Dredging Processes

Dr.ir. Sape A. Miedema

7. Erosion

Dredging A Way Of Life

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Offshore A Way Of Life

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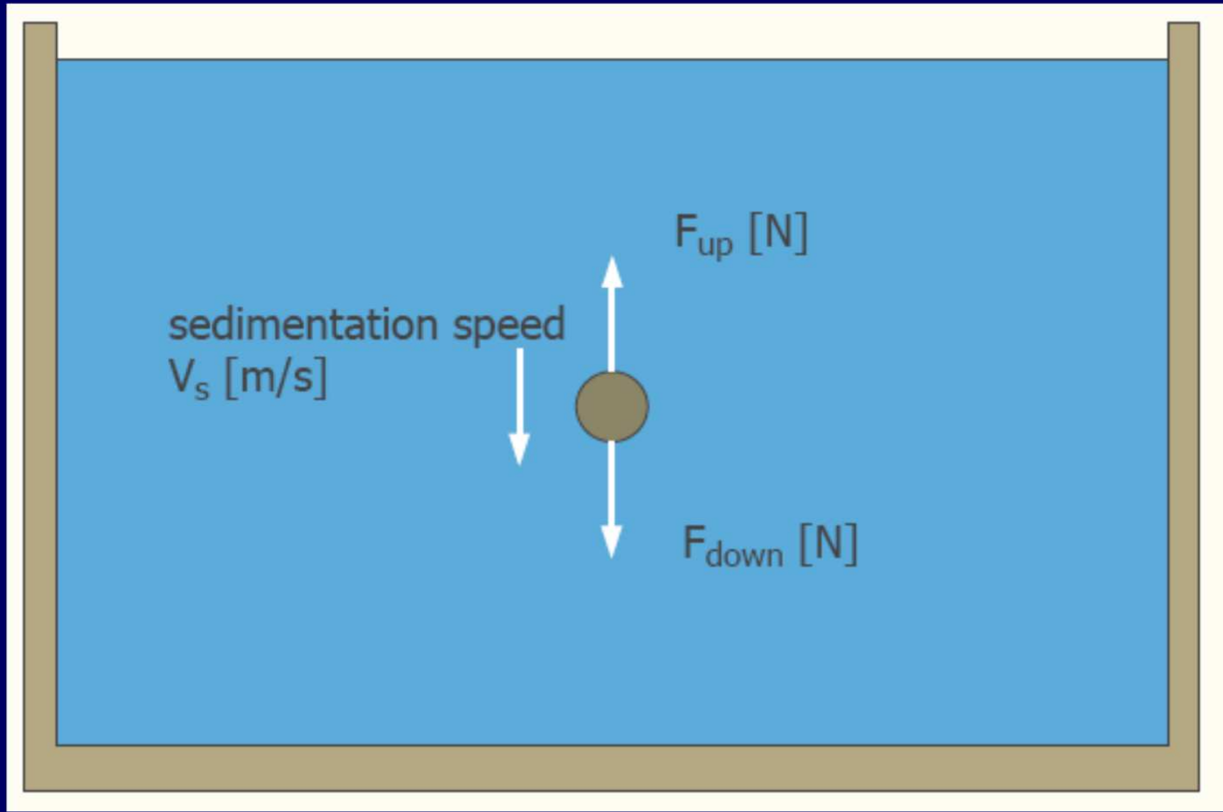
The Settling Velocity

Forces on a settling particle

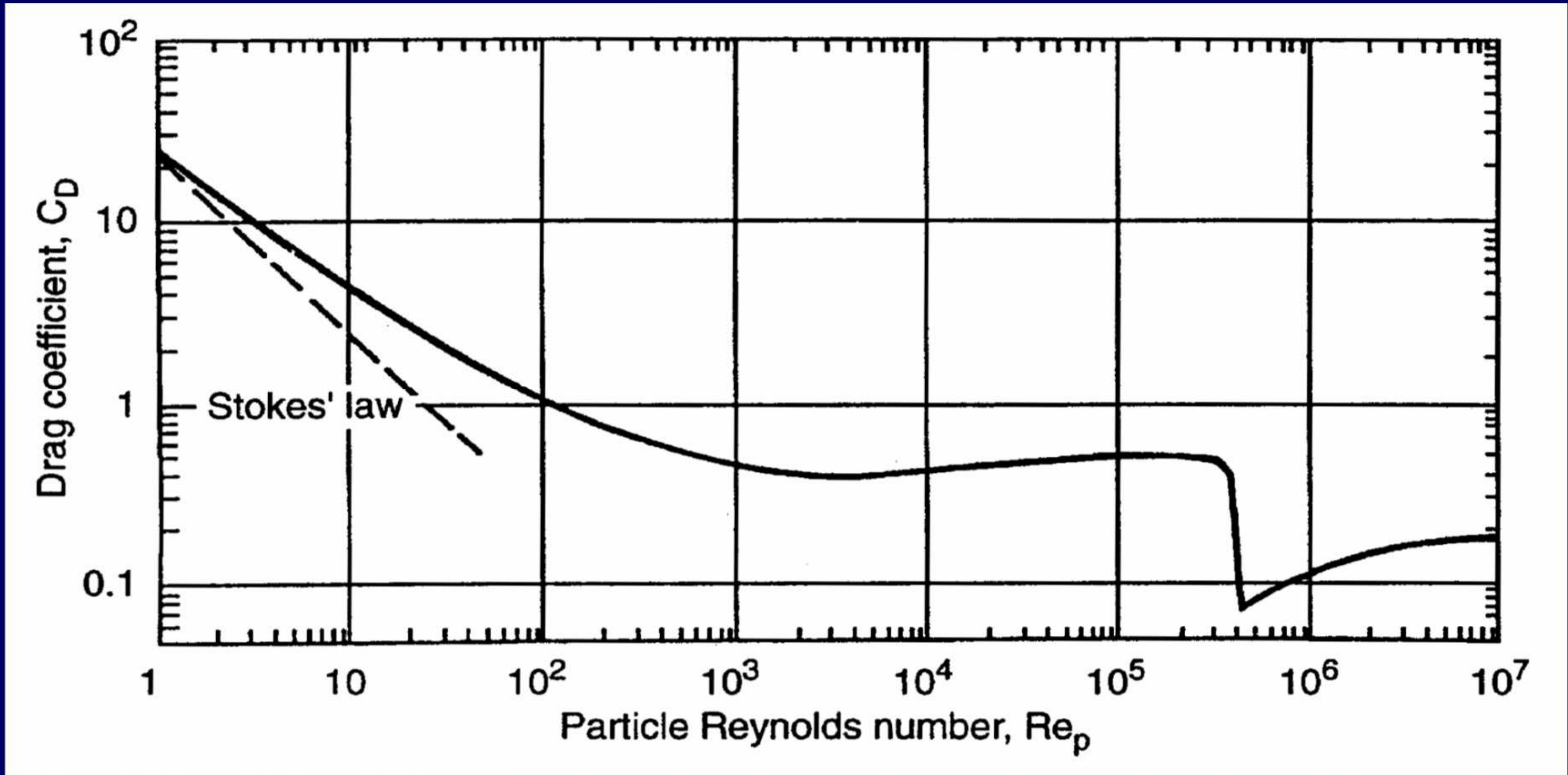


$$F_{up} = C_D \cdot \frac{1}{2} \cdot \rho_w \cdot v_s^2 \cdot A$$

$$F_{down} = (\rho_q - \rho_w) \cdot g \cdot V \cdot \psi$$

$$v_s = \sqrt{\frac{4 \cdot g \cdot (\rho_q - \rho_w) \cdot d \cdot \psi}{3 \cdot \rho_w \cdot C_d}}$$

Standard drag coefficient curve for spheres



$Re_p < 1$	$\Rightarrow$	$C_d = \dfrac{24}{Re_p}$
$1 < Re_p < 2000$	$\Rightarrow$	$C_d = \dfrac{24}{Re_p} + \dfrac{3}{\sqrt{Re_p}} + 0.34$
$Re_p > 2000$	$\Rightarrow$	$C_d = 0.445$

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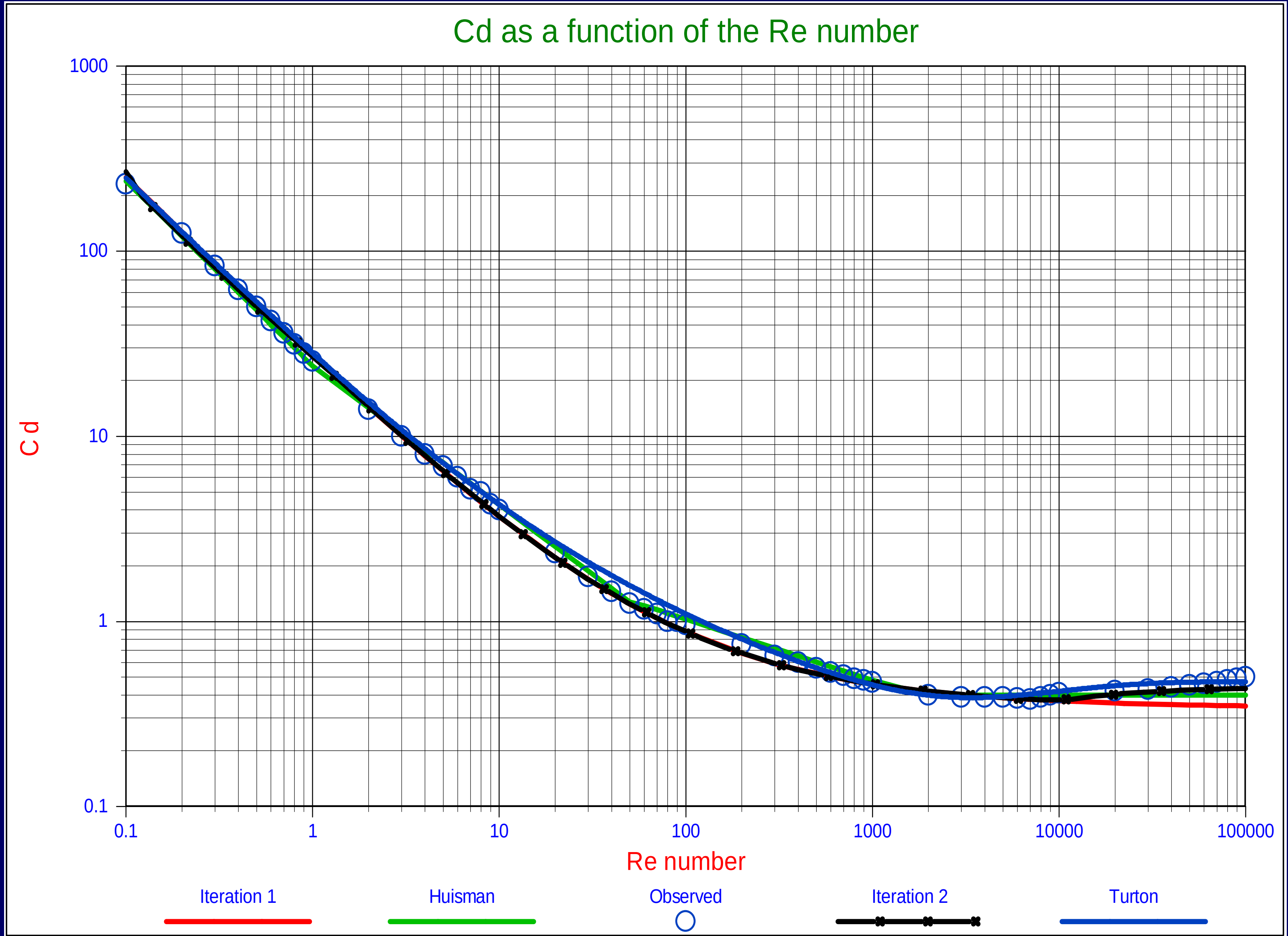
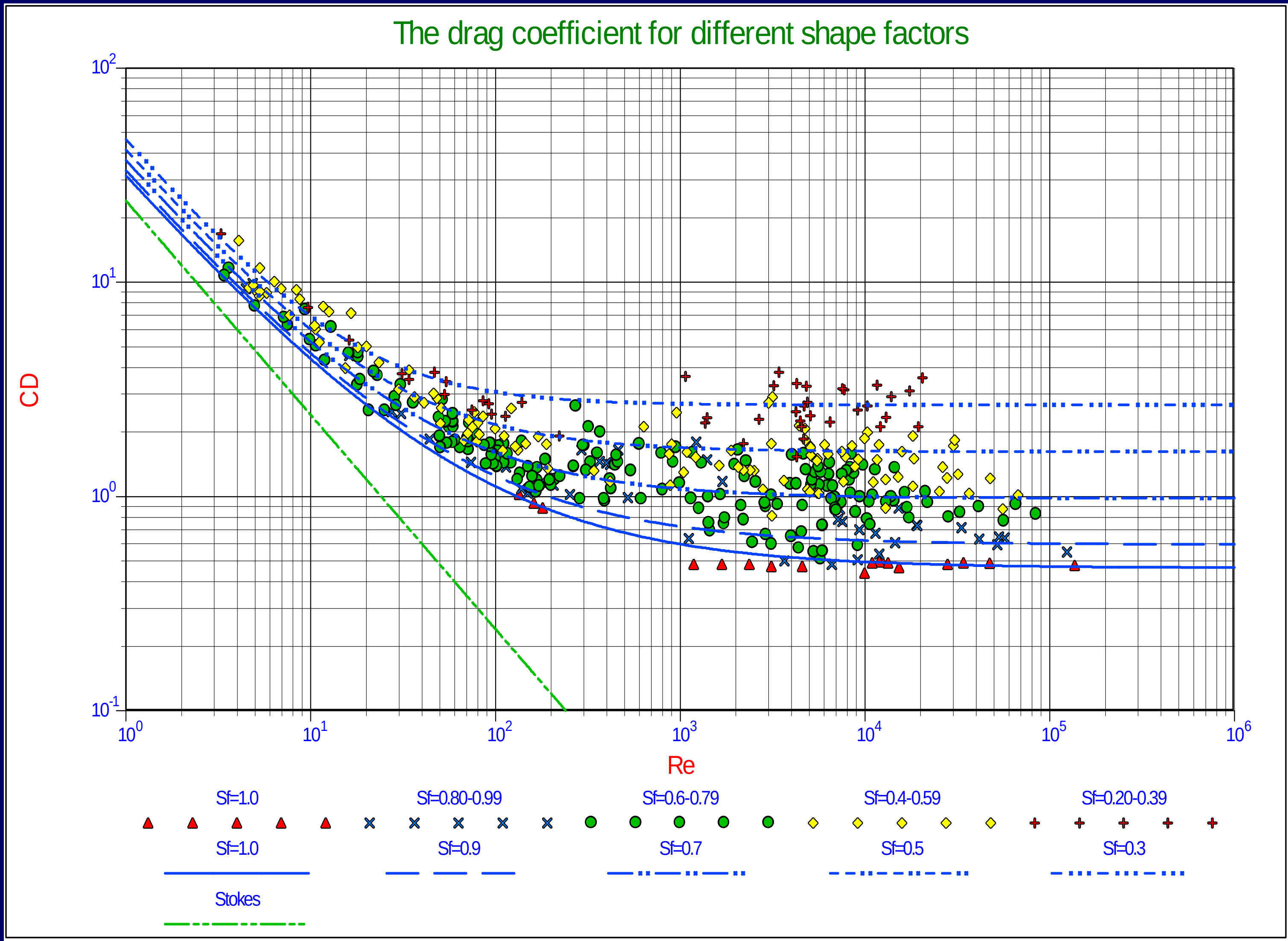
The drag coefficient as a function of the particle Reynolds number



The drag coefficient as a function of the particle Reynolds number



The settling velocity of individual particles

Laminar flow, **d<0.1 mm**, according to Stokes.

$$\mathbf{v_s = 424 \cdot R_d \cdot d^2}$$

Transition zone, **d>0.1 mm** and **d<1 mm**, according to Budryck.

$$\mathbf{v_s = 8.925 \cdot \frac{\left(\sqrt{(1 + 95 \cdot R_d \cdot d^3)} - 1\right)}{d}}$$

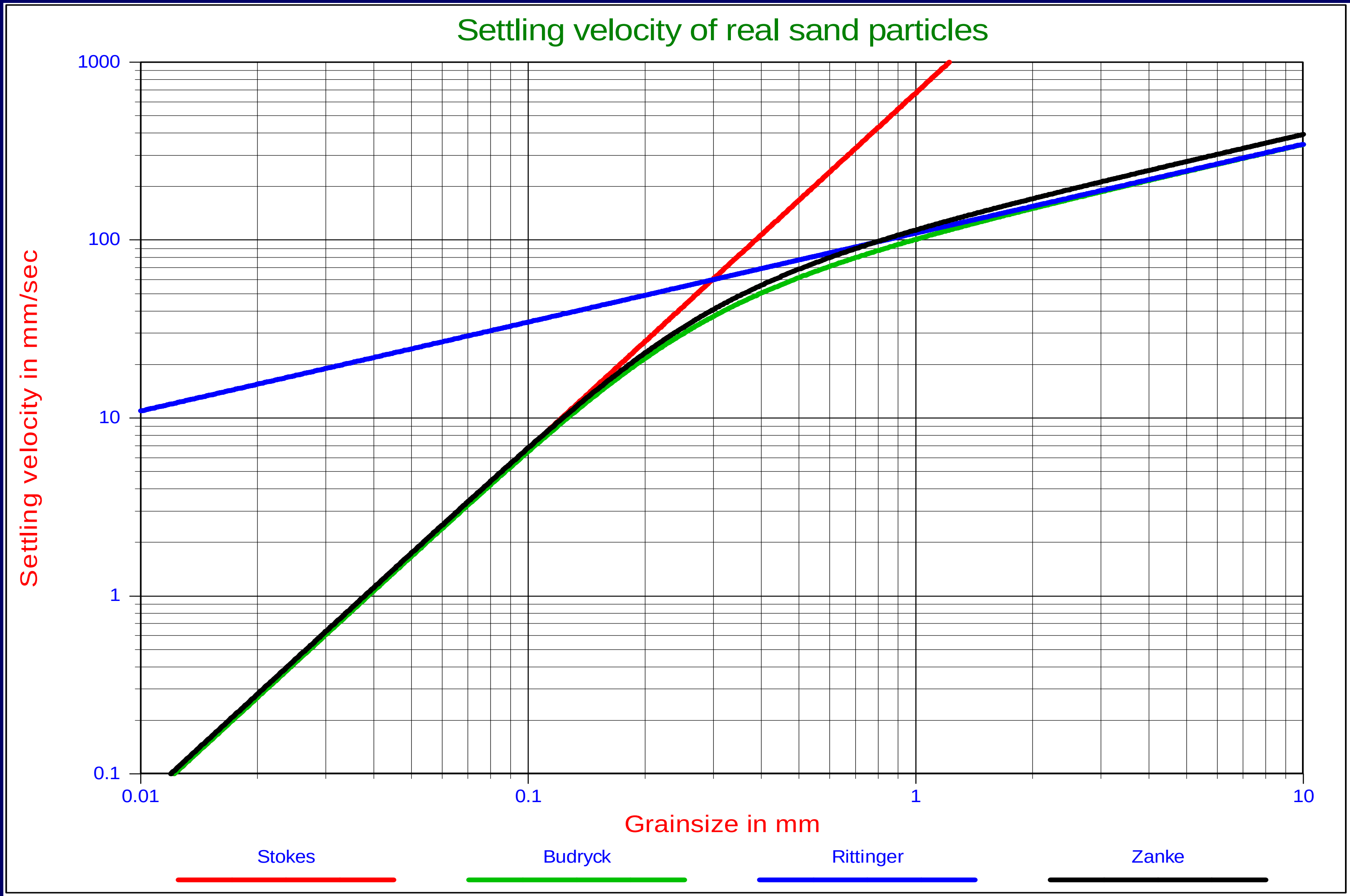
Turbulent flow, **d>1 mm**, according to Rittinger.

$$\mathbf{v_s = 87 \cdot \sqrt{R_d \cdot d}}$$

With the relative density $\mathbf{R_d}$ defined as:

$$\mathbf{R_d = \frac{\rho_q - \rho_w}{\rho_w}}$$

The settling velocity of individual particles



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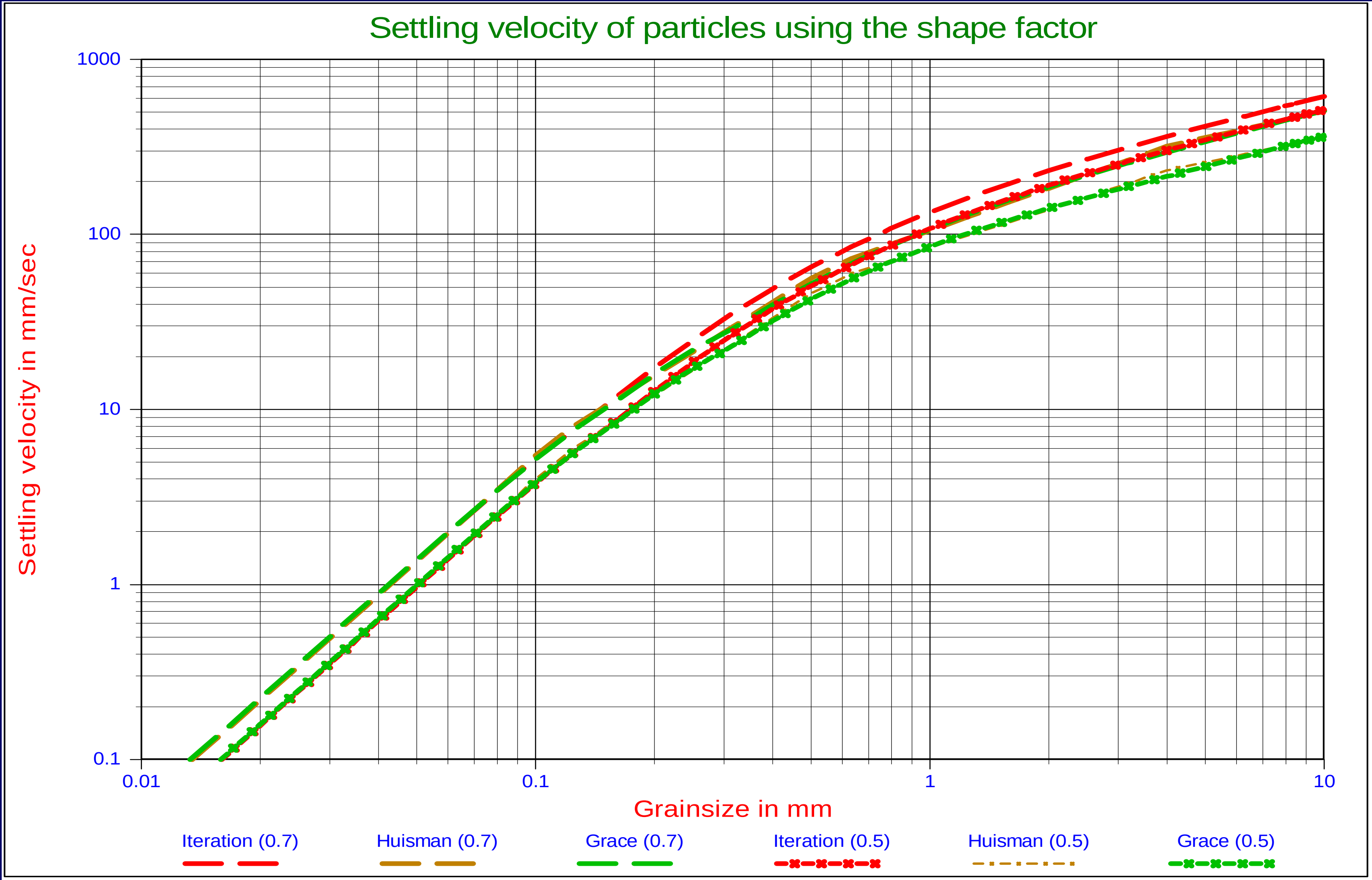
The settling velocity of individual particles using the shape factor



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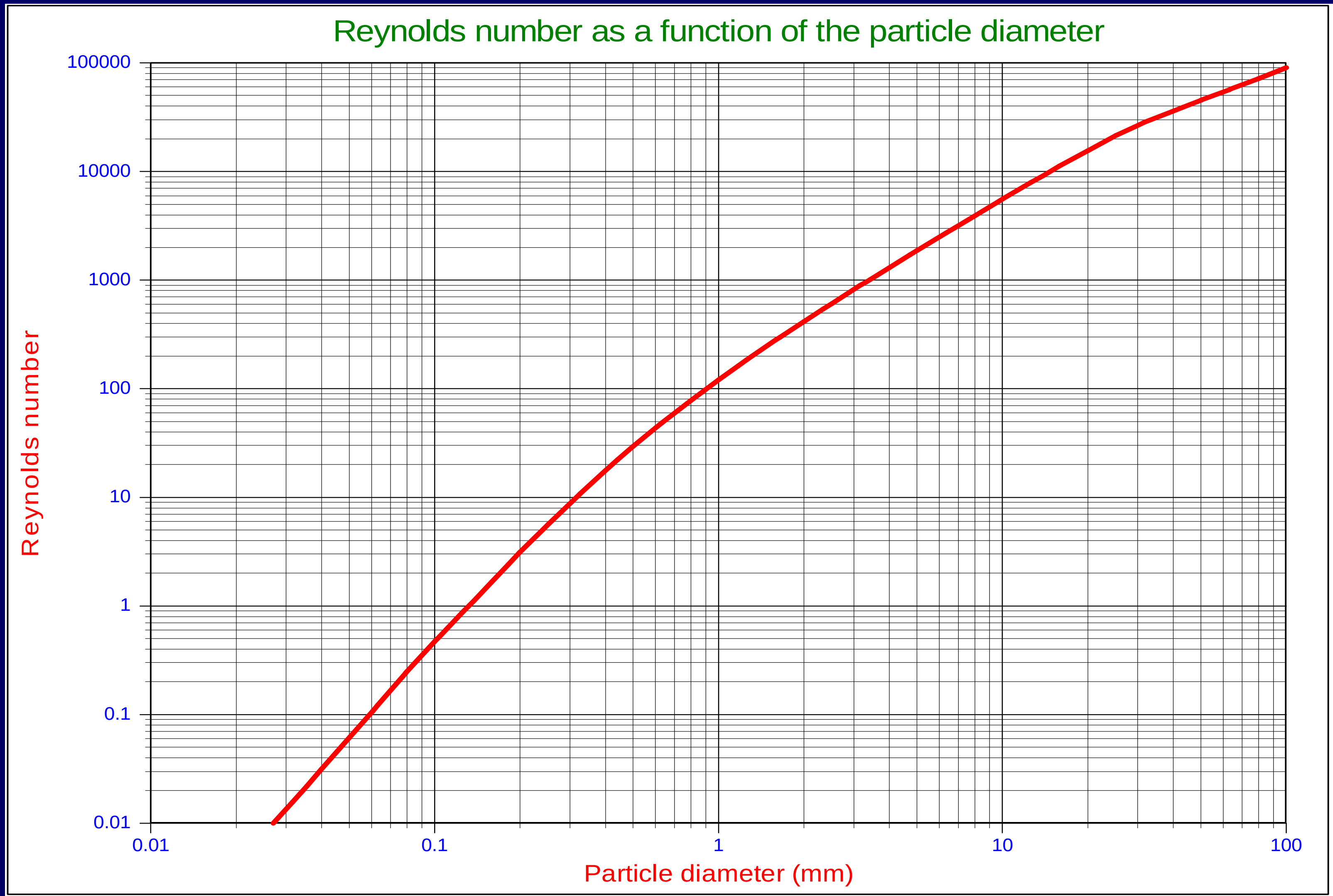
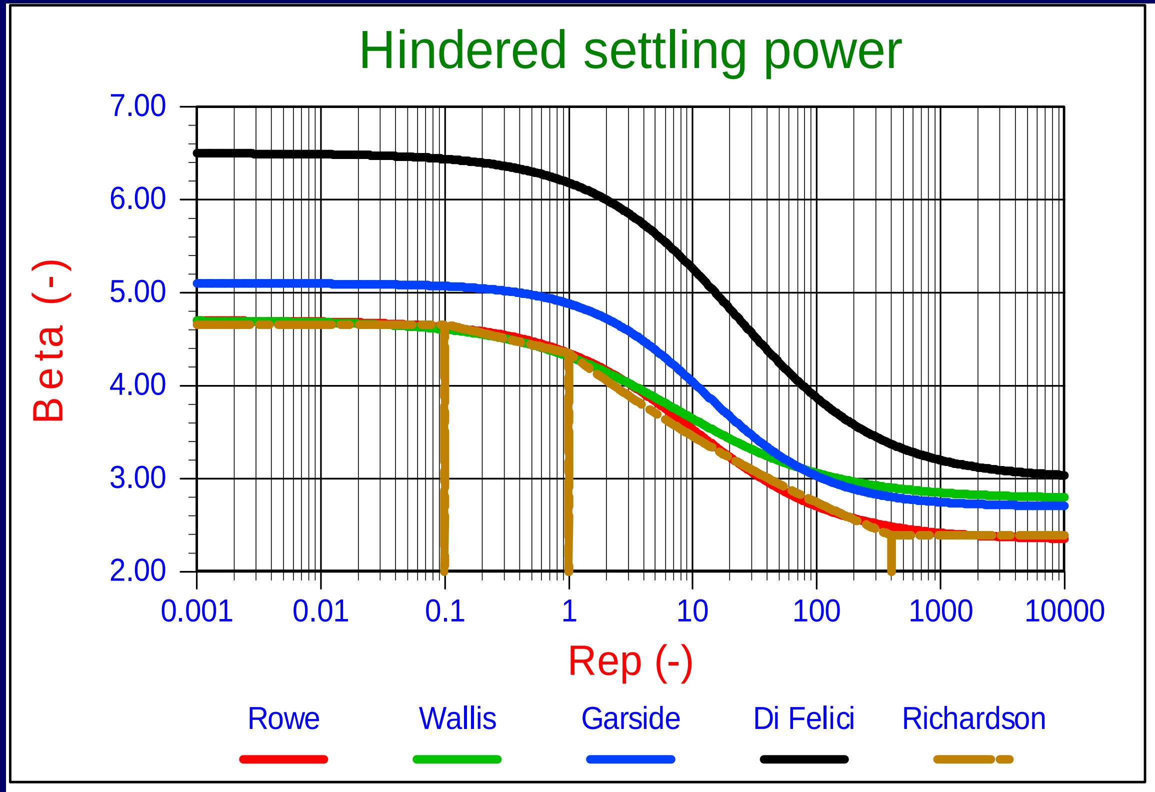
The Reynolds number as a function of the particle diameter



The hindered settling power according to several researchers



$$\frac{v_c}{v_s} = (1 - C_v)^{\beta}$$

$$\beta = \frac{4.7 + 0.41 \cdot Re_p^{0.75}}{1 + 0.175 \cdot Re_p^{0.75}}$$

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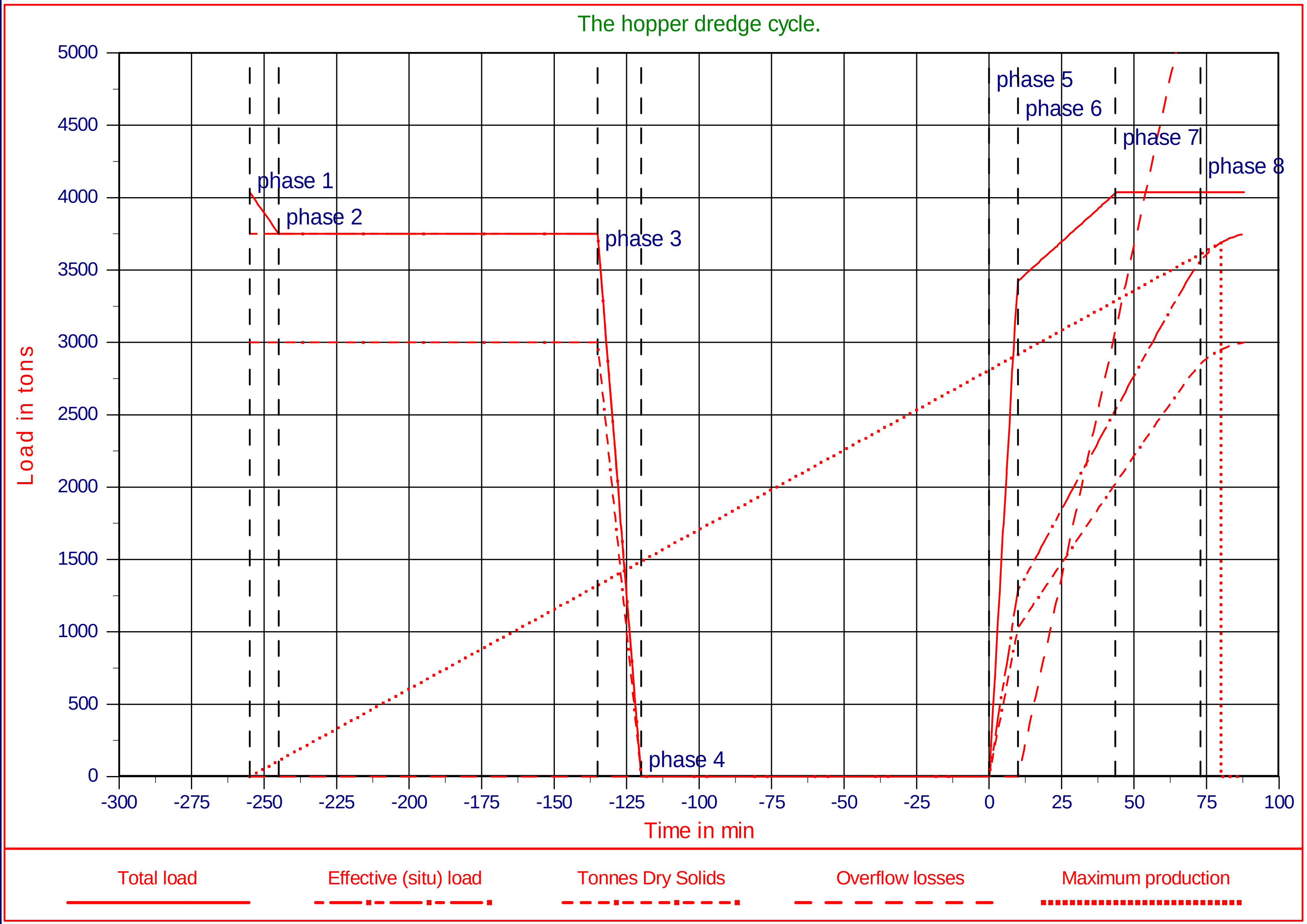
Erosion/Scour

The Amsterdam


[4]

The loading cycle of a TSHD



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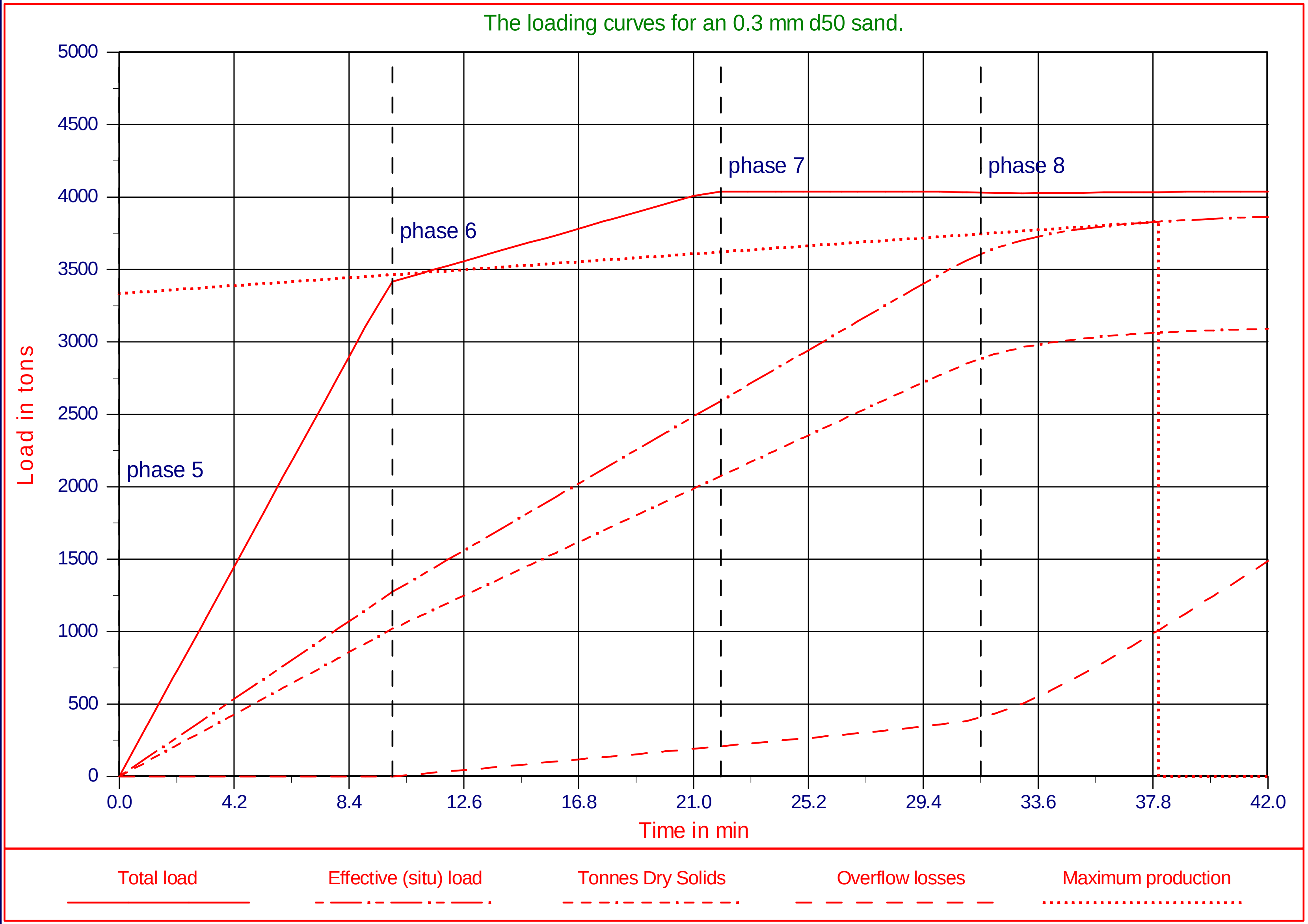
The loading part of the cycle of a TSHD



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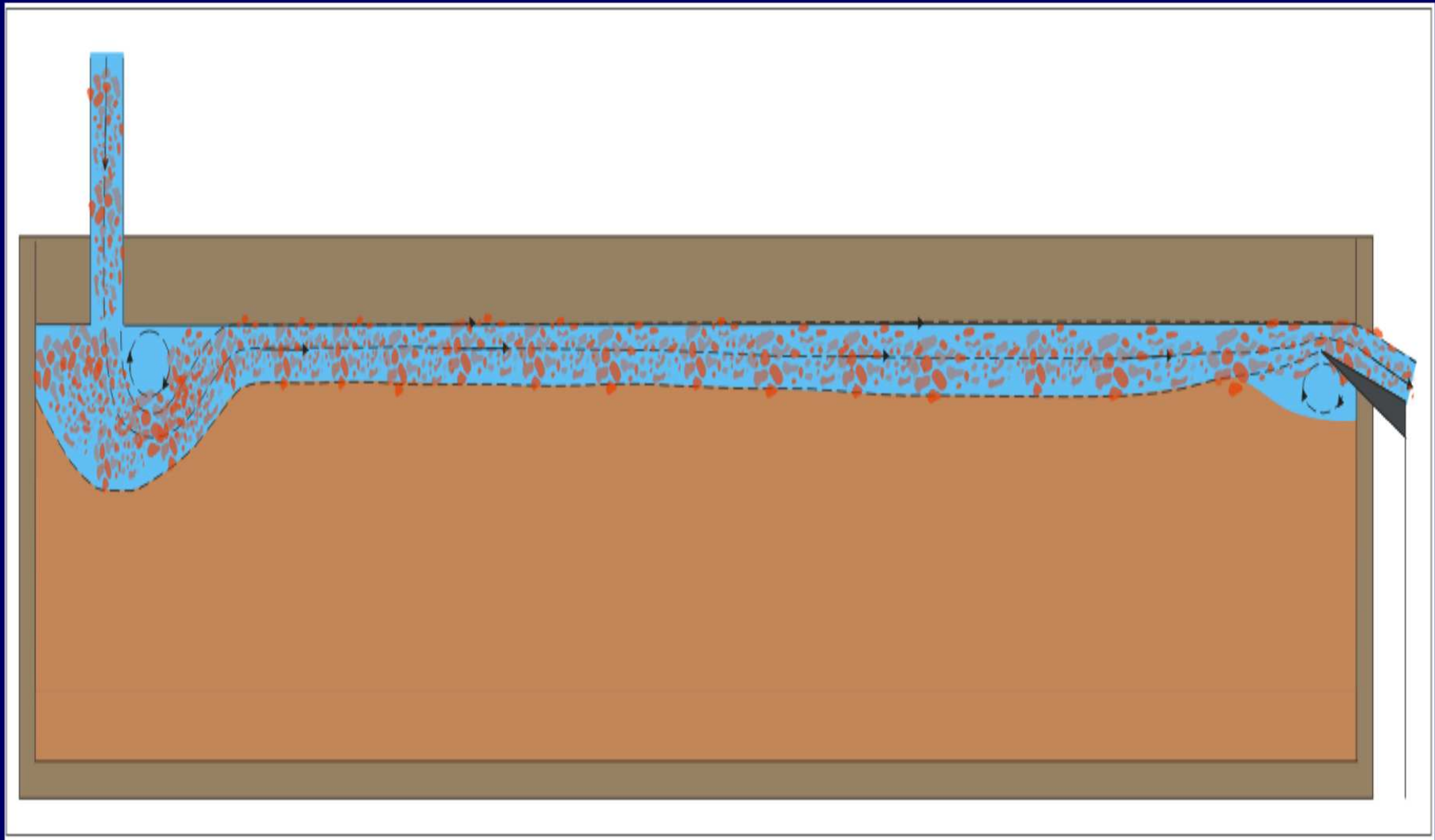
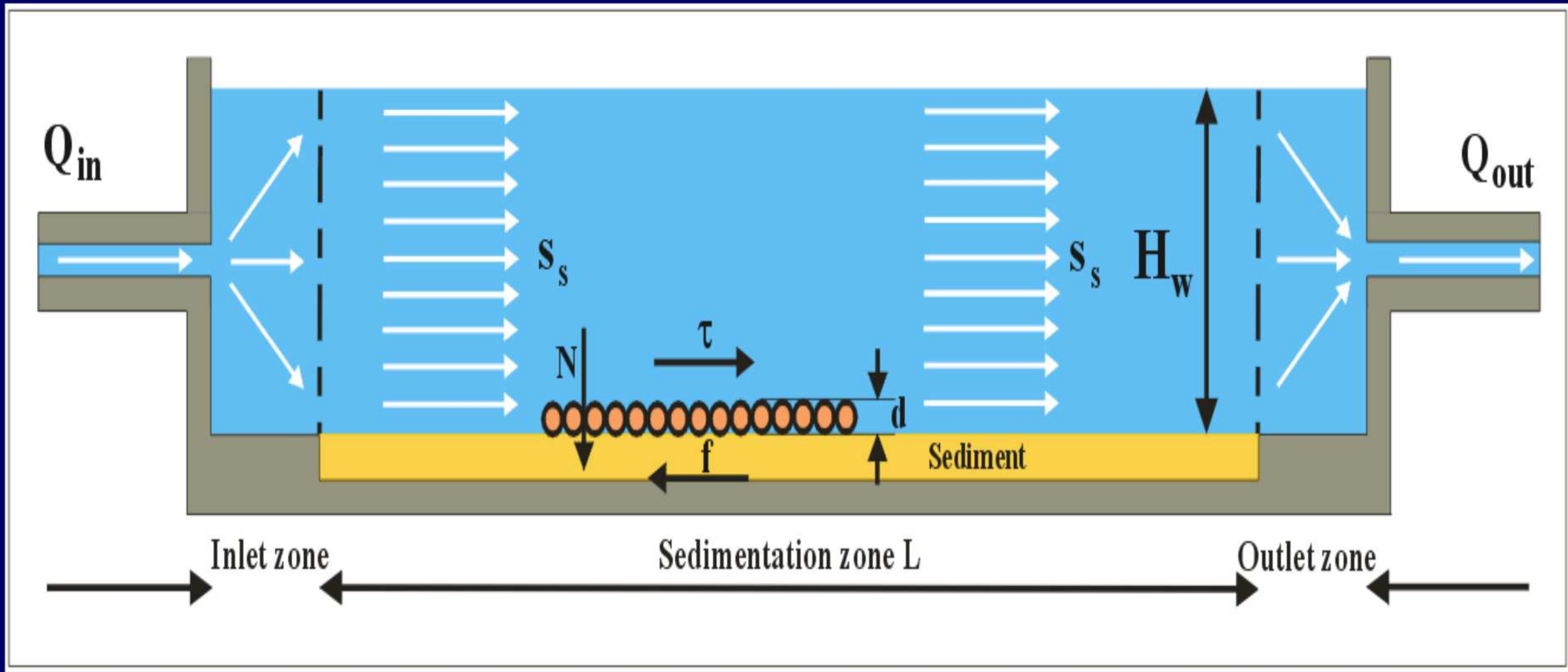
Phase 8 of the loading cycle



Erosion/scour starts to occur.

The equilibrium of forces on a particle
Camp approach



$$s_s = \sqrt{\frac{8 \cdot \mu \cdot (1 - n) \cdot (\rho_q - \rho_w) \cdot g \cdot d_s}{\lambda \cdot \rho_w}}$$

$$s_s = \sqrt{\frac{40 \cdot (\rho_q - \rho_w) \cdot g \cdot d_s}{3 \cdot \rho_w}}$$

$$d_s = \frac{3 \cdot \rho_w}{40 \cdot (\rho_q - \rho_w) \cdot g} \cdot s_s^2$$

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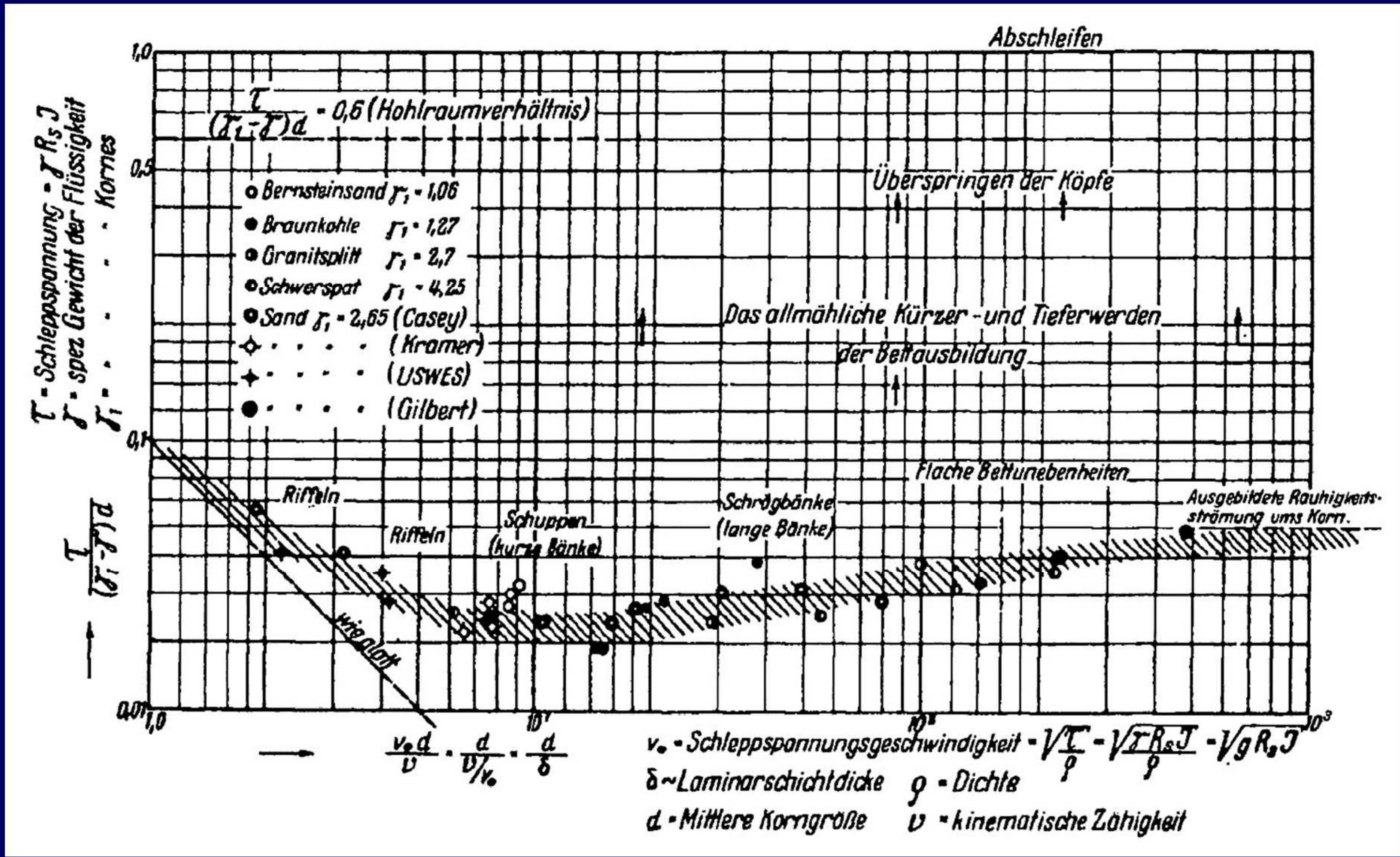
History

Shields
Experiments
Hjulstrom
Sundborg

The original Shields curve



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A modified Shields diagram

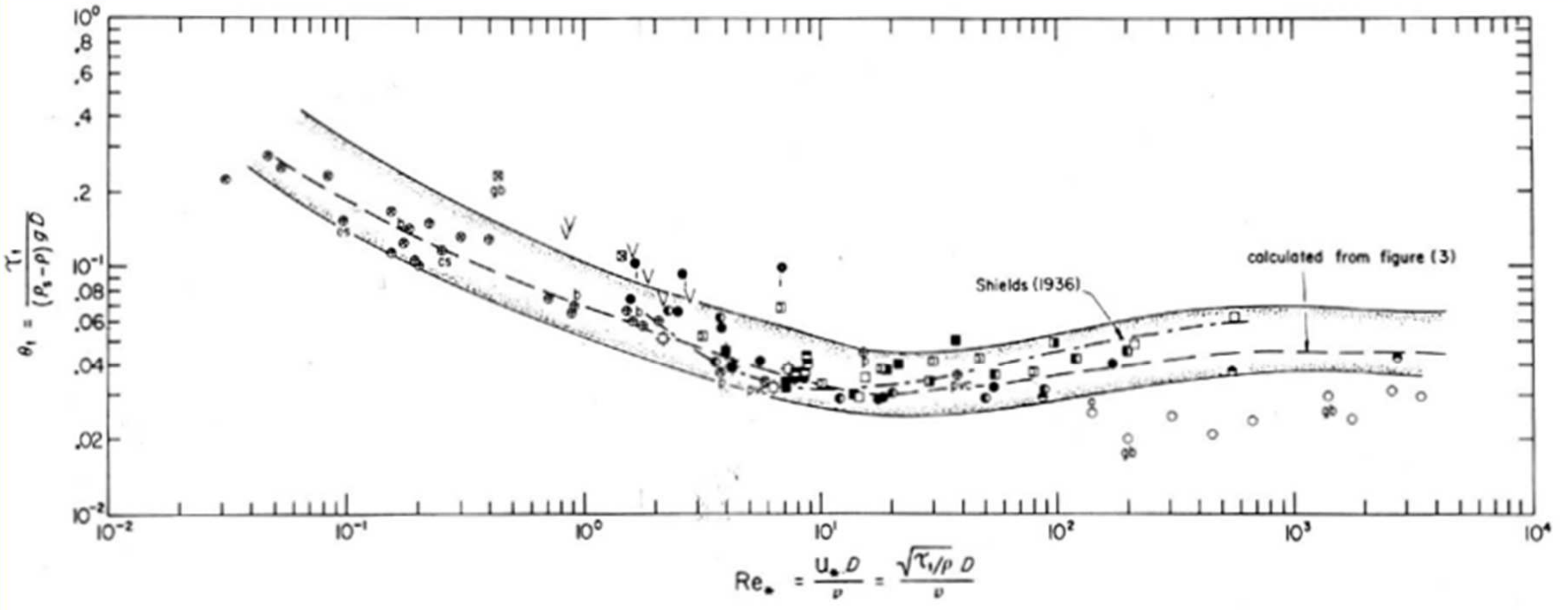
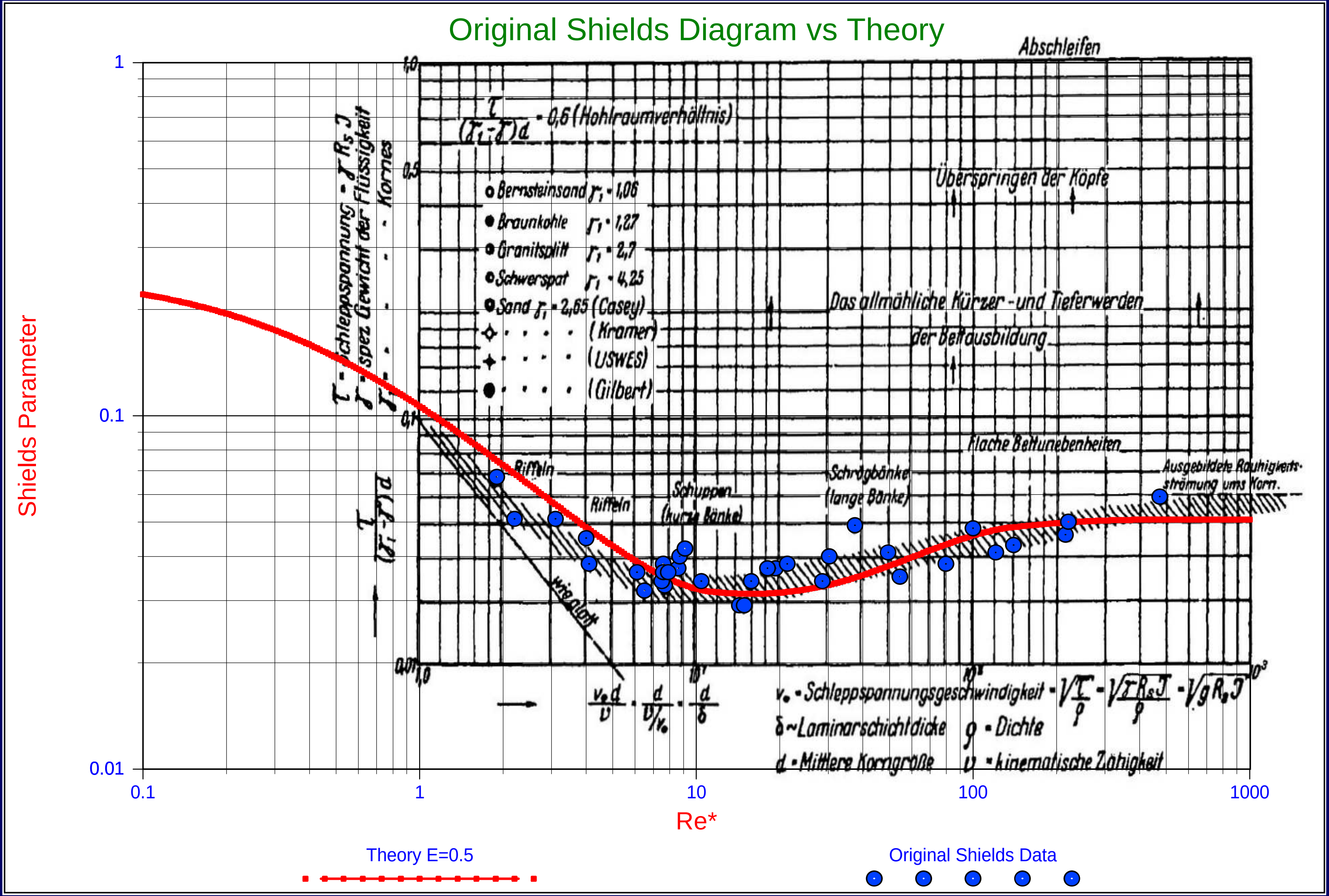
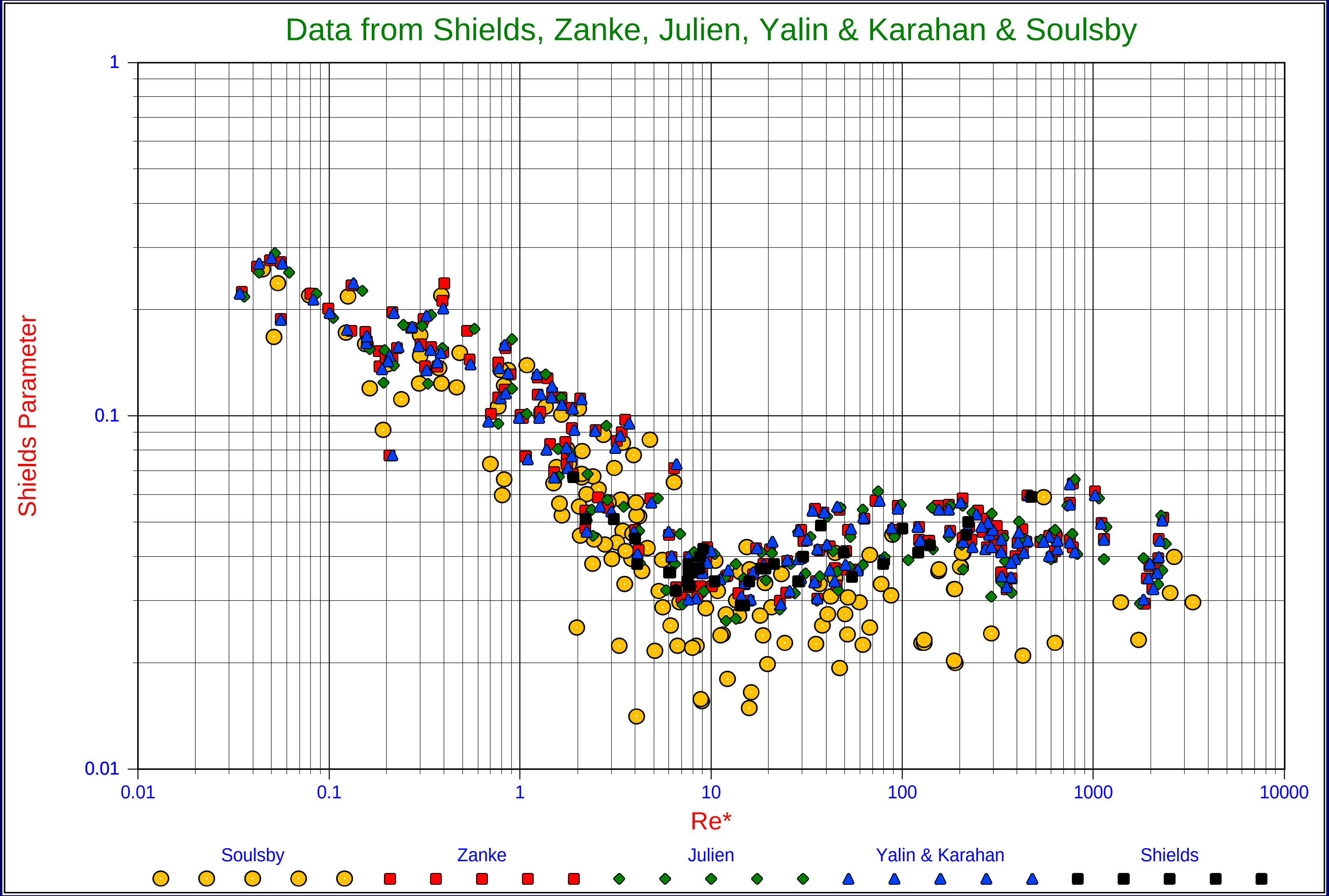


Fig. 2. The proposed modified Shields curve of θ_t versus Re_* based on additional carefully selected data. See Table 1 for identification of the symbols.

The original Shields diagram



Data points



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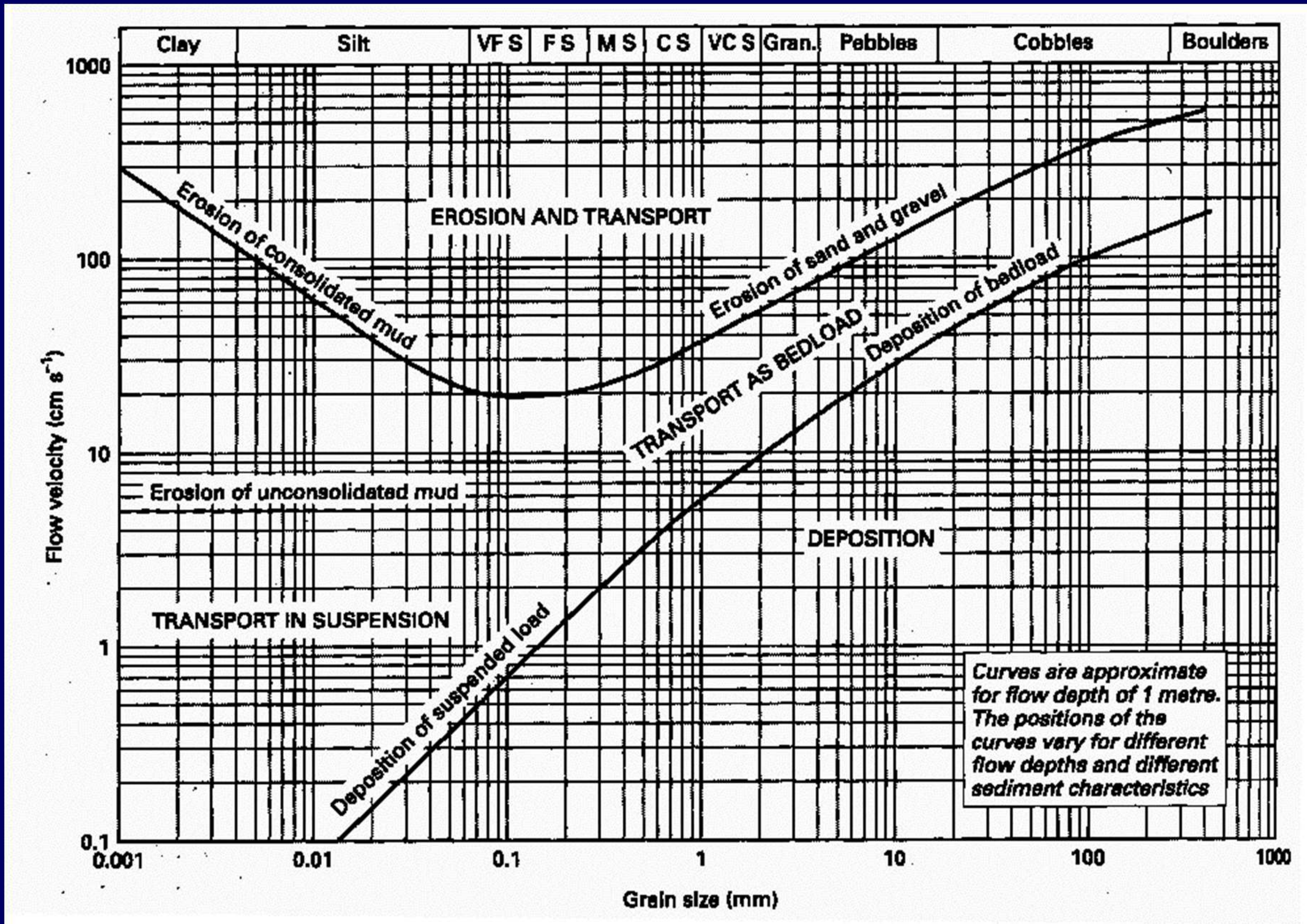
The Hjulstrom curve



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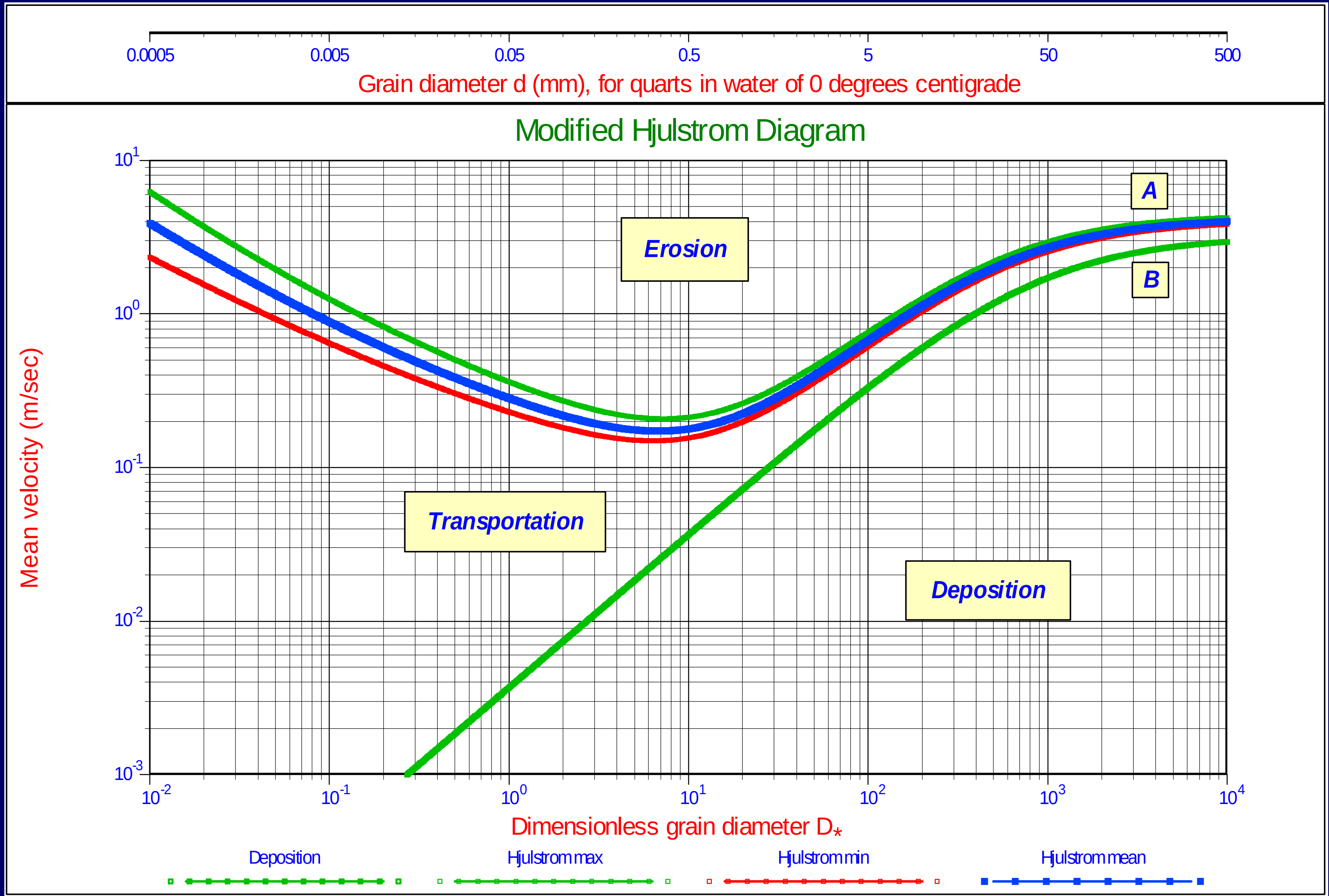
The Hjulstrom diagram



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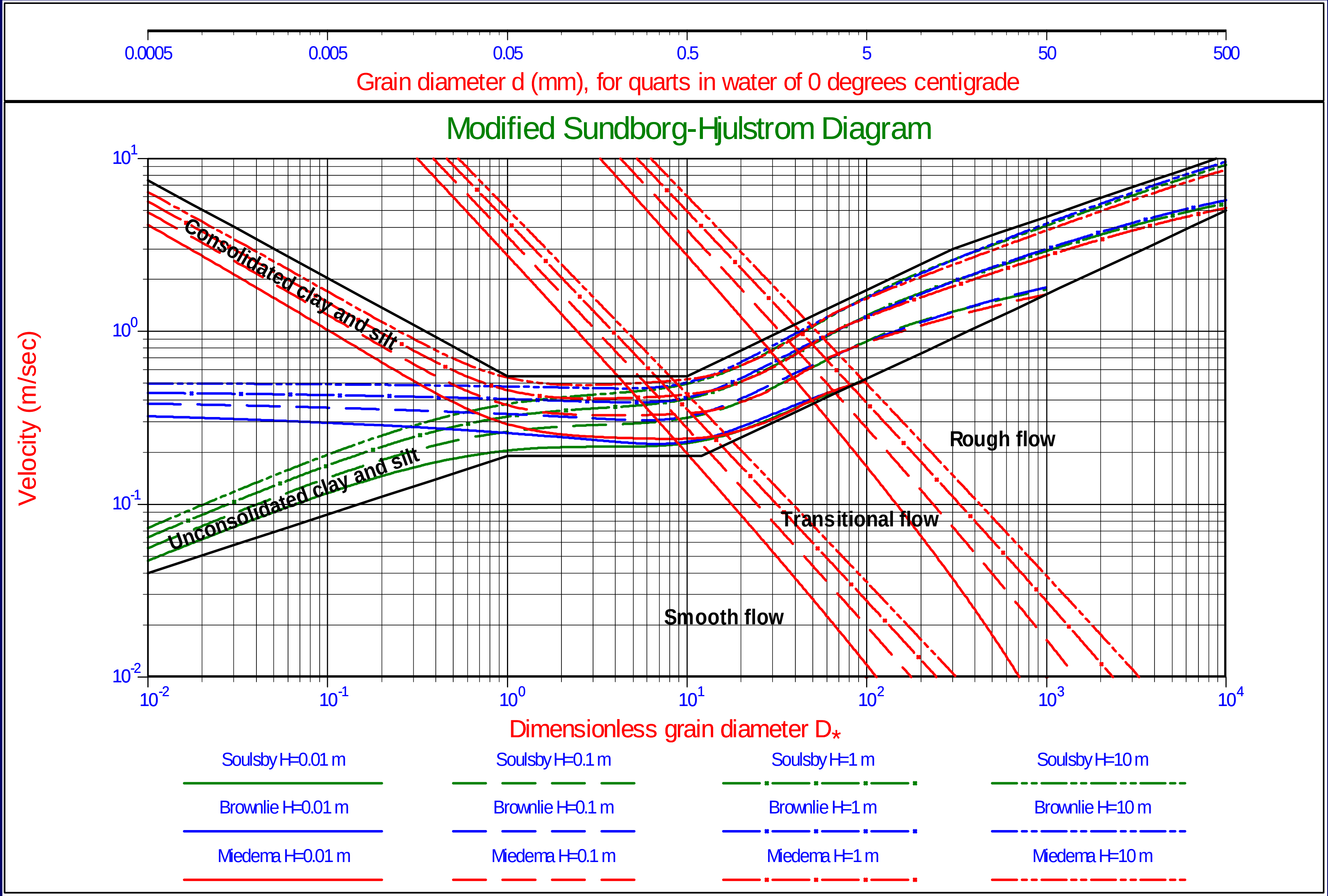
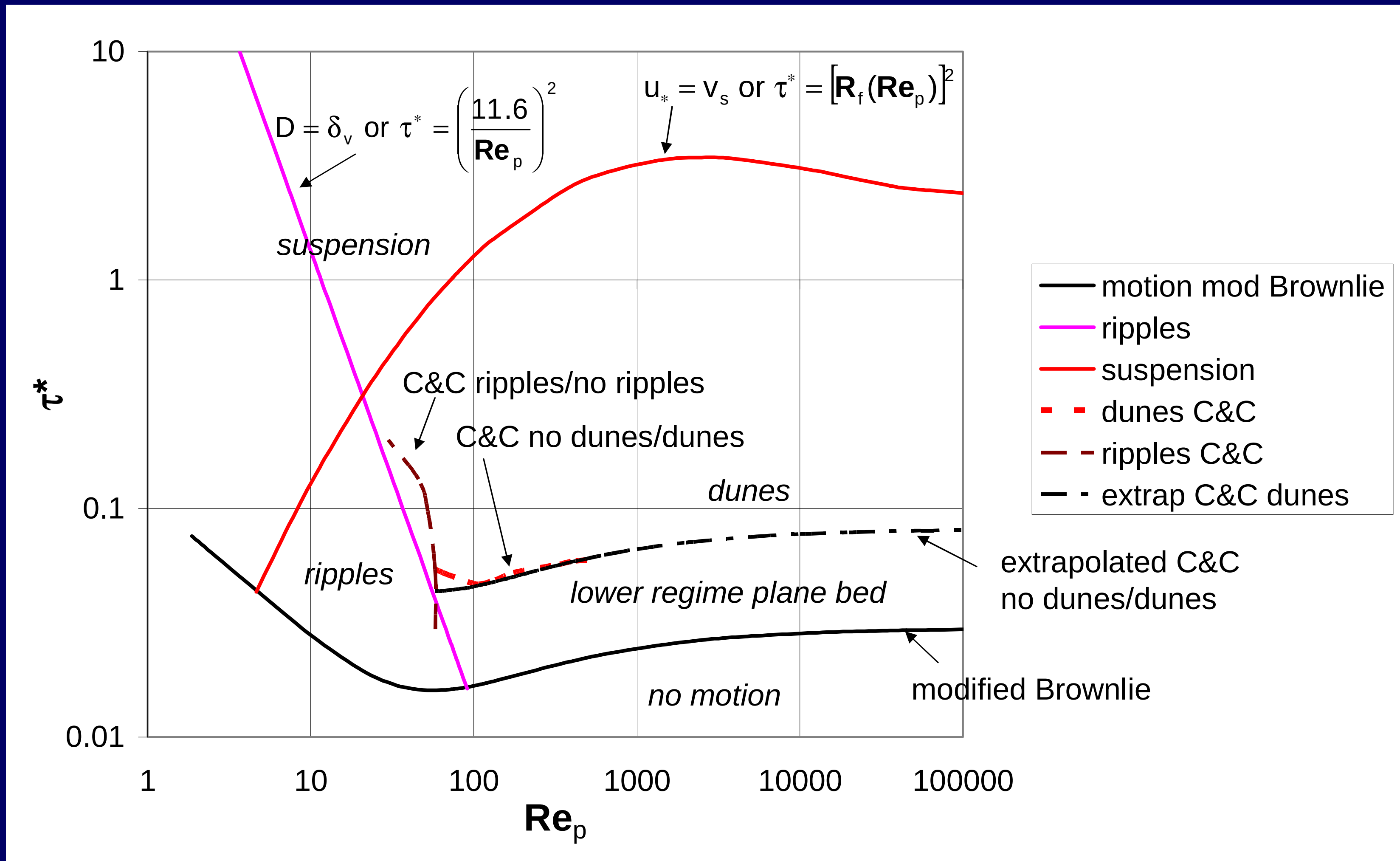
The Sundborg-Hjulstrom diagram



Shields Diagram with Criterion for Ripples (Chabert and Chauvin (1963))



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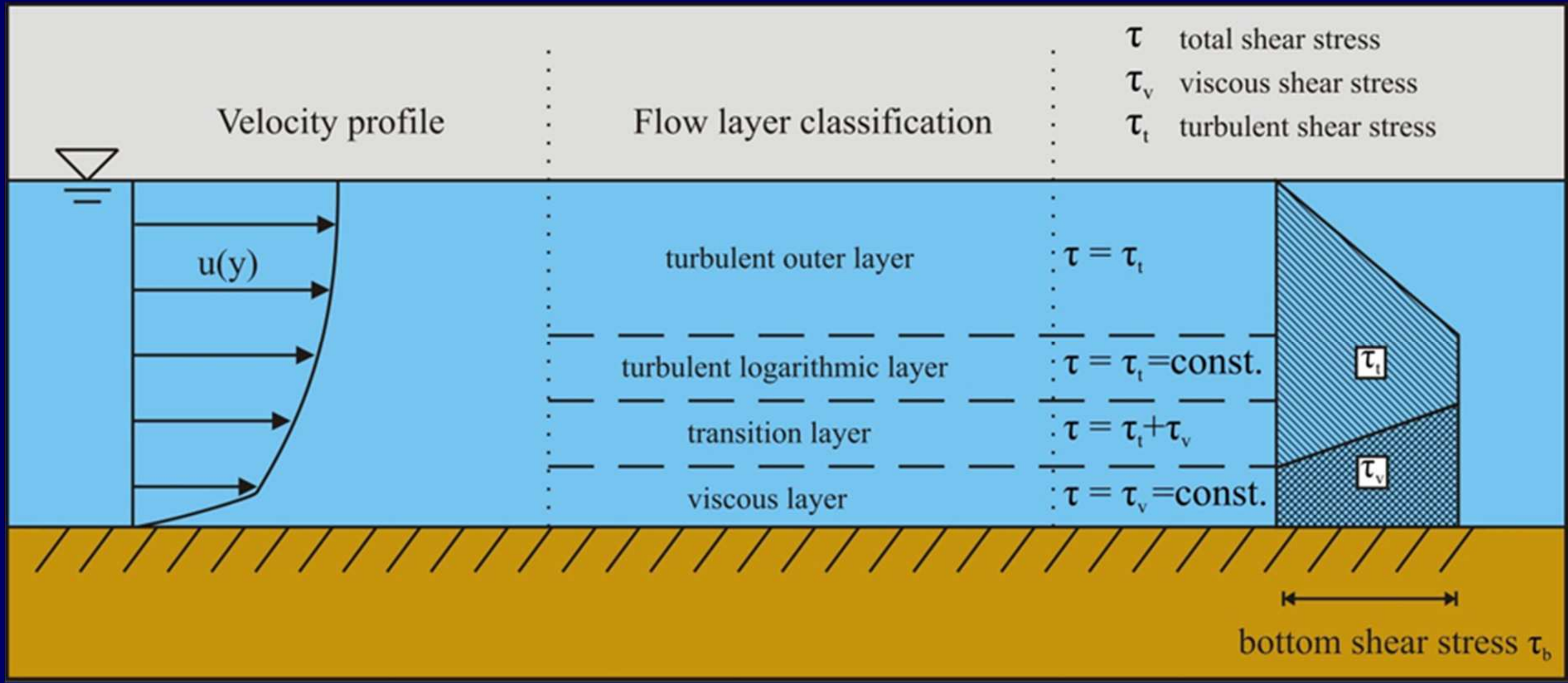
Classification of flow layers



Classification of flow layers

•Viscous sublayer: a thin layer just above the bottom. In this layer there is almost no turbulence. Measurement shows that the viscous shear stress in this layer is constant. The flow is laminar. Above this layer the flow is turbulent.

•Transition layer: also called buffer layer. viscosity and turbulence are equally important.

•Turbulent logarithmic layer: viscous shear stress can be neglected in this layer. Based on measurement, it is assumed that the turbulent shear stress is constant and equal to bottom shear stress. It is in this layer where Prandtl introduced the mixing length concept and derived the logarithmic velocity profile.

•Turbulent outer layer: velocities are almost constant because of the presence of large eddies which produce strong mixing of the flow.

Friction velocity

The bottom shear stress is often represented by friction velocity, defined by

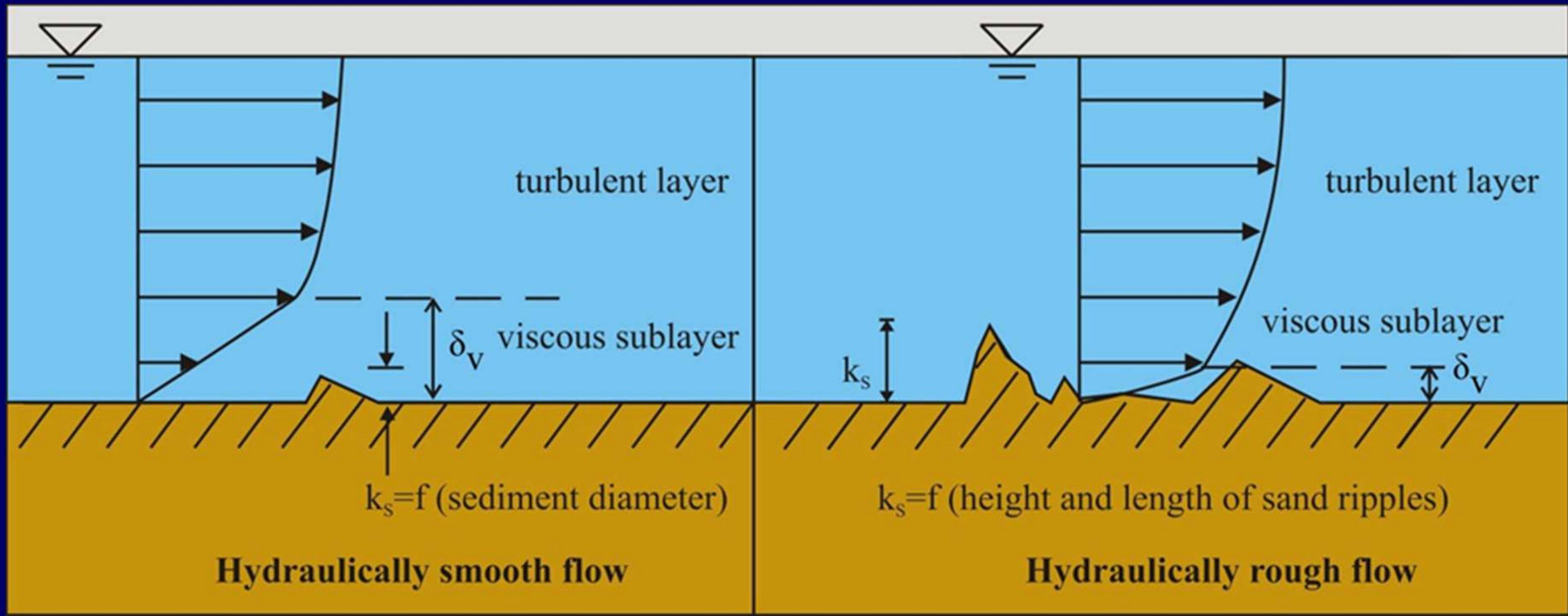
$$u_* = \sqrt{\frac{\tau_b}{\rho}} \qquad u_*^2 = \frac{\lambda}{8} \cdot U_{cr}^2$$

The term *friction velocity* comes from the fact that $\sqrt{\tau_b / \rho}$

has the same unit as velocity and it has something to do with friction force

$$\lambda = \frac{1.325}{\left(\ln\left(\frac{d}{3.7 \cdot D} + \frac{5.75}{Re^{0.9}}\right)\right)^2} = \frac{0.25}{\left(\log\left(\frac{d}{3.7 \cdot D} + \frac{5.75}{Re^{0.9}}\right)\right)^2}$$

Engineering classification



Velocity distribution:

Viscous sublayer

$$u(z) = \frac{\tau_b}{\rho} \cdot \frac{z}{\nu} = \frac{u_*^2}{\nu} \cdot z$$

Turbulent layer

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

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Engineering classification

- Hydraulically smooth flow for $\frac{u_* k_s}{\nu} \leq 5$

Bed roughness is much smaller than the thickness of viscous sublayer. Therefore, the bed roughness will not affect the velocity distribution

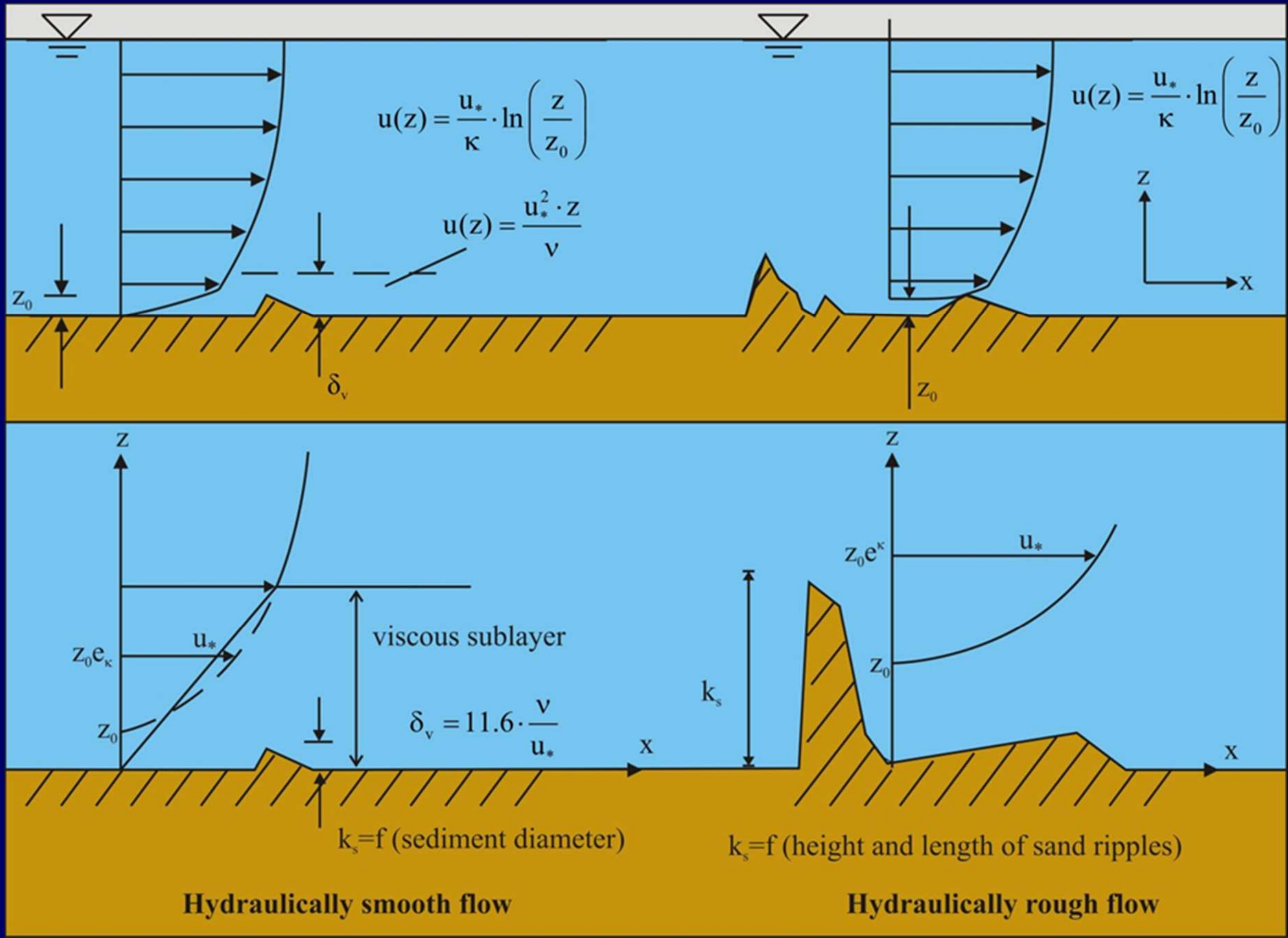
- Hydraulically rough flow for $\frac{u_* k_s}{\nu} \geq 70$

Bed roughness is so large that it produces eddies close to the bottom. A viscous sublayer does not exist and the flow velocity is not dependent on viscosity.

- Hydraulically transitional flow for $5 \leq \frac{u_* k_s}{\nu} \leq 70$

The velocity distribution is affected by bed roughness and viscosity.

The velocity distribution



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The velocity distribution

Hydraulically smooth flow $\frac{u_* k_s}{\nu} \leq 5$ $\qquad z_0 = 0.11 \cdot \frac{\nu}{u_*}$

Hydraulically rough flow $\frac{u_* k_s}{\nu} \geq 70$ $\qquad z_0 = 0.033 \cdot k_s$

Hydraulically transitional flow $5 \leq \frac{u_* k_s}{\nu} \leq 70$ $\qquad z_0 = 0.11 \cdot \frac{\nu}{u_*} + 0.033 \cdot k_s$

Theoretical viscous sub layer thickness: $\delta_\nu = 11.6 \cdot \frac{\nu}{u_*}$

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Literature

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Wiberg & Smith (1987)

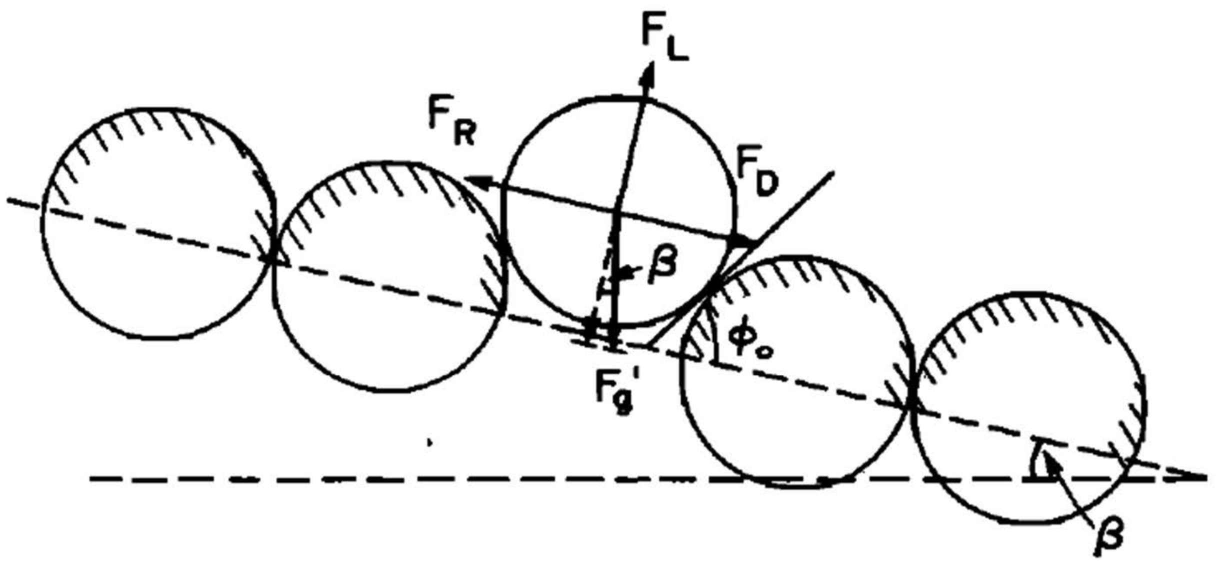

Fig. 1. Forces balance on a particle at the surface of a bed. F_L, F_D, $F_g{}'$, and F_R are the lift drag, gravitational, and resisting forces, respectively; β is the slope of the bed, and ϕ_0 is the particle angle of repose.

$$(\tau_*)_{cr} = \frac{2}{(C_D)_{cr}\alpha} \frac{1}{\langle f^2(z/z_0)\rangle} \frac{(\tan\phi_0 \cos\beta - \sin\beta)}{[1 + (F_L/F_D)_{cr} \tan\phi_0]} \qquad (8)$$

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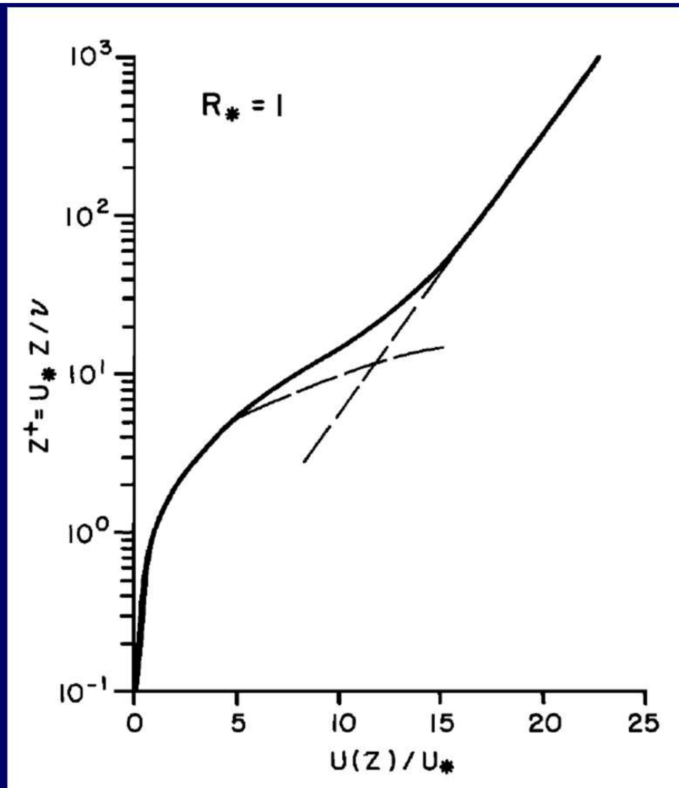
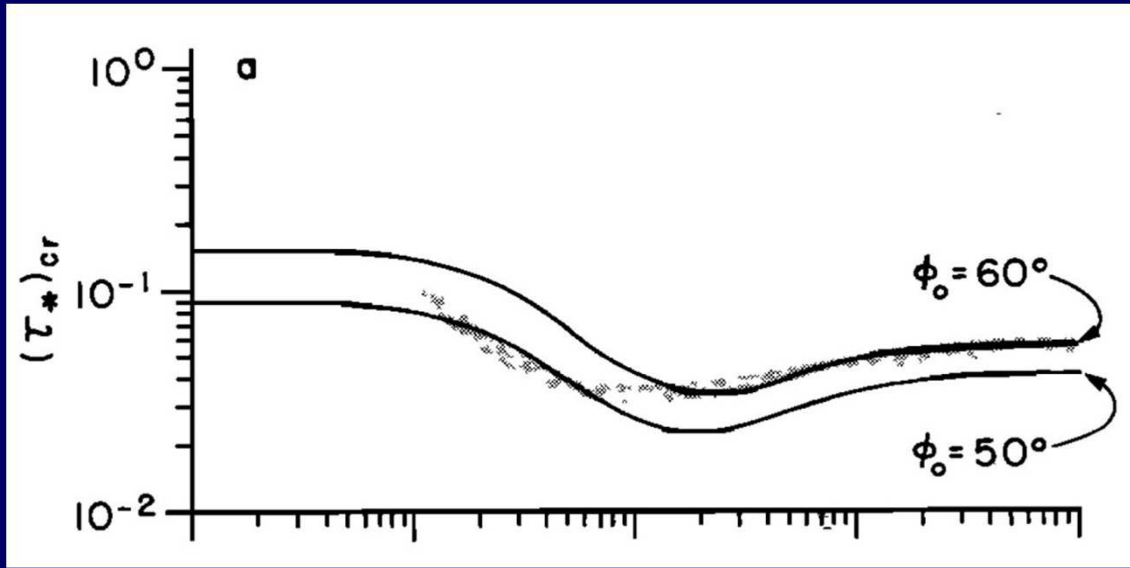
Wiberg & Smith (1987)

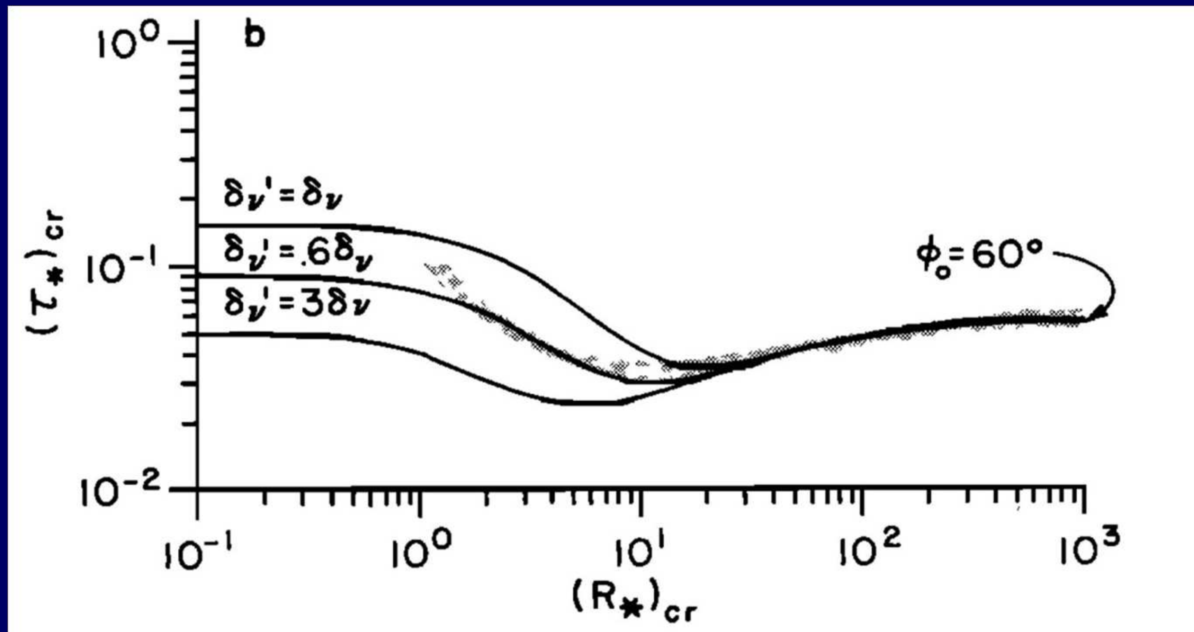
$$u(z) = u_*\left[\frac{1}{\kappa}\ln\left(1+\kappa z^+\right) - c\left(1 - e^{-z^+/11.6} - \frac{z^+}{11.6}e^{-0.33z^+}\right)\right] \tag{10}$$

where $z^+ = u_* z/\nu = R_* z/k_s$ and $z_0{}^+ = u_* z_0/\nu = R_* z_0/k_s$. The coefficient $c = \kappa^{-1}[\ln(z_0{}^+) + \ln\kappa] = -7.78$ for hydraulically smooth flow, since $z_0 = \nu/(9u_*)$. Figure 2 shows the velocity profile calculated from (10) for $R_* = 1.0$.



Wiberg & Smith (1987)





The Physics

The equilibrium equations for sliding and rolling

The velocity distribution

The transition smooth-rough

The drag coefficient C_D

The lift coefficient C_L

The friction coefficient/angle of internal friction

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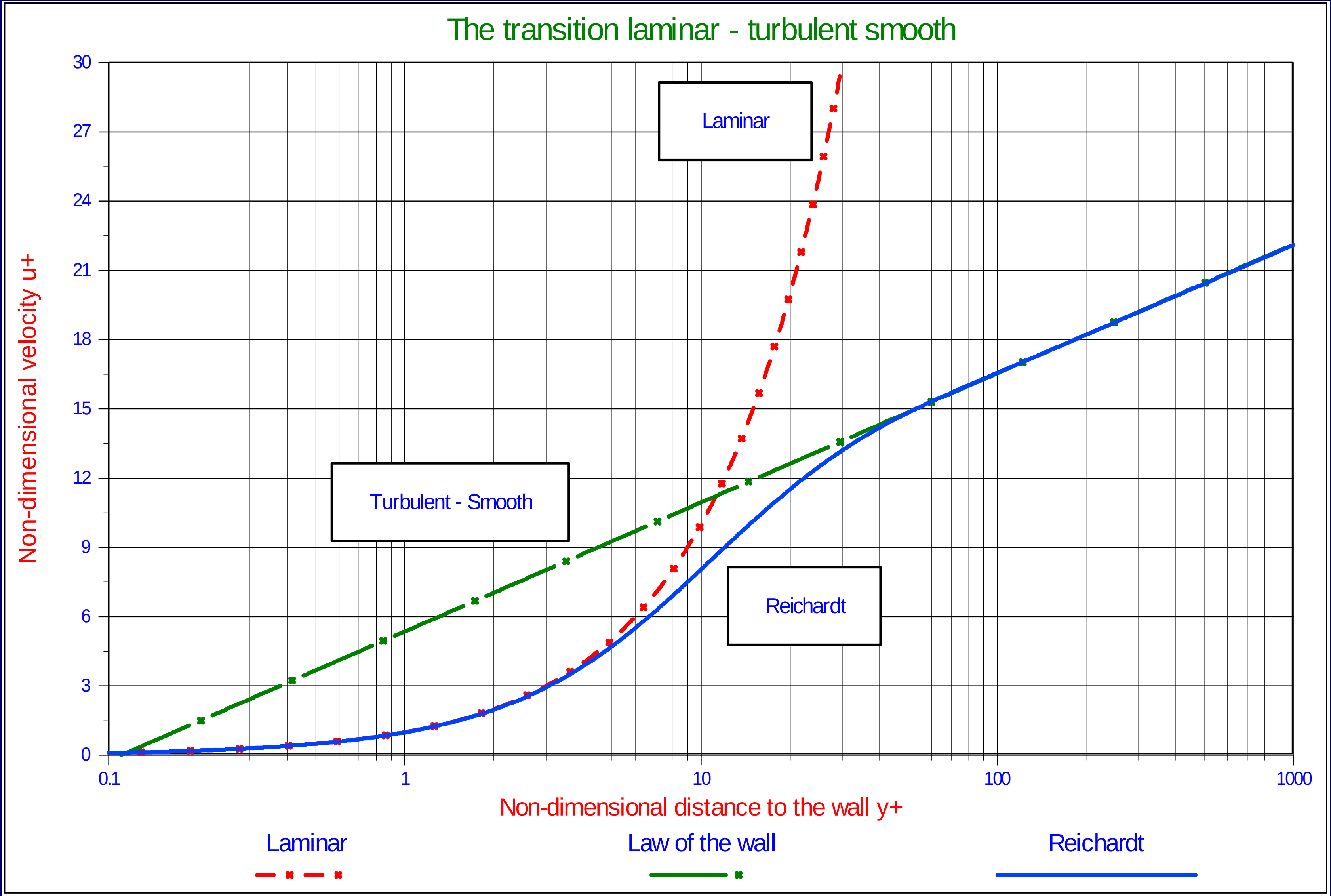
The velocity profile near the wall



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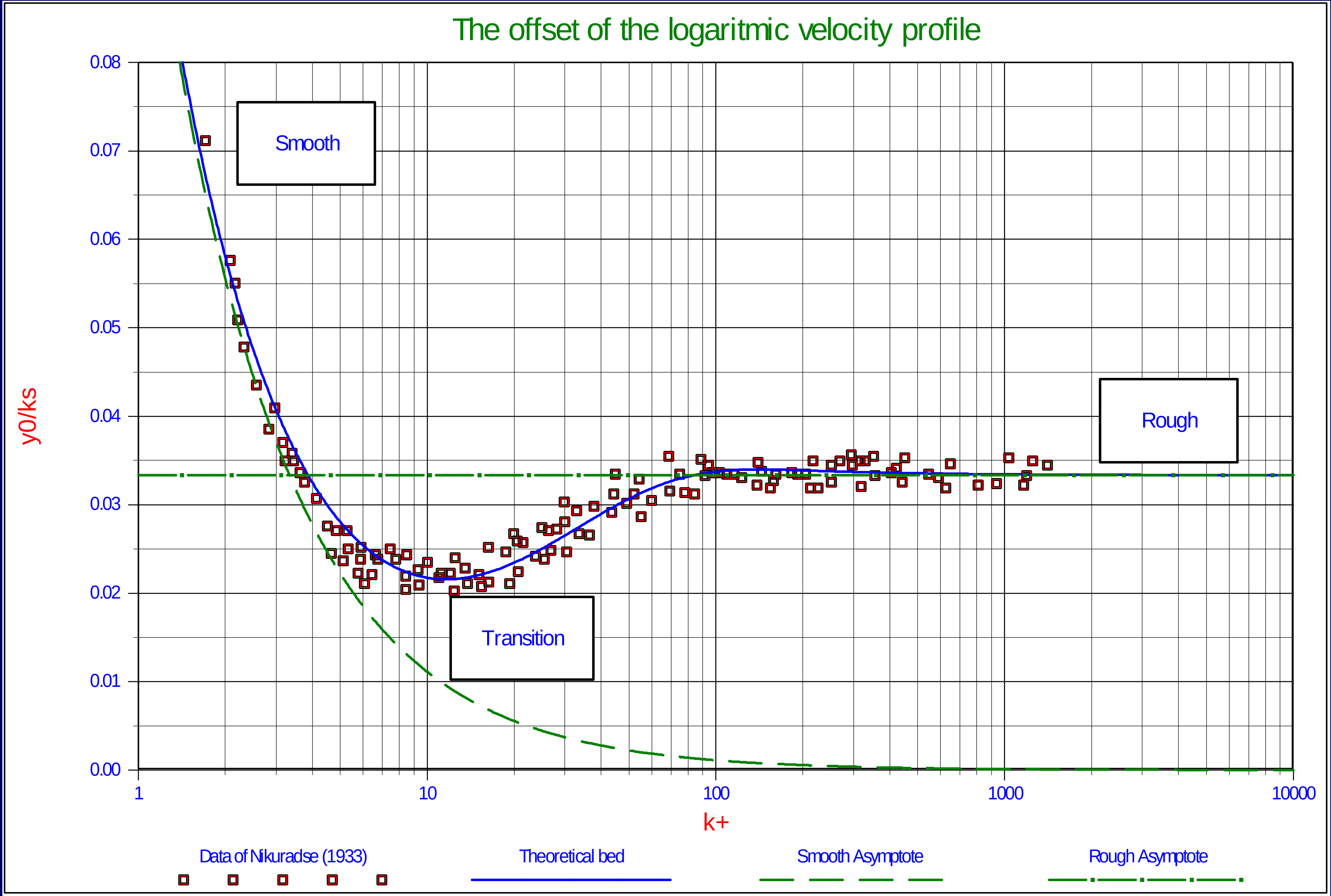
The transition smooth-rough



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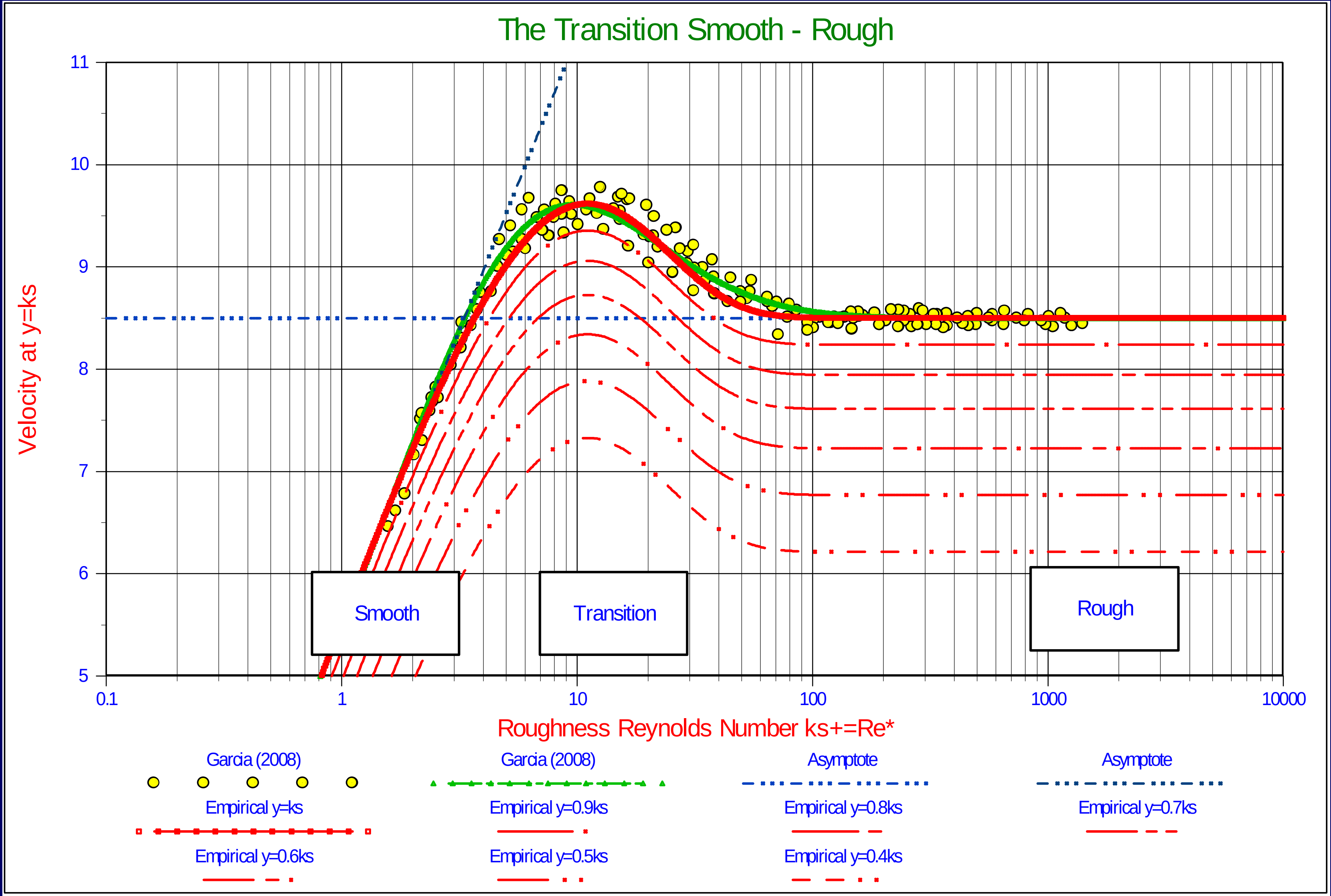
The transition rough-smooth



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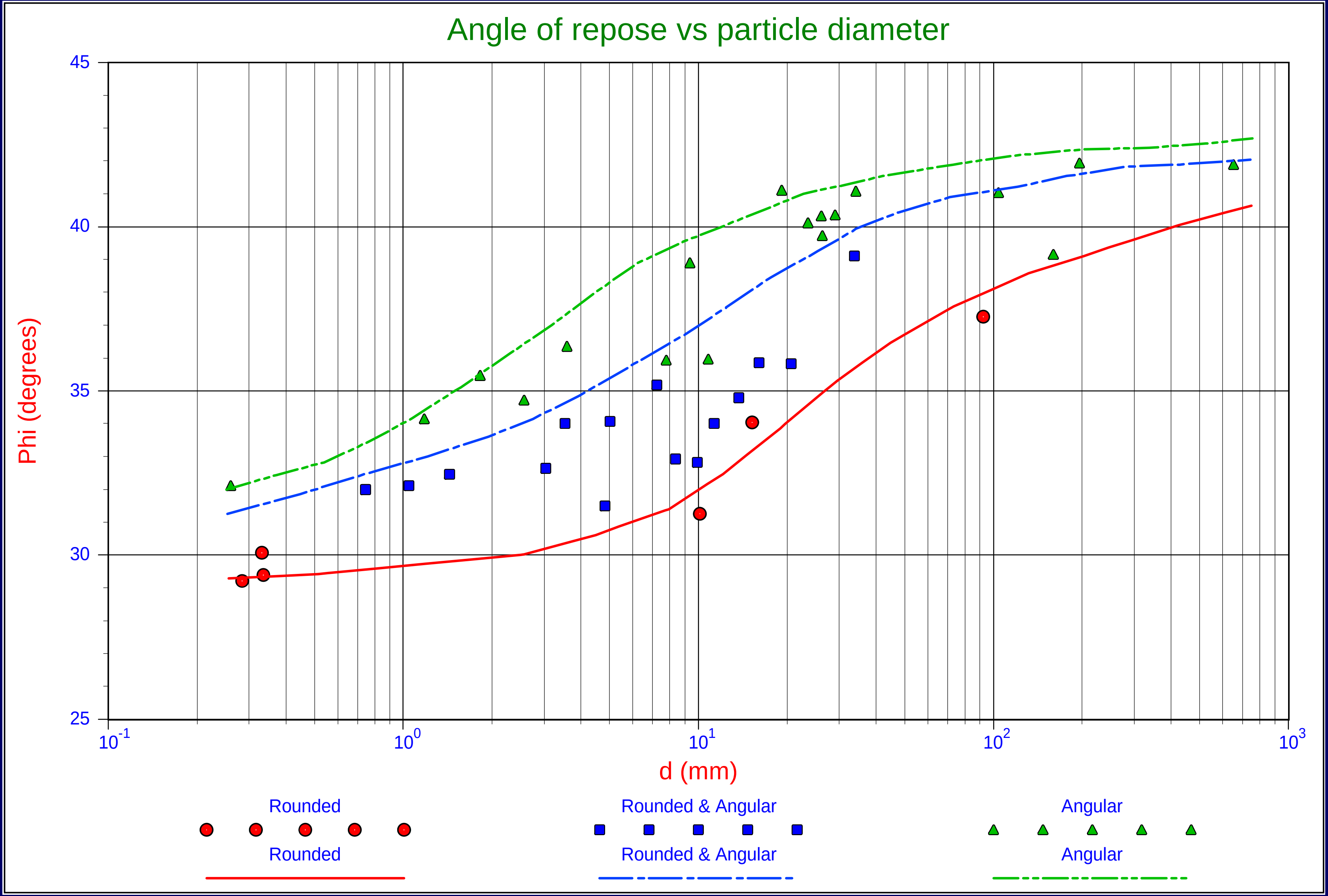
The angle of repose for granular material



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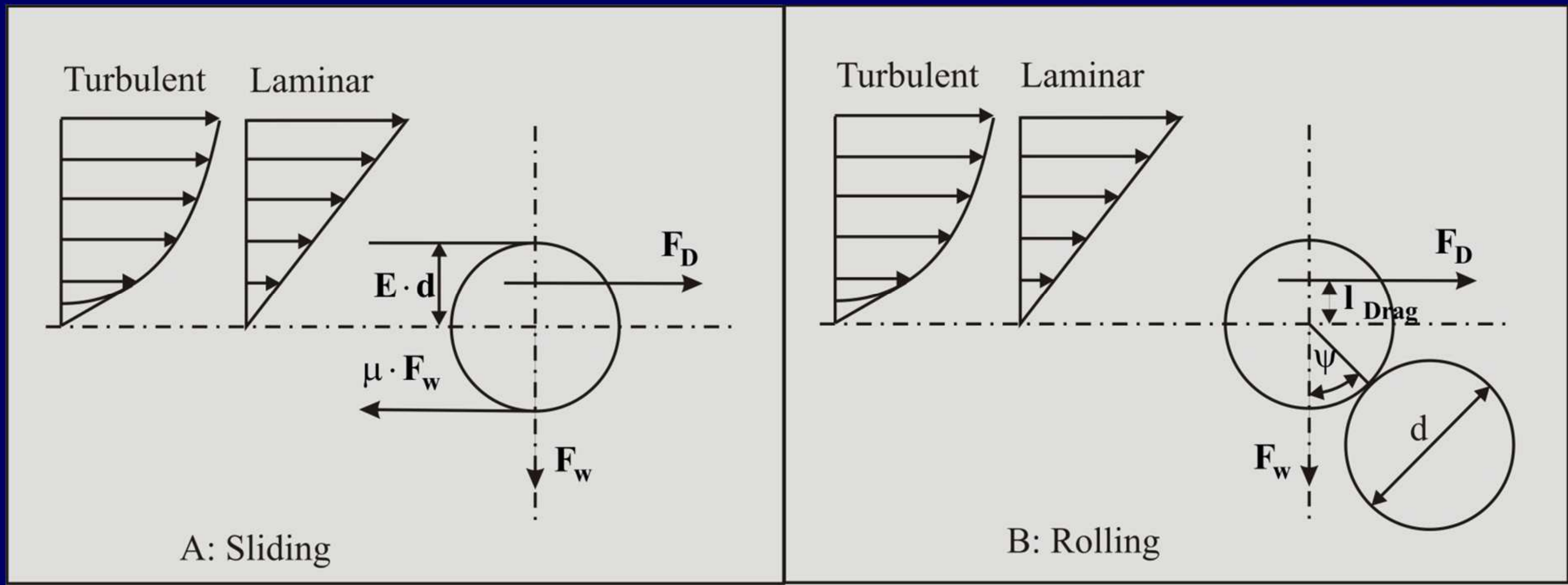
Drag induced sliding & rolling



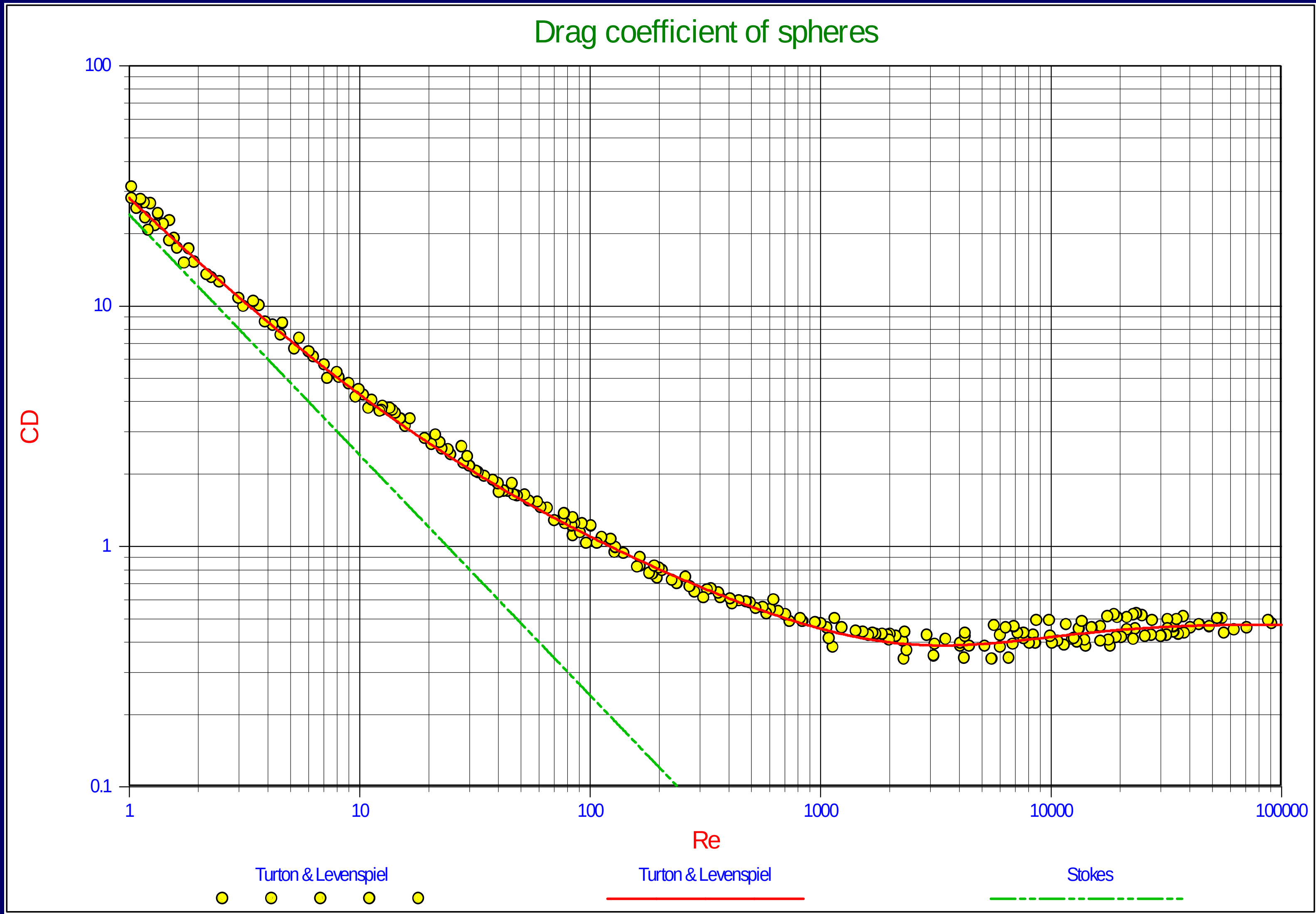
Sliding

$$\theta = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\mu}{\ell_{Drag}^2 \cdot f_D \cdot C_D}$$

Rolling

$$\theta = \frac{u_*^2}{R \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\sin(\psi + \phi_{Roll})}{\ell_{Drag}^2 \cdot f_D \cdot C_D \cdot (\ell_{Lever} + \cos(\psi + \phi_{Roll}))}$$

Thye Drag Coefficient of Spheres



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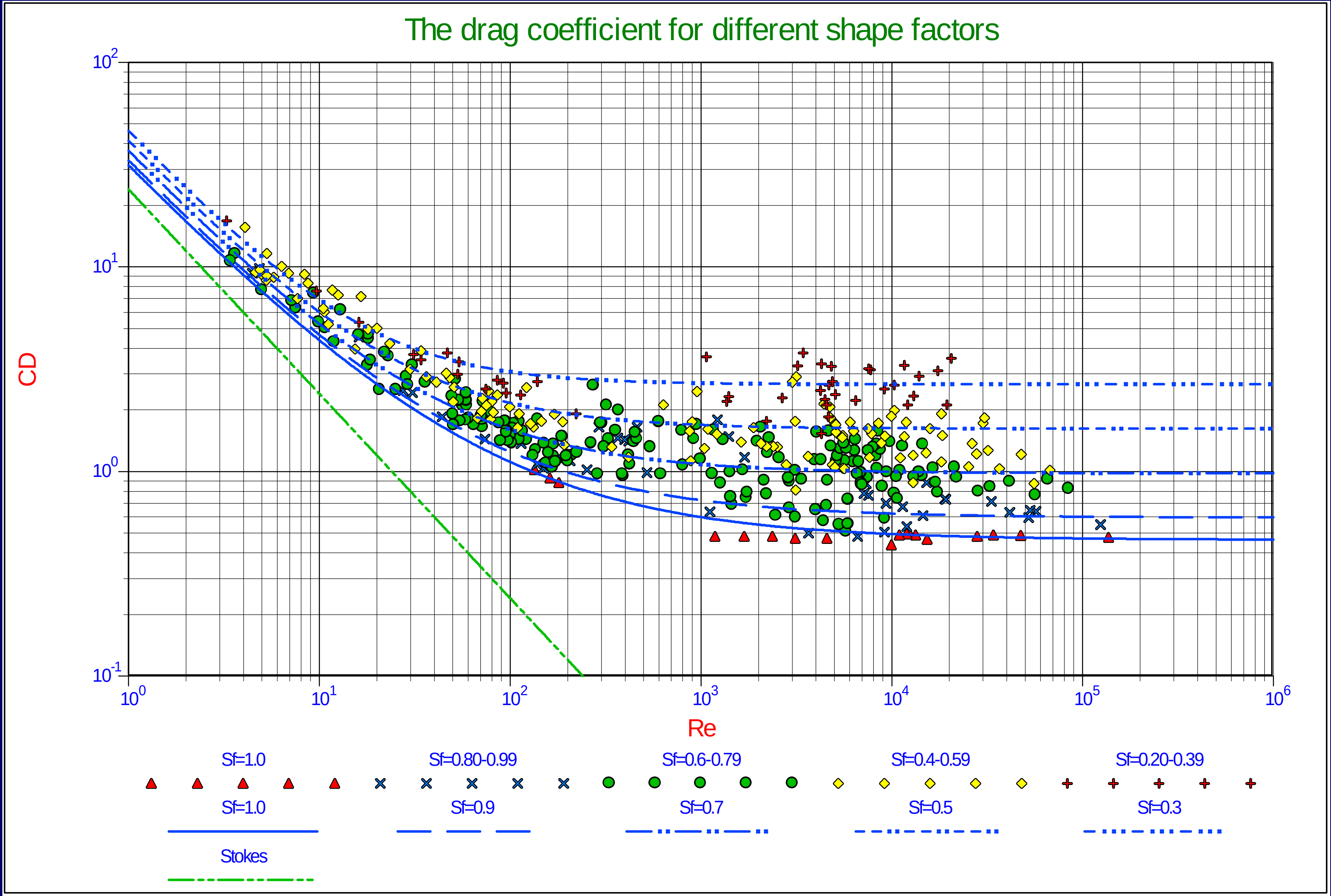
The drag coefficient C_D



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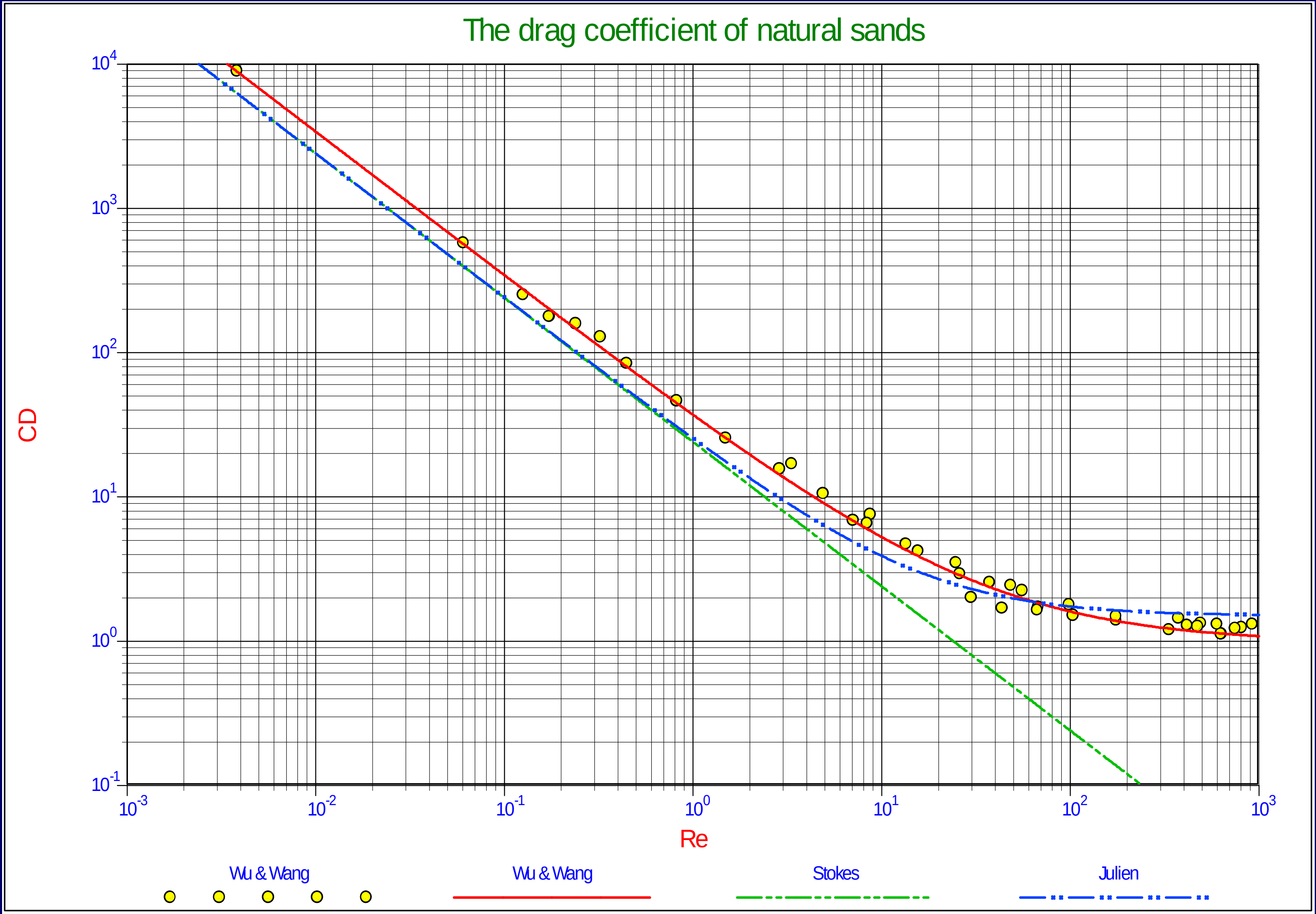
The Drag Coefficient for Natural Sediments



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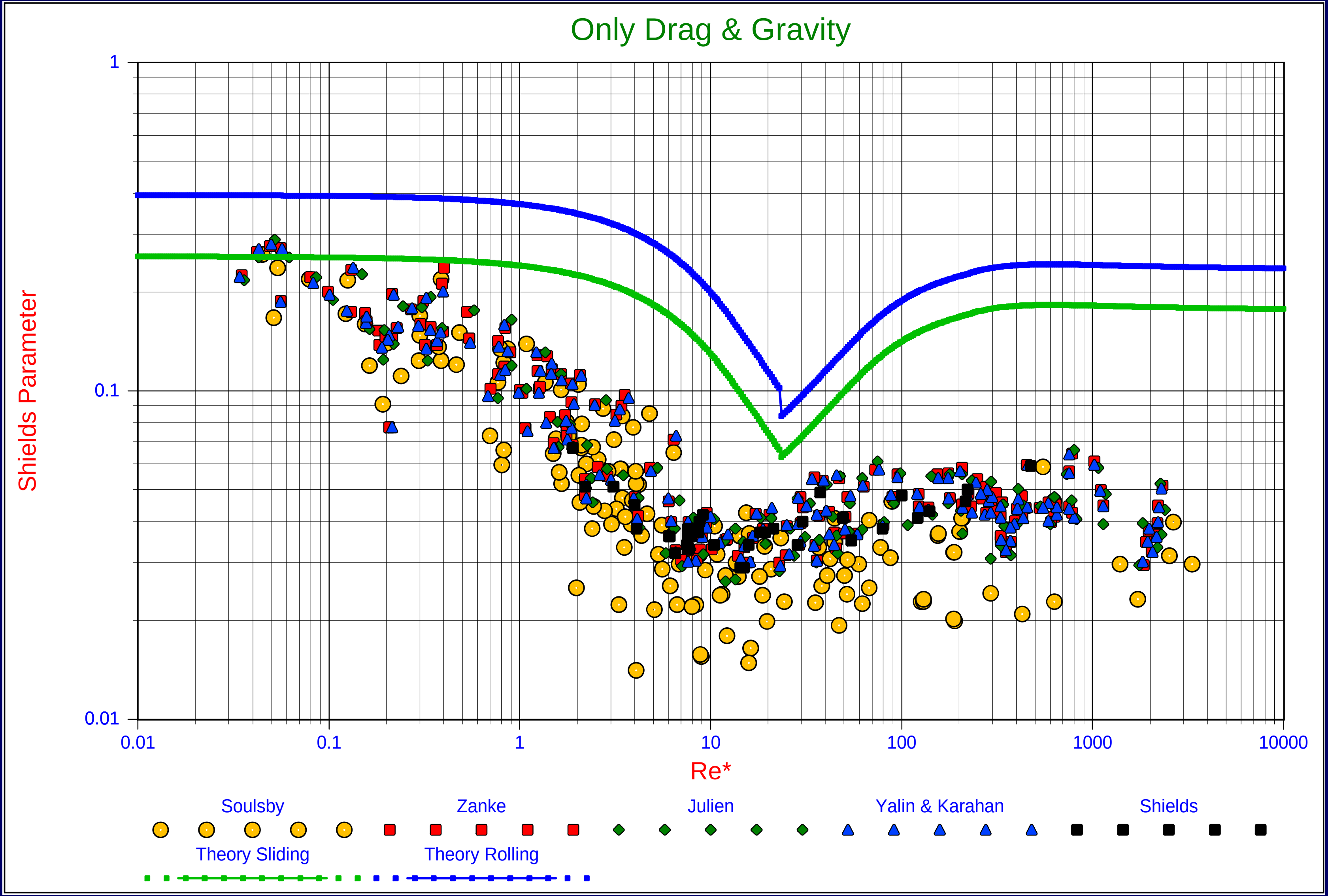
Drag induced sliding & rolling



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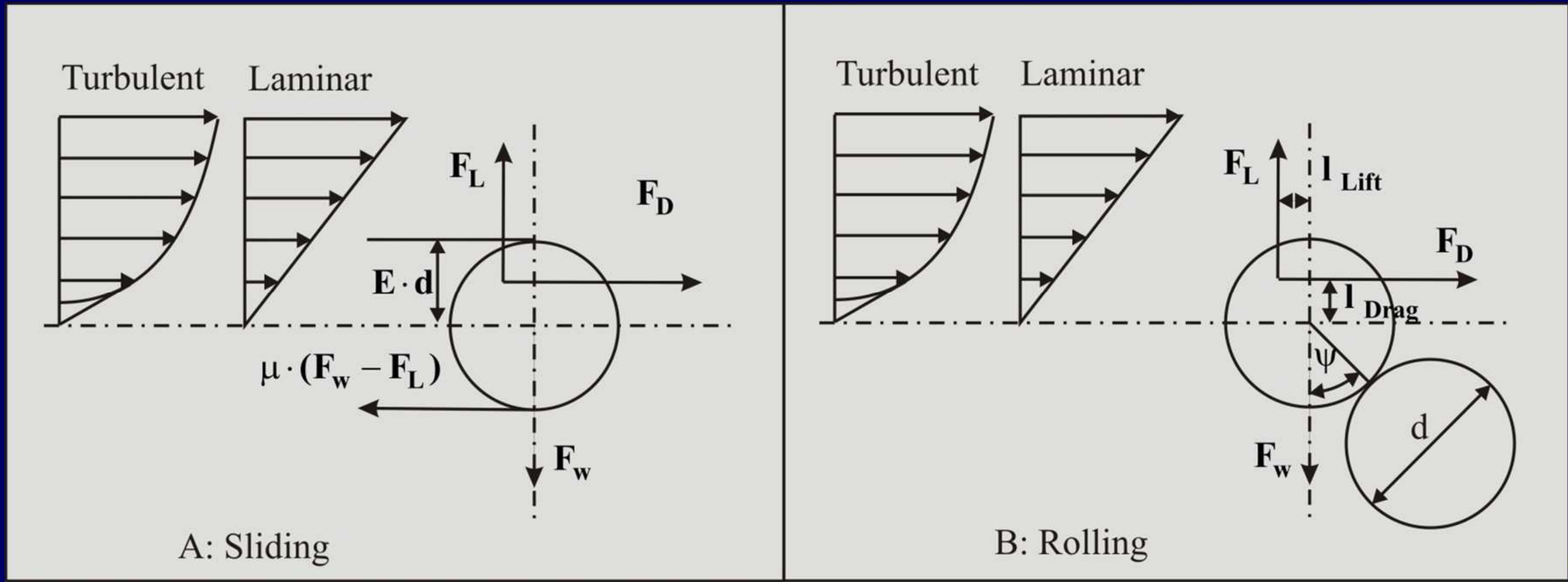
Drag & Lift induced sliding & rolling



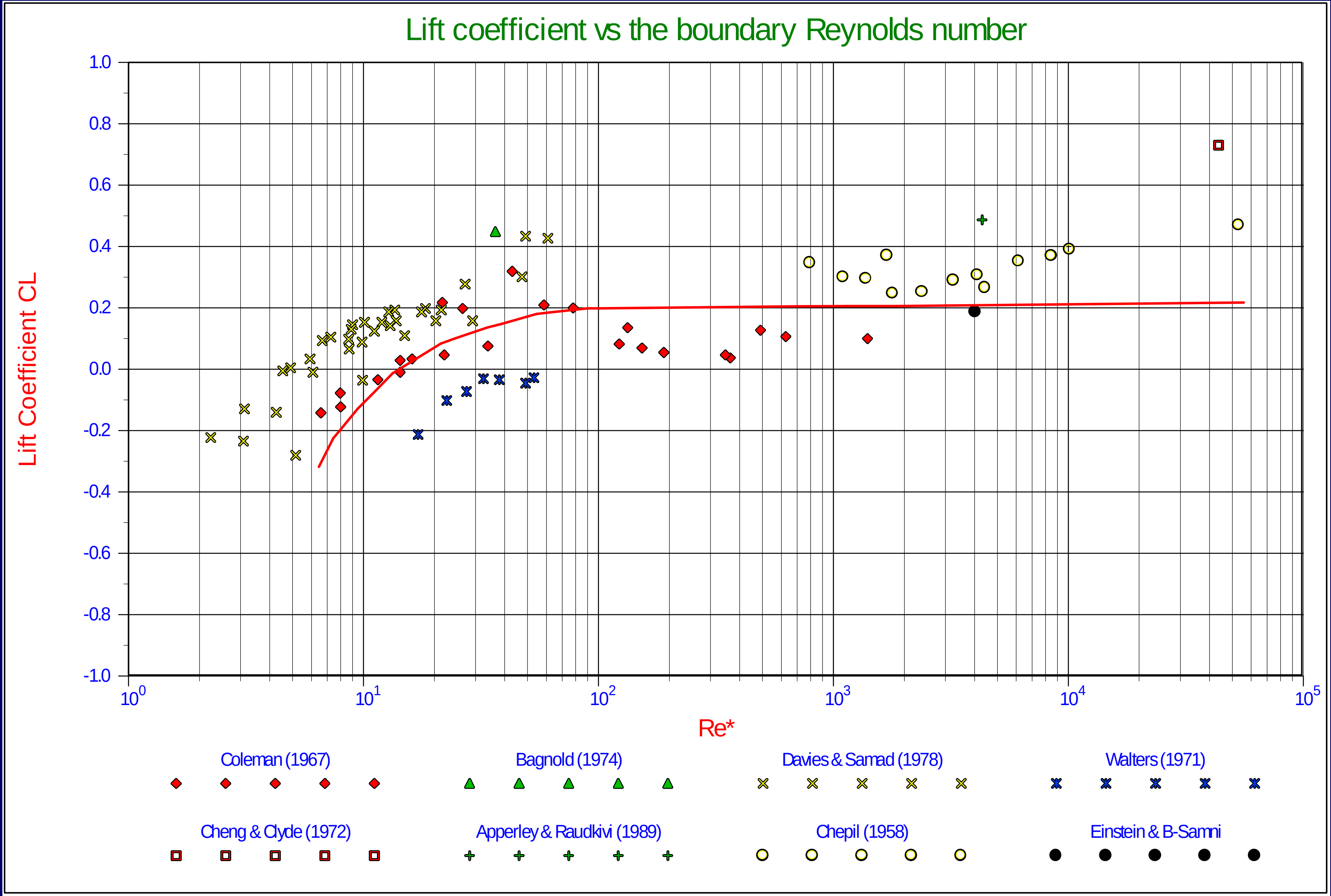
Sliding

$$\theta = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\mu}{\ell_{Drag}^2 \cdot f_D \cdot C_D + \mu \cdot f_L \cdot C_L}$$

Rolling

$$\theta = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\sin(\psi + \phi_{Roll})}{\ell_{Drag}^2 \cdot f_D \cdot C_D \cdot (\ell_{Lever-D} + \cos(\psi + \phi_{Roll})) + f_L \cdot C_L \cdot (\ell_{Lever-L} + \sin(\psi + \phi_{Roll}))}$$

The lift coefficient C_L



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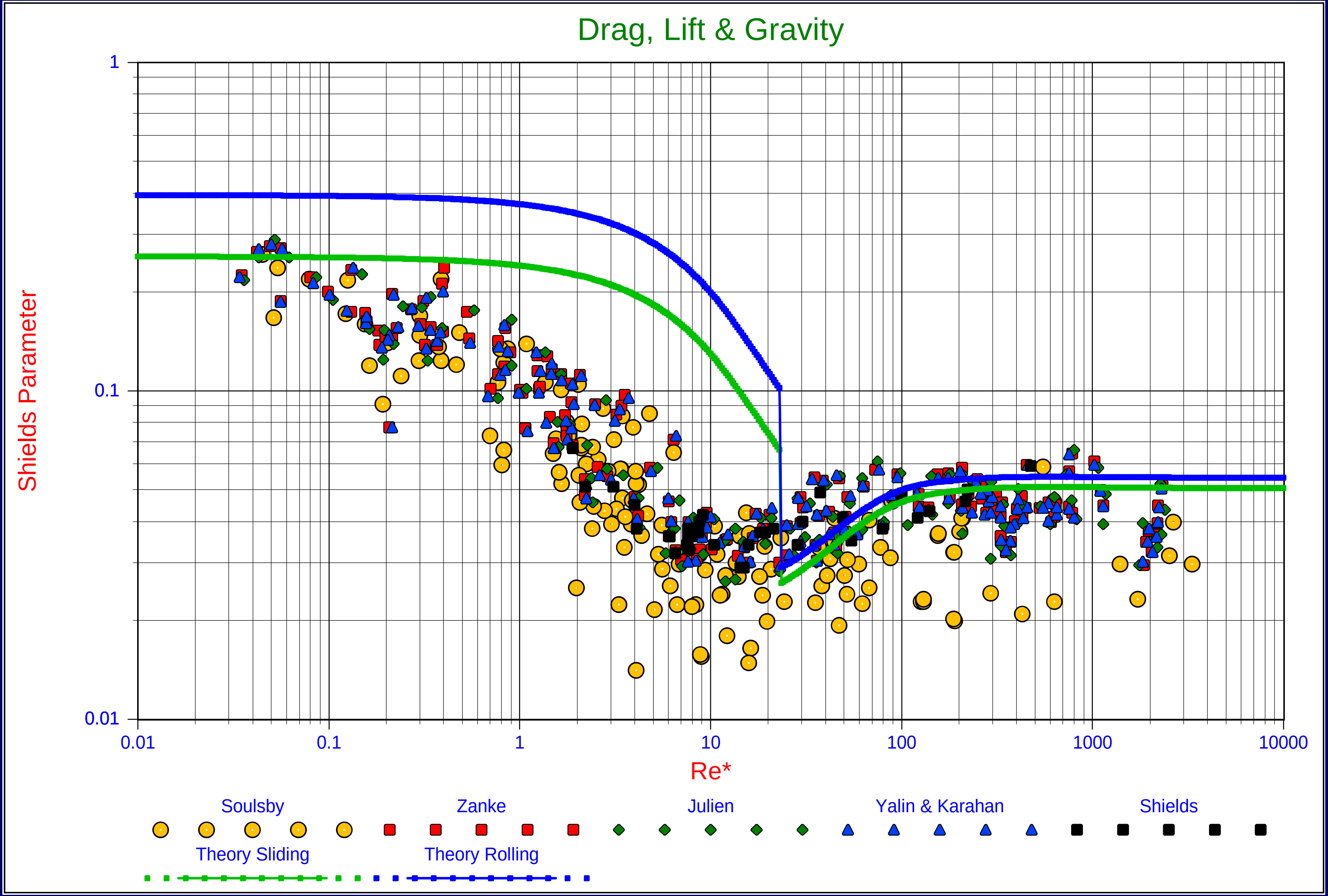
Drag & Lift induced sliding & rolling



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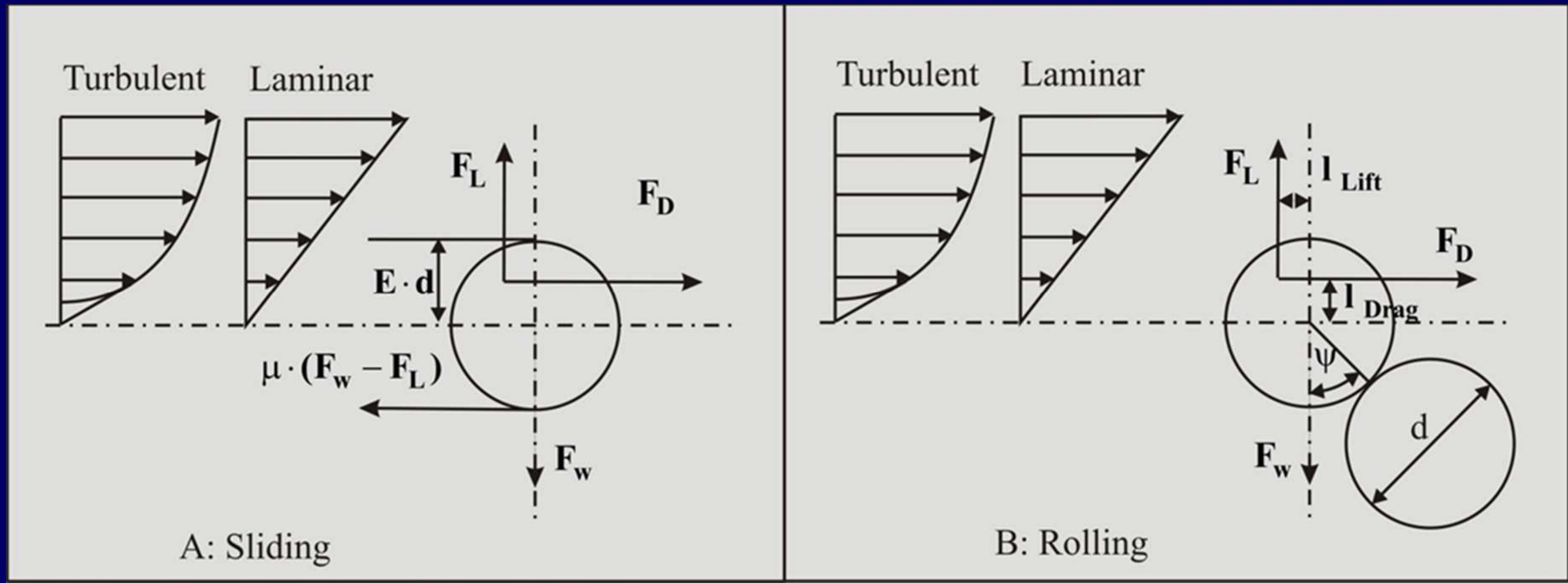
Drag & Lift induced sliding & rolling



Sliding

$$\theta = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\mu}{\ell_{Drag}^2 \cdot f_D \cdot C_D + \mu \cdot f_L \cdot C_L}$$

Rolling

$$\theta = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{4}{3} \cdot \frac{1}{\alpha^2} \cdot \frac{\sin(\psi + \phi_{Roll})}{\ell_{Drag}^2 \cdot f_D \cdot C_D \cdot (\ell_{Lever-D} + \cos(\psi + \phi_{Roll})) + f_L \cdot C_L \cdot (\ell_{Lever-L} + \sin(\psi + \phi_{Roll}))}$$

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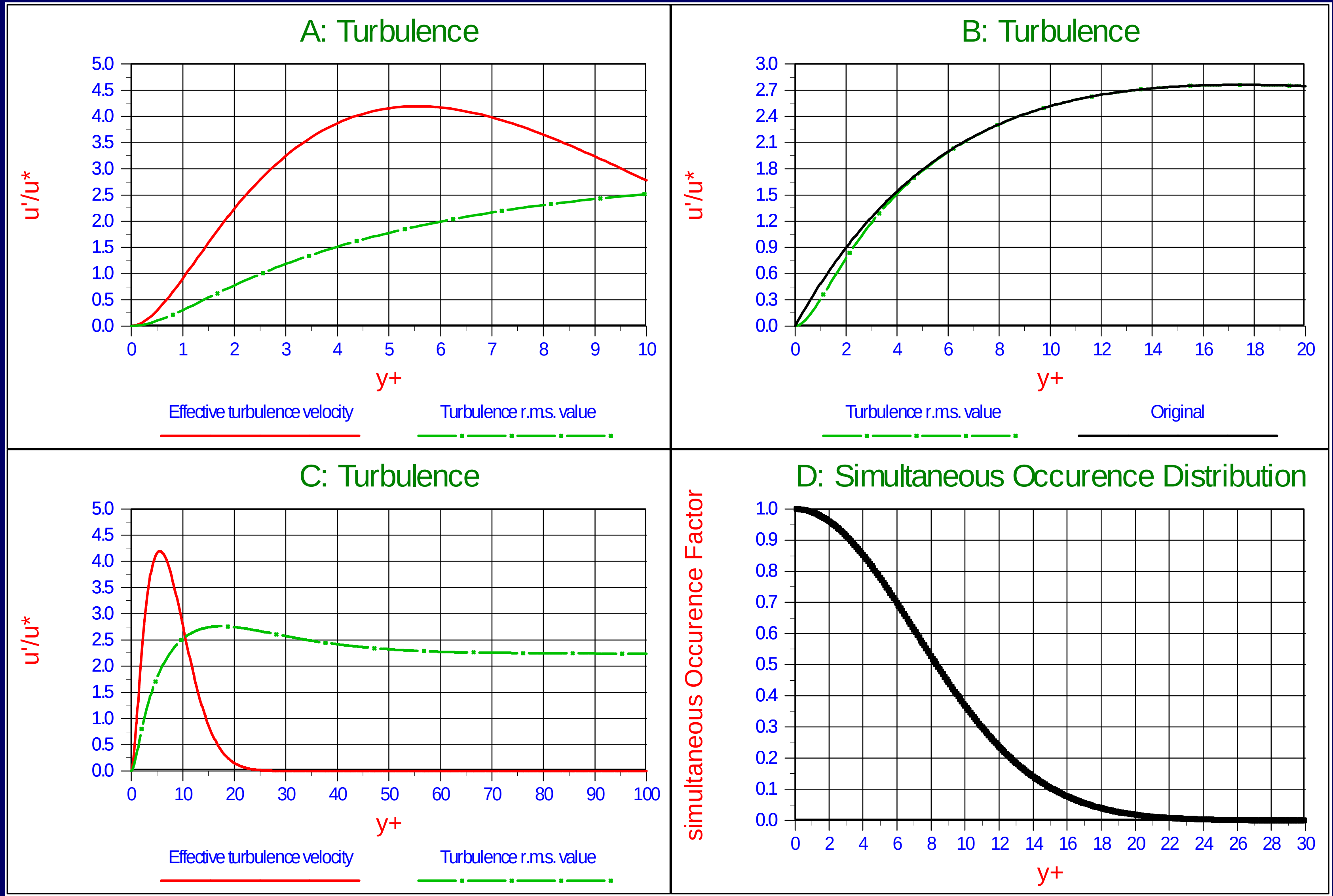
Turbulence



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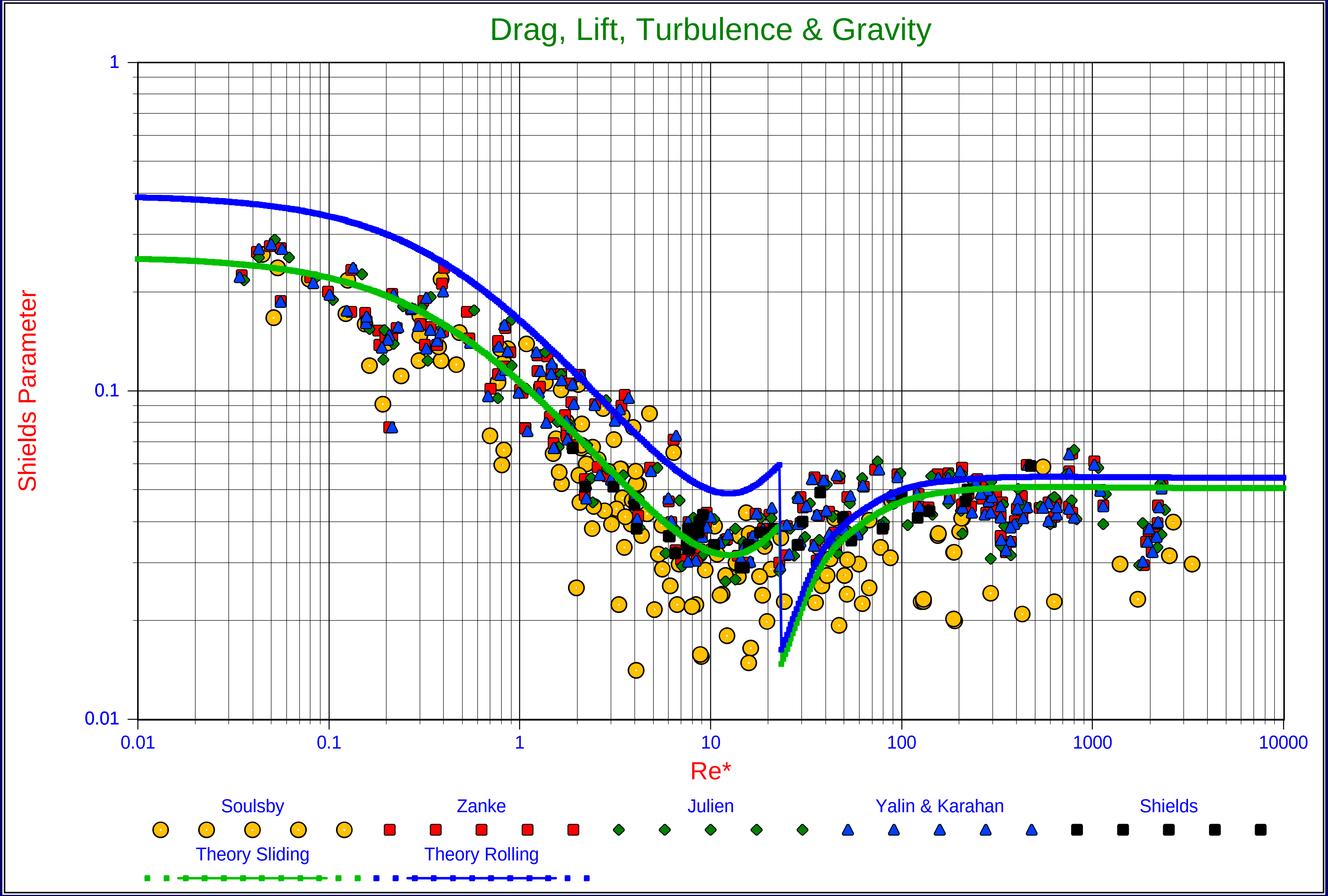
Drag, Lift & Turbulence induced sliding & rolling



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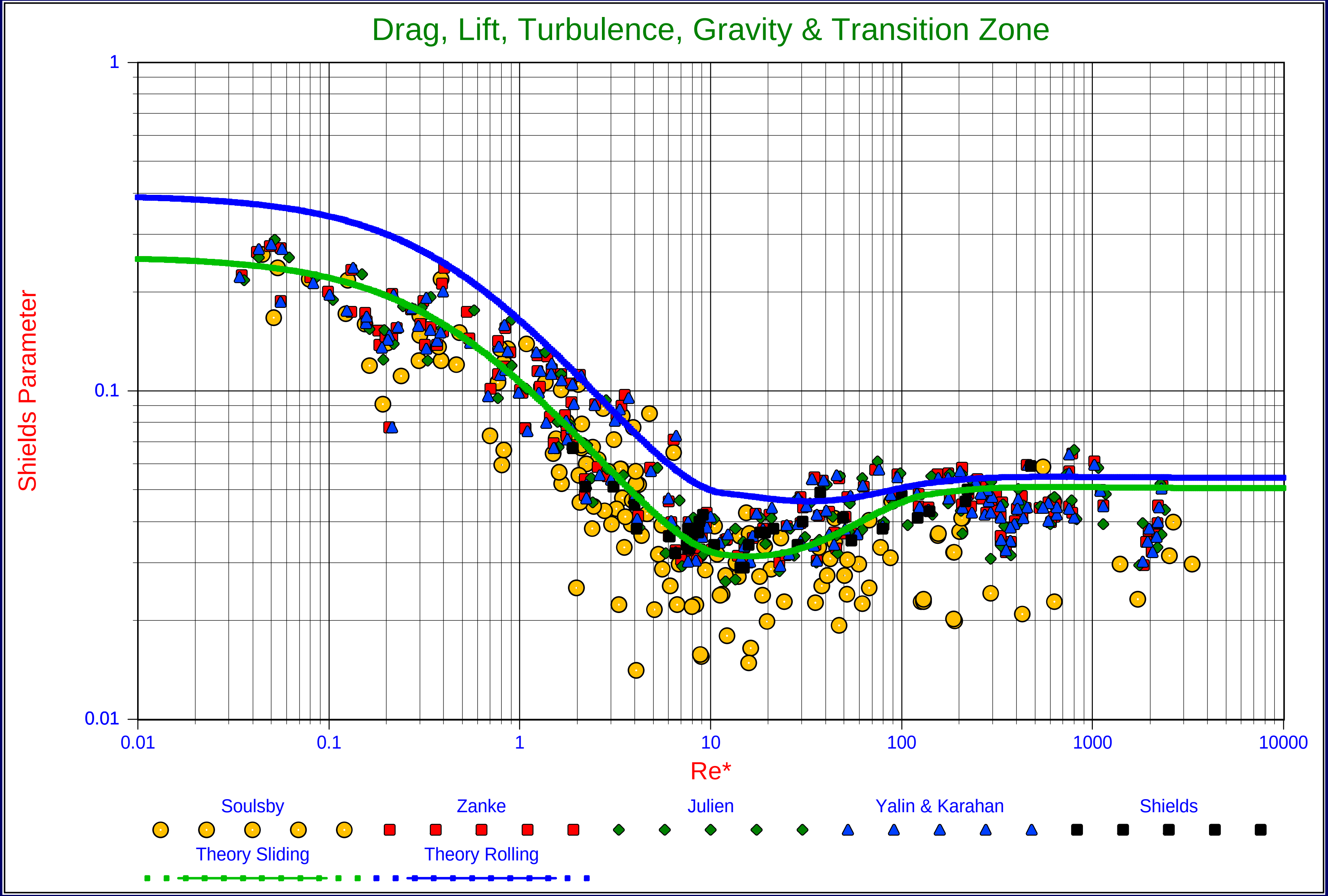
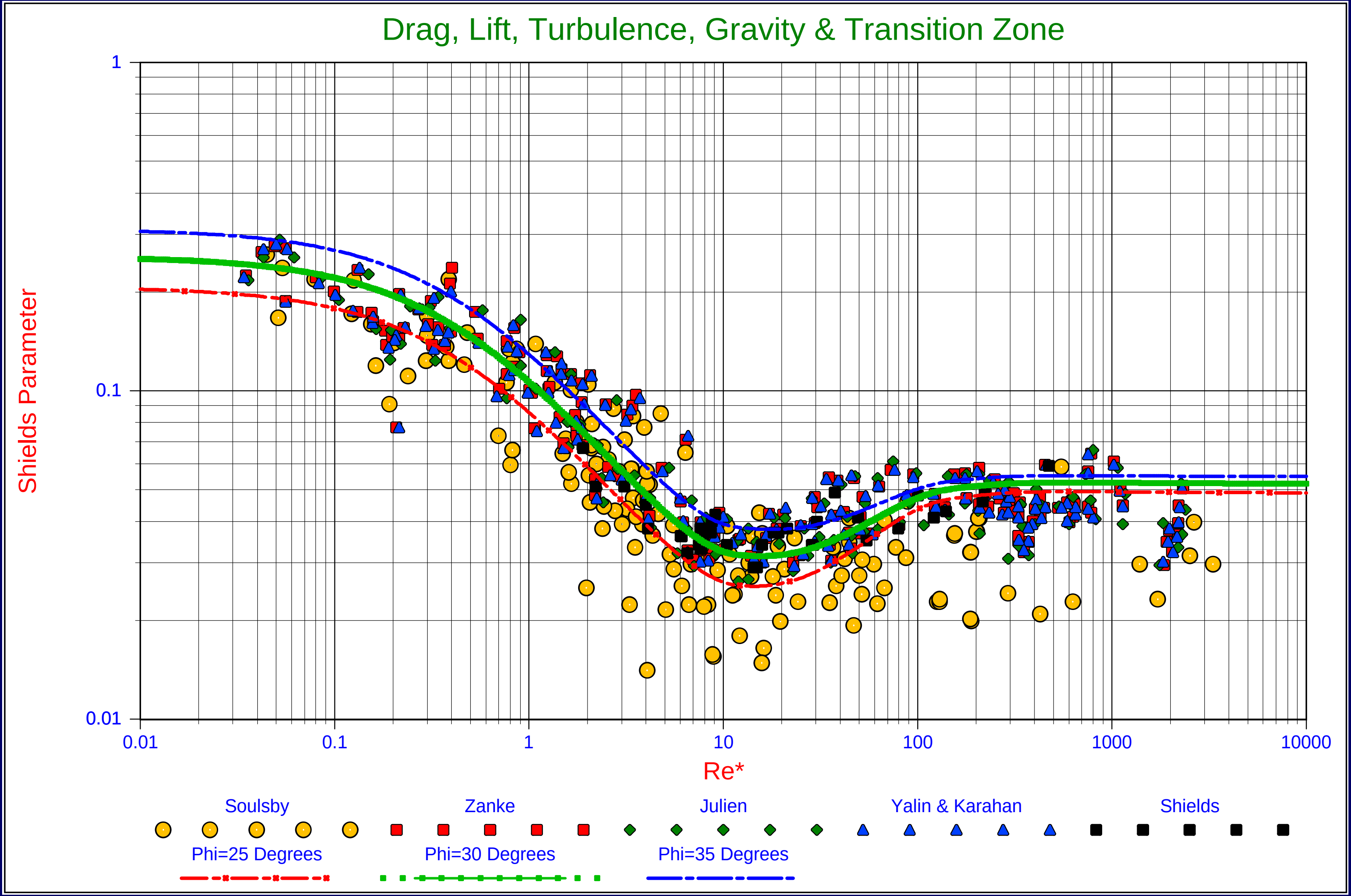
Initiation of motion for sliding & rolling



Sensitivity Analysis Shields Curve

Different Angles of Internal Friction



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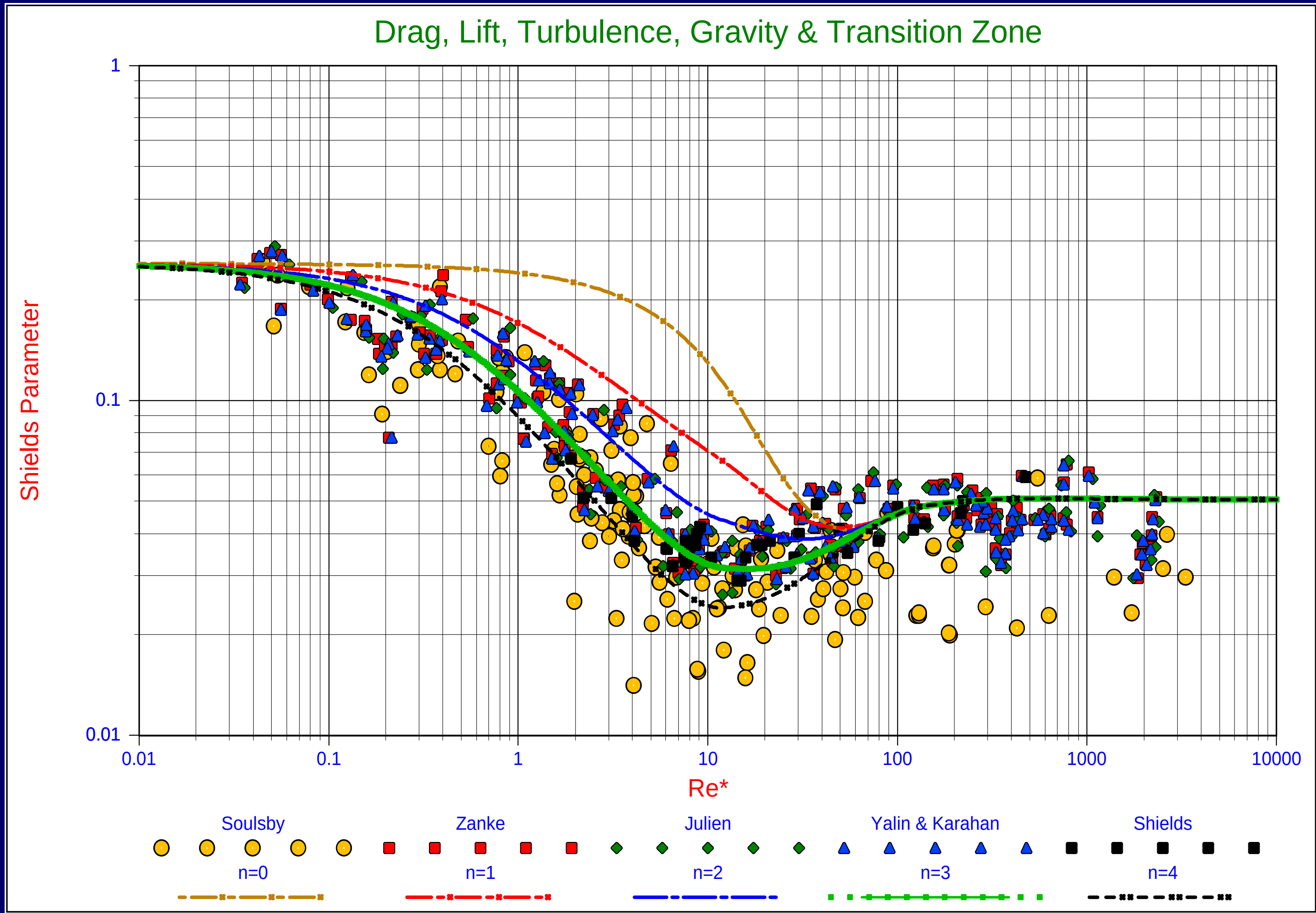
Different Levels of Turbulence



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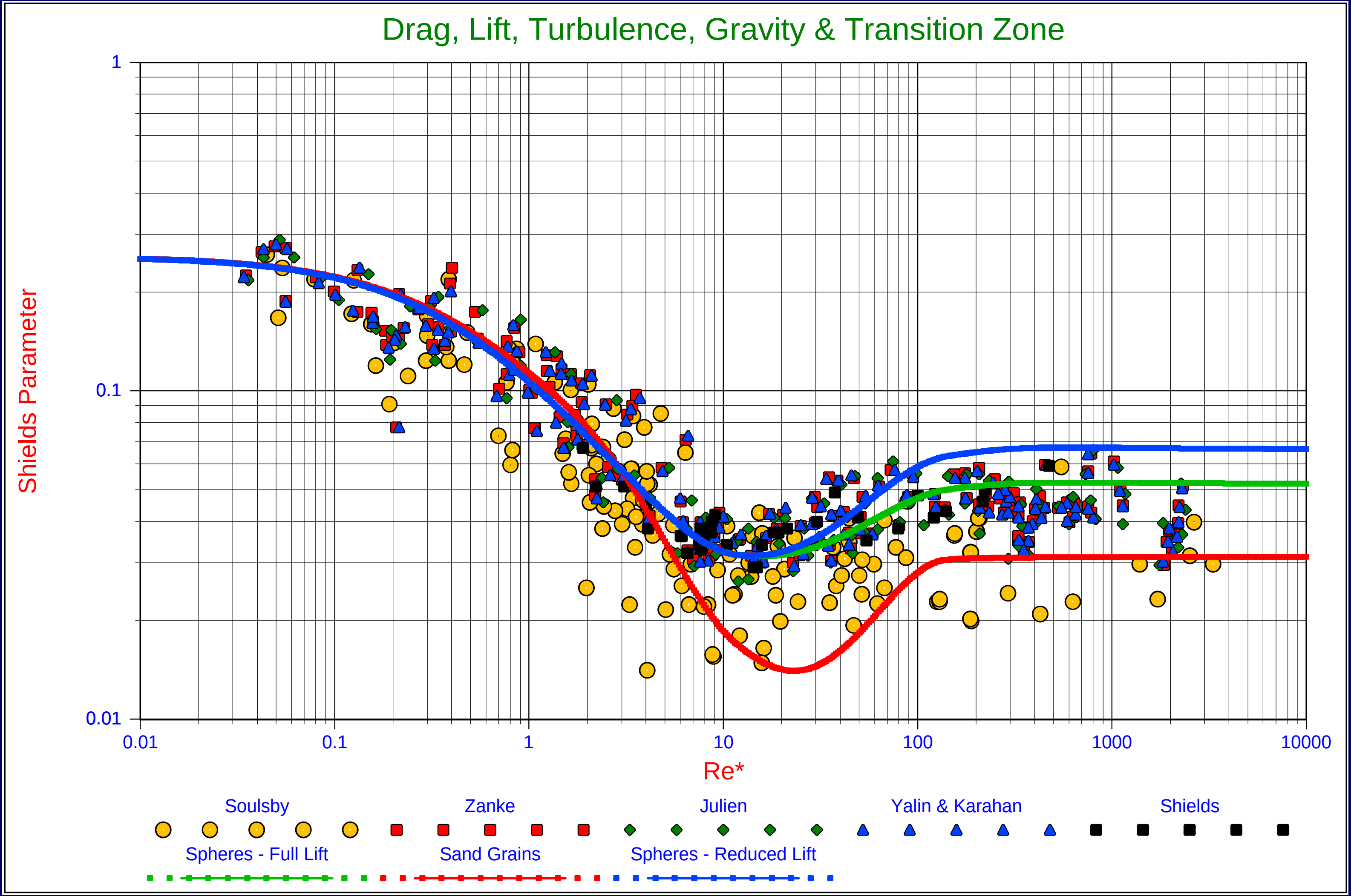
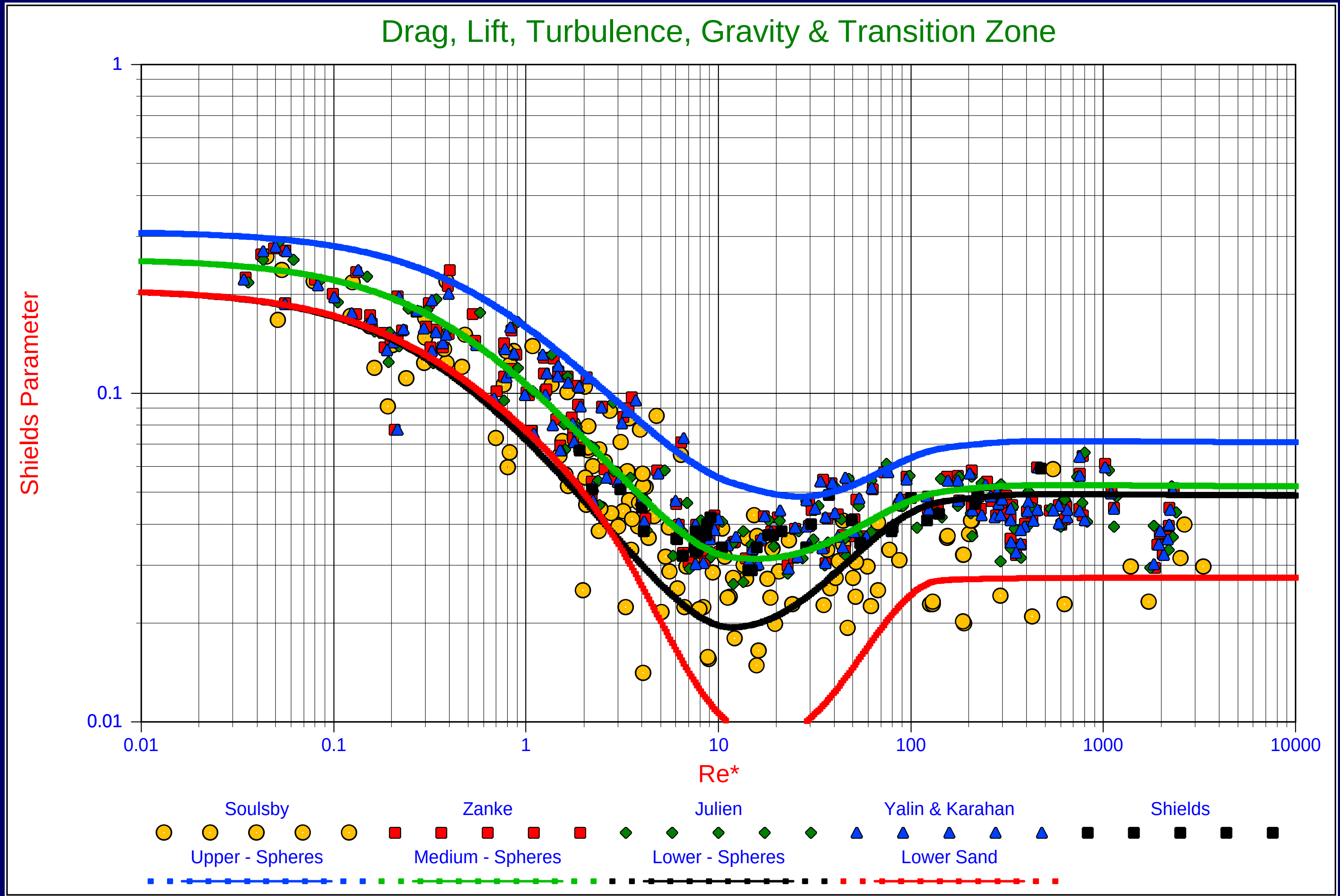
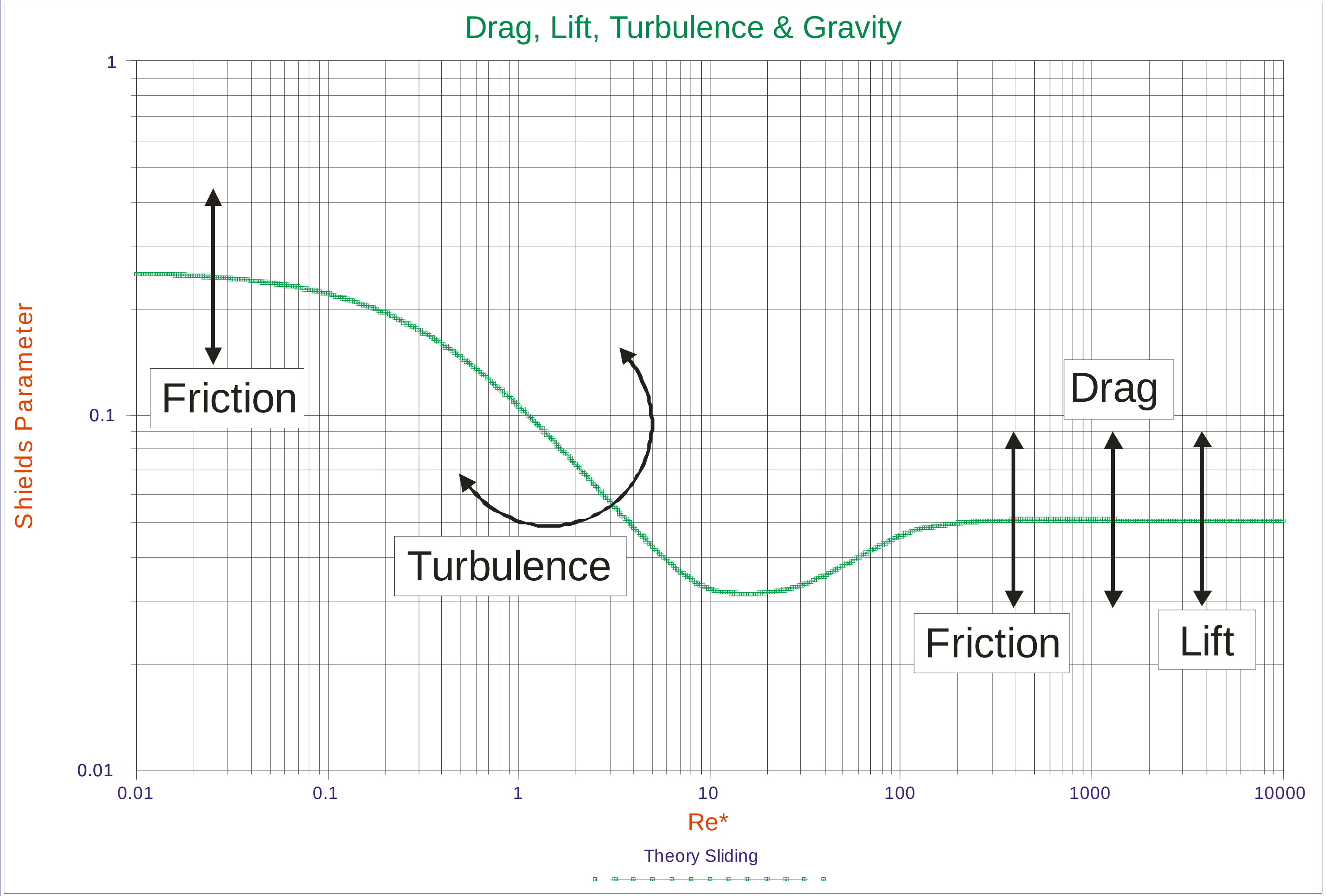
Sand Standard & Spheres with 2 C_L's



Resulting Curves



Sensitivities



The resulting curves

Sliding versus rolling for spheres
Different protrusion levels for spheres
Different protrusion levels for sand
The Shields-Parker diagram

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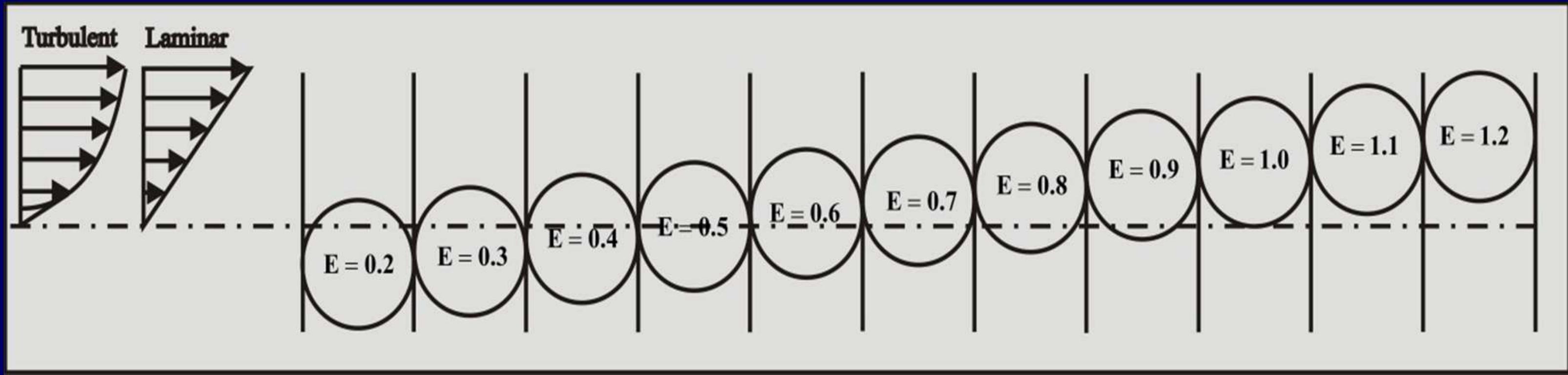
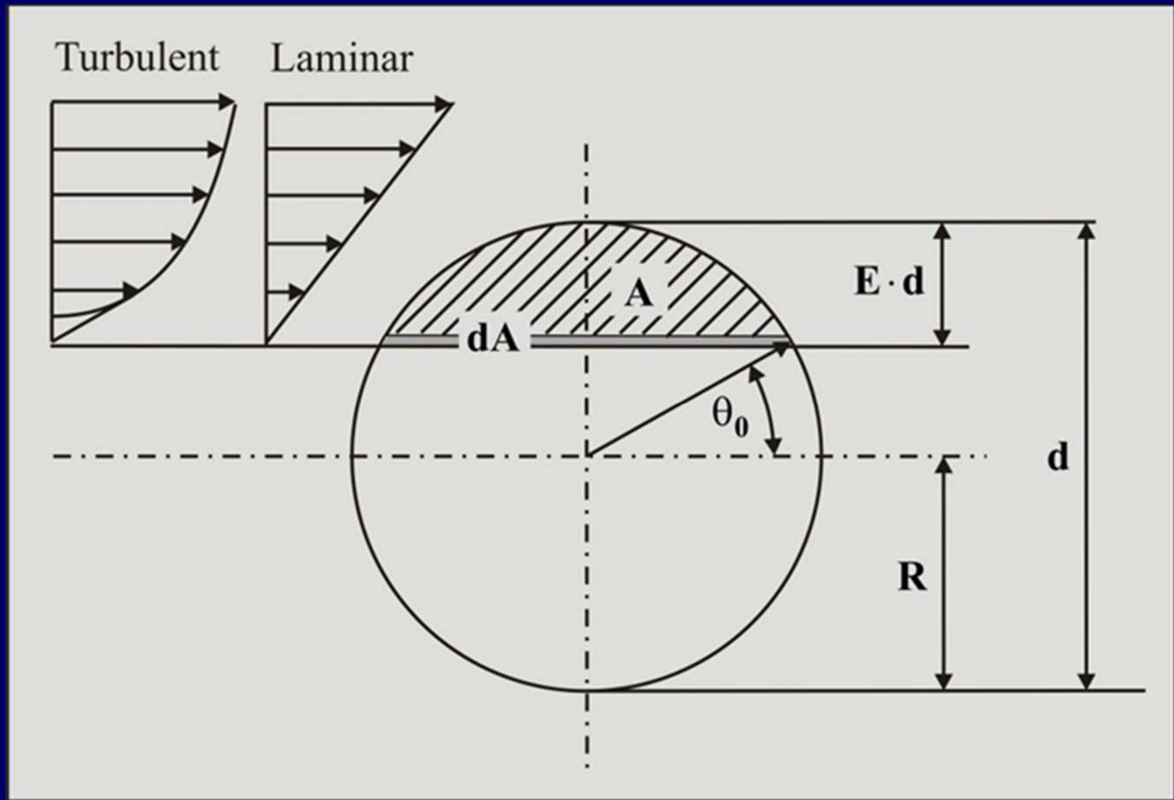
Exposure Levels - Protrusion Levels





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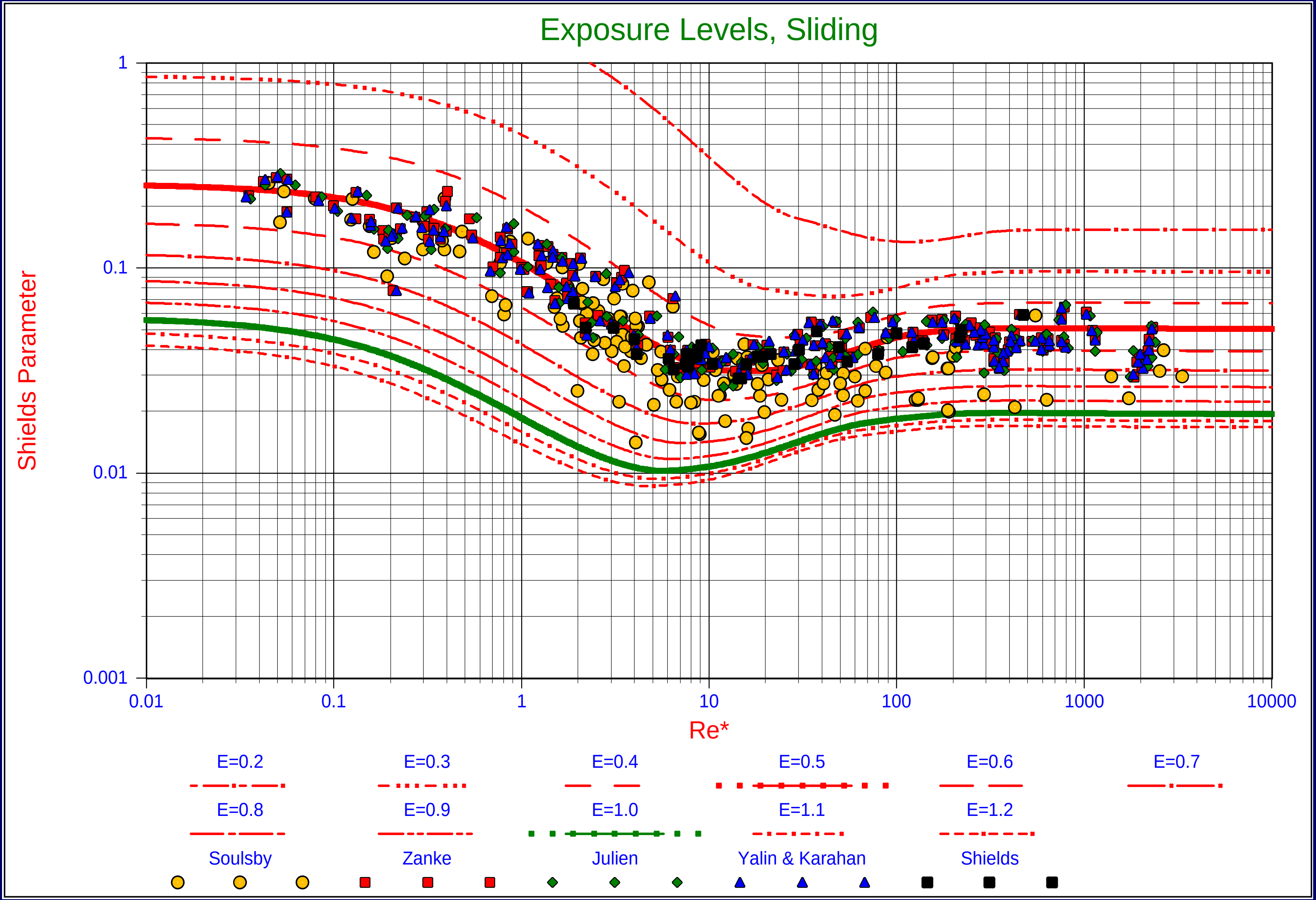
Exposure Levels Sliding



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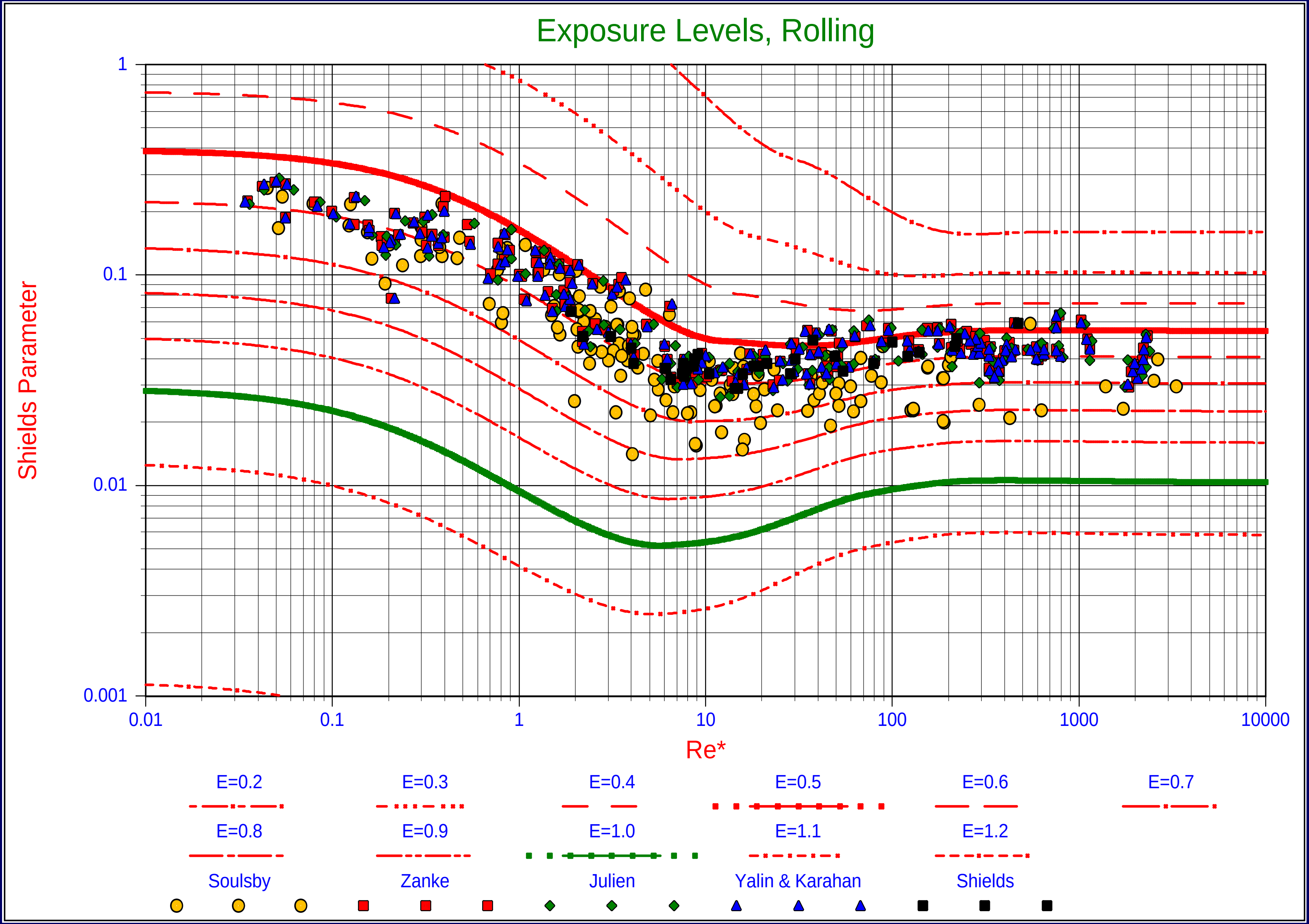
Exposure Levels Rolling



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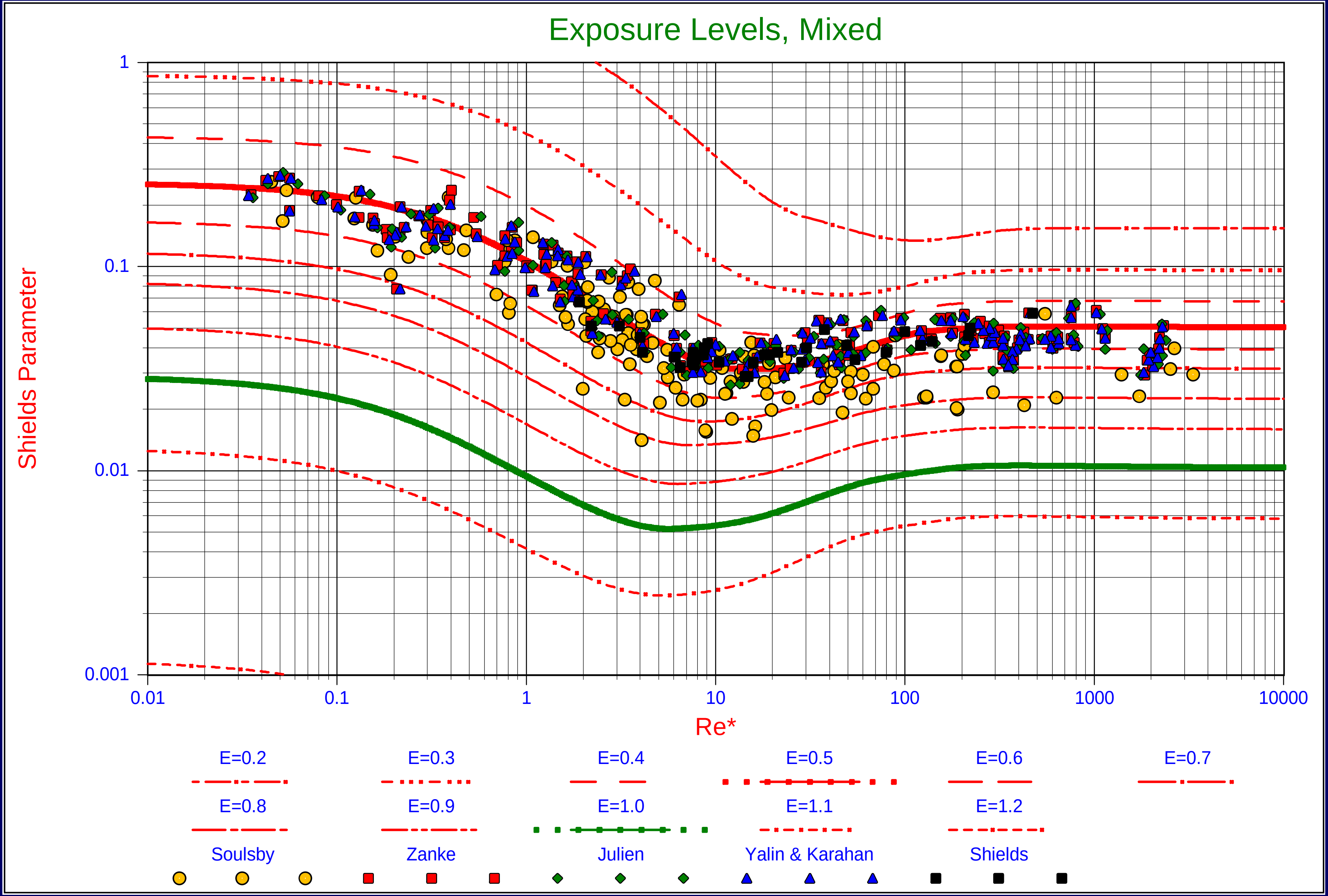
Exposure Levels Both (Spheres)



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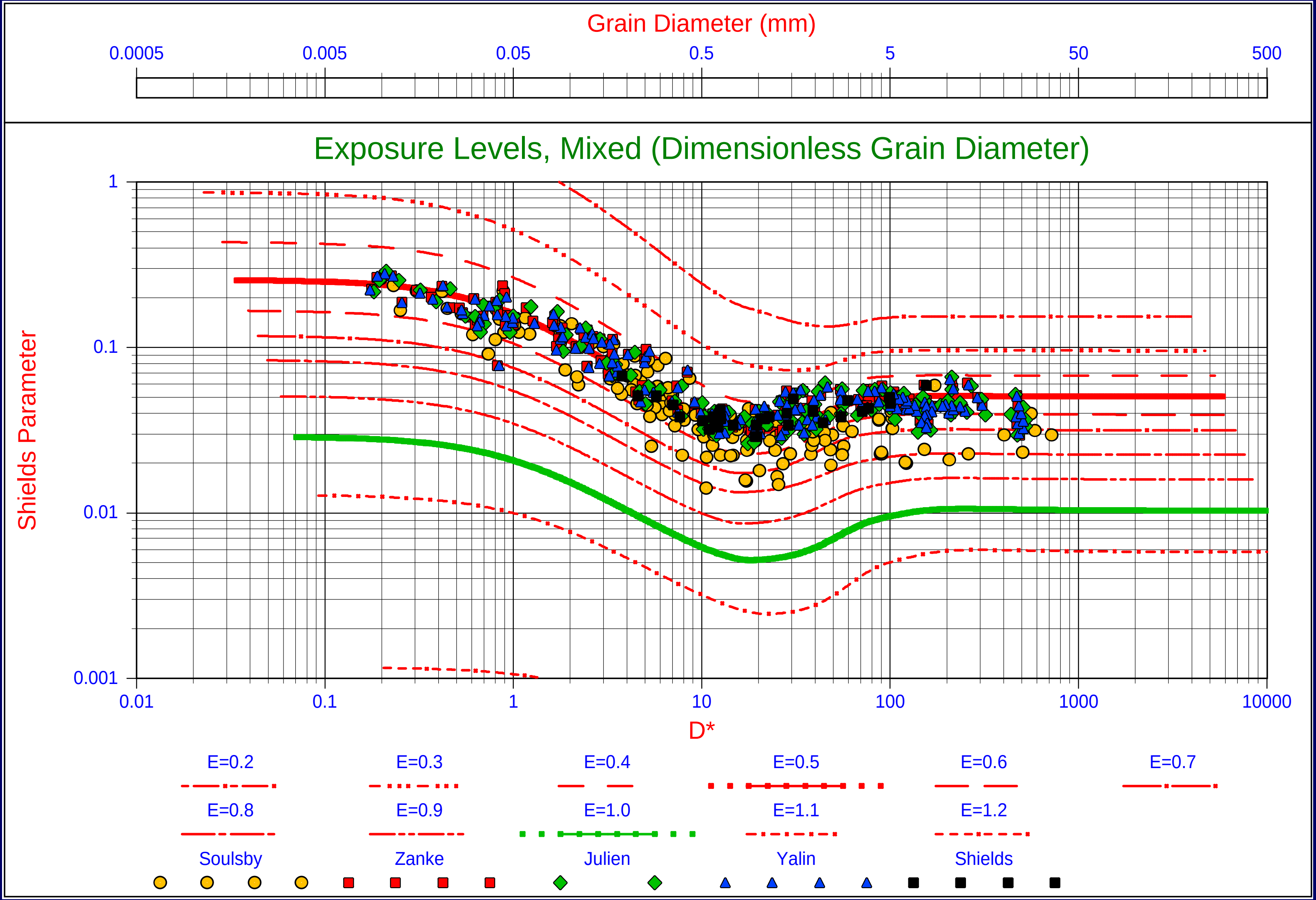
Exposure Levels Both, Bonneville Parameter



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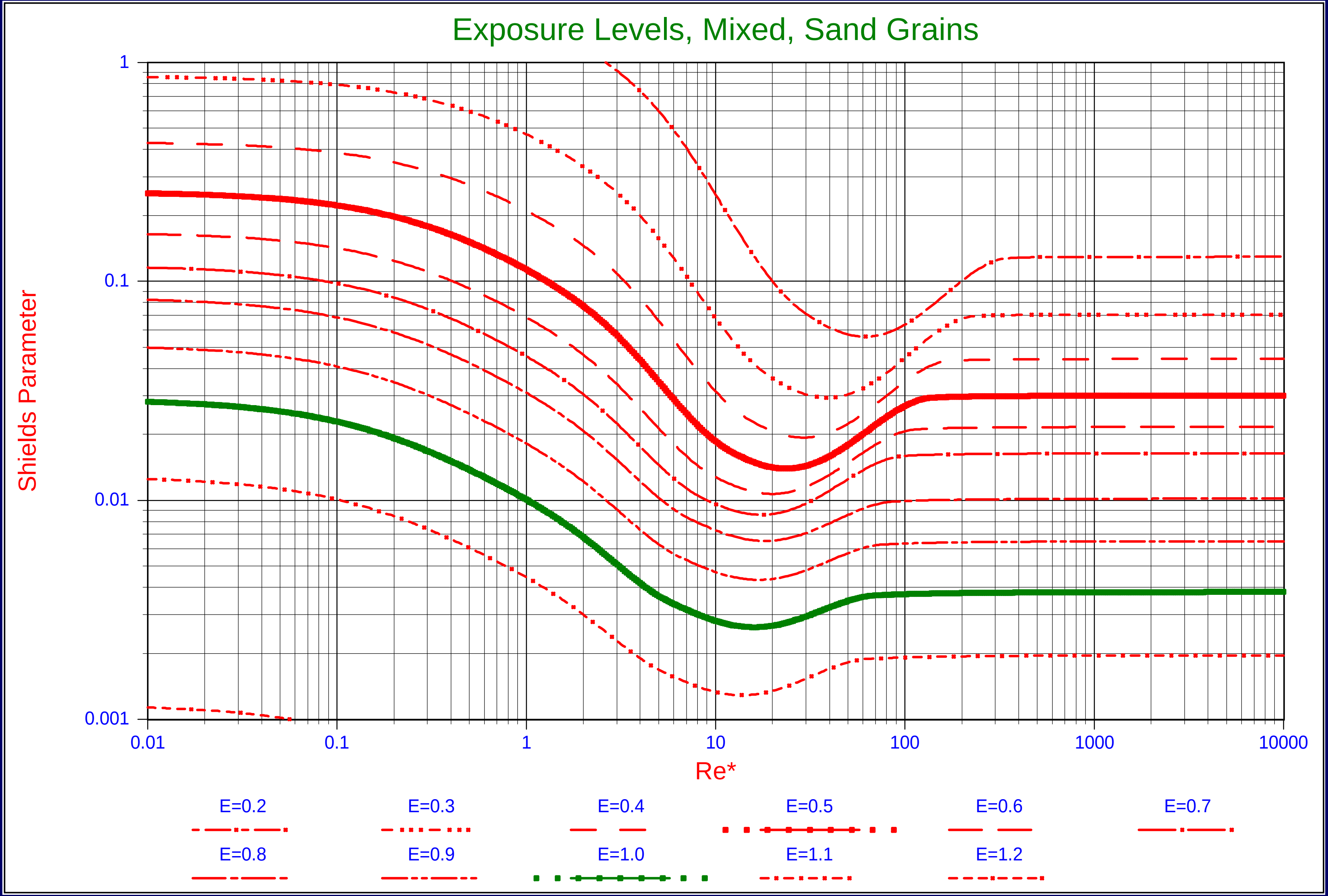
Different protrusion levels (sand)



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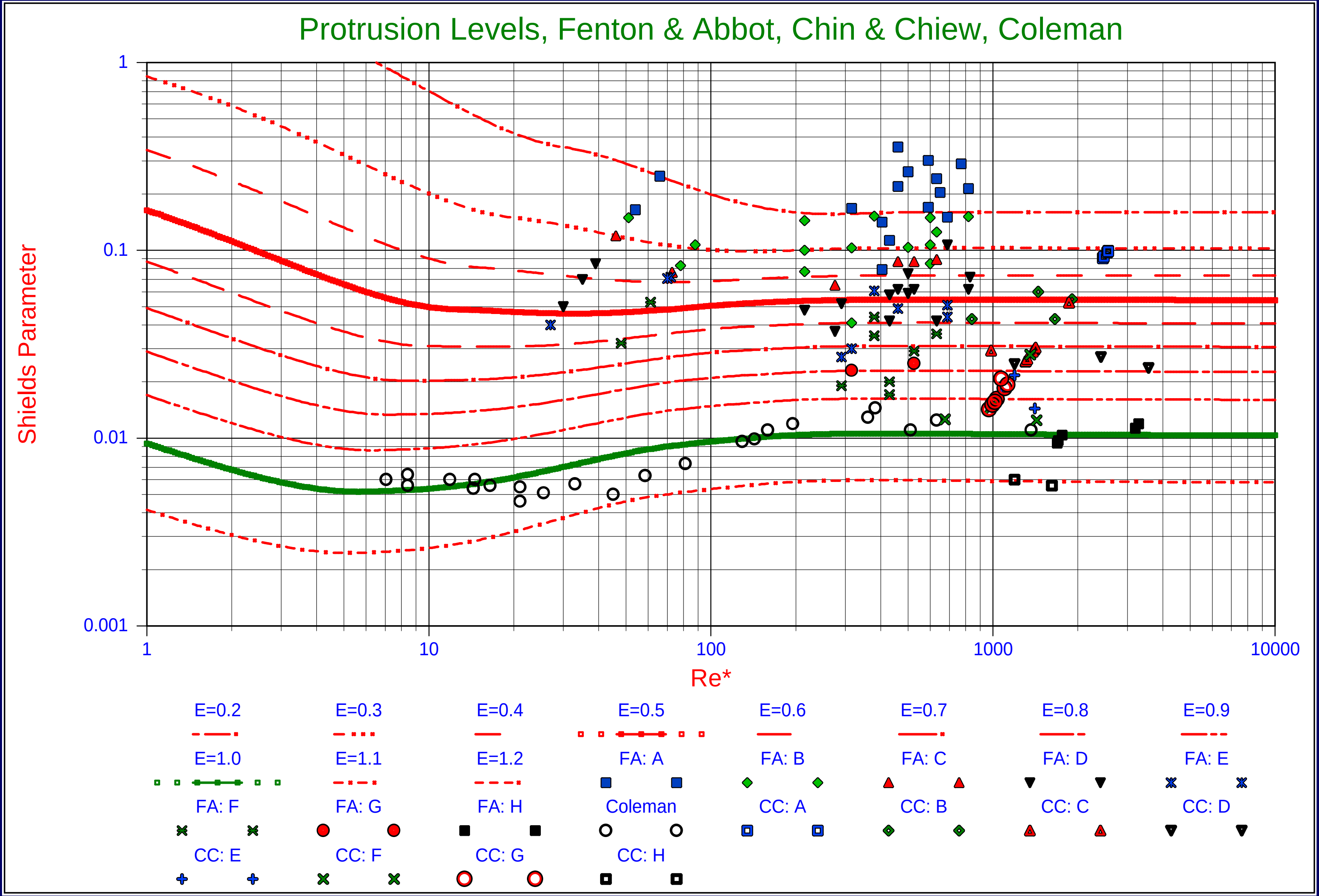
Exposure Levels Experiments



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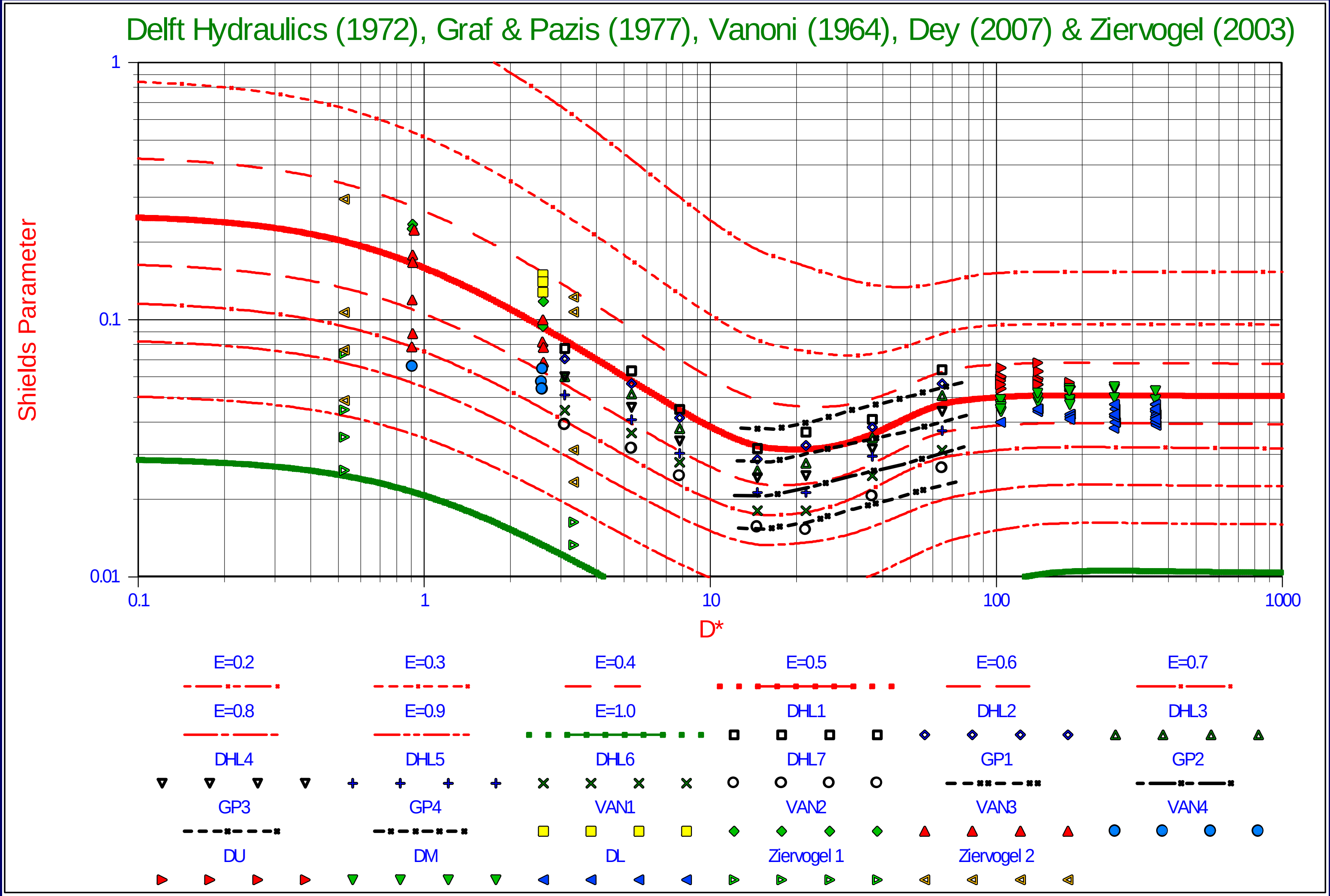
Stages of Entrainment



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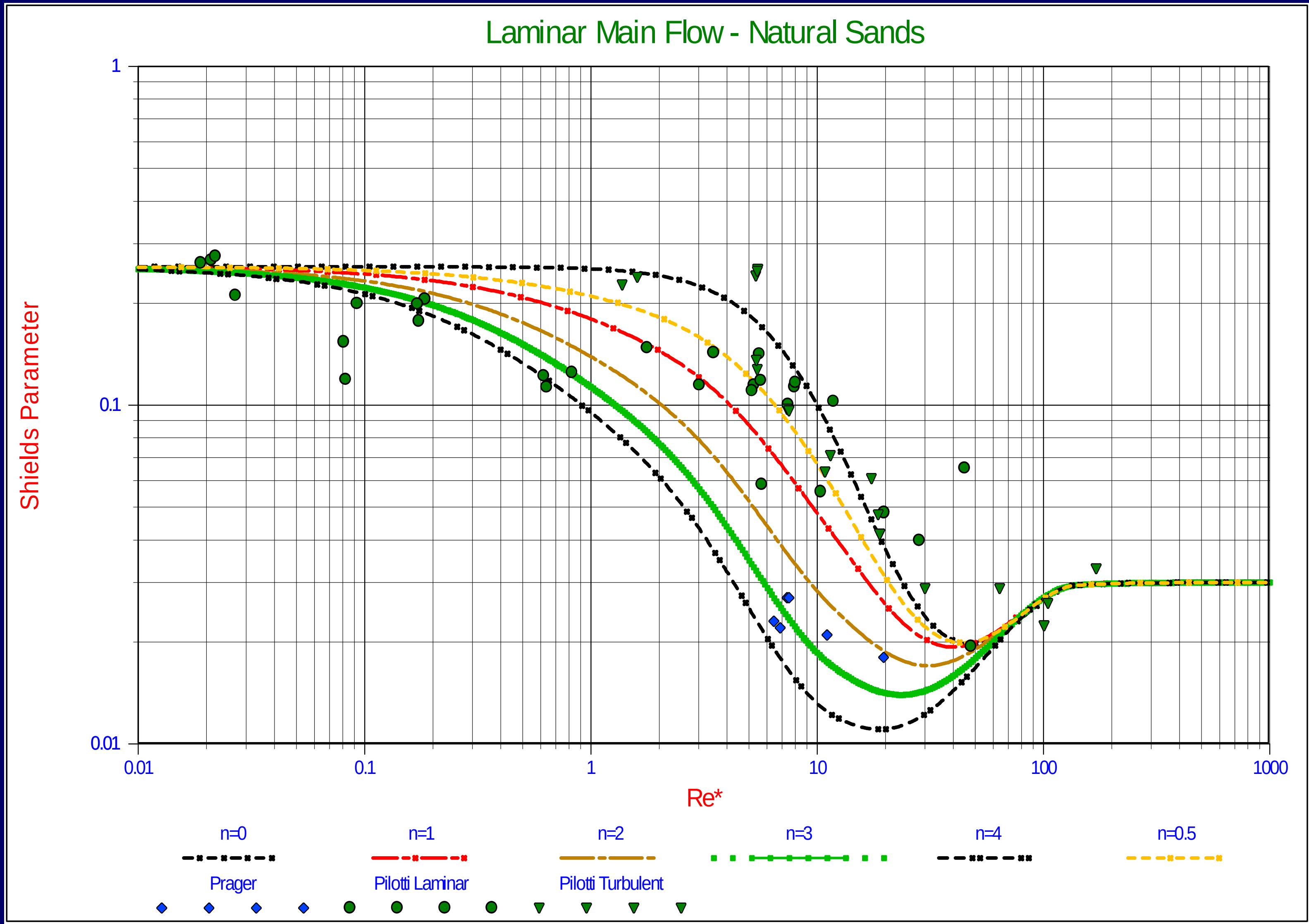
Laminar Main Flow



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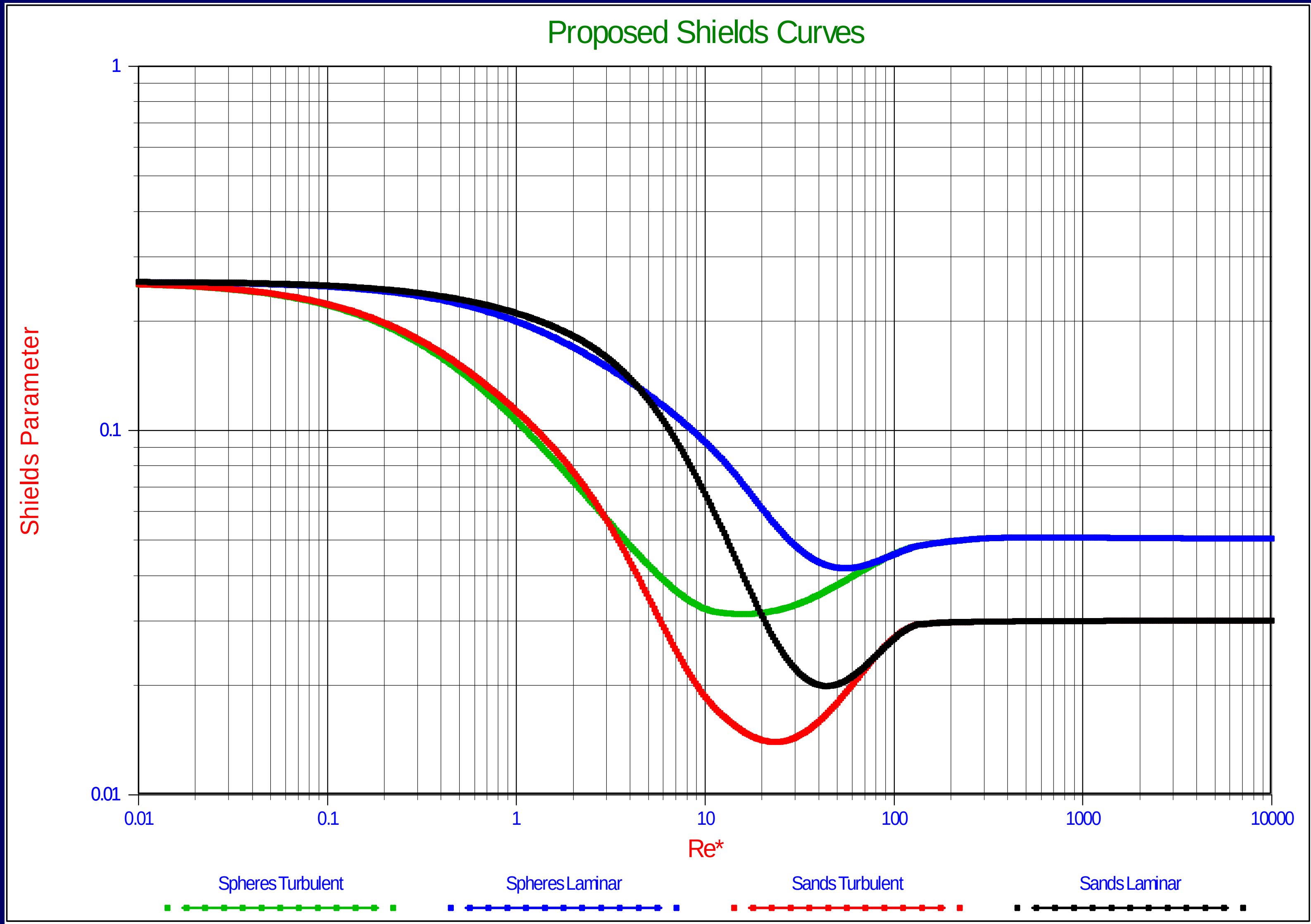
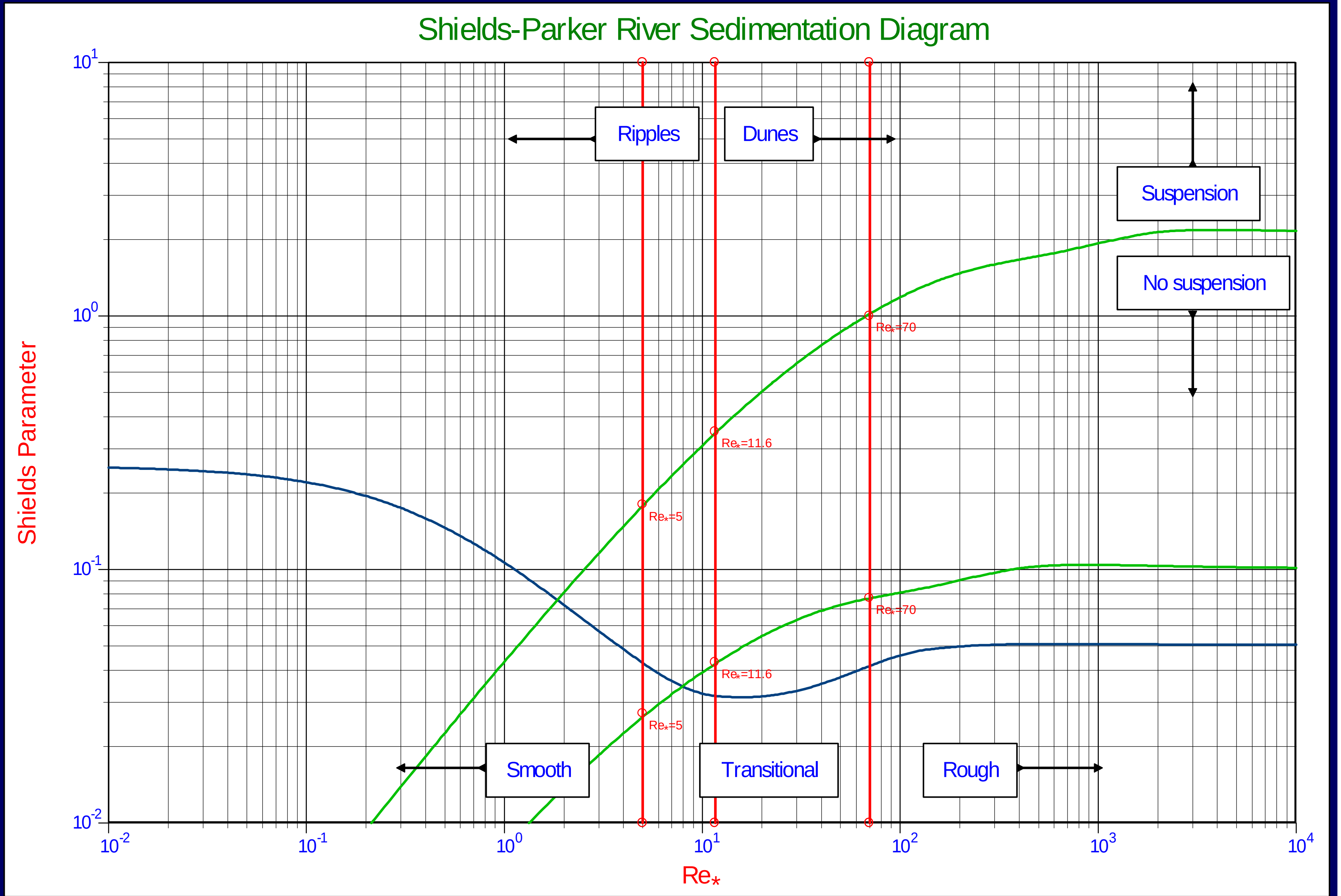
Resulting Curves



The Shields-Parker diagram



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Faculty of 3mE – Chair of Dredging Engineering

Application of the model

The governing equations
The friction coefficient

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Application to scour in a TSHD

First determine the friction velocity and the friction coefficient:

$$u_*^2 = \frac{\lambda}{8} \cdot U_{cr}^2$$

$$\lambda = \frac{1.325}{\left(\ln\left(\frac{d}{3.7 \cdot D} + \frac{5.75}{Re^{0.9}}\right)\right)^2} = \frac{0.25}{\left(\log\left(\frac{d}{3.7 \cdot D} + \frac{5.75}{Re^{0.9}}\right)\right)^2}$$

Second determine the Shields parameter for the grain diameter:

$$\theta_{cr} = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{\lambda}{8} \cdot \frac{U_{cr}^2}{R_d \cdot g \cdot d}$$

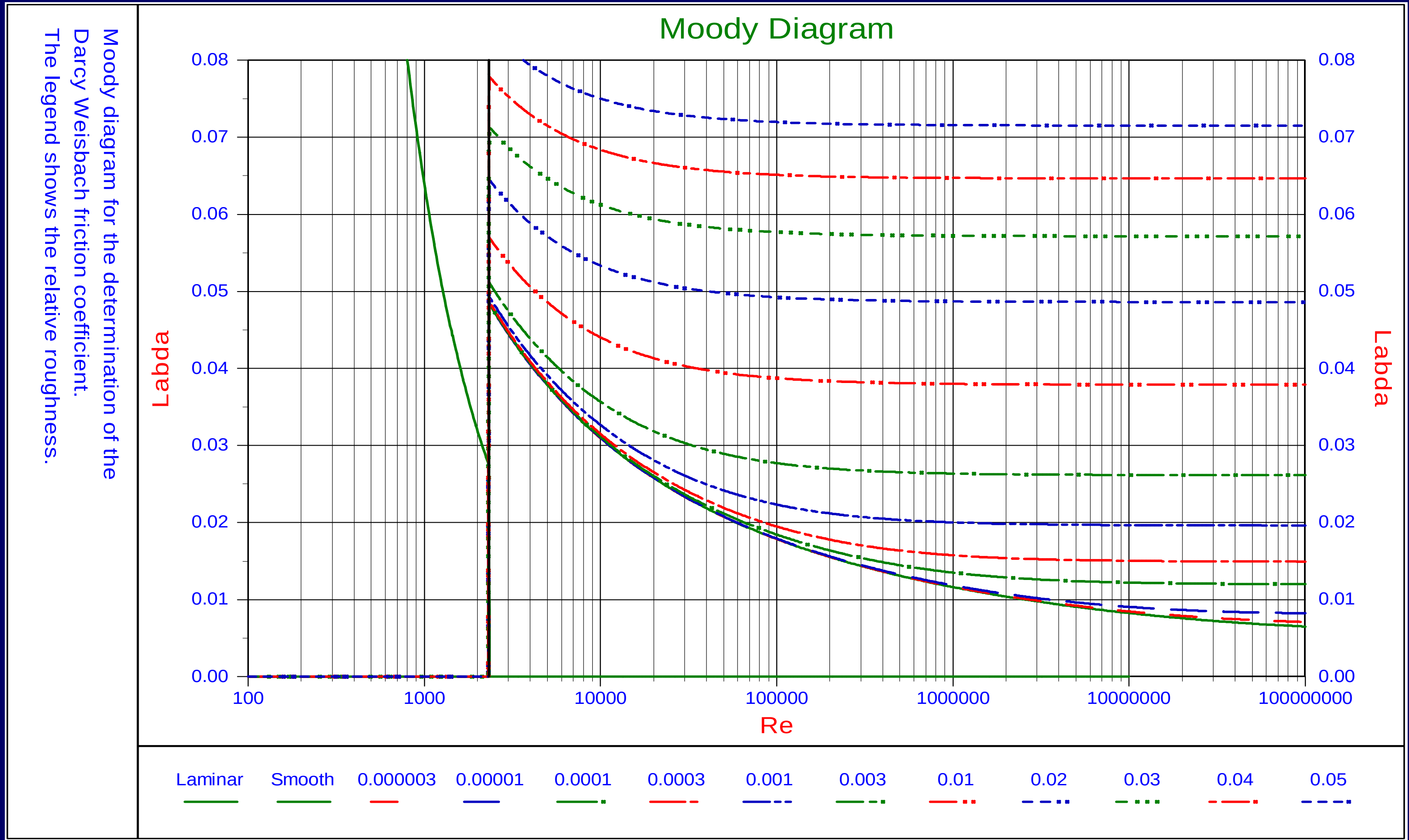
Third, determine the average velocity above the bed given a grain diameter:

$$U_{cr} = \sqrt{\frac{8 \cdot \theta_{cr} \cdot R_d \cdot g \cdot d_s}{\lambda}}$$

or, determine the grain diameter given an average velocity:

$$d_s = \frac{u_*^2}{R_d \cdot g \cdot d} = \frac{\lambda}{8} \cdot \frac{U_{cr}^2}{R_d \cdot g \cdot \theta_{cr}}$$

The friction coefficient



$$\lambda = \frac{1.325}{\left(\ln\left(\frac{d}{3.7\cdot D}+\frac{5.75}{Re^{0.9}}\right)\right)^2} = \frac{0.25}{\left(\log\left(\frac{d}{3.7\cdot D}+\frac{5.75}{Re^{0.9}}\right)\right)^2}$$

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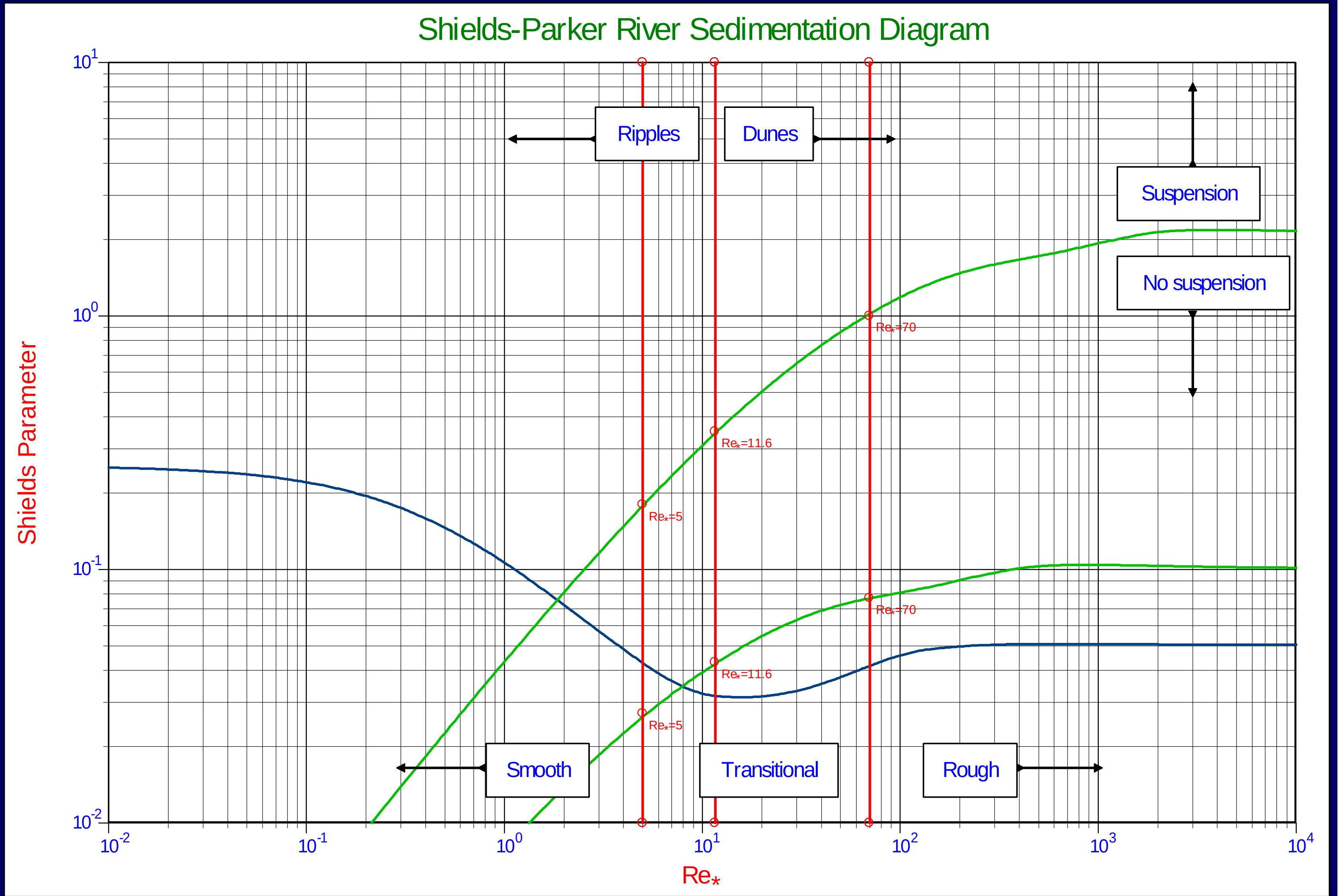
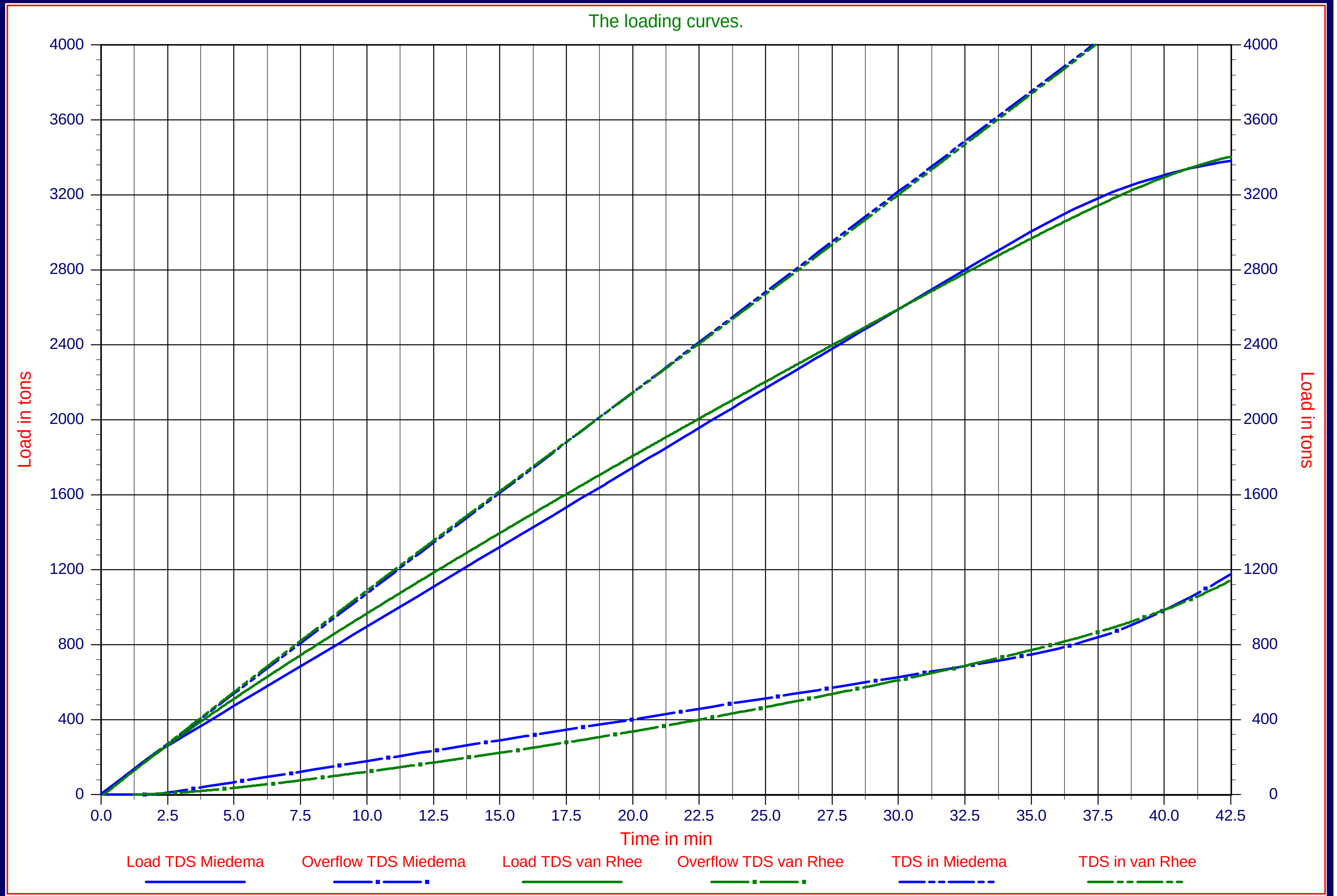
The Shields-Parker diagram



Hopper Sedimentation, verification



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Questions?

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Sources images

1. A model cutter head, source: Delft University of Technology.
2. Off shore platform, source: Castrol (Switzerland) AG
3. Off shore platform, source: http://www.wireropetraining.com
4. The Amsterdam, source: IHC Merwede.