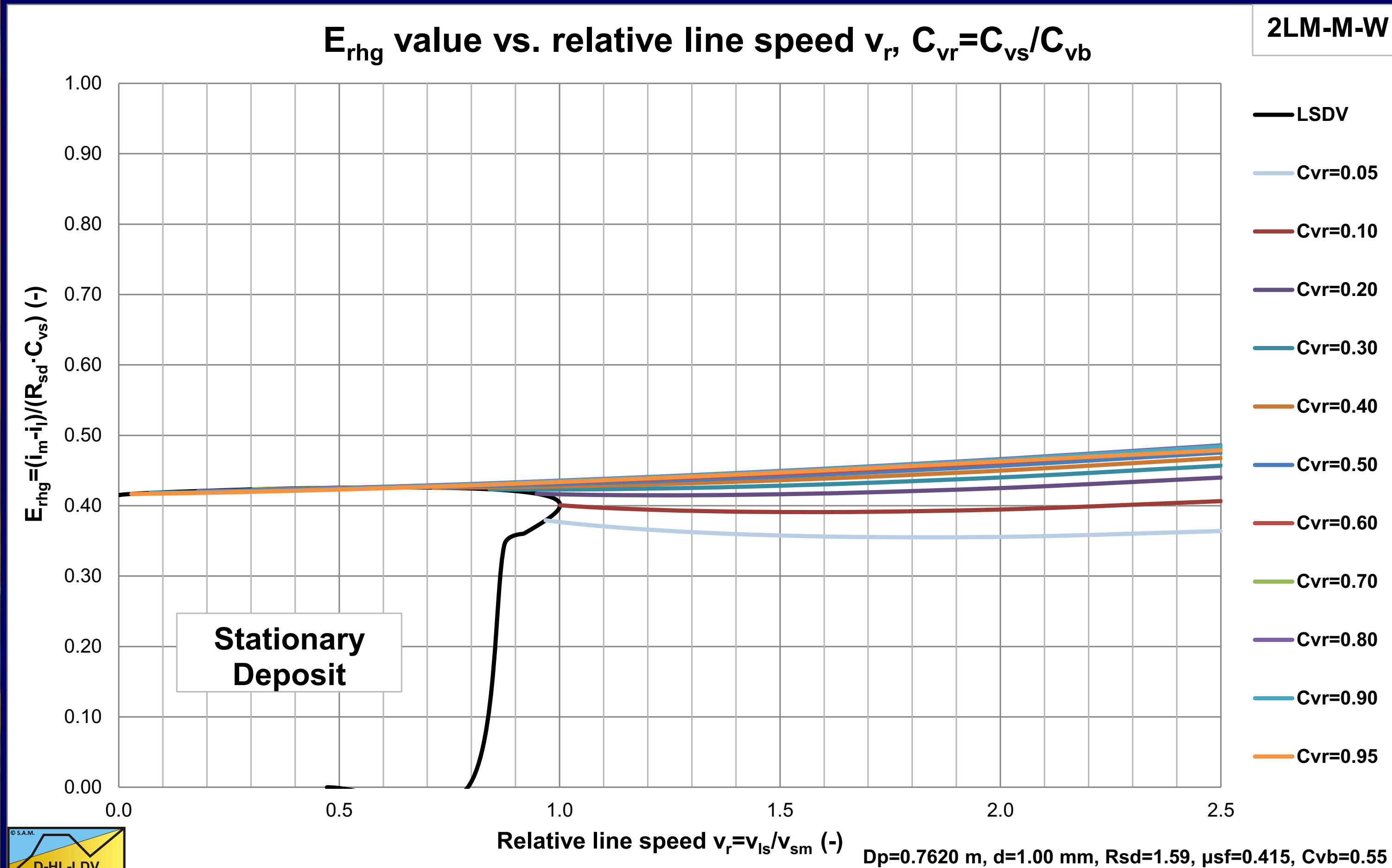
Delft University of Technology
Offshore & Dredging Engineering

The Limit of Stationary Deposit Velocity



$$F_{2,sf} + F_{2,l} = F_{12,sf} + \Delta p \cdot A_2$$

The E_{rhg} Value is almost μ_{sf}

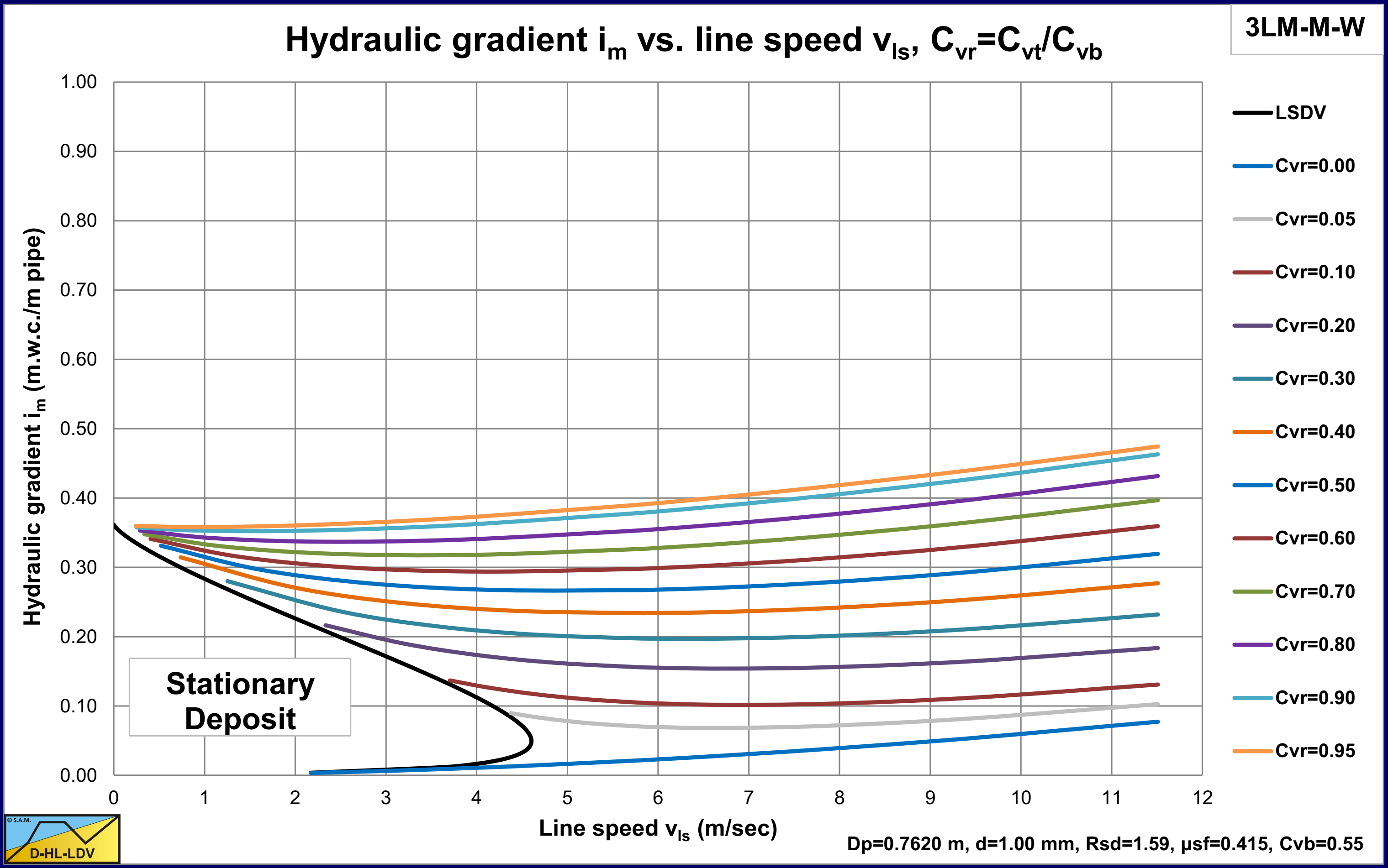


$$E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot C_{vs}} = \mu_{sf} \quad \text{and} \quad i_m - i_l = \mu_{sf} \cdot R_{sd} \cdot C_{vs}$$

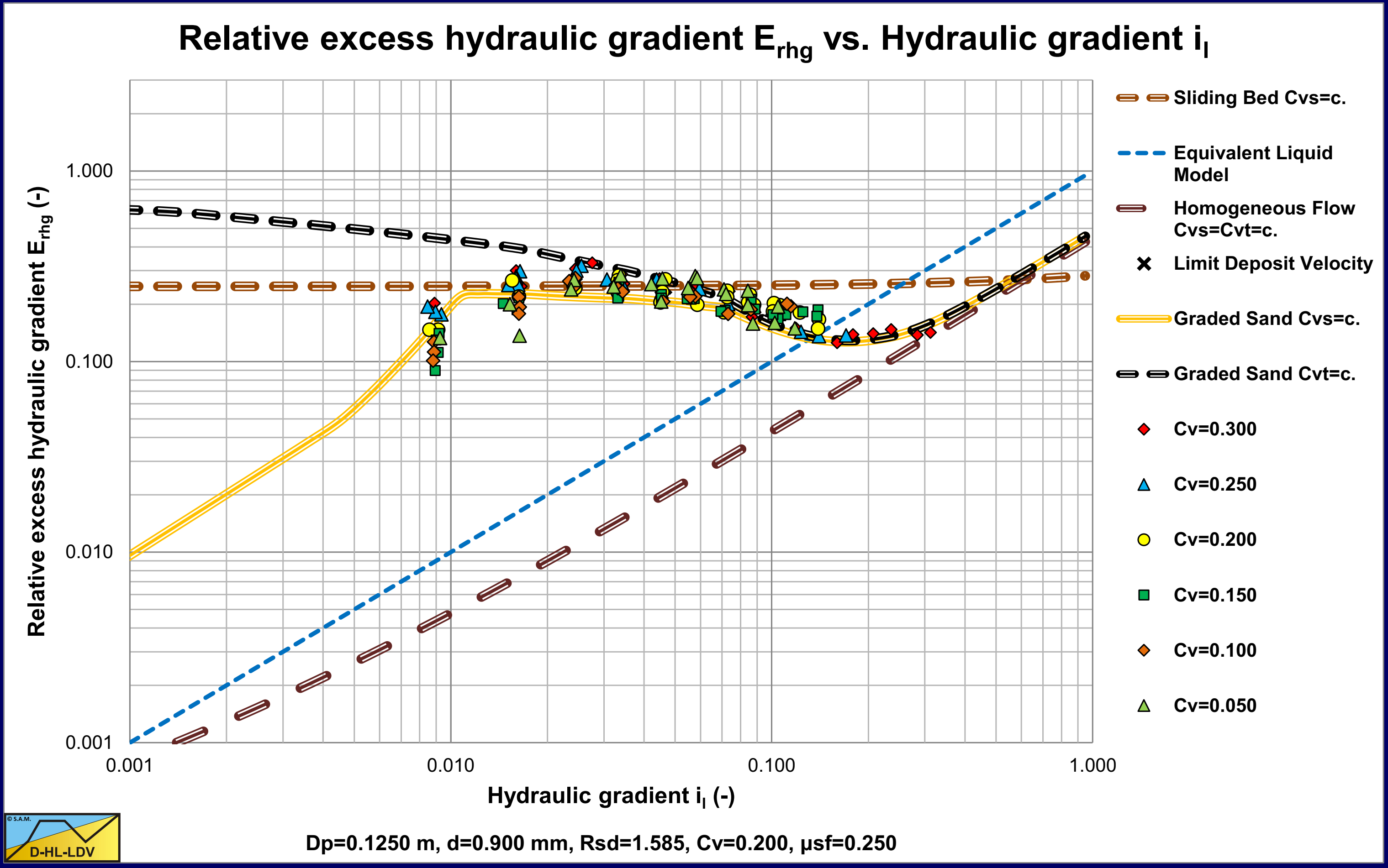
Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Resulting Hydraulic Gradient Graph, C_{vt}



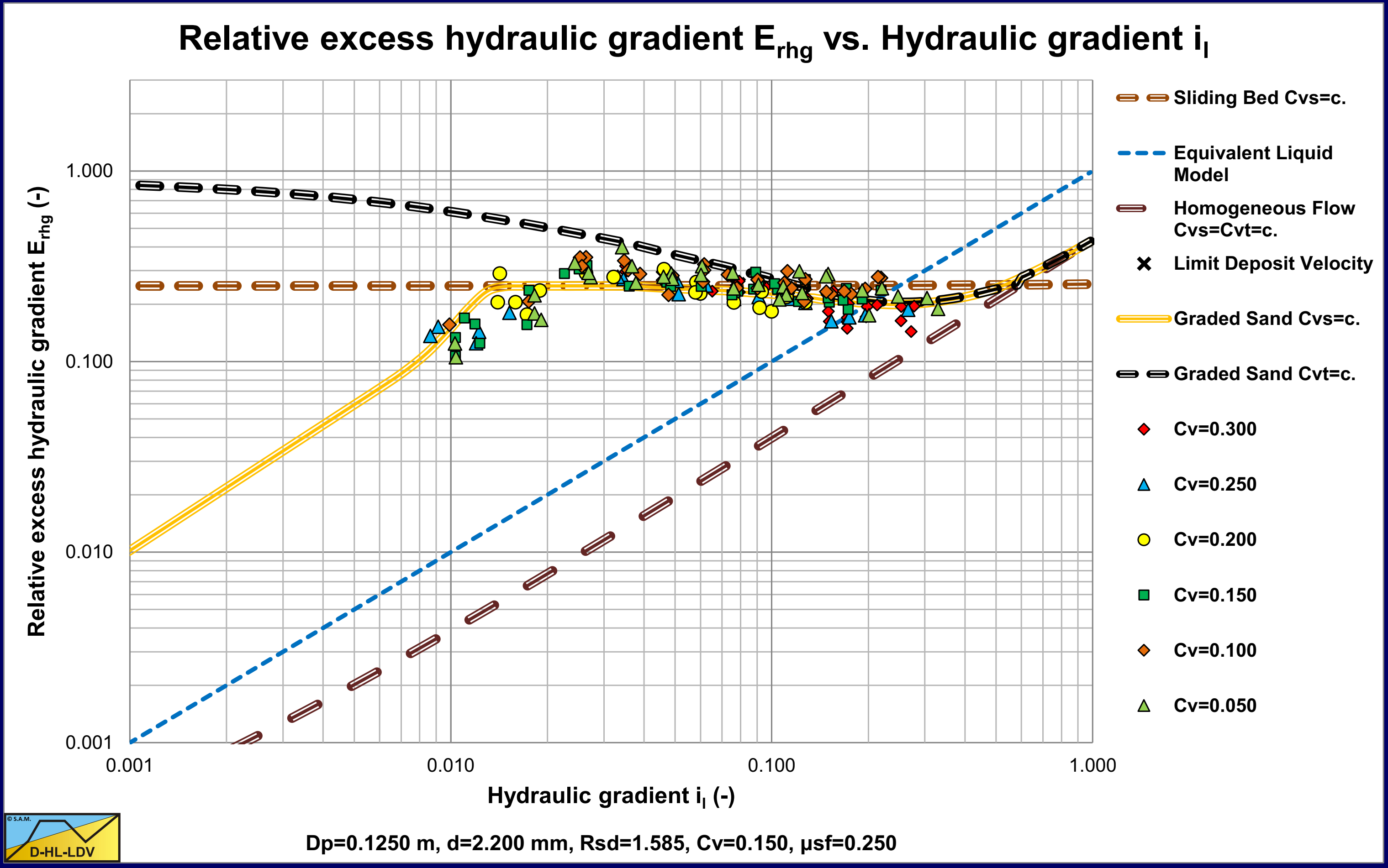
Wiedenroth (1967), Medium Sand



Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Wiedenroth (1967), Coarse Sand



TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Heterogeneous Flow Regime

Chapter 7.5 & 8.5

Durand & Condolios

Newitt et al.

Jufin & Lopatin

Fuhrboter – Wilson et al.

DHLLDV Framework

Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Existing Equations Depending on i_l

$$\Delta p_m = \Delta p_l \cdot \left(1 + \Phi \cdot C_{vt}\right) \quad \text{with:} \quad \Phi = \frac{i_m - i_l}{i_l \cdot C_{vt}} = \frac{\Delta p_m - \Delta p_l}{\Delta p_l \cdot C_{vt}}$$

Durand, Condolios & Gibert based on Froude numbers

$$\Phi = K \cdot \psi^{-3/2} = K \cdot \left(\frac{v_{ls}^2}{g \cdot D_p \cdot R_{sd}} \cdot \sqrt{C_x} \right)^{-3/2} \quad \text{with:} \quad K \approx 85$$

Newitt et al. based on potential energy losses

$$\Delta p_m = \Delta p_l \cdot \left(1 + K_1 \cdot \left(g \cdot D_p \cdot R_{sd} \right) \cdot v_t \cdot C_{vt} \cdot \left(\frac{1}{v_{ls}} \right)^3 \right) \quad K_1 = 1100$$

Jufin & Lopatin empirical large diameters

$$\Delta p_m = \Delta p_l \cdot \left(1 + 2 \cdot \left(\frac{v_{min}}{v_{ls}} \right)^3 \right) \quad \Rightarrow v_{min} = 5.5 \cdot \left(C_{vt} \cdot \psi^* \cdot D_p \right)^{1/6}$$

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Existing Equations Independent of i_l

Fuhrboter medium diameters

$$\Delta p_m = \Delta p_l + \rho_l \cdot g \cdot \Delta L \cdot \frac{S_k}{v_{ls}} \cdot C_{vs}$$

$$i_m - i_l = \frac{S_k}{v_{ls}} \cdot C_{vs} \quad \Rightarrow \quad E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot C_{vs}} = \frac{S_k}{R_{sd} \cdot v_{ls}}$$

Wilson heterogeneous empirical (Stratification Ratio)

$$\Delta p_m = \Delta p_l + \frac{\mu_{sf}}{2} \cdot \rho_l \cdot g \cdot R_{sd} \cdot \Delta L \cdot \left(\frac{v_{50}}{v_{ls}}\right)^M \cdot C_{vt}$$

$$i_m - i_l = \frac{\mu_{sf}}{2} \cdot R_{sd} \cdot \left(\frac{v_{50}}{v_{ls}}\right)^M \cdot C_{vt} \quad \Rightarrow \quad E_{rhg} = \frac{\mu_{sf}}{2} \cdot \left(\frac{v_{50}}{v_{ls}}\right)^M = R$$

DHLLDV Framework

Energy Dissipation by:

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

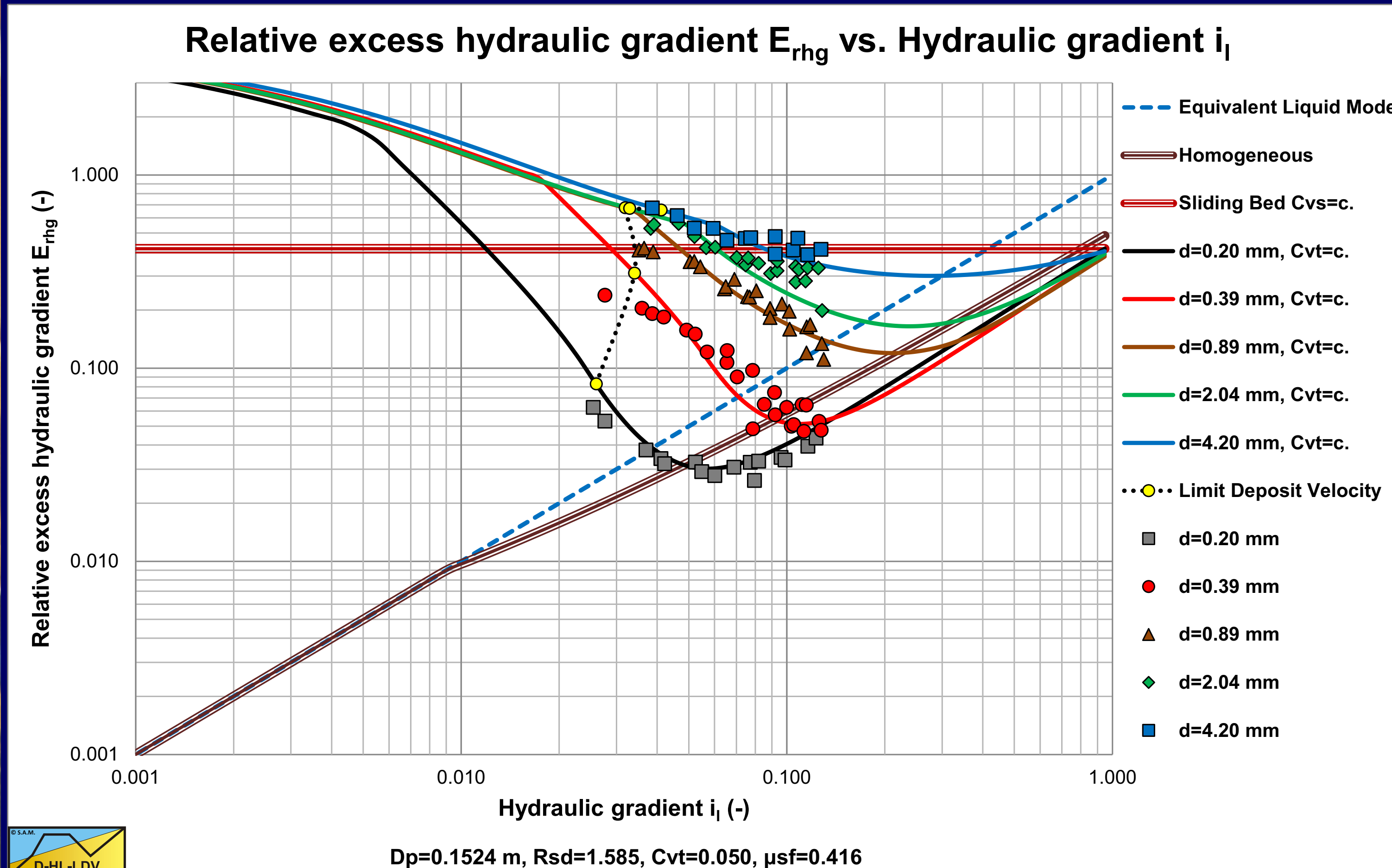
$$\Delta p_m = \Delta p_{l,visc} + \Delta p_{s,pot} + \Delta p_{s,kin} = \Delta p_{l,visc} \cdot \left(1 + \frac{\Delta p_{s,pot}}{\Delta p_{l,visc}} + \frac{\Delta p_{s,kin}}{\Delta p_{l,visc}} \right)$$

$$\frac{\Delta p_m}{\Delta L} = \lambda_l \cdot \frac{1}{D_p} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{ls}^2 + \rho_l \cdot g \cdot R_{sd} \cdot C_{vs} \cdot \left(\frac{v_t \cdot \left(1 - C_{vs} / \kappa_C\right)^{\beta}}{v_{ls}} \right) + \rho_l \cdot g \cdot R_{sd} \cdot C_{vs} \cdot \left(\frac{v_{sl}}{v_t} \right)^2$$

$$\Delta p_m = \Delta p_l \cdot \left(1 + \frac{\left(2 \cdot g \cdot R_{sd} \cdot D_p\right)}{\lambda_l} \cdot C_{vs} \cdot \frac{1}{v_{ls}^2} \cdot \left(\frac{v_t \cdot \left(1 - C_{vs} / \kappa_C\right)^{\beta}}{v_{ls}} + \left(\frac{v_{sl}}{v_t} \right)^2 \right) \right)$$

Slip

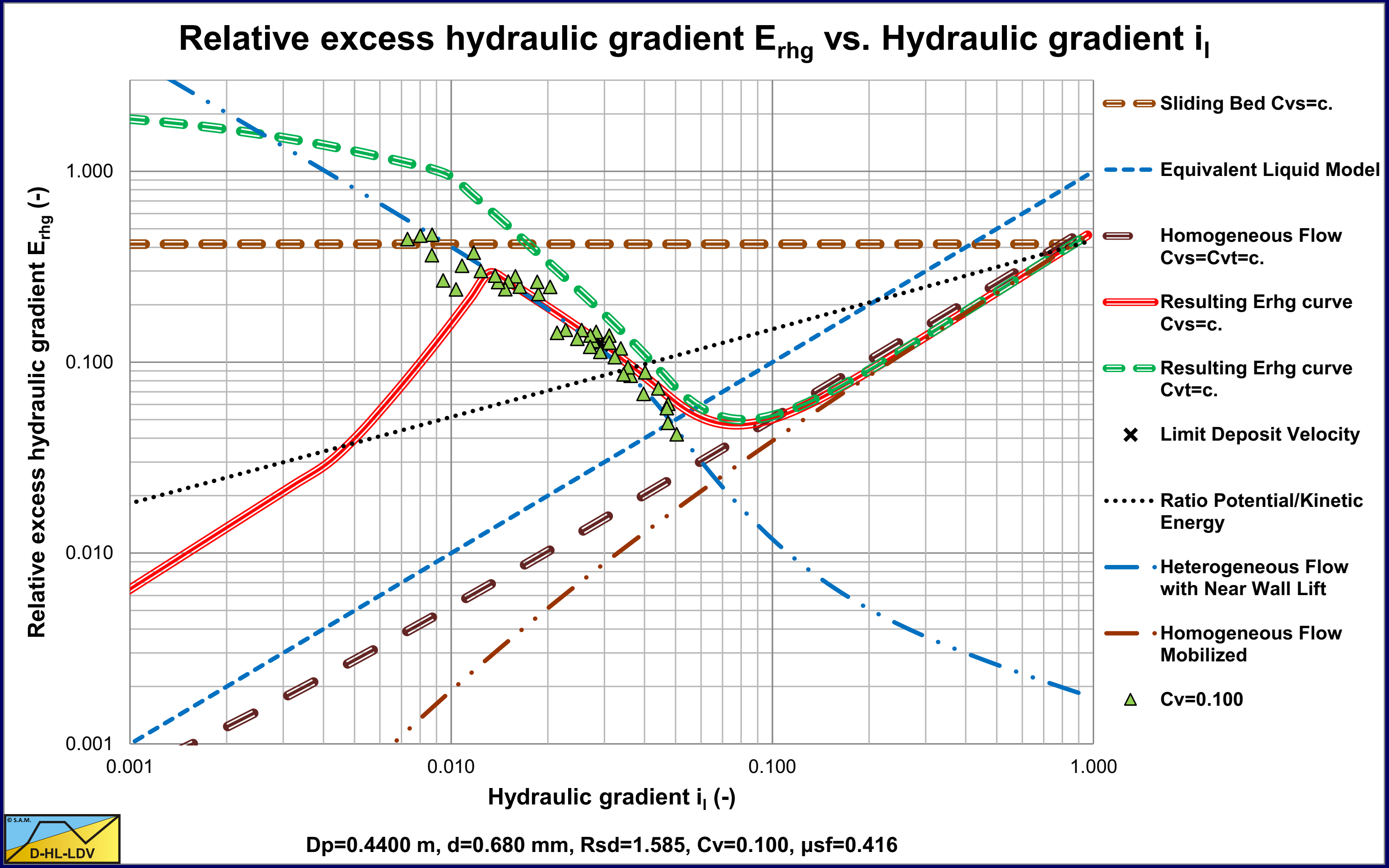
Verification & Validation, Durand et al.



Durand & Condolios (1952)

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Verification & Validation, Clift et al.



Clift (1982)

Homogeneous Flow Regime

Chapter 7.6 & 8.6

Equivalent Liquid Model

Newitt et al.

Wilson et al.

Talmon

DHLLDV Framework

Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

The Equivalent Liquid Model (ELM)

$$\Delta p_m = \lambda_l \cdot \frac{\Delta L}{D_p} \cdot \frac{1}{2} \cdot \rho_m \cdot v_{ls}^2$$

$$i_m = \frac{\Delta p_m}{\rho_l \cdot g \cdot \Delta L} = \frac{\rho_m}{\rho_l} \cdot \frac{\lambda_l \cdot v_{ls}^2}{2 \cdot g \cdot D_p}$$

$$= i_l \cdot \left(1 + A \cdot R_{sd} \cdot C_{vs}\right)$$

$$E_{rhg} = \frac{i_m - i_l}{R_{sd} \cdot C_{vs}} = A \cdot i_l$$

Delft University of Technology
Offshore & Dredging Engineering

Phenomena

- Very fine particles: The liquid properties have to be adjusted. The ELM can be used with the adjusted liquid properties.
- Fine particles: The ELM can be used with the original liquid properties. At high line speeds the lubrication effect will be mobilized.
- Medium/Coarse particles: The lubrication effect is mobilized, due to a particle poor viscous sub-layer. This gives a reduction of the solids effect in the ELM.

Very Fine Particles

$$d_{lim} = \sqrt{\frac{Stk \cdot 9 \cdot \rho_l \cdot \nu_l \cdot D_p}{\rho_s \cdot v_{ls,ldv}}} \approx \sqrt{\frac{Stk \cdot 9 \cdot \rho_l \cdot \nu_l \cdot D_p}{\rho_s \cdot 7.5 \cdot D_p^{0.4}}} \qquad X=1$$

$$\rho_x = \rho_l + \rho_l \cdot \frac{X \cdot C_{vs} \cdot R_{sd}}{\left(1 - C_{vs} + C_{vs} \cdot X\right)}$$

$$C_{vs,x} = \frac{X \cdot C_{vs}}{\left(1 - C_{vs} + C_{vs} \cdot X\right)} \quad \text{and} \quad C_{vs,r} = \left(1 - X\right) \cdot C_{vs}$$

$$\mu_x = \mu_l \cdot \left(1 + 2.5 \cdot C_{vs,x} + 10.05 \cdot C_{vs,x}^2 + 0.00273 \cdot e^{16.6 \cdot C_{vs,x}}\right)$$

$$\nu_x = \frac{\mu_x}{\rho_x} \quad \text{and} \quad R_{sd,x} = \frac{\rho_s - \rho_x}{\rho_x}$$

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

The Models

- Newitt et al. use a factor A=0.6 in the ELM.
- Wilson et al. Use different factors for A in the ELM.
- Talmon determined A based on a particle free viscous sublayer in 2D channel flow.
- The DHLLDV Framework determined A based on a concentration distribution in a circular pipe. This way the viscous sublayer is particle poor, but not completely particle free. The result is an equation for A, depending on the concentration.
- The DHLLDV Framework also assumes that particles fitting in the viscous sublayer do not result in a particle free viscous sublayer and thus have A=1. The larger the particles the more the particle free sublayer is mobilised.

Fine Particles

$$E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=i_l\cdot\left(1-\left(1-\frac{1+R_{sd}\cdot C_{vs}-\left(\frac{A_{C_v}}{\kappa}\cdot\ln\left(\frac{\rho_m}{\rho_l}\right)\cdot\sqrt{\frac{\lambda_l}{8}}+1\right)^2}{R_{sd}\cdot C_{vs}\cdot\left(\frac{A_{C_v}}{\kappa}\cdot\ln\left(\frac{\rho_m}{\rho_l}\right)\cdot\sqrt{\frac{\lambda_l}{8}}+1\right)^2}\right)\cdot\left(1-\left(\frac{\delta_v}{d}\right)\right)\right)$$

$$E_{rhg}=\frac{i_m-i_l}{R_{sd}\cdot C_{vs}}=i_l\cdot\left(1-\left(1-\alpha_E\right)\cdot\left(1-\left(\frac{\delta_v}{d}\right)\right)\right)$$

$$i_m=i_l+i_l\cdot R_{sd}\cdot C_{vs}\cdot\left(1-\left(1-\alpha_E\right)\cdot\left(1-\left(\frac{\delta_v}{d}\right)\right)\right)$$

$$\left(\frac{\delta_v}{d}\right)=\max=1 \quad\Rightarrow\quad i_m=i_l+i_l\cdot R_{sd}\cdot C_{vs}=i_l\cdot\left(1+R_{sd}\cdot C_{vs}\right)\ \text{ELM}$$

$$\left(\frac{\delta_v}{d}\right)=0 \quad\Rightarrow\quad i_m=i_l+i_l\cdot R_{sd}\cdot C_{vs}\cdot\alpha_E=i_l\cdot\left(1+R_{sd}\cdot C_{vs}\cdot\alpha_E\right)$$

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

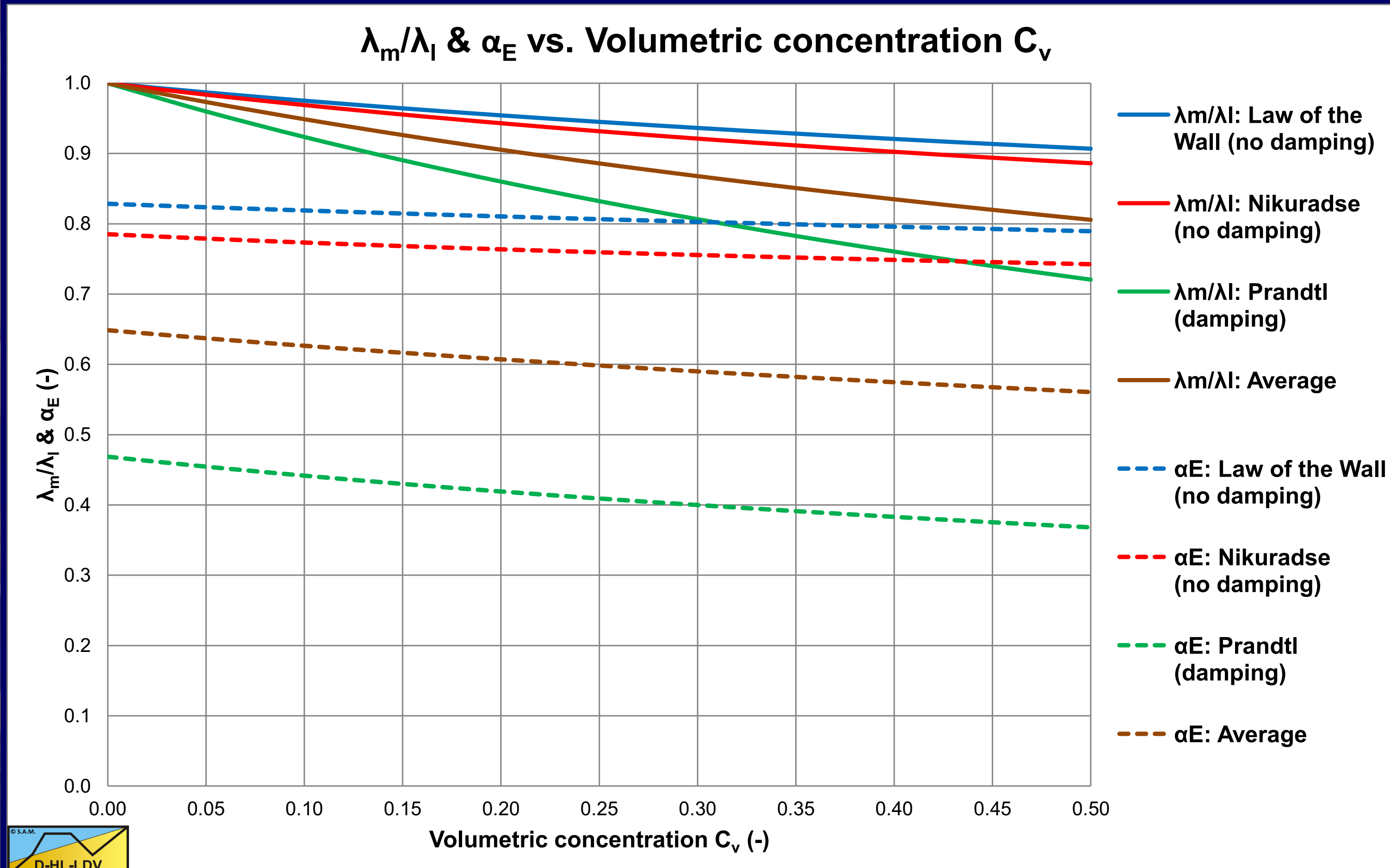
Medium/Coarse Particles

$$E_{rhg} = i_l \cdot \frac{1 + R_{sd} \cdot C_{vs} - \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2}{R_{sd} \cdot C_{vs} \cdot \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2} = \alpha_E \cdot i_l$$

$$i_m = i_l + i_l \cdot \frac{1 + R_{sd} \cdot C_{vs} - \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2}{\left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2}$$

$$p_m = p_l + p_l \cdot \frac{1 + R_{sd} \cdot C_{vs} - \left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2}{\left(\frac{A_{C_v}}{\kappa} \cdot \ln\left(\frac{\rho_m}{\rho_l}\right) \cdot \sqrt{\frac{\lambda_l}{8}} + 1 \right)^2}$$

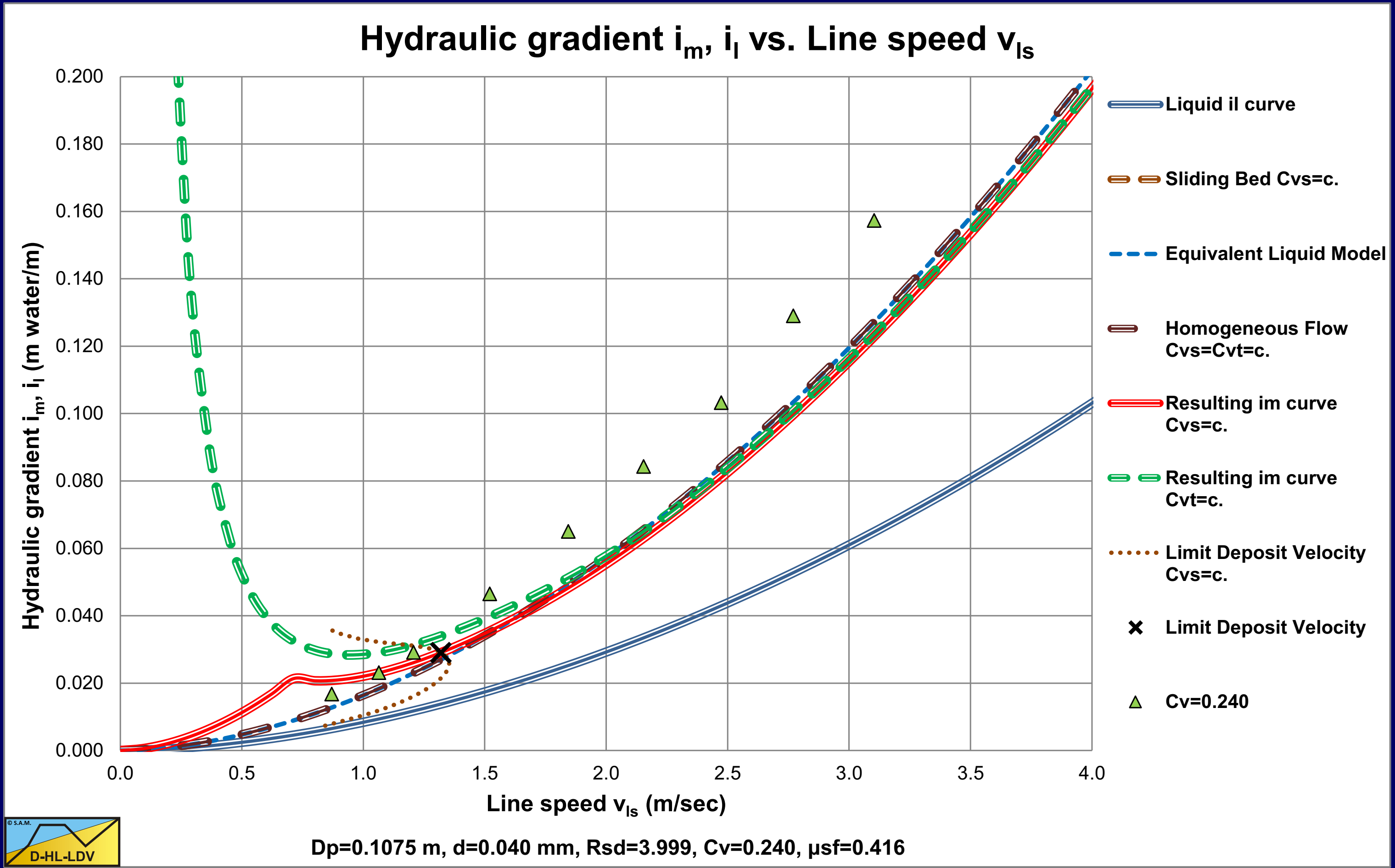
Lubrication Factor α_E



Delft University of Technology
Offshore & Dredging Engineering

Delft University of Technology – Offshore & Dredging Engineering

Very Fine Particles

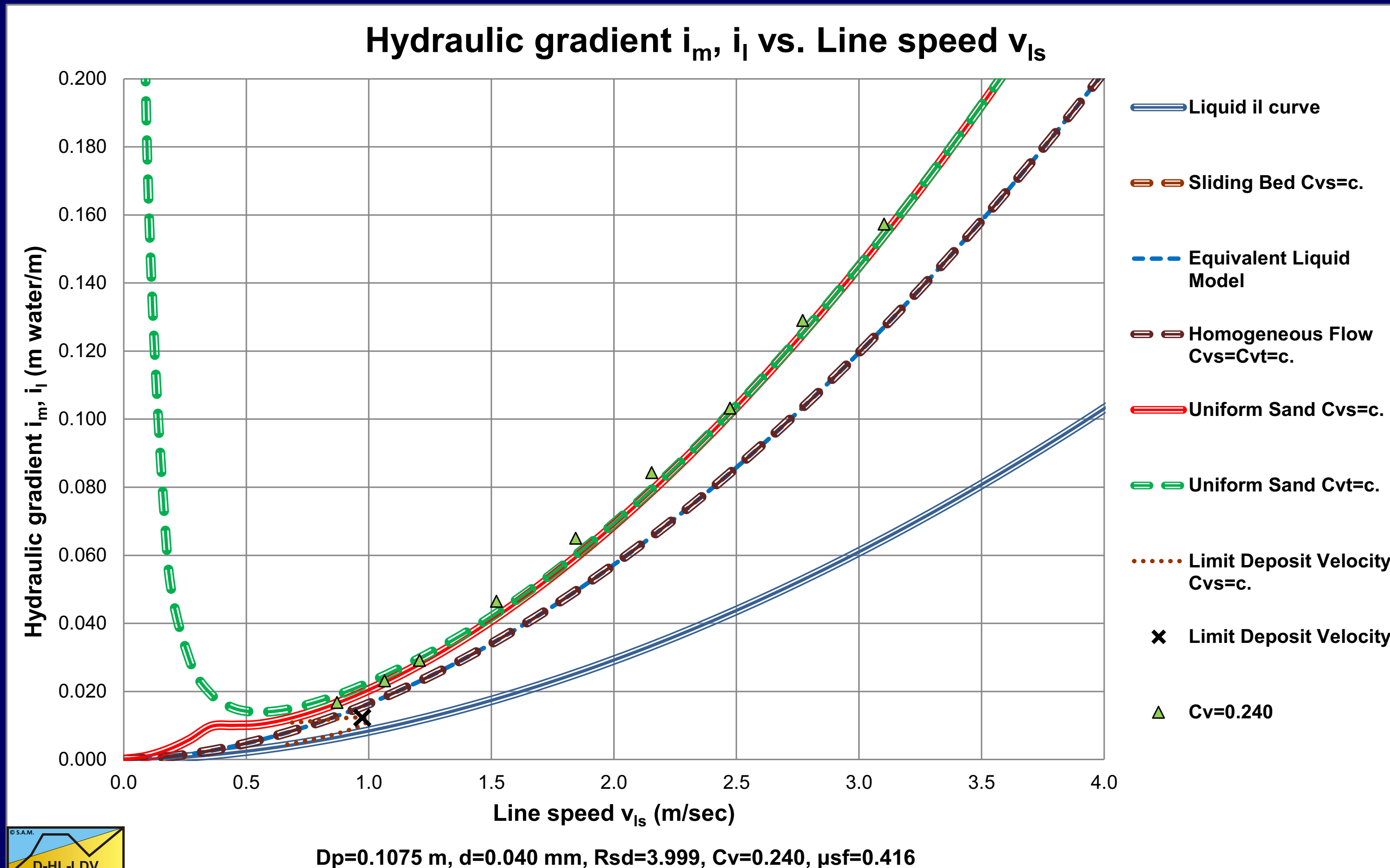


Thomas (1976)

Delft University of Technology – Offshore & Dredging Engineering

TUDelft
Delft University of Technology
Offshore & Dredging Engineering

Very Fine Particles, with Thomas (1965)

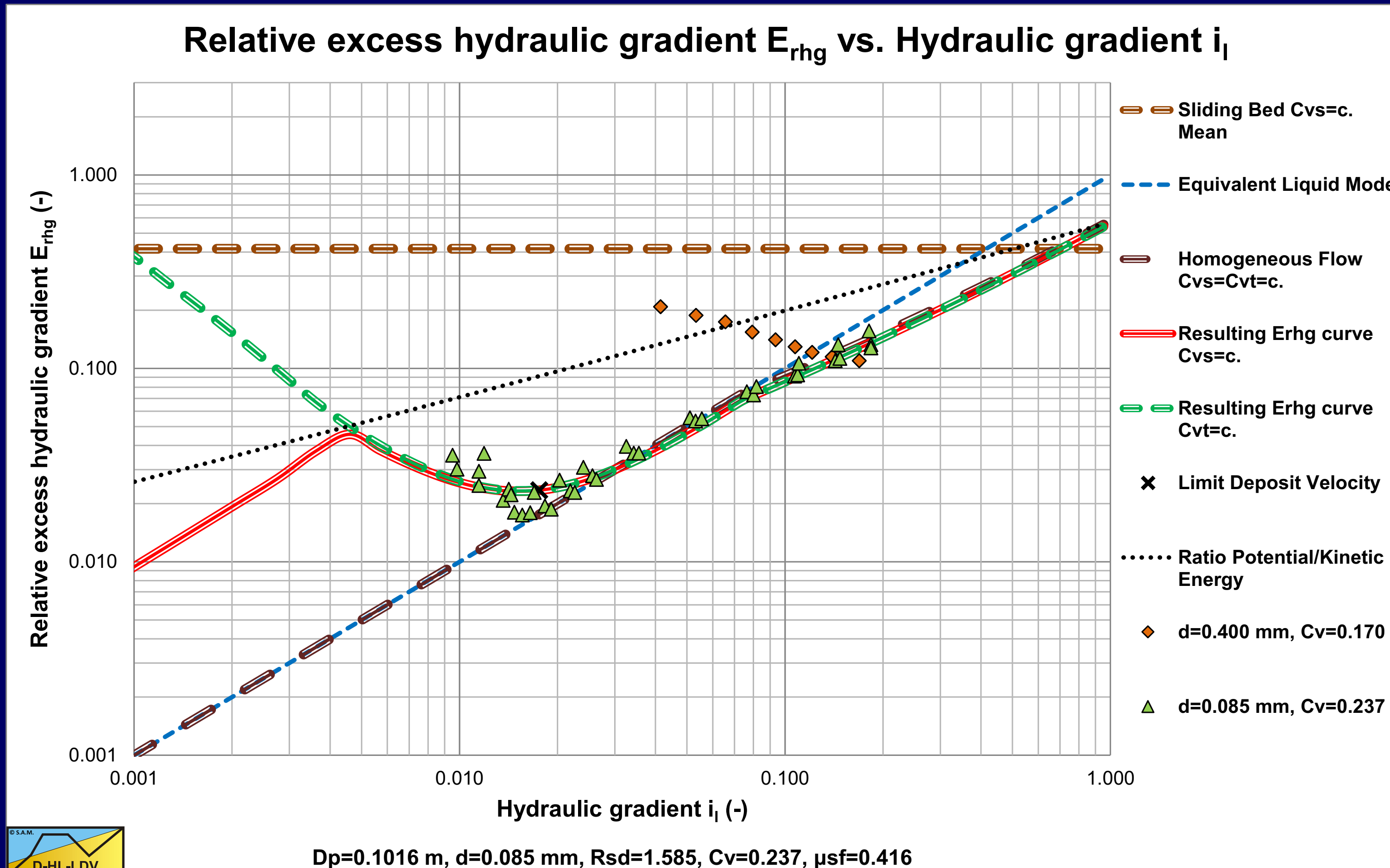


Thomas (1976) Adjusted Liquid Properties

Delft University of Technology – Offshore & Dredging Engineering

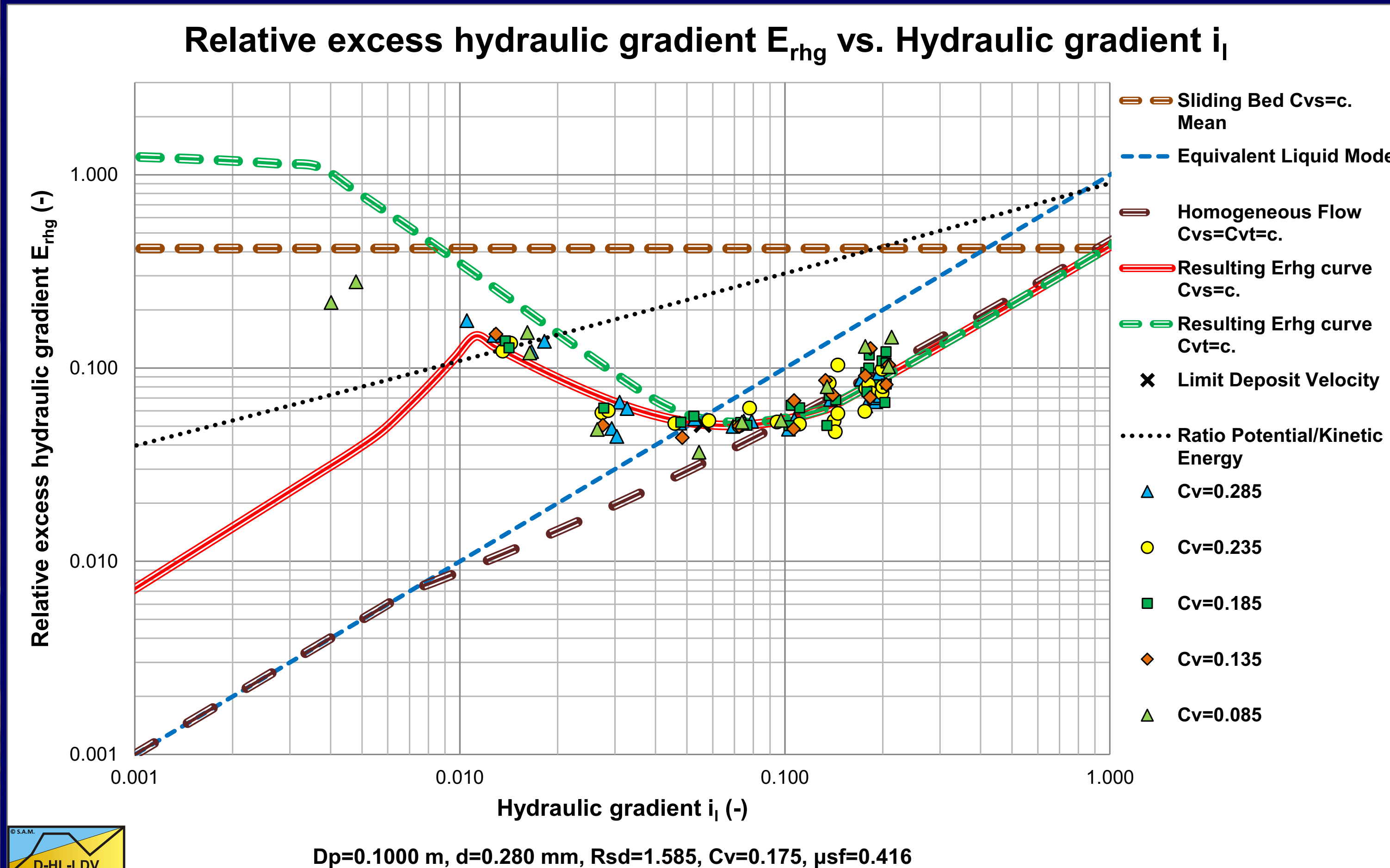
TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Fine Particles



Whitlock (2004)

Medium/Coarse Particles



Blythe & Czarnotta (1995)

Delft University of Technology – Offshore & Dredging Engineering

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Sliding Flow Regime

Chapter 7.7 & 8.8

SRC Model

DHLLDV Framework

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Phenomena

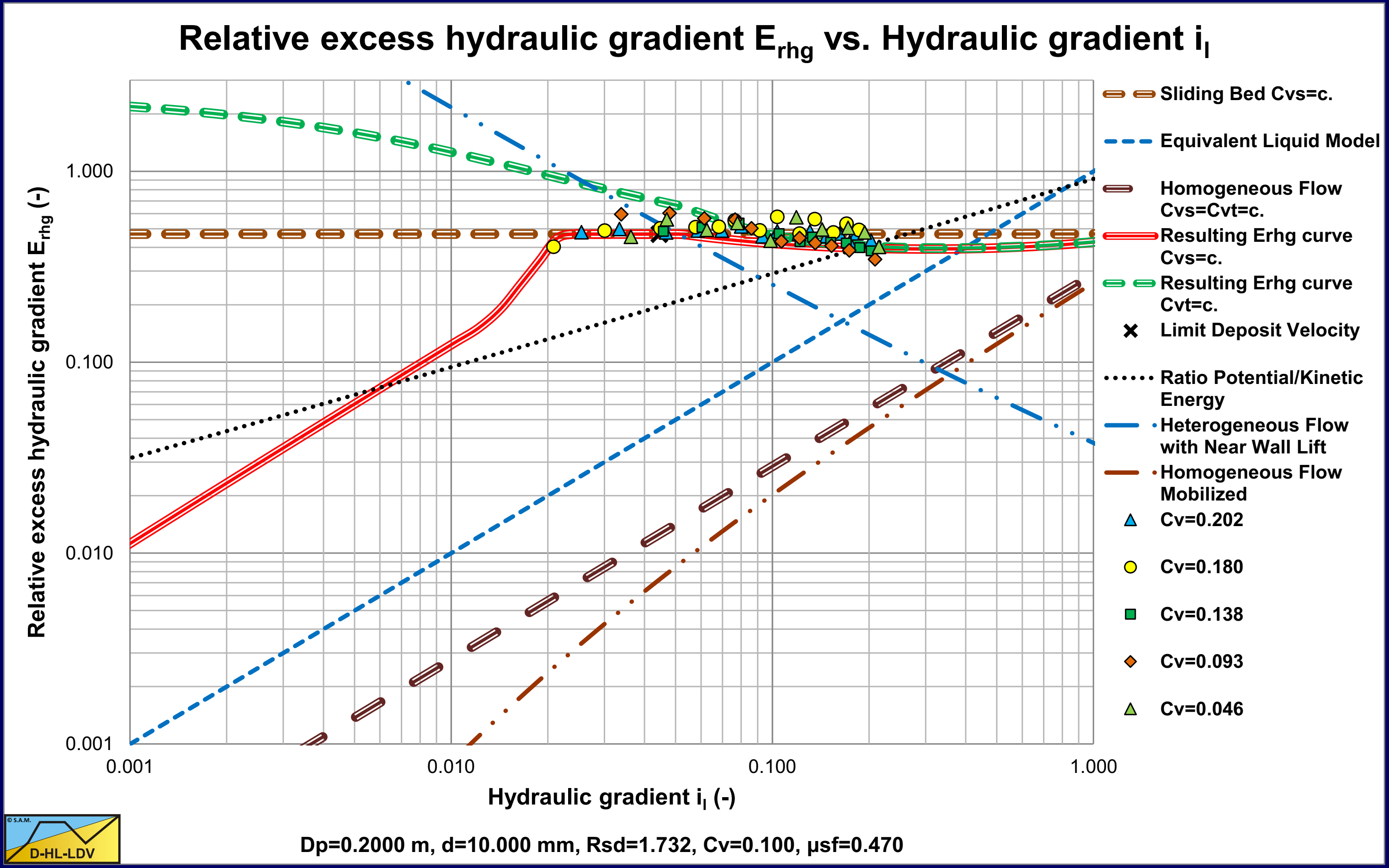
If the particle diameter to pipe diameter is larger than about 0.015, the particles will not be suspended anymore, but stay in a fast flowing sort of bed.

The behavior is a mix of the heterogeneous flow regime and the sliding bed regime.

At $d/D_p=0.015$ the behavior is still heterogeneous, but the larger the particle diameter the more it is sliding bed behavior.

The higher the line speed the smaller the concentration of the flowing particles at the bottom of the pipe.

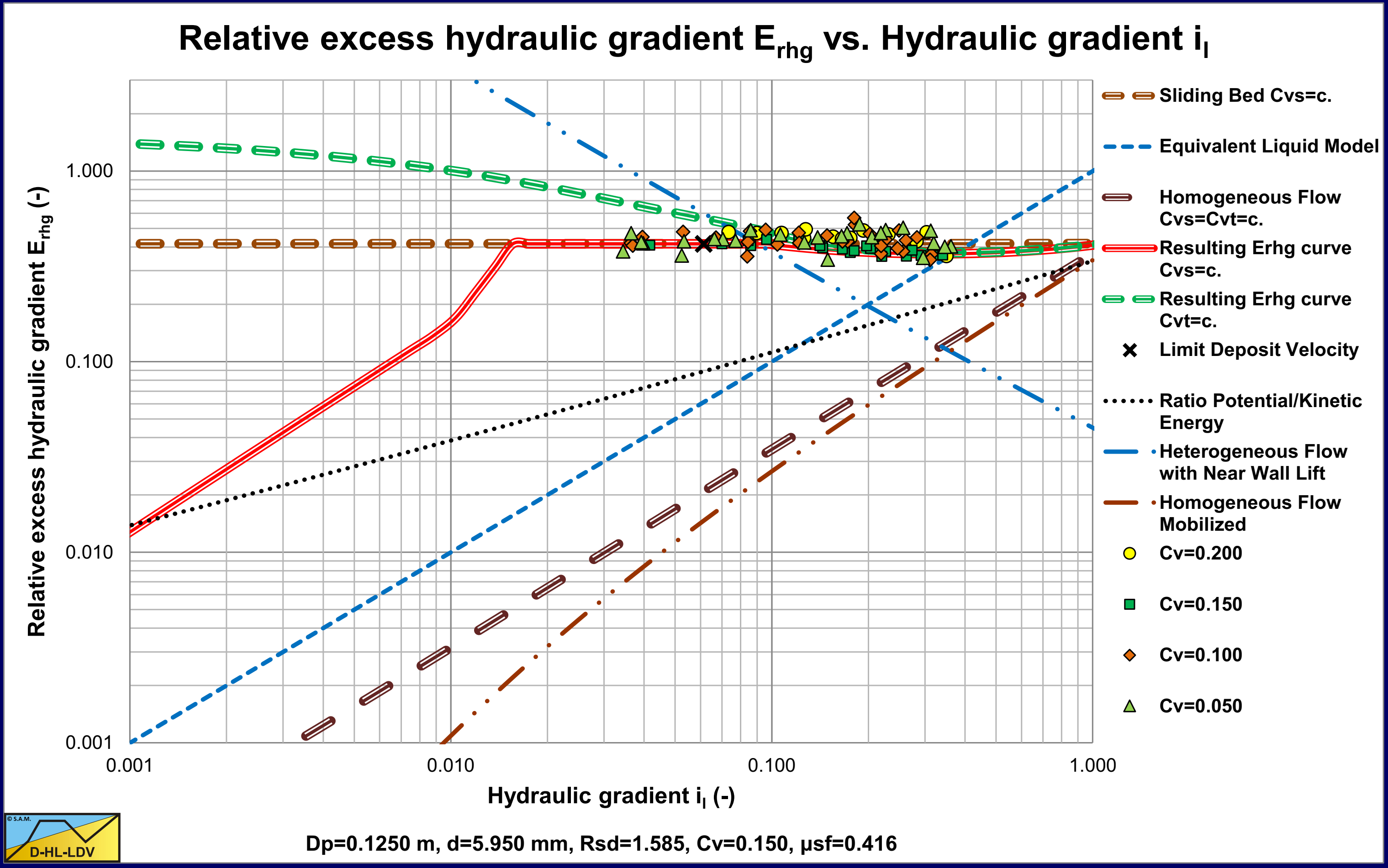
Verification & Validation, Boothroyde



Boothroyde et al. (1979)

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Verification & Validation, Wiedenroth



Wiedenroth (1967)

TU Delft
Delft University of Technology
Offshore & Dredging Engineering

Main Conclusion

Conclusions

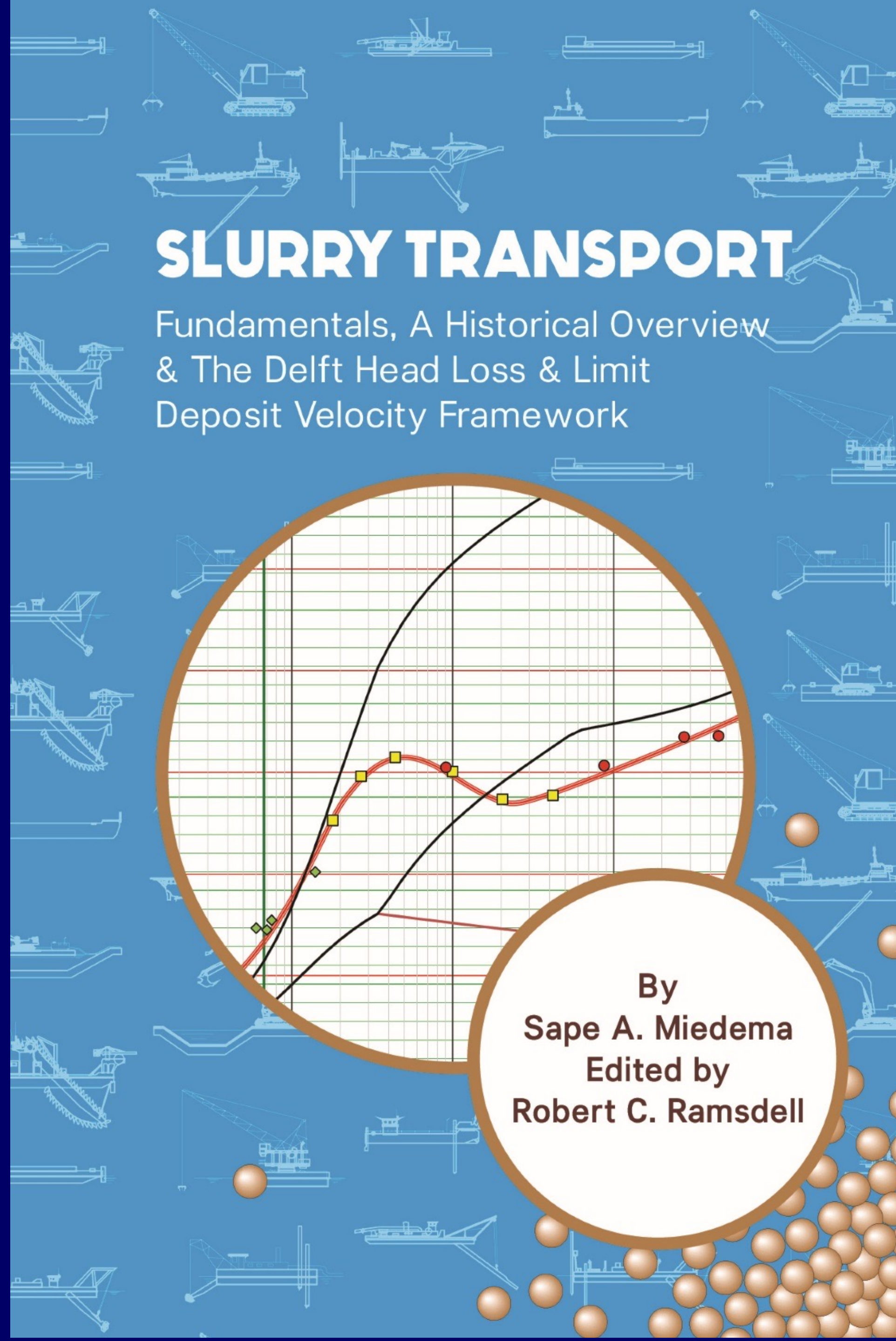
Models are valid for the parameters the experiments were carried out with.

The correct flow regime has to be identified for each (sub) model.

For heterogeneous flow the solids effect is independent of the Darcy Weisbach component.

Models validated with a wide range of parameters are: Jufin & Lopatin, Wilson et al., the SRC model and the DHLLDV Framework.

These 4 models give similar results for medium and coarse sands over a wide range of pipe diameters.



TU Delft
Delft University of Technology
Offshore & Dredging Engineering

The Elephant of Wilson is our best Friend