Hydraulic Dredging: horizontal transport Part 1: Transport of dredged mixtures trough pipes (2009/2010)

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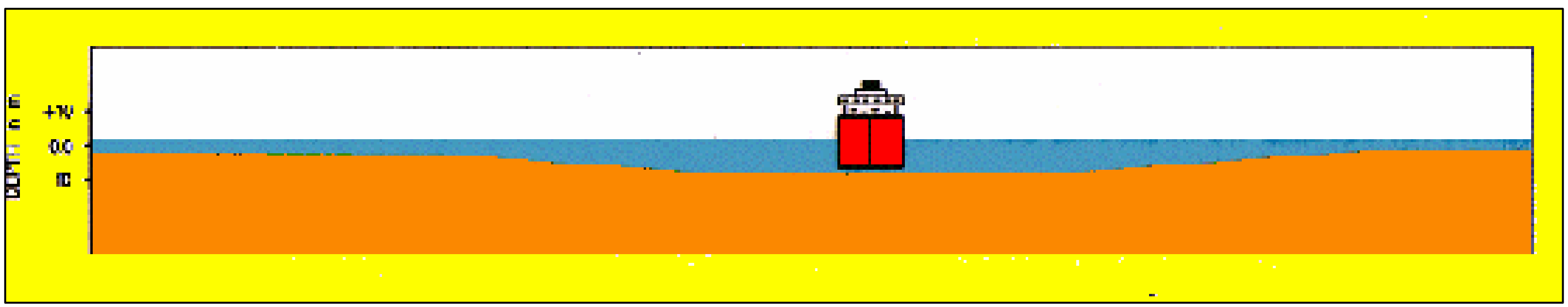
Why Dredging ?

Scope of Works of Dredging:

- **Realize or Improve or Maintain Nautical Accessibility for Ships to Ports, Fairways,…: Capital Dredging and Maintenance Dredging**
- **Reclaim New Land for housing, industrial development**
- **Coastal Protection: restaure beach & dune system, dykes,..**
- **Seabed preparation for offshore infrastructures : pipelines, cables, GBS platforms, scour-protection, windmill-farms,…**
- **Morphological compensations linked to maritime works**
- **Sanitation of contaminated sediments**



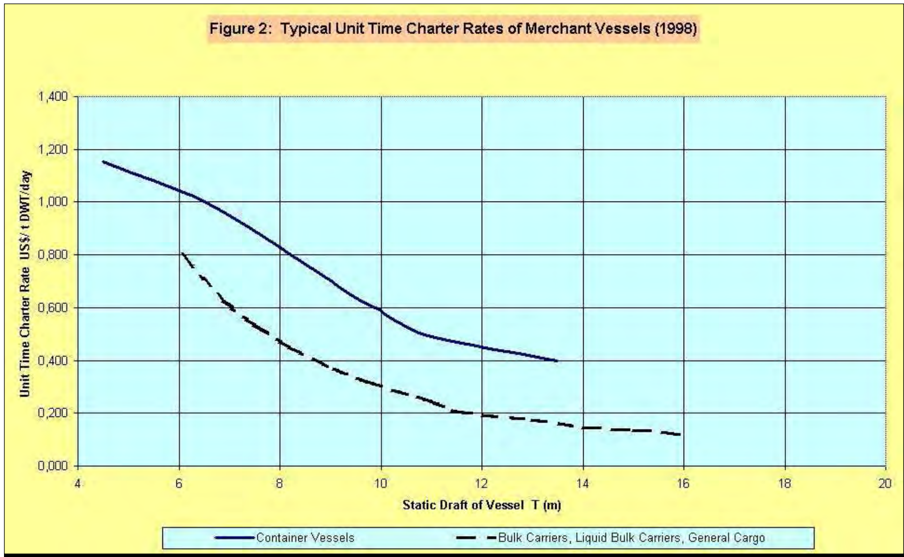
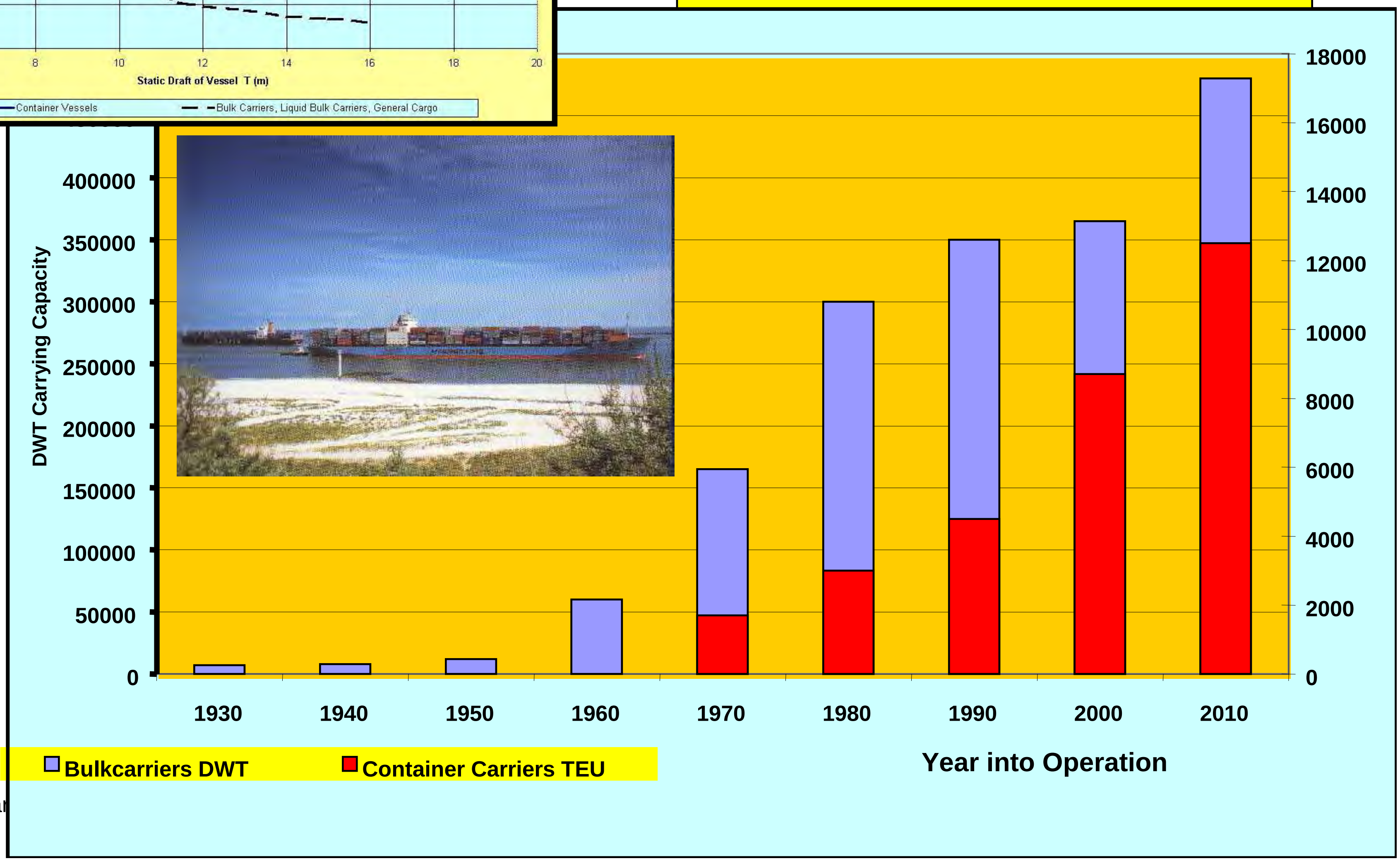


Figure 2: Typical Unit Time Charter Rates of Merchant Vessels (1998)

ECONOMY OF SCALE : EVER INCREASING SHIP'S SIZES

Figure 1-4:Evolution of Maximum Size of Maritime Vessel



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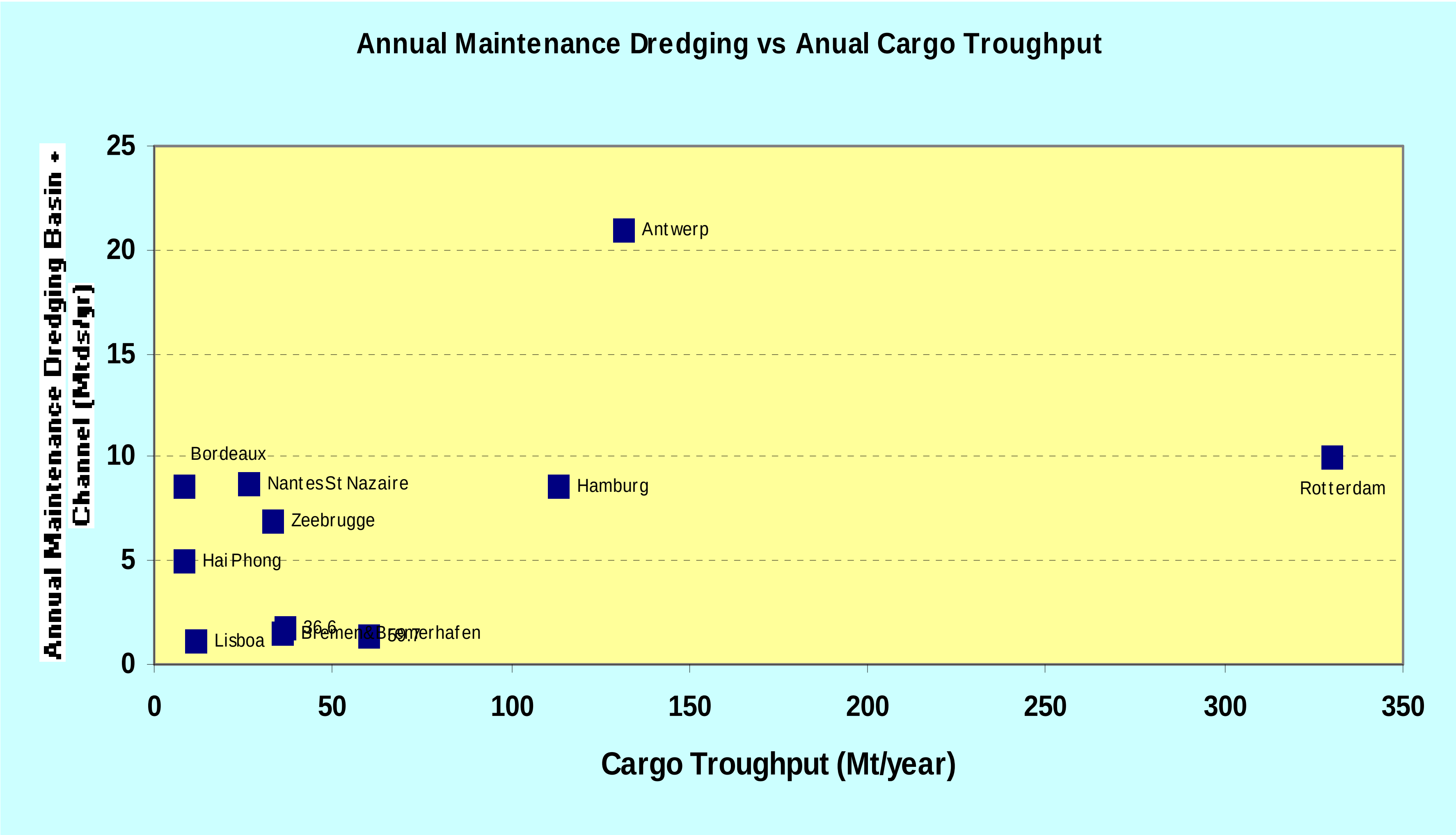
ANNUAL MAINTENANCE DREDGING CAN BE A SIGNIFICANT COST-ITEM IN THE OVERALL PORT'S ECONOMIC BALANCE



Dredging & Reclamation: it's all about soil and dredgers

The CSD "JFJ De Nul" cutter dredger with worldst largest cutter-power

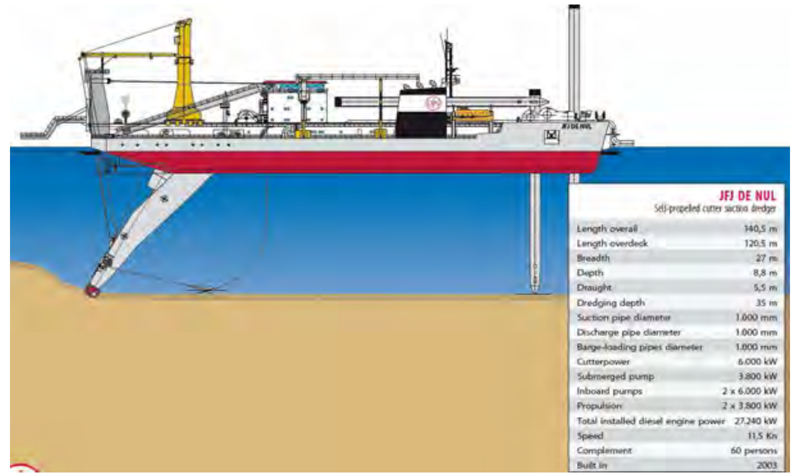


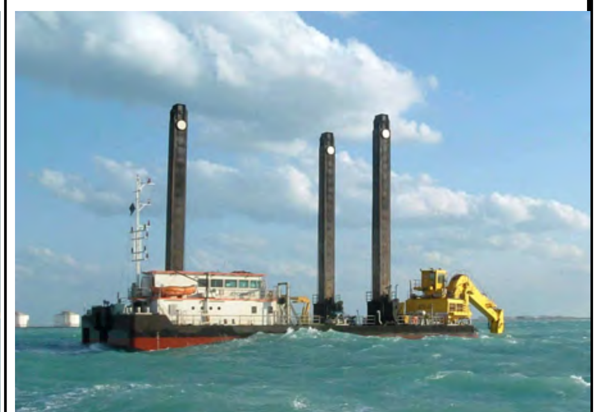
PHOTO 3: Vasco crew removing coral blocks between the ripper teeths.

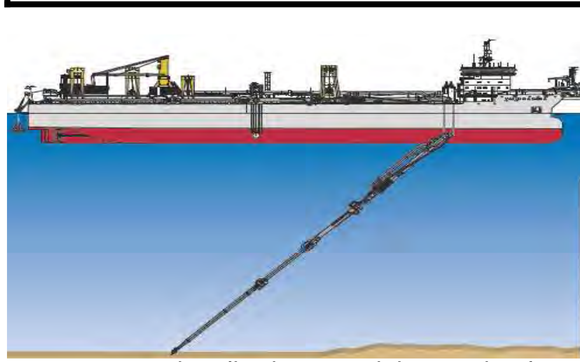
Dredging equipment:

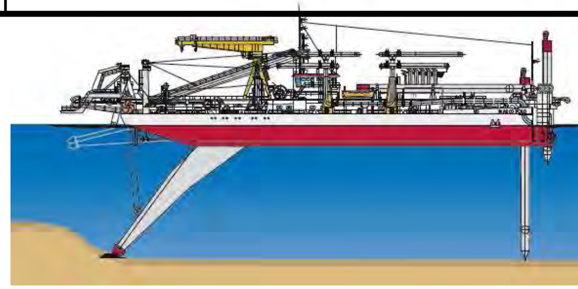
Hydraulic dredgers: Trailing Suction Hopper Dredger (TSHD)

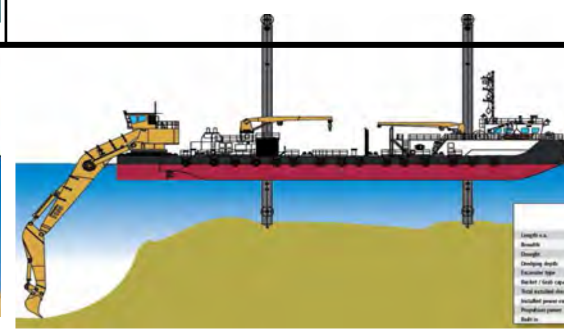
Cutter Suction Dredger (CSD)

Mechanical dredgers: Backhoe Dredger (BHD)

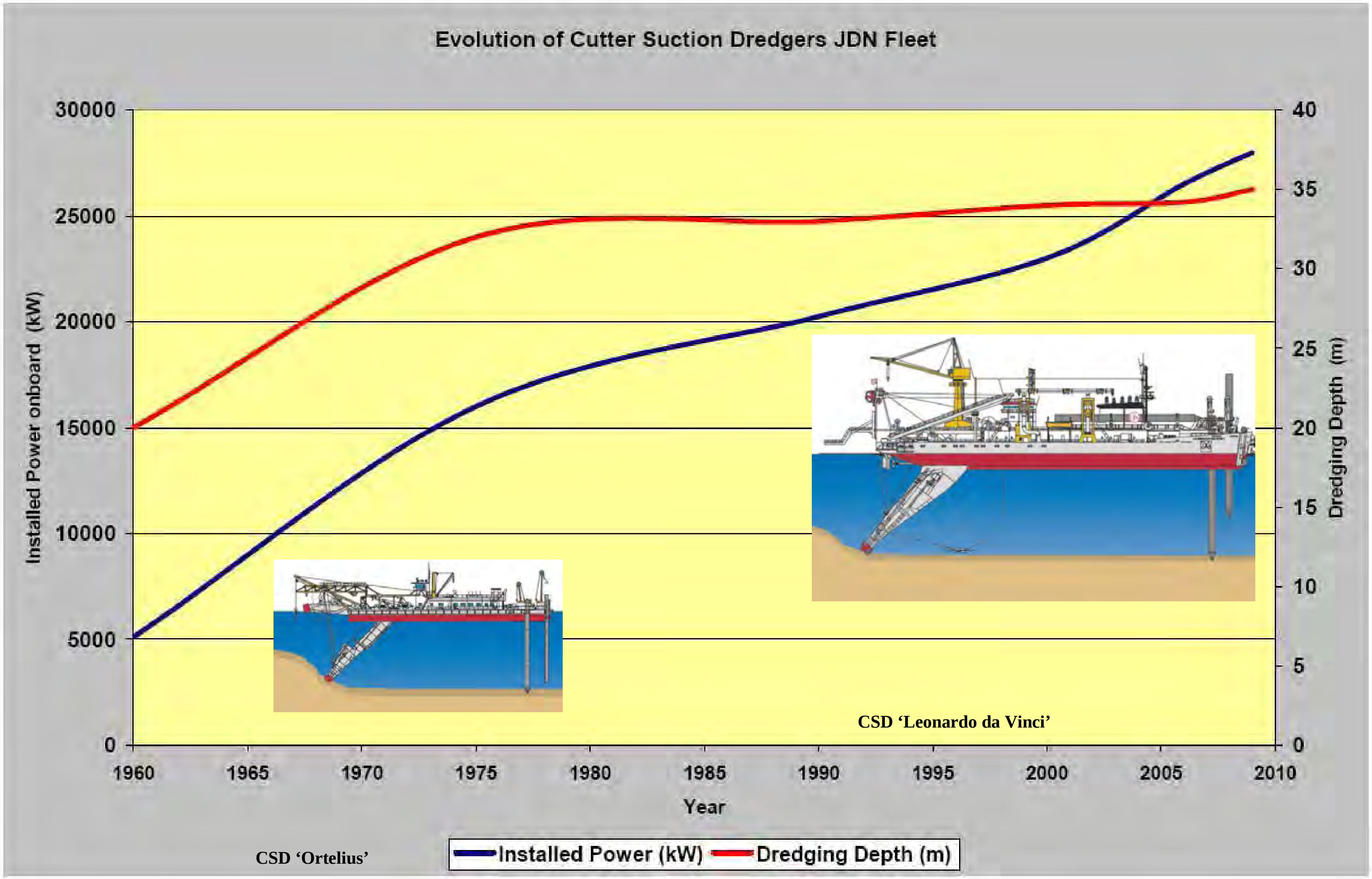
TSHD	CSD	BHD
		



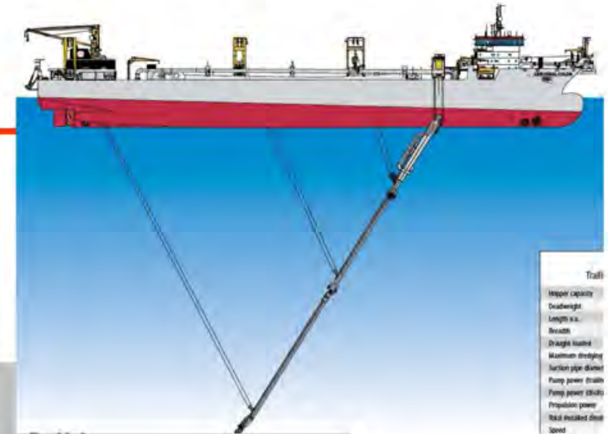


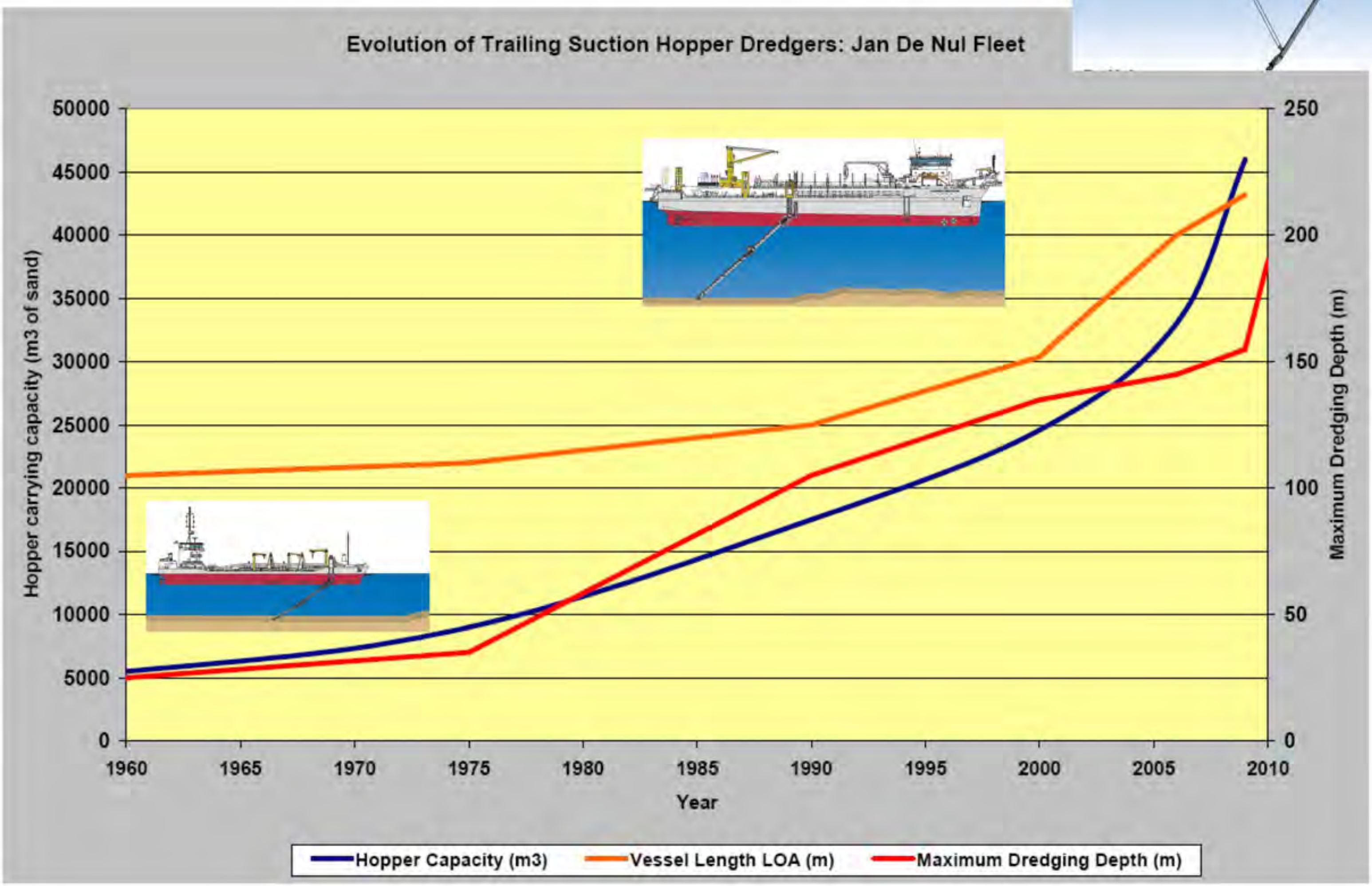


Evolution of Cutter Suction Dredging Fleet



Evolution of Trailing Suction Hopper Dredging Fleet



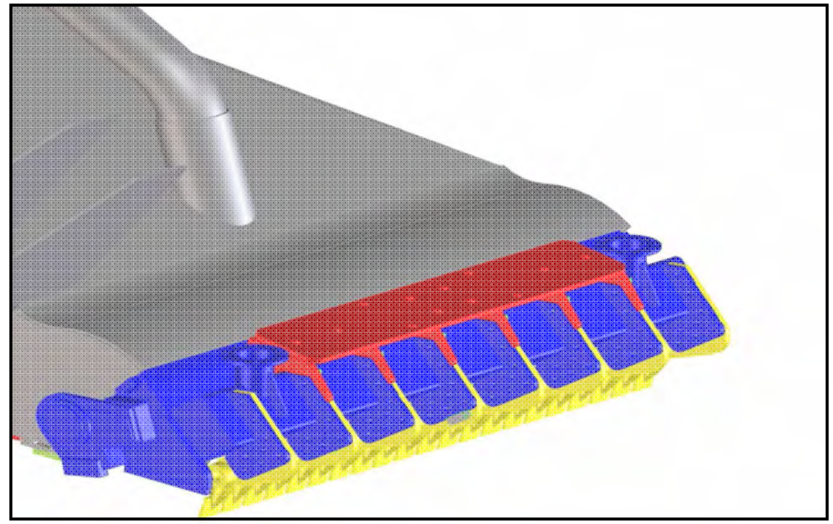


Dredging Tools: mechanical rupture of cohesion of soil + hydraulic jetting & erosion-transport

3 methods

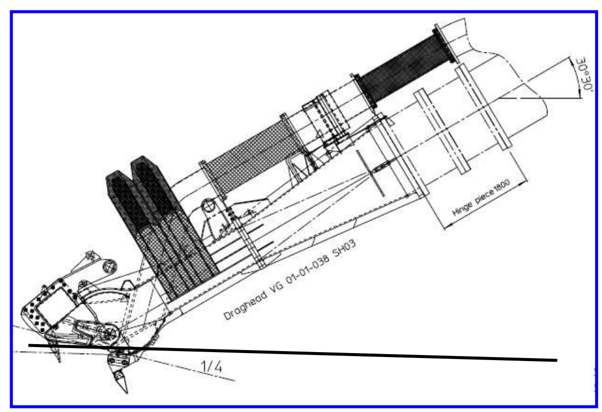
TSHD	CSD	BHD
Draghead	Cutterhead	Bucket
		

Soil-cutting tools



Cutterheads fitted with Pickpoints (left) or Cutter-Teeth (right)

Draghead fith with Trailer-Teeth



Transport of dredged material

Transport over sea : 3

TSHD	CSD	BHD
Hopper	Barge	Side casting
		

Pipeline

Transport of dredged material

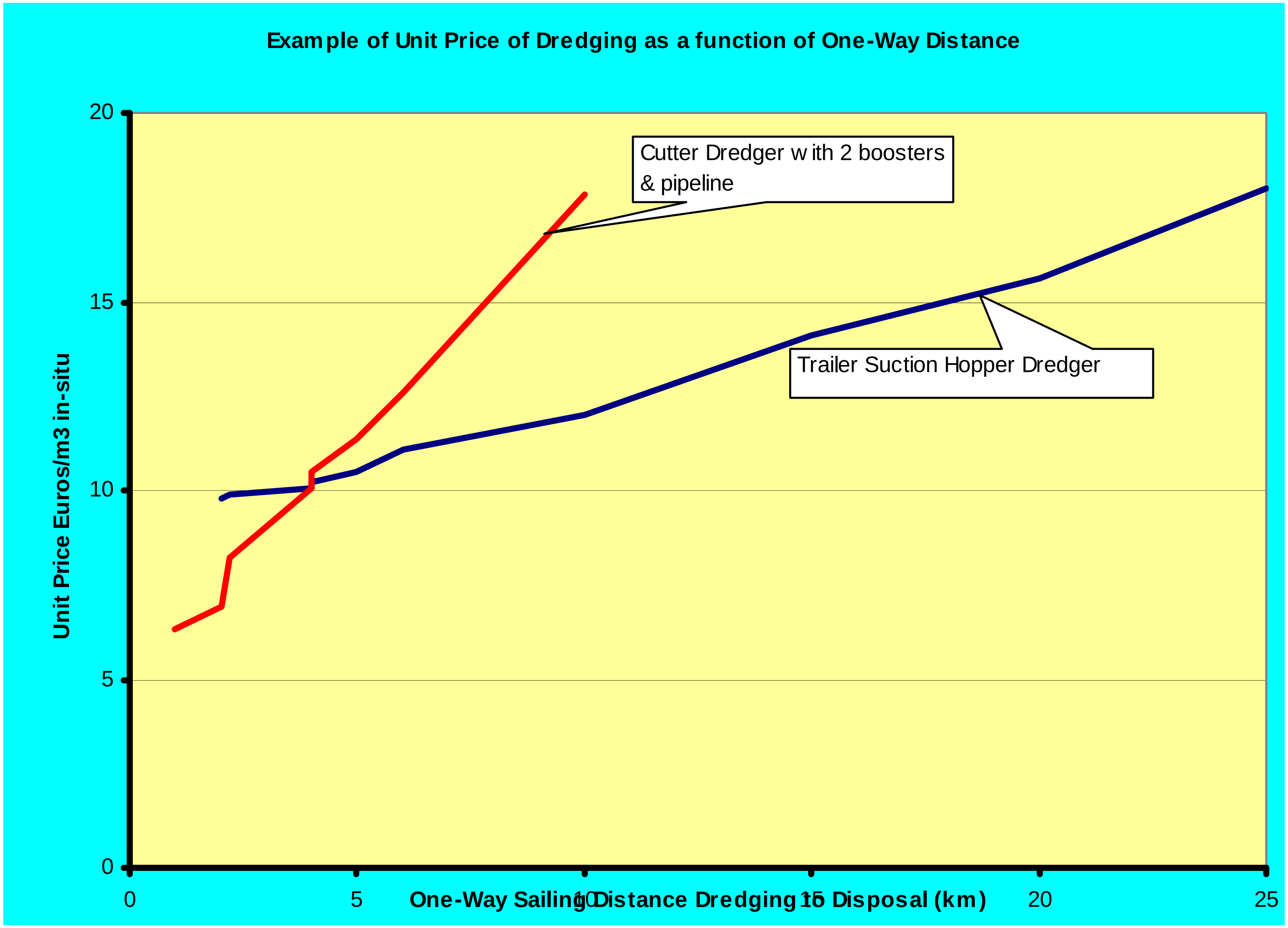
Transport over land : 3 methods

Dumptrucks	Trestles	Pipeline
		

Hydraulisch Transport with pipelines offers many advantages:

- Continu process, fit for huge quantities & productivities: 20.000 to 100.000 m3/day
- Swift mobilisation & readyness
- Limited maintenance
- Limited Personnel

Dredging & Transport Distance: influence on Unit Price



Principles of hydraulic transport of dredged material

- **Disrupted soil or rock – individual particles, heavy suspensions or fragments – are mixed with water to form a slurry (typical densities: 1,15 to 1,50)**
- **Mixture-forming happens in draghead or cutterhead and is then sucked into the suction pipe, via hydraulic depression**
- **Mixture velocity and turbulence (Re > 4.000) prevent the mixture from settling down**
- **After discharge, turbulence decreases and particles are allowed to settle down**

Drawbacks of hydraulic transport

- **Limited transport-distances: 2 tot 10 km**
- **Differential settling: siltpockets**
- **Increase of suspension load of transport-water: visual impact of turbidity**
- **Wear of pipes**

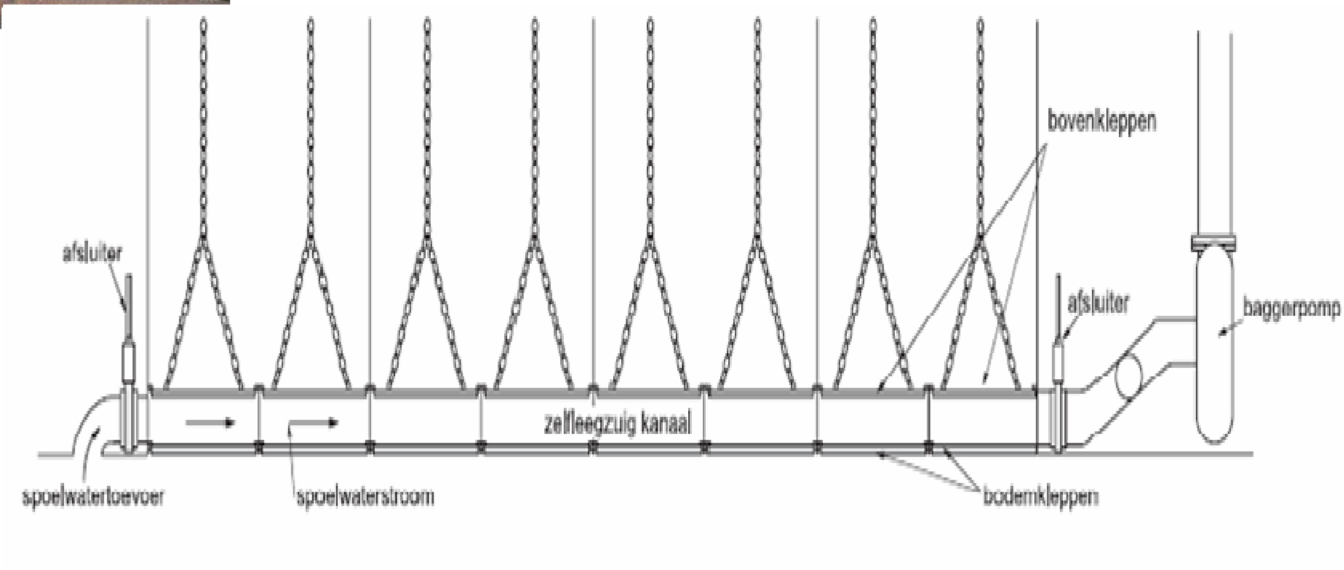
Hydraulic transport: practical application in dredging

Shipborne pipeline systems

Working principles of a TSHD and a CSD

Hydraulic transport via shipborne & external pipeline systems

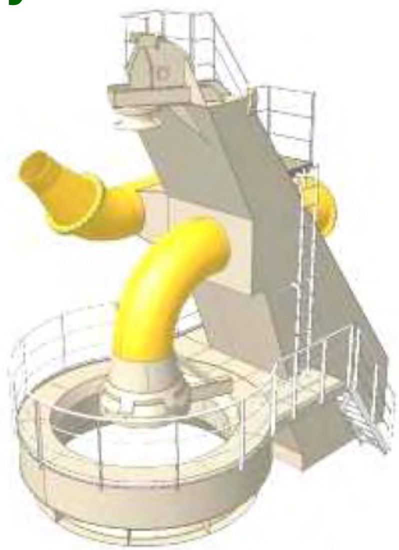
TSHD reclaiming

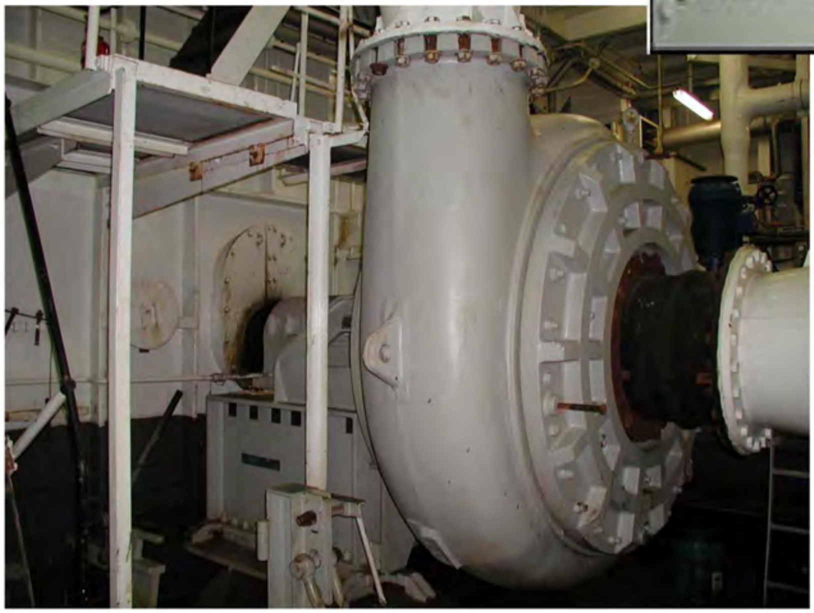


Principe van leegzuigkanaal in de lengterichting

Hydraulic transport via shipborne & external pipeline systems

TSHD reclaiming





Hydraulic transport via external pipelines

Floating & Land pipeline

Hydraulic transport via floating/land pipelines

Cutter-dredging and direct upland reclamation

CSD Leonardo da Vinci in Port Hedland, australia

Hydraulic transport & reclamation

Reclamation
Area: dredged mixture with high solids concentrations

Hydraulic transport & reclamation

Hydraulic transport & reclamation

Beach restauration

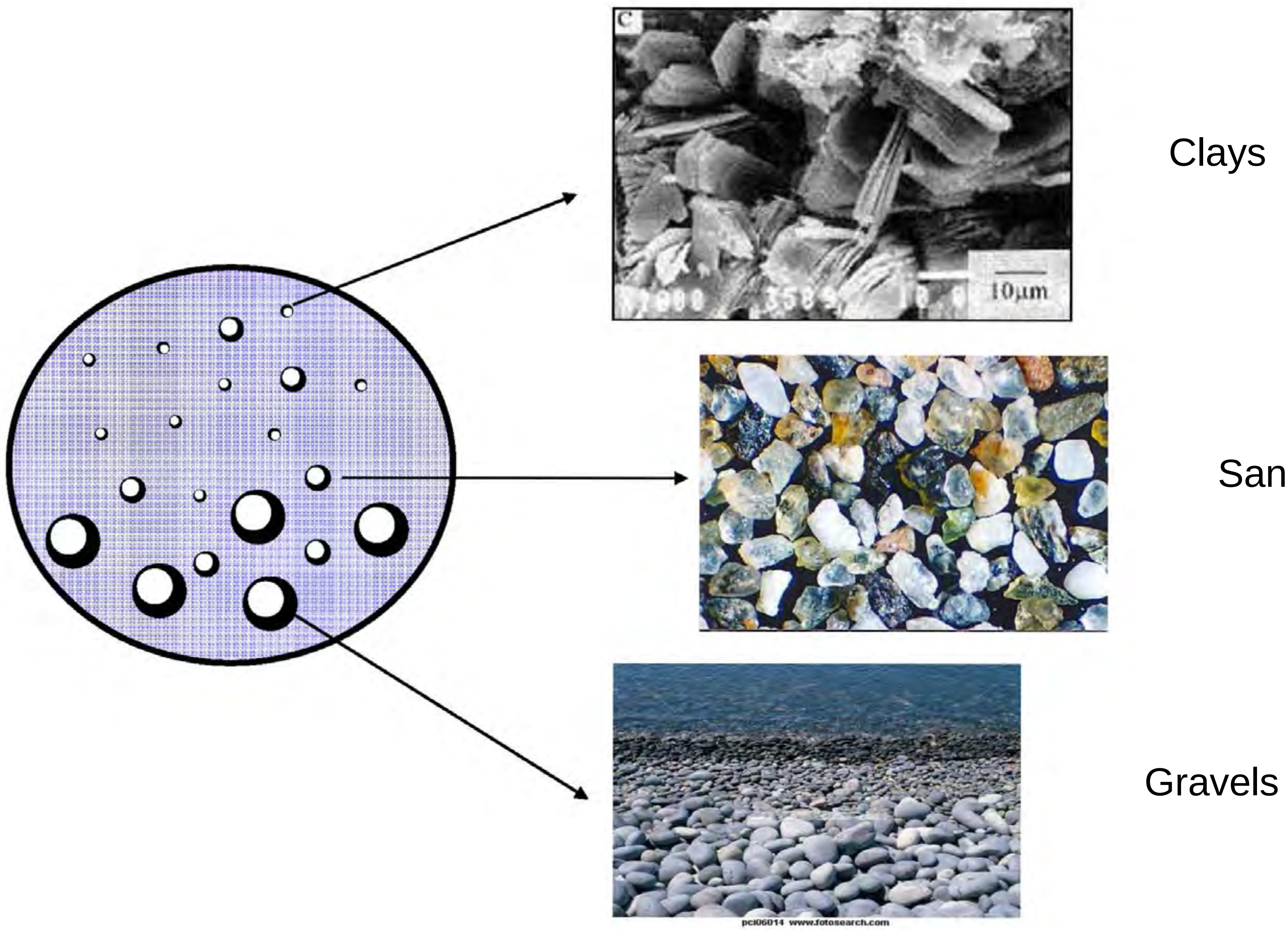
direct settling & open-water discharge

(Sylt, Germany),

Hydraulic Transport: Hydraulic-production computations

- cost-estimates for tender-preparation
- dimensioning of dredge-pumps and shipborne pipe systems for the design of dredgers
- Dimensioning of jet-devices and nozzles for fluidisation of soil prior to suction
- Control of performance of dredge-pumps
- Development of simulators

Horizontal Transport = transport of a mixture of (sea)water and particles



Dredging operation: disruption of aquatic soils (rocks, sediments, …) + transport + disposal

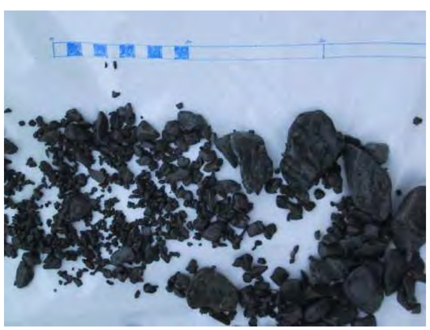
Dredgeable Rocks

Soft Rocks (UCS < 12,5 MPa)	Intermediate Hard Rocks (UCS = 12,5 – 30 MPa)	Hard Rocks (UCS 30 – 60 MPa)
		
Tertiary Claystones, Mudstones, … **Quaternary Calcarenites, cap-rocks, Corals,……**	**Limestones, Sandstones, .**	**Hard Limestones, Arenites, Basalts…..**

In hydraulic dredging the maximum allowable grain-size diameter of dredged soil is determined by the spherical aperture of the dredge pumps.

Products of Rock Dredging by Cutter Suction Dredger

Cap-Rock dredged by CSD (Persian Gulf)



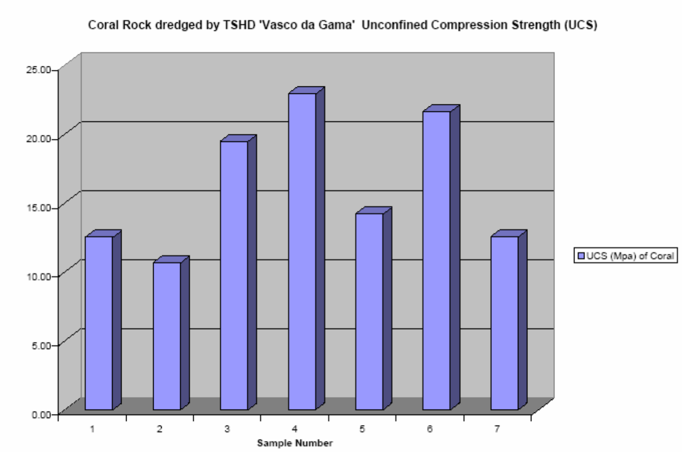
Tertiary Claystones dredged by CSD “JFJ DE Nul” (UCS = 11 MPa)

Products of Rock Dredging by Backhoe Dredger

Coral Reef-Flat (UCS = 10 -15 MPa)

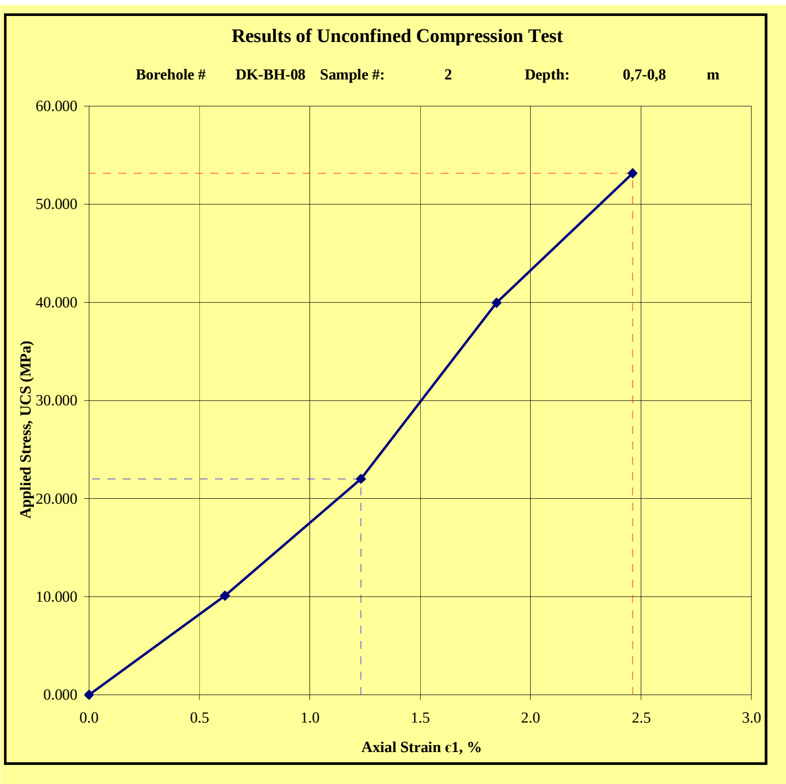
Basalt boulders (UCS = 32 -72 MPa)

Products of Rock Dredging by Trailing Suction Hopper Dredger : Ripping mode (only applicable for large TSHD with high installed power, e.g. > 30.000 kW)



Coral Reef-Flat (UCS = 10- 23 MPa)

Rock testing: UCS test result

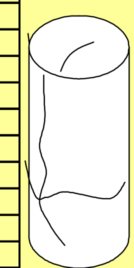


Standard Test Method for Elastik Moduli of Intact Rock Core Specimens is Uniaxial comhression. (ASTM D 3148-96)

Contract: #	EPC 2-04-P902	Borehole: #	DK-BH-08	Sample: #	2	Depth, (m)	0,7-0,8
Job:	**Nearshore Chihacheva Bay**						

Height #1 (mm)	81.2	**Diameter #1 (mm)**	71.9	**Weight (g)**	914.00
Height #2 (mm)	81.3	**Diameter #2 (mm)**	72.5	**Area (sq.m)**	0.004128
Height #3 (mm)	81.2	**Diameter #3 (mm)**	73.1	**Temperature (C)**	16
Average Height (cm)	**8.1**	**Average Diameter (cm)**	**7.3**	**Volume, (cm^3)**	**335.351**

Tare: #	48	**Unit wet weight (g/cm^3)**	2.73	**Machine #:**	MC-500
Tare weight (g)	32.32	**Unit dry weight (g/cm^3)**	2.62	**Date:**	4.03.05.
Wet weight + Tare (g)	83.98	**Rate (mm/min)**	0.2	**Technician:**	Timchenko L.
Dry weight + Tare (g)	82.00	**Load Constant, (kN/dv)**	1.000		
Moisture content (%)	**3.99**	**Sample Description:**	***Basalt***		

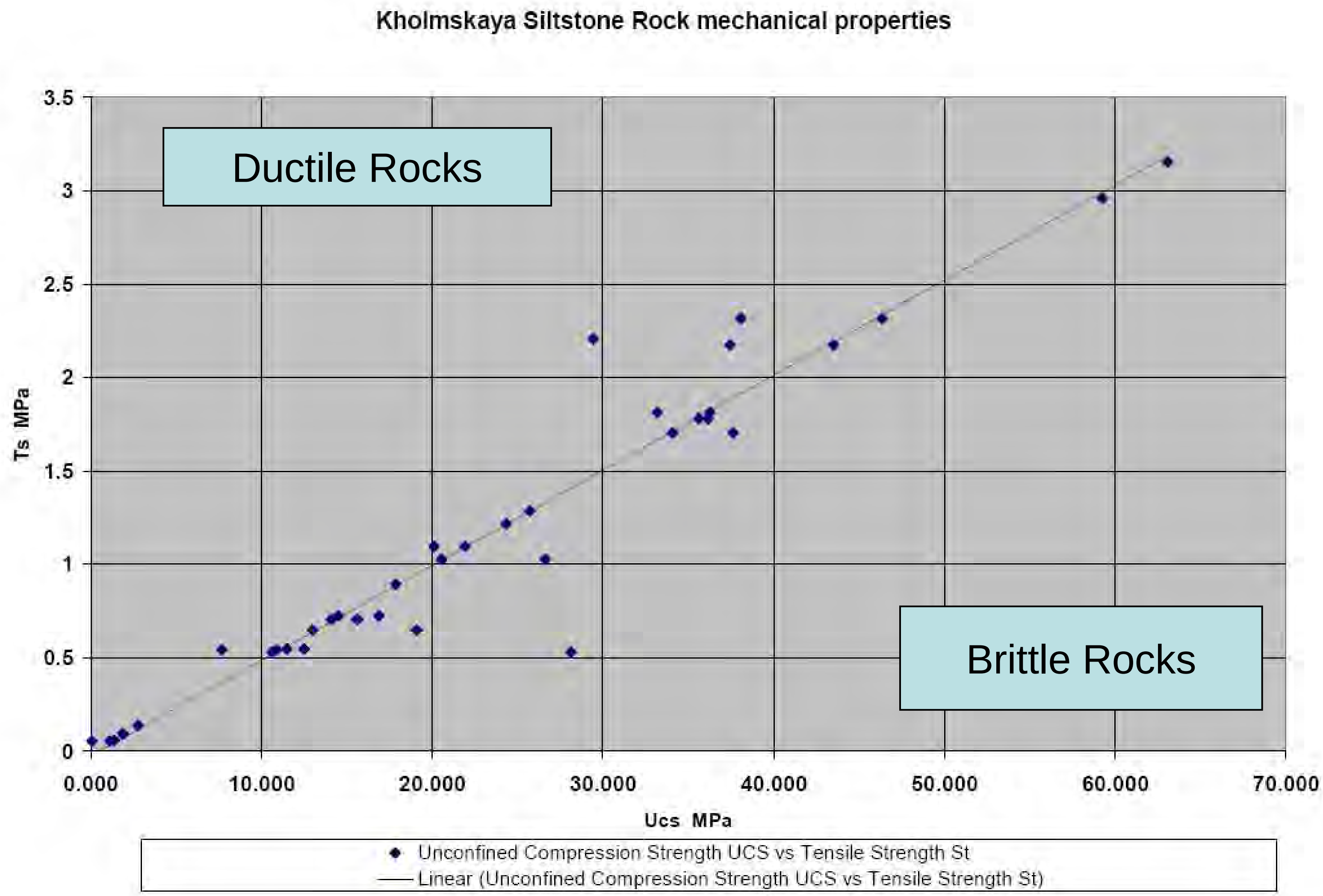
Deformation (mm)		Average Deformation (mm)	Load (Rdg.)	Load (kN)	Axial Strain ϵ1, %	Corrected area, A' (sq.m)	Applied Stress, UCS (MPa)	Type of failure:
0.00	0.00	0.00	0.0	0.00	0.000000	0.004128	0.000	
0.50	0.50	0.50	42.0	42.00	0.615511	0.004154	10.111	
1.00	1.00	1.00	92.0	92.00	1.231022	0.004180	22.011	
1.50	1.50	1.50	168.0	168.00	1.846533	0.004206	39.944	
2.00	2.00	2.00	225.0	225.00	2.462043	0.004232	53.161	
		UCS =	53.161	MPa				
		UCS* =	51.318	MPa				
		E*=	2.150	GPa		Interval of Stress, (MPa)		
		E =	1.788	GPa		0.000	22.011	

UCS* = UCS - corrected for sample L/D

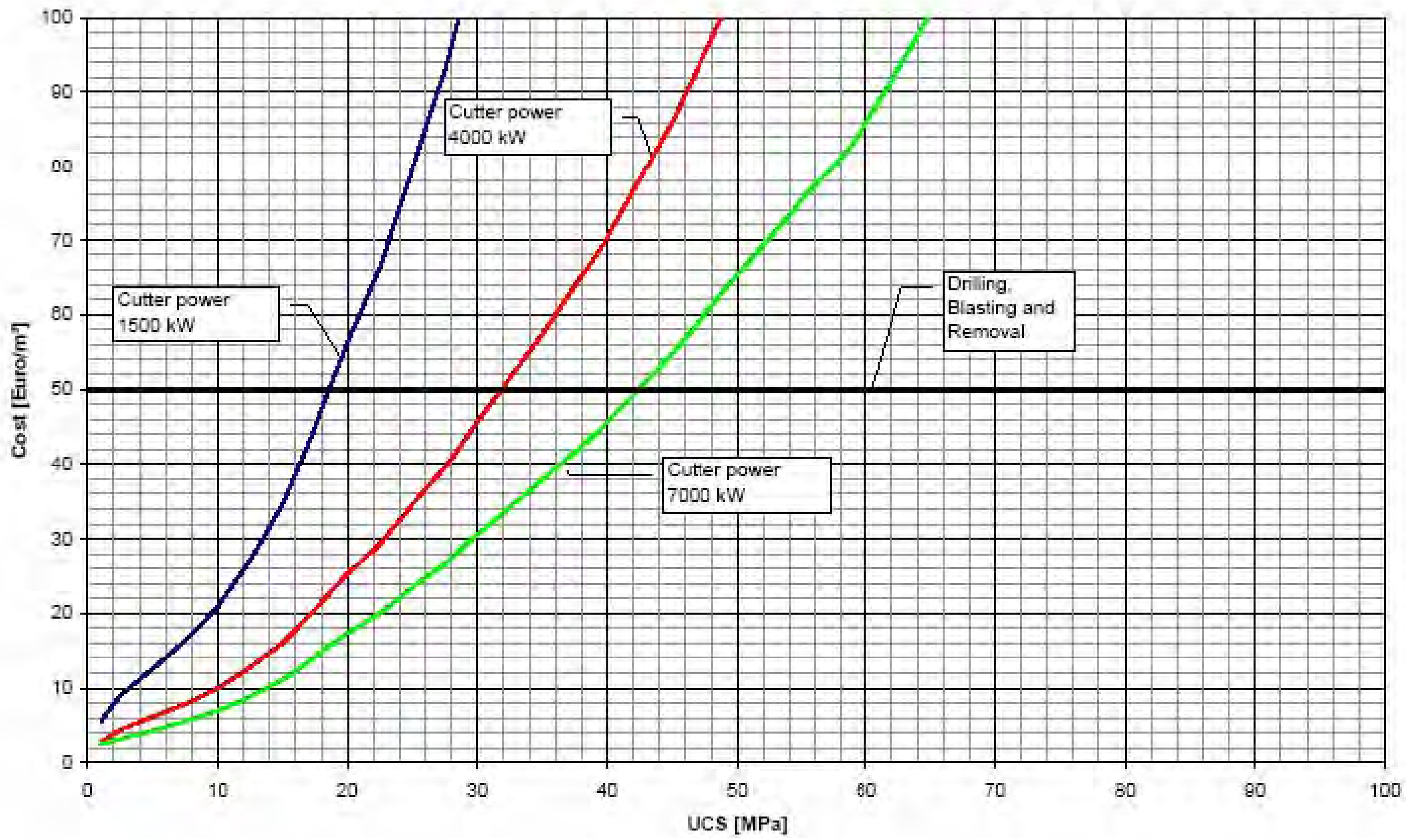
E*= E - corrected for sample L/D

E = Initial linear elastic modulus

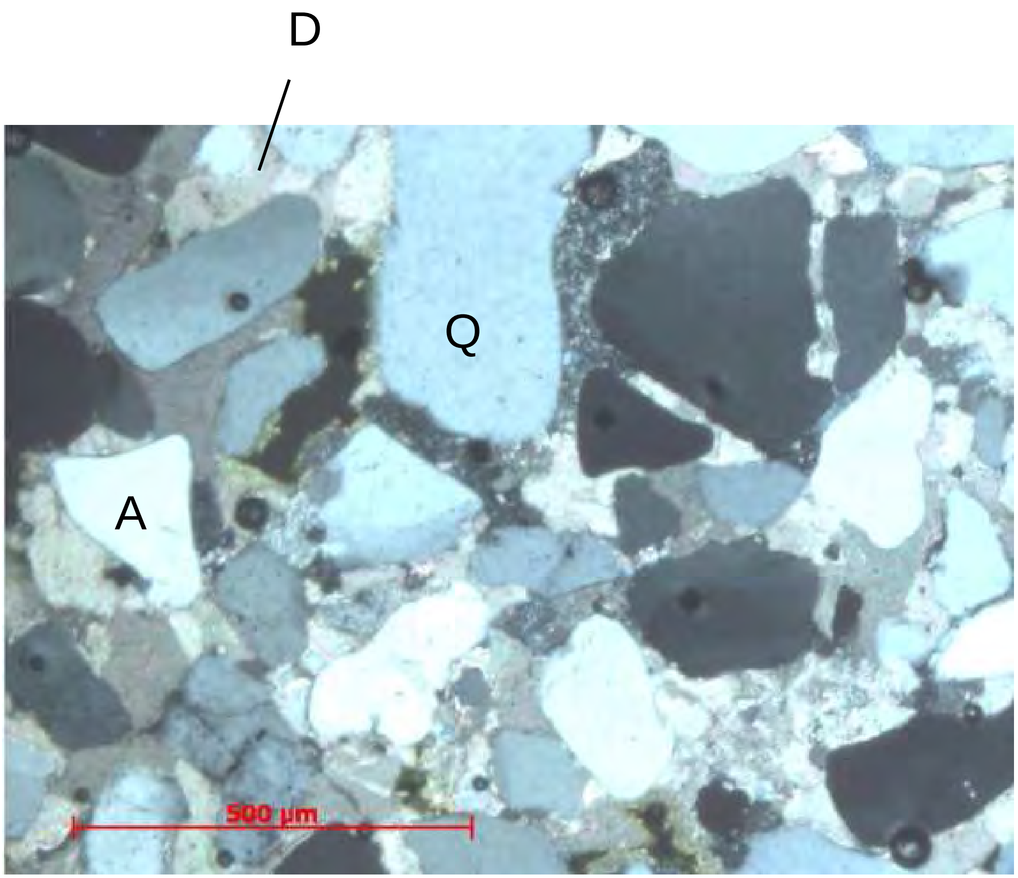
Basic Rock-Mechanical Characteristics for Rock-Dredging



Dredging of Rock: Blasting or Rock-Cutter-Dredging ? A matter of rock and cuttingpower.



Mineralogy of Rocks: Calcirudite (UCS = 13 MPa)



Polarizing Microscope Photograph

Calcirudite:

- **C : Calcite**
- **D: Dolomite**
- **A: Aragonite (Shell-fragments)**
- **Q: Quartz**

Mineralogy of Rocks: Granite (UCS = 95 MPa)

Macro-Cristalline Pink Granite (Magmatic Intrusive Rock):

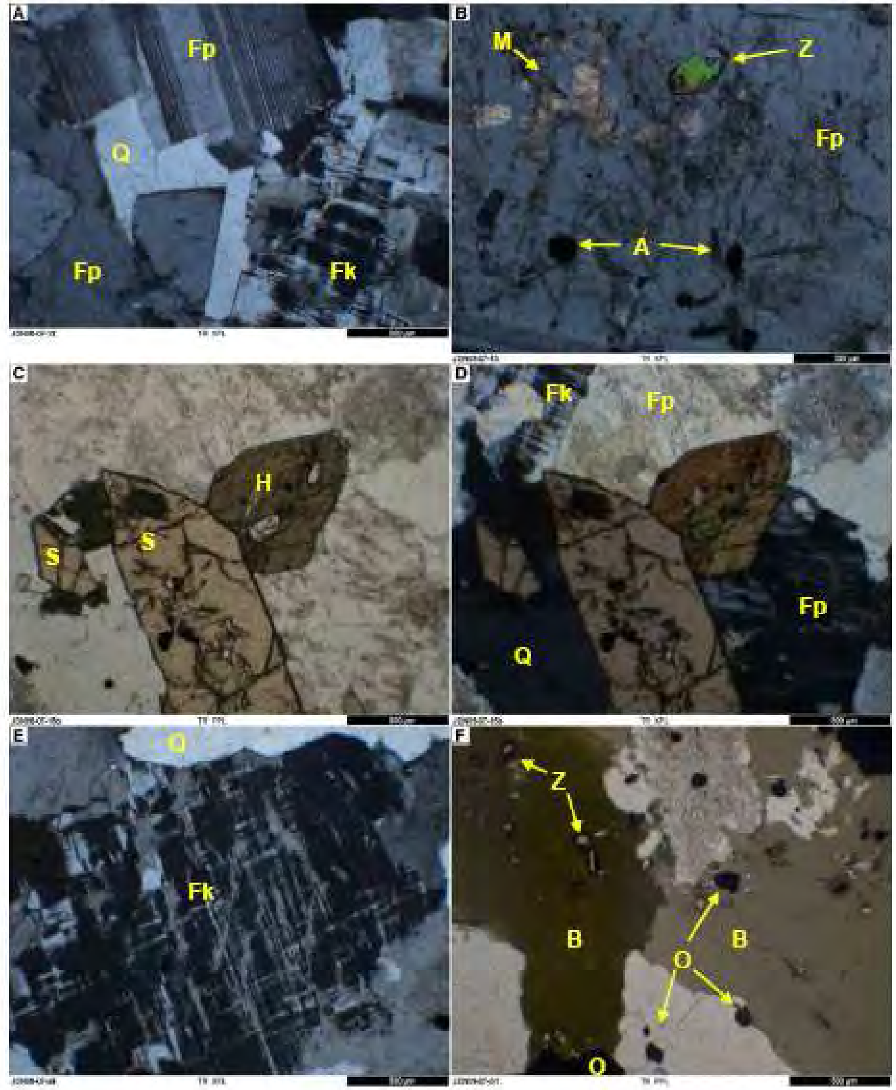
Q : Quartz

Fp: Feldspars Plagioclase

Fk: Feldspars Orthoclase

M: Muscovite (Mica)

Z: Zircon



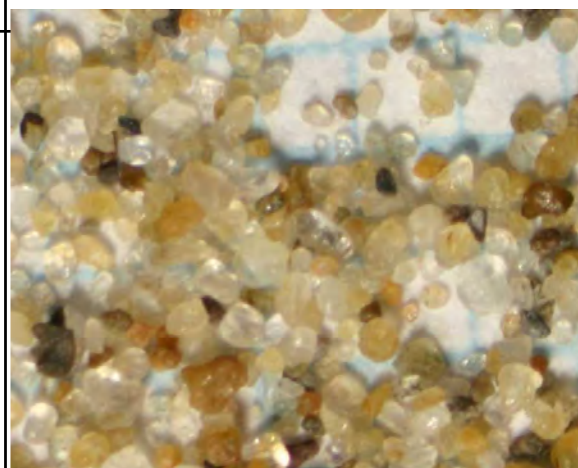
Polarizing Microscope Photograph

Rock Mechanics for Dredging: examples

Parameter	Basalt	Porphyre	Limestone	Sandstone
Uniaxial Compression Strength UCS (MPa)	**180**	**220**	**160**	**40**
Puncture Resistance Is50 (MPa)	**16**	**19**	**9**	**5**
Abrasivity Index FPMs	**150**	**300**	**5 - 10**	**10 - 150**
Shore Hardness	**50 - 90**	**80 - 100**	**60 - 80**	**15 - 30**
Rock-Strength Device RSD (MPa)	**100**	**150**	**50**	**40**
Rock-Quality Designation RQD (%)	**60**	**90**	**50**	**40**

Dredging operation: disruption of aquatic soils (sediments, rocks,…) + transport + disposal

Sediments: mainly 3 types

Cohesive sediments: Clay & Silts	Granular sediments: Sand	Granular sediments: gravel, boulders, . . .
		
d50 < 63 µm	63 µm < d50 < 2 mm	2 mm < d50

In hydraulic dredging the maximum allowable grain-size diameter of dredged soil is determined by the spherical aperture of the dredge pumps.

Geotechnical characteristics of some common sediments

Sediment Type	Porosity n (%)	Water Content w (%)	Volume-mass Dry (tds/m3)	Volume-mass Sat (tds/m3)	Sand Content > 0,063mm (%)	Relative Density Dr (%)
Uniform loose sand	**46**	**32**	**1,43**	**1,89**	**97**	**< 35**
Uniform dense sand	**34**	**19**	**1,50**	**2.09**	**97**	**65 - 85**
Well-graded sand	**26**	**16**	**1.86**	**2.16**	**85**	**88**
Glacial till	**20**	**9**	**2.12**	**2.32**	**20**	
Mud (silt-clay)	**84**	**195**	**0.43**	**1.27**	**15**	

AASHTO material designation

Size in millimeters	Size class
500	Cobbles
76.2	Coarse Gravel
19.05	Fine Gravel
4.75	Coarse Sand
2.0	Medium Sand
0.425	Fine Sand
0.075	Silt or Clay

Udden-Wentworth scale

Size in millimeters	Size class
4096	Boulder
256	Cobble
64	Pebble
4	Granule
2.0	Very Coarse Sand
1.0	Coarse Sand
0.5	Medium Sand
0.25	Fine Sand
0.125	Very Fine Sand

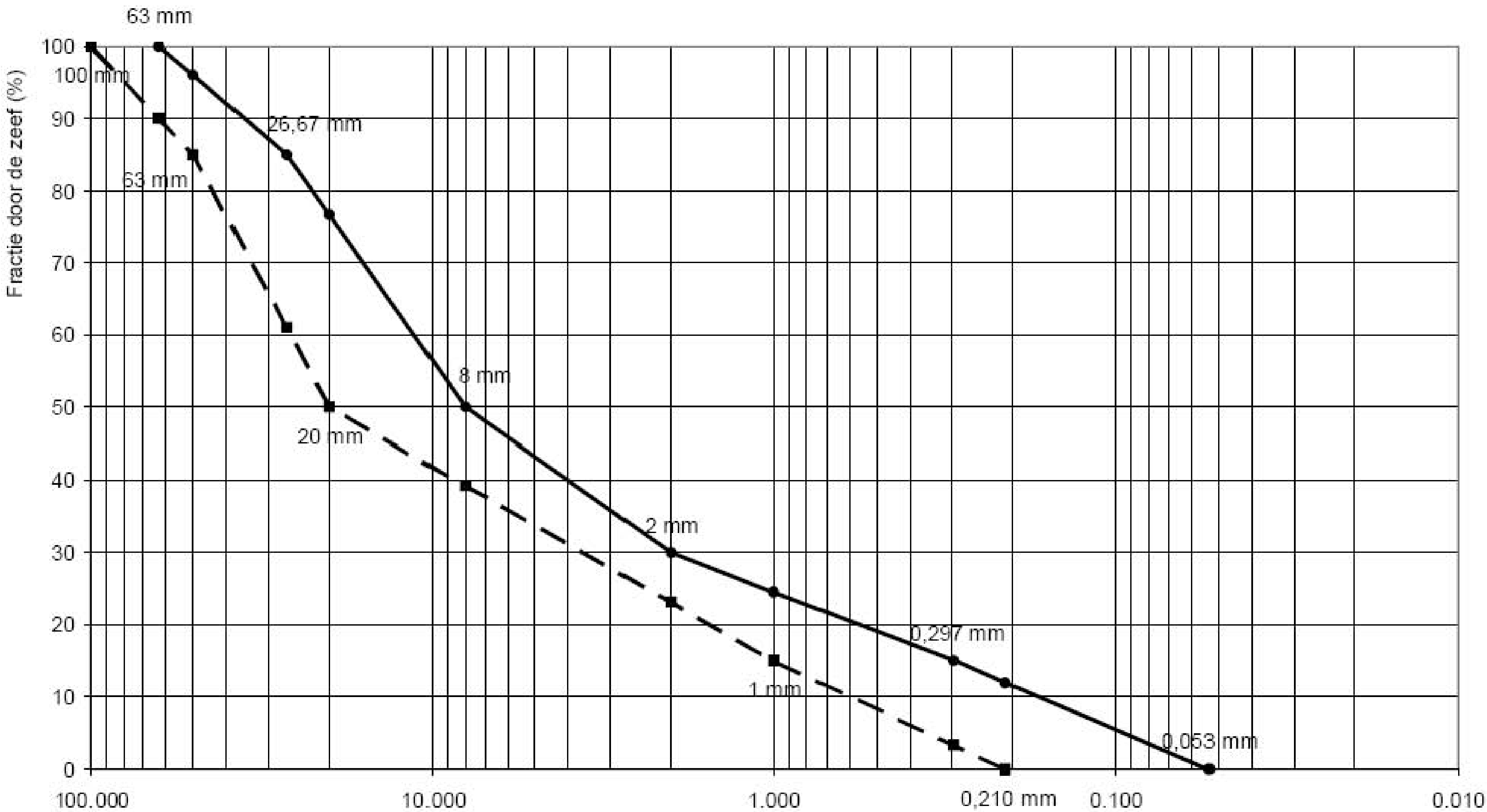
Geotechnical properties of soils in the horizontal transport process of mixtures

Cobbles, boulders, gravels,…

- **Main in-situ geotechnical properties (before dredging)**
  - **Grain-size distribution, including d50 (median particle-size), dmf (determining particle-size = (d10+ d20+…d90)/9), sorting degree,…**
  - **Angularity and grain-form**
  - **Angle of Internal Friction,**
  - **Specific volume-mass, ρs of individual particles**
    - **Quartzite: 2,660 kg/m3**
    - **Basalt : 2,900 kg/m3**
    - **Claystone :2,300 kg/m3**
- **Main mixture properties (during transport)**
  - **Grain-size distribution**
  - **Angularity, abrasivity,..**
  - **Specifiv volume-mass**

- **Critical velocity**
- **Wear**
- **Equilibrium slope**
- **Settling velocity**

Grain-Size distribution of dredged gravel



Granular sediments: gravels and sands

Basic Geotechnics of granular sediments and soils: sands. Dredging is a rapid deformation-process (xx m/sec) versus the evacuation velocity of excess pore-water pressure (< 10^{-3} m/sec) >> Undrained Conditions

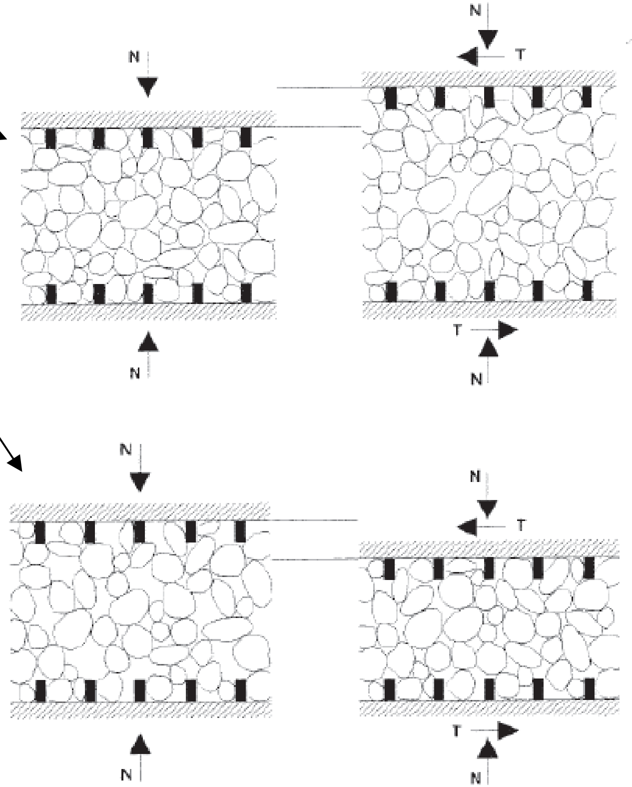
Relative Density (%) >> Degree of Compaction of granular soil

$$Dr = \frac{\rho_d - \rho_{dmin}}{\rho_{dmax} - \rho_{dmin}} \times 100 \ (\%)$$

and Drcrit (Casagrande) : no volume-char

Dr > Drcrit >> Dilatancy
Dr < Drcrit >> Contractancy

With: Dr < 25 % : very loosely packed
Dr : 50 – 75 %: densely packed
ρ_{dmax}: determined by Modified Proctor Test



Cohesion, c (kPa)

- **Fine sand (d50 = 0,200 mm) : c = 4 kPa**
- **Very coarse sand (d50 = 0,900 mm): c = 0,8 kPa**

Angle of Internal Friction, φ (degrees)

- **Angular sand-grains (river sand) : φ = 38°**
- **Spherical sand-grains (eolian sand) : φ = 25°**

Permeability Coefficient, k (m/sec)

- **Fine sand : k = 10^{-5} m/sec**
- **Very coarse sand : k = 10^{-3} m/sec**

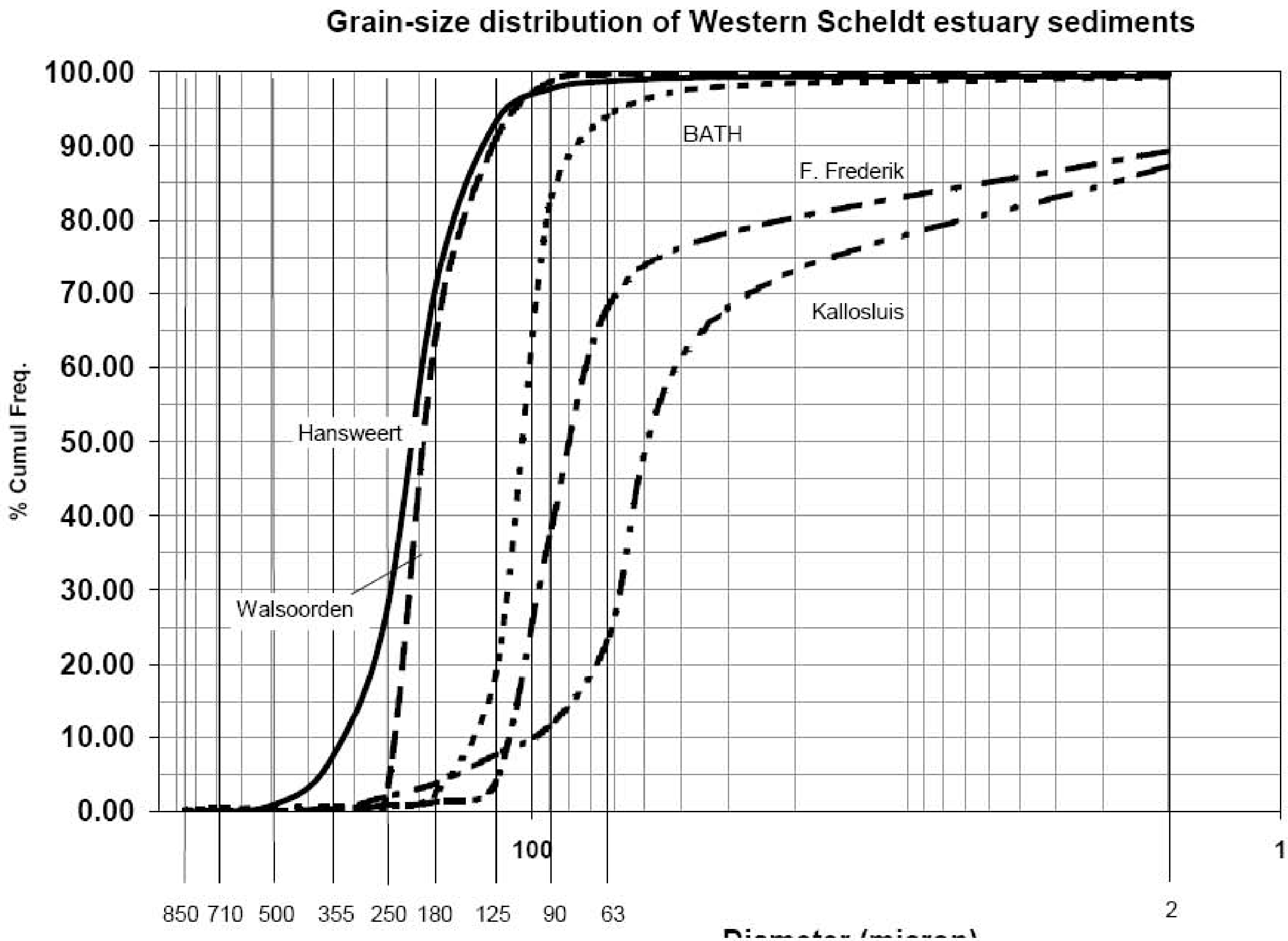
Shell-fragment content

Critical erosion velocity (at large flow velocities (> 3 m/sec)

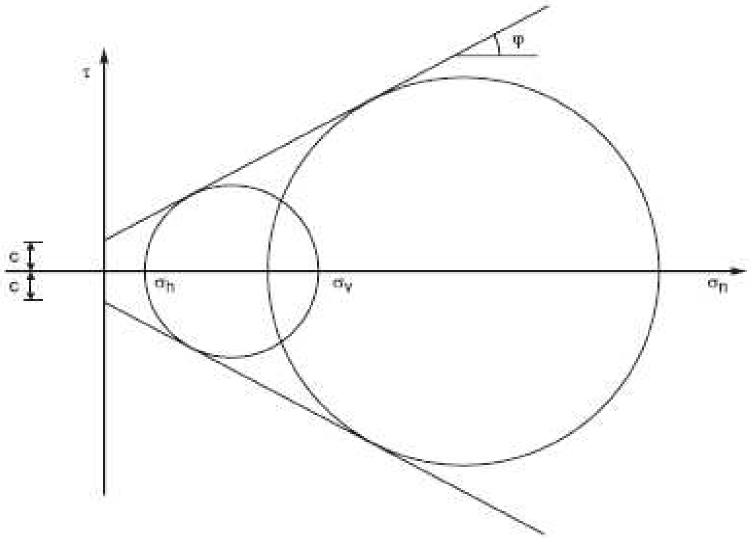
At low flow velocities : cfr Shields
At high flow velocities: cfr van Rhee

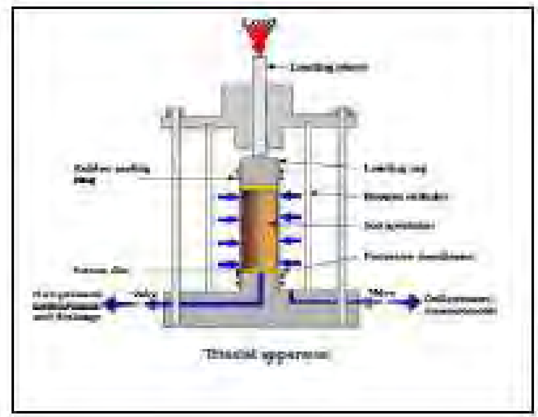
(Drawings after Lübling, 2004)

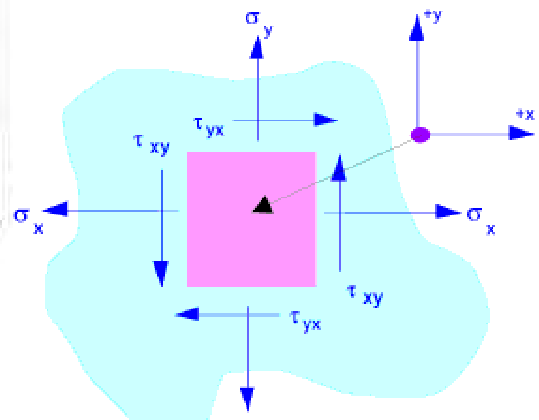
Grain-size distributions of dredged materials in Western Scheldt



Basic Geotechnics : Mohr's Circle describing the stress conditions in soils







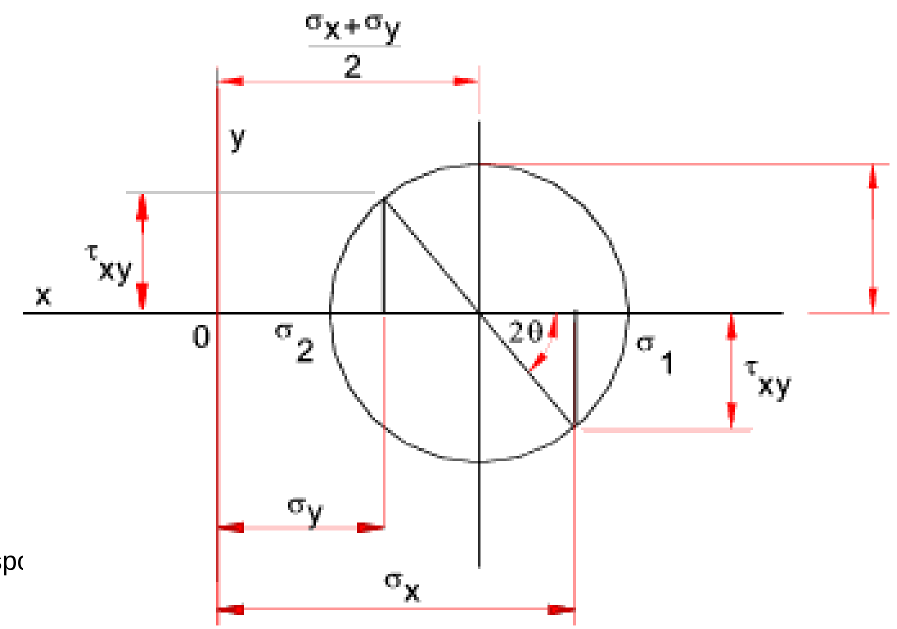
Total Stress:

$$\tau = \sigma_n \cdot \tan \varphi + C$$

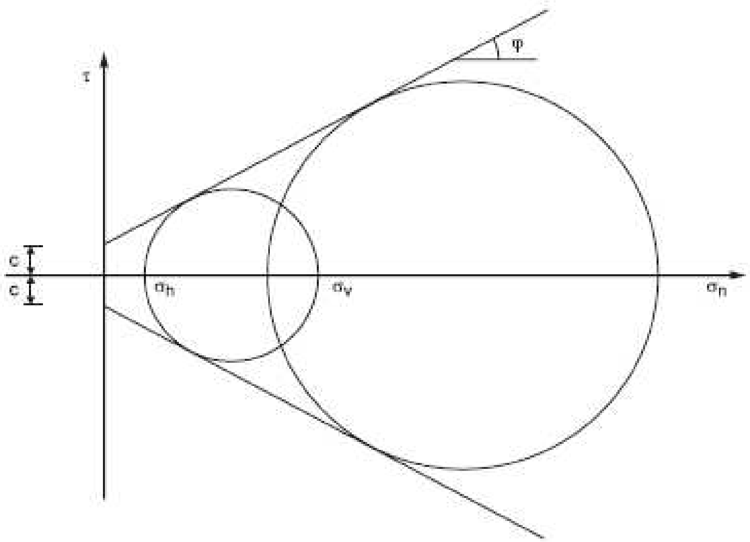
Effective Stress:

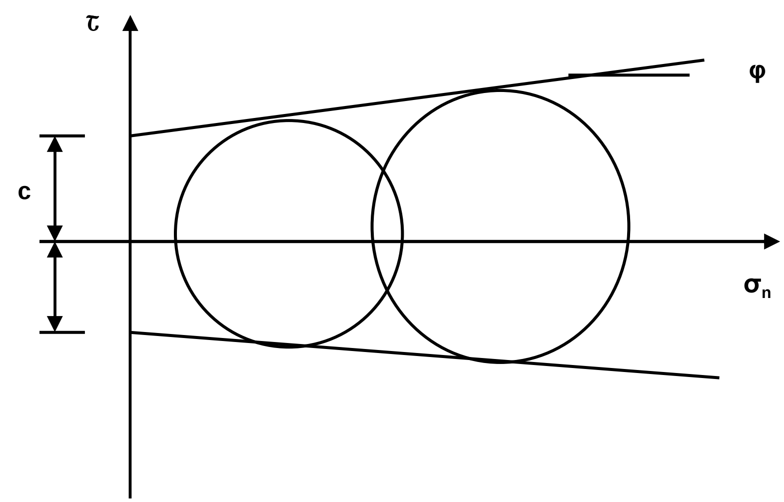
$$\tau' = (\sigma_n - u) \cdot \tan \varphi' + C$$

τ = (Undrained) Shear-Strength
σn = total Normal Stress
u = pore-water pressure
φ = angle of Internal Friction
C = cohesion



Basic Geotechnics : Mohr's Circle describing the stress conditions in soils





Granular Soils: sands

- **low C & τ = increasing with depth**
- **high φ**

Cohesive Soils: clays

- **high C & τ =~ C**
- **low φ**

Basic geotechnics: vertical and horizontal stresses

Active & Passive Horizontal Soil Pressure cfr Rankine:

In dredging, overburden normal stresses are (generally) low:

- **>> low horizontal soil pressure…and equilibrium inflow slope , θ, is generally close to φ**

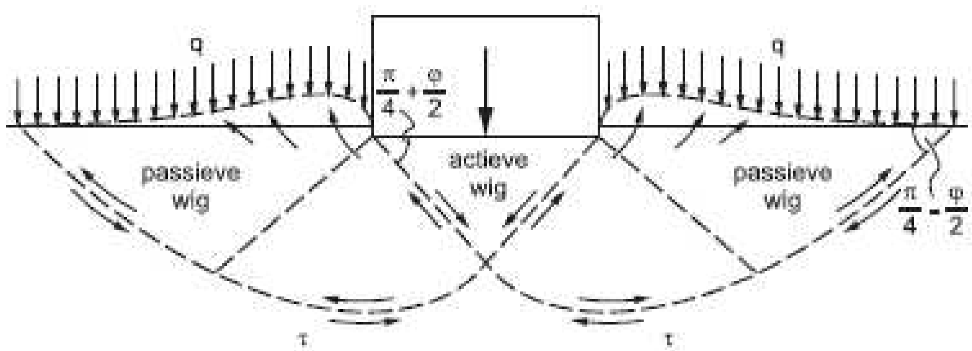
$$tg\,\theta = tg\,\varphi \times \frac{\rho_s^2}{(\rho_s^2 + \rho_w \cdot (\rho_s - \rho_d))}$$

- **angle (π/4 +/- φ'/2) is determining the optimal cutting angle**

$$\sigma_h' = K_0 \cdot \sigma_v'$$

$$K_a = \tan^2\left(\frac{\pi}{4} - \frac{\phi'}{2}\right)$$

$$K_p = \tan^2\left(\frac{\pi}{4} + \frac{\phi'}{2}\right)$$



Erosion-sensitivity of sand at large flow velocities (cfr Bischop et al, 2009)

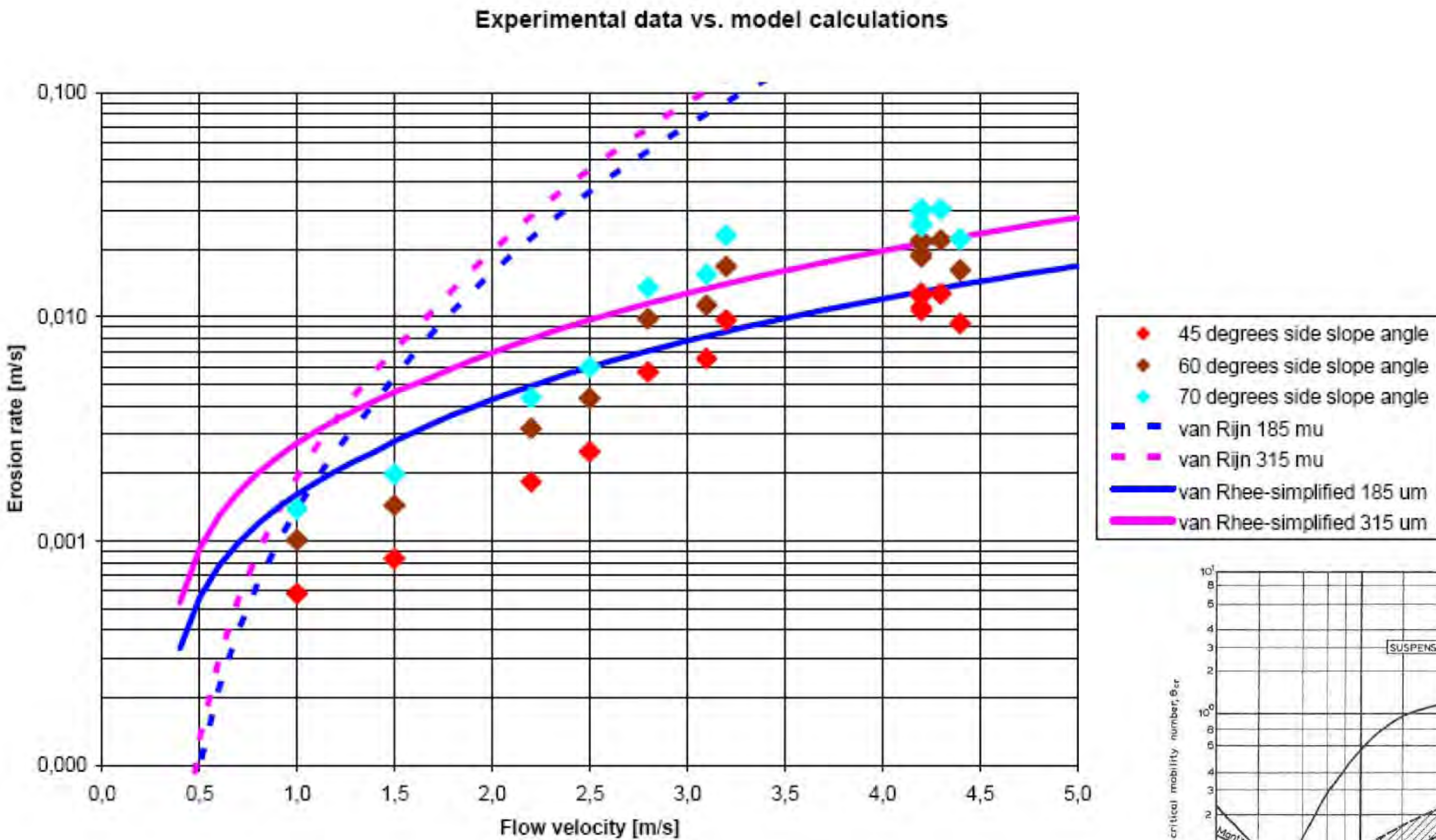
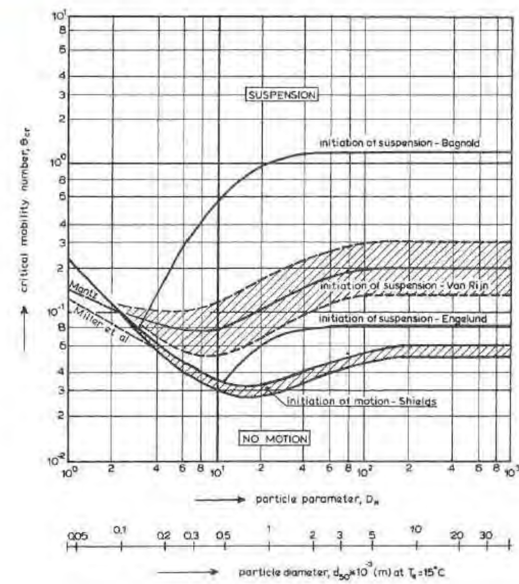
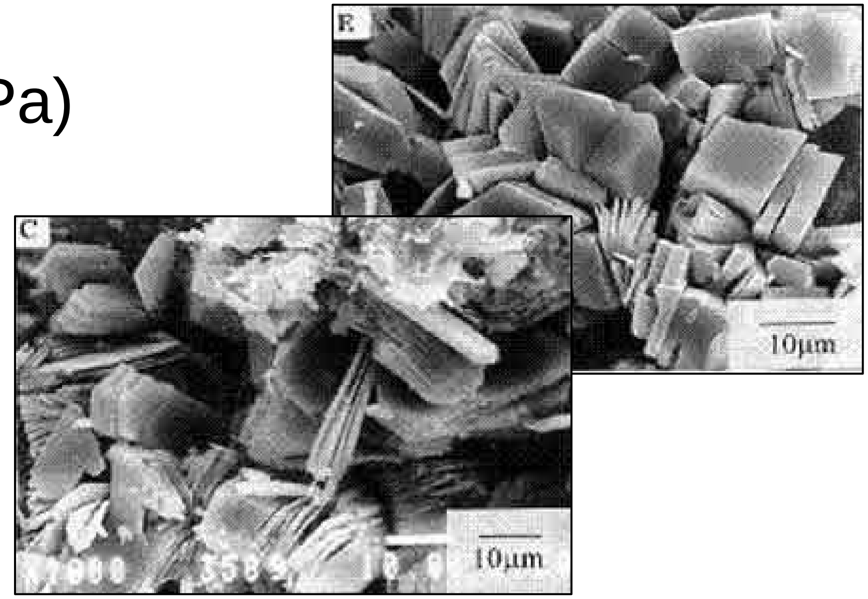


Fig. 9: Erosion rates for Zwin'94-experiment



Cohesive Soils in hydraulic transport : Clays, Silts, Muds,…



Undrained Shear-Strength, cu (kPa)

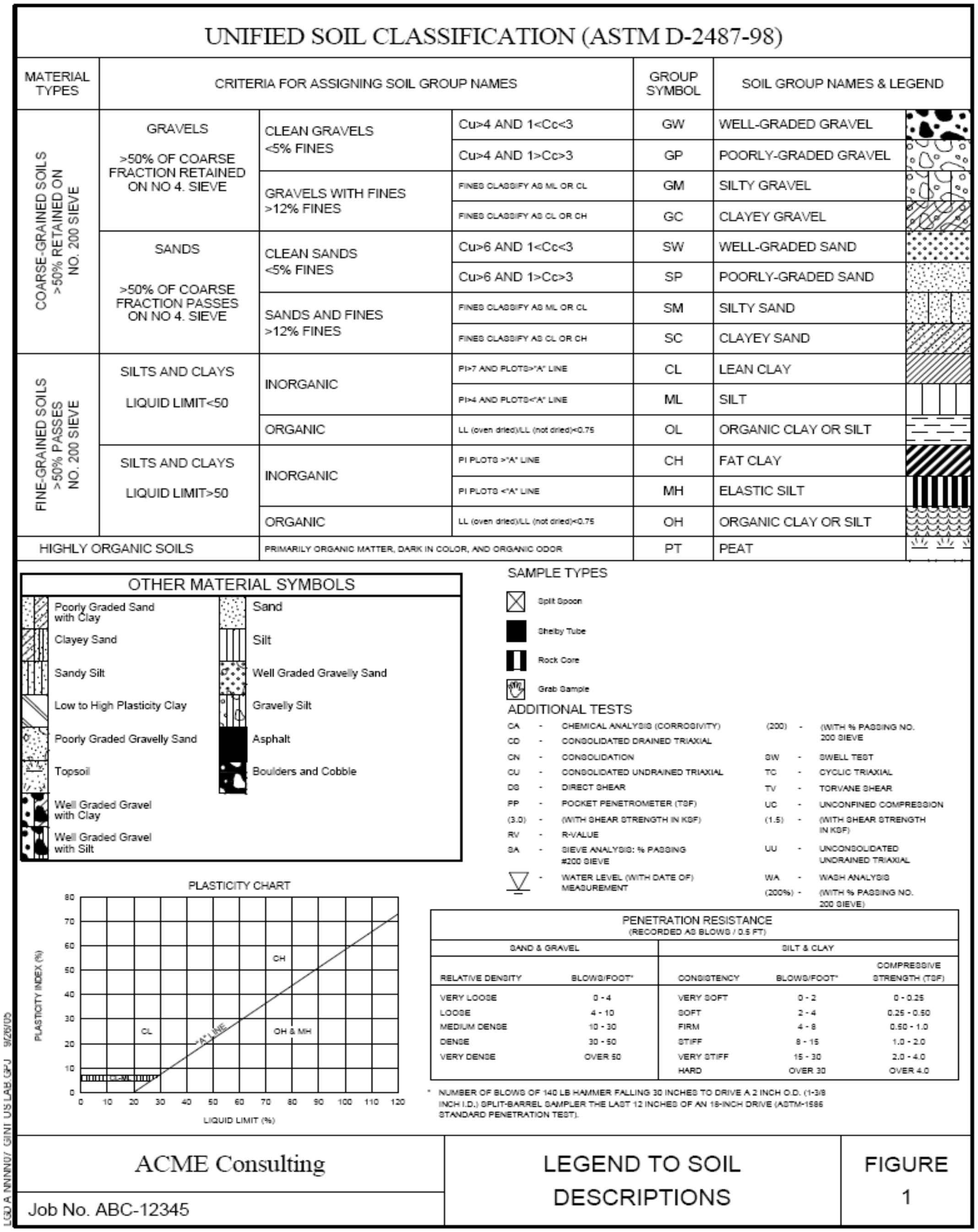
Liquidity Index (n

$$I_L = \frac{w - w_p}{w_L - w_p}$$

Yield Stress, τy (Pa)

Dynamic Viscosity, η (Pasec)

Thixotropy (Pasec or Watt)



UNIFIED SOIL CLASSIFICATION (ASTM D-2487-98)

MATERIAL TYPES	CRITERIA FOR ASSIGNING SOIL GROUP NAMES			GROUP SYMBOL	SOIL GROUP NAMES & LEGEND
COARSE-GRAINED SOILS >50% RETAINED ON NO. 200 SIEVE	GRAVELS >50% OF COARSE FRACTION RETAINED ON NO 4. SIEVE	CLEAN GRAVELS <5% FINES	Cu>4 AND 1<Cc<3	GW	WELL-GRADED GRAVEL
			Cu>4 AND 1>Cc>3	GP	POORLY-GRADED GRAVEL
		GRAVELS WITH FINES >12% FINES	FINES CLASSIFY AS ML OR CL	GM	SILTY GRAVEL
			FINES CLASSIFY AS CL OR CH	GC	CLAYEY GRAVEL
	SANDS >50% OF COARSE FRACTION PASSES ON NO 4. SIEVE	CLEAN SANDS <5% FINES	Cu>6 AND 1<Cc<3	SW	WELL-GRADED SAND
			Cu>6 AND 1>Cc>3	SP	POORLY-GRADED SAND
		SANDS AND FINES >12% FINES	FINES CLASSIFY AS ML OR CL	SM	SILTY SAND
			FINES CLASSIFY AS CL OR CH	SC	CLAYEY SAND
FINE-GRAINED SOILS >50% PASSES NO. 200 SIEVE	SILTS AND CLAYS LIQUID LIMIT<50	INORGANIC	PI>7 AND PLOTS>"A" LINE	CL	LEAN CLAY
			PI>4 AND PLOTS<"A" LINE	ML	SILT
		ORGANIC	LL (oven dried)/LL (not dried)<0.75	OL	ORGANIC CLAY OR SILT
	SILTS AND CLAYS LIQUID LIMIT>50	INORGANIC	PI PLOTS >"A" LINE	CH	FAT CLAY
			PI PLOTS <"A" LINE	MH	ELASTIC SILT
		ORGANIC	LL (oven dried)/LL (not dried)<0.75	OH	ORGANIC CLAY OR SILT
HIGHLY ORGANIC SOILS		PRIMARILY ORGANIC MATTER, DARK IN COLOR, AND ORGANIC ODOR		PT	PEAT

OTHER MATERIAL SYMBOLS

Poorly Graded Sand with Clay; Clayey Sand; Sandy Silt; Low to High Plasticity Clay; Poorly Graded Gravelly Sand; Topsoil; Well Graded Gravel with Clay; Well Graded Gravel with Silt; Sand; Silt; Well Graded Gravelly Sand; Gravelly Silt; Asphalt; Boulders and Cobble

SAMPLE TYPES

Split Spoon; Shelby Tube; Rock Core; Grab Sample

ADDITIONAL TESTS

CA	CHEMICAL ANALYSIS (CORROSIVITY)	(200)	(WITH % PASSING NO. 200 SIEVE
CD	CONSOLIDATED DRAINED TRIAXIAL		
CN	CONSOLIDATION	SW	SWELL TEST
CU	CONSOLIDATED UNDRAINED TRIAXIAL	TC	CYCLIC TRIAXIAL
DS	DIRECT SHEAR	TV	TORVANE SHEAR
PP	POCKET PENETROMETER (TSF)	UC	UNCONFINED COMPRESSION
(3.0)	(WITH SHEAR STRENGTH IN KSF)	(1.5)	(WITH SHEAR STRENGTH IN KSF)
RV	R-VALUE		
SA	SIEVE ANALYSIS: % PASSING #200 SIEVE	UU	UNCONSOLIDATED UNDRAINED TRIAXIAL
▽	WATER LEVEL (WITH DATE OF) MEASUREMENT	WA	WASH ANALYSIS
		(200%)	(WITH % PASSING NO. 200 SIEVE)

PLASTICITY CHART

PENETRATION RESISTANCE (RECORDED AS BLOWS / 0.5 FT)

SAND & GRAVEL		SILT & CLAY		
RELATIVE DENSITY	BLOWS/FOOT*	CONSISTENCY	BLOWS/FOOT*	COMPRESSIVE STRENGTH (TSF)
VERY LOOSE	0 - 4	VERY SOFT	0 - 2	0 - 0.25
LOOSE	4 - 10	SOFT	2 - 4	0.25 - 0.50
MEDIUM DENSE	10 - 30	FIRM	4 - 8	0.50 - 1.0
DENSE	30 - 50	STIFF	8 - 15	1.0 - 2.0
VERY DENSE	OVER 50	VERY STIFF	15 - 30	2.0 - 4.0
		HARD	OVER 30	OVER 4.0

* NUMBER OF BLOWS OF 140 LB HAMMER FALLING 30 INCHES TO DRIVE A 2 INCH O.D. (1-3/8 INCH I.D.) SPLIT-BARREL SAMPLER THE LAST 12 INCHES OF AN 18-INCH DRIVE (ASTM-1586 STANDARD PENETRATION TEST).

ACME Consulting	LEGEND TO SOIL DESCRIPTIONS	FIGURE 1
Job No. ABC-12345		

Determining for Cohesive soils:

- water-content (w) and Atterberg limits (SL, PL, LL)
- Plasticity-Index : PI = LL – PL

  (PI = high >Clay; PI = low > Silt)
- Liquidity Index: LI = (w-PL)/(LL-PL)
- Activityt : A = PI / (% < 0,075mm)

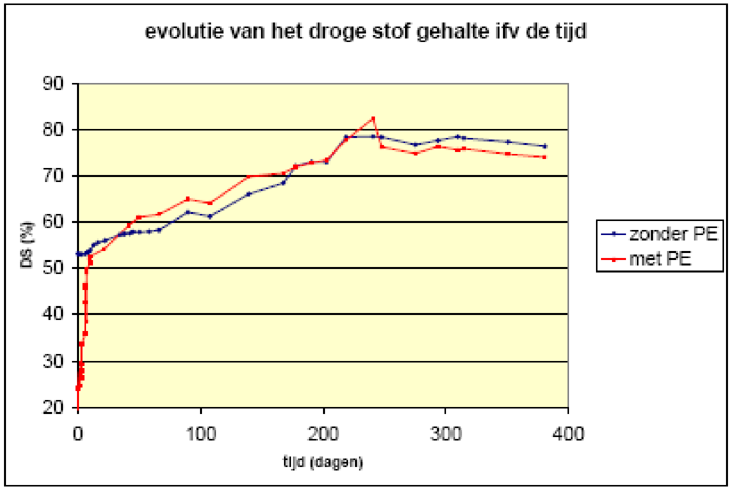
  (A < 0,75 Inactive; A 0,75-1,25: Normal; A > 1,25: Active)
- Shear-strength and Cohesion
- Stress-Strain behaviour

Cohesive sediments dredged and lagooned

After filling at ρ_{sat} = 1,32 t/m3

After 1 month: consolidation & dessication

ρ_{sat} = 1,60 t/m3



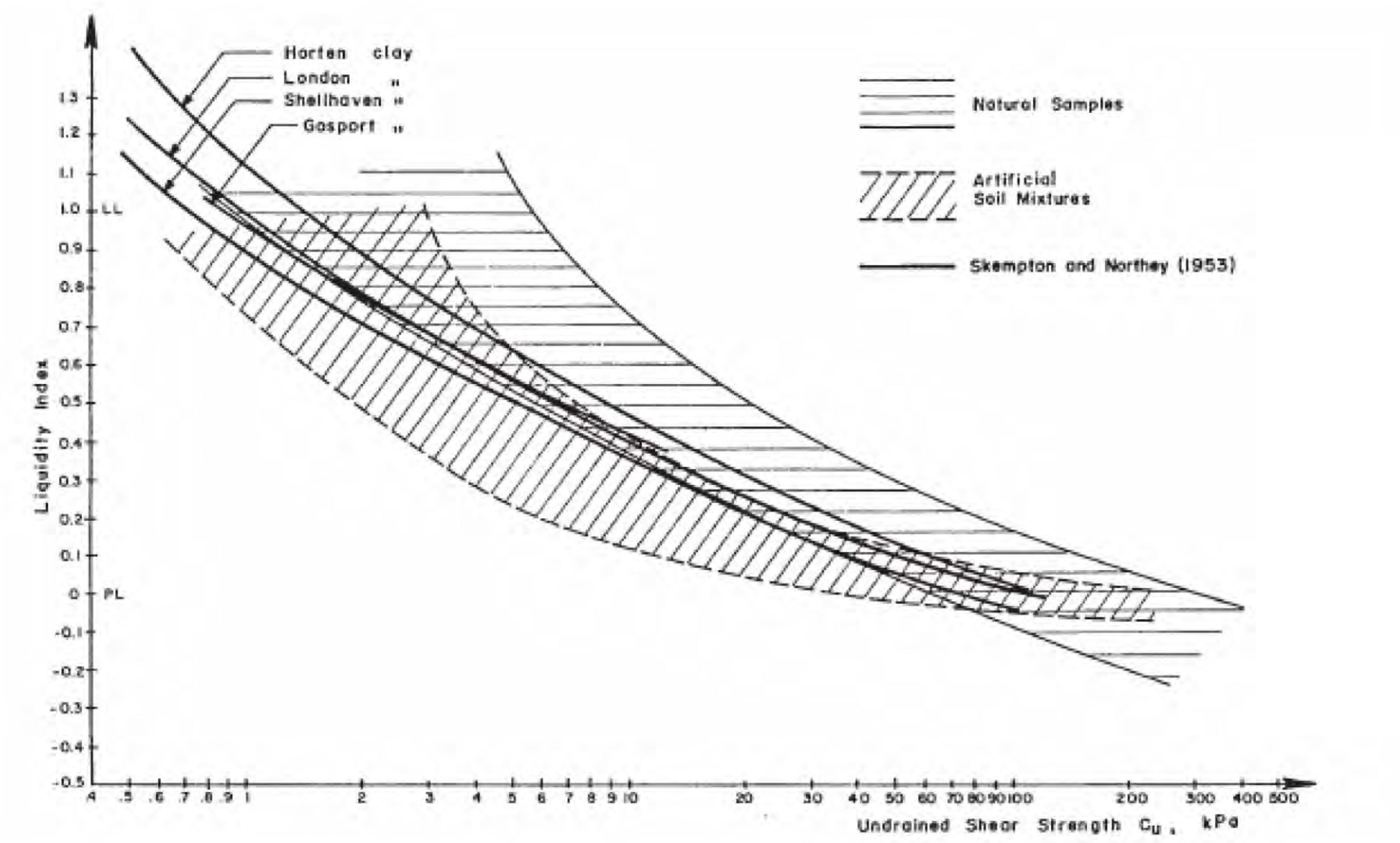
Cohesive Soils in hydraulic transport : indicative values

Type of clay	wL (Casagrande's Flow Limit)	wP (Casagrande's Plasticity Limit)	Liquidity Index In-Situ LI_{si}	Liquidity Index As slurry LI_m
Kaolinite (weathering of granite)	50	30	2,5	12,5
Illite (most common clay)	100	50	0	4
Montmorillonite (swelling clay)	500	80	-0,95	-0,5

Description	Undrained Shear Strength , cu (kPa)
Soft	< 40
Firm	40 - 75
Stiff	75 - 150
Hard	> 150

In cohesive sediments, the φ is very low, not to say sometimes close to 0. This means that shear-strengths of cohesive sediments are determined by c, the cohesion (which is intrinsic at σ_n =0. But c is observed to increase slightly with depth in loose cohesive muds due to consolidation

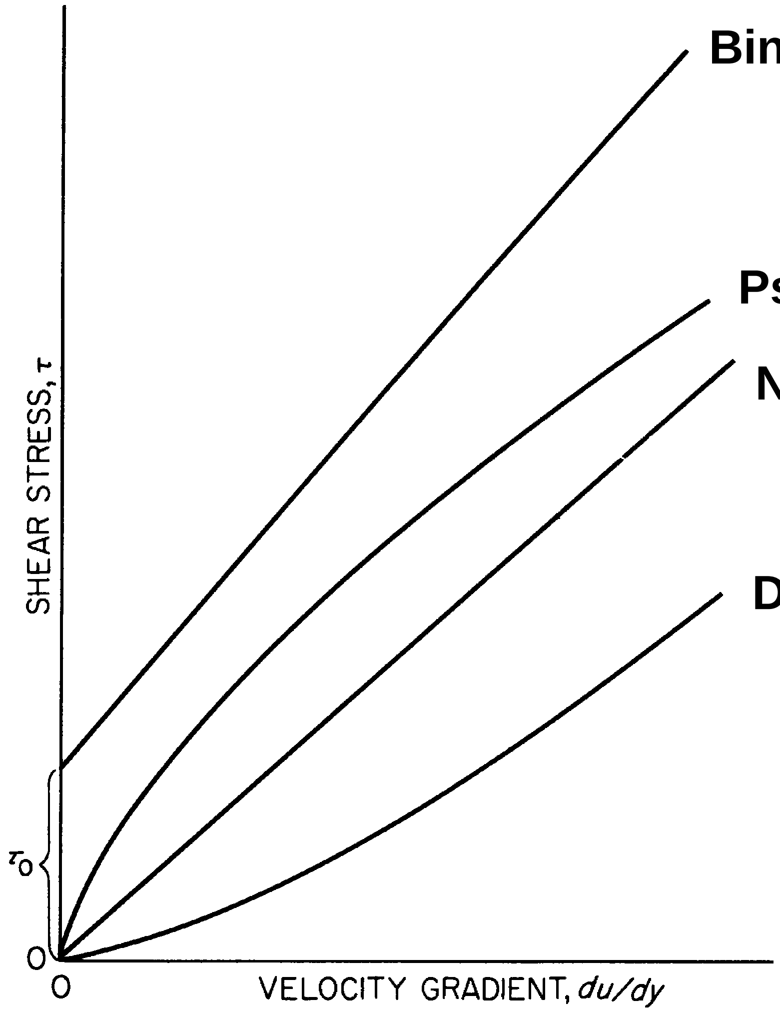
Cohesive soils & sediments: Undrained Shear Strength and Liquidity Index



Frictional Behaviour of Fluids in Flow

- Water and individual particles: slurry transport
  - Reynold's Number
  - Determining parameters:
    - dynamic viscosity of transport fluid (termperature, salinity,…)
    - Volumetric mass of fluid (kg / m3 or kgds/m3)
    - Particle dimensions determining Critical speed and Slip-Factor
    - Velocity, vs Critical Speed
- Viscuous flow of cohesive particles: Non-Newtonian Bingham fluids
  - Hedström Number & Reynold's Number
  - Determining parameters:
    - Dynamic viscosity of suspension (temperature, salinity, volumetric mass, sand-content)
    - Initial rigidity τy (or Yield Stress τo)
    - Thixotropy

Stress-Strain behaviour of Newtonian and Non-Newtonian Fluids



Bingham Plastic: Cohesive sediment suspensions, sludge, paint, blood, ketchup

Pseudoplastic: latex, paper pulp,.

Newtonian : Water

Dilatant: quicksand

Rheology of cohesive-sediment suspensions: initial rigidity, dynamic viscosity and thixotropy (after Malherbe, 1987)

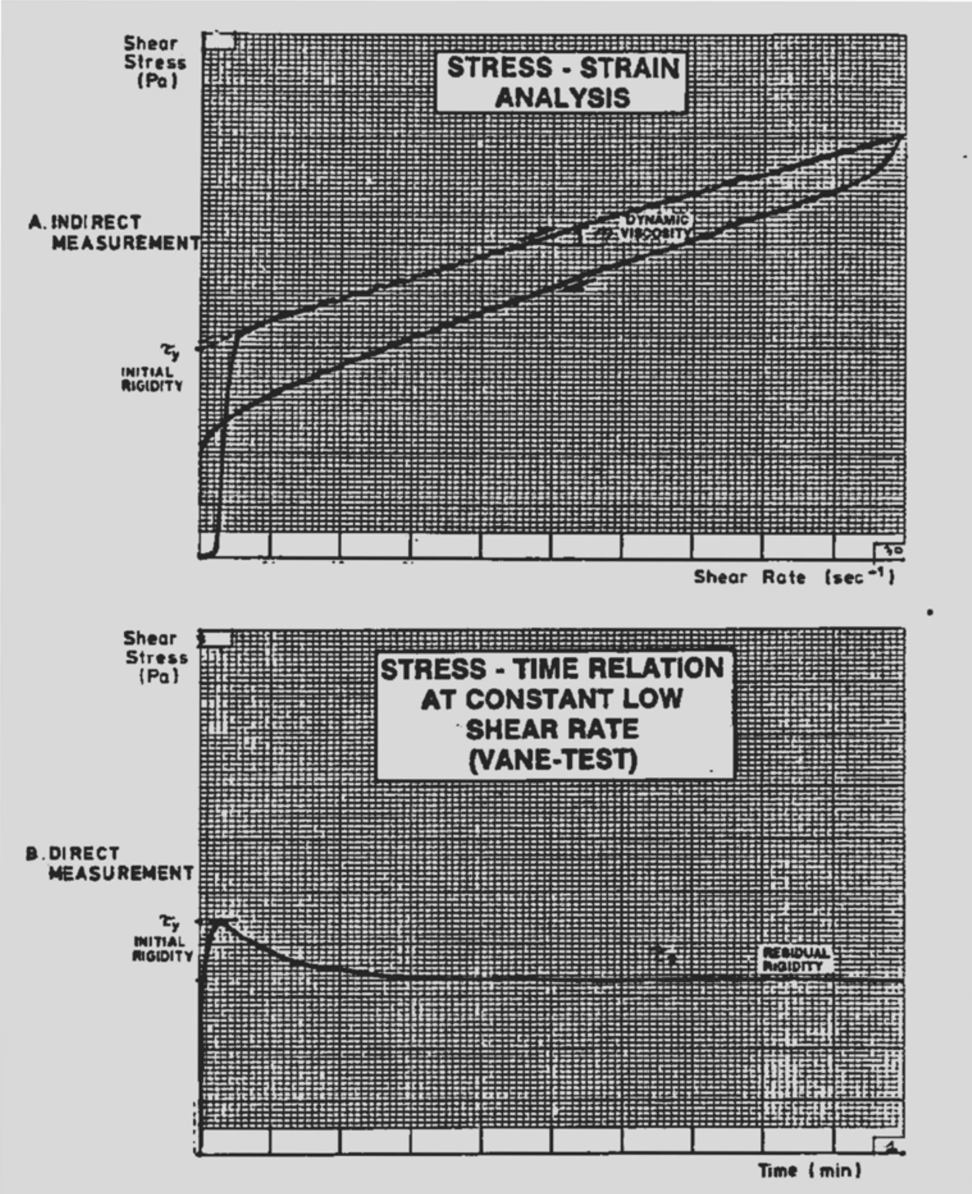


FIGURE 5 : Typical rheograms of mud (harbour of Zeebrugge) together with the definition of initial rigidity and dynamic viscosity.

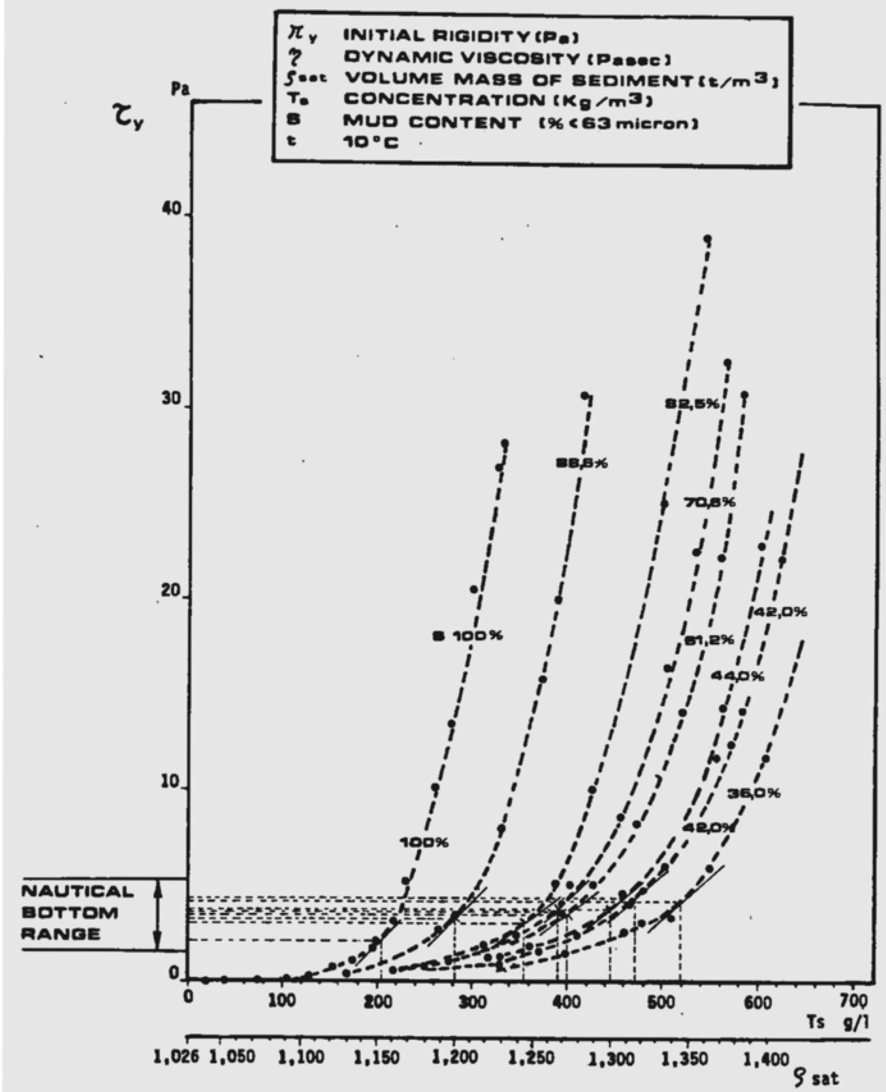


FIGURE 6 : Results of rheologic investigations on mud out of the harbour of Zeebrugge. Relation between the initial rigidity, the density and the sand-content of the mud. The figure illustrates also the "rheologic behaviour transition", R.T.

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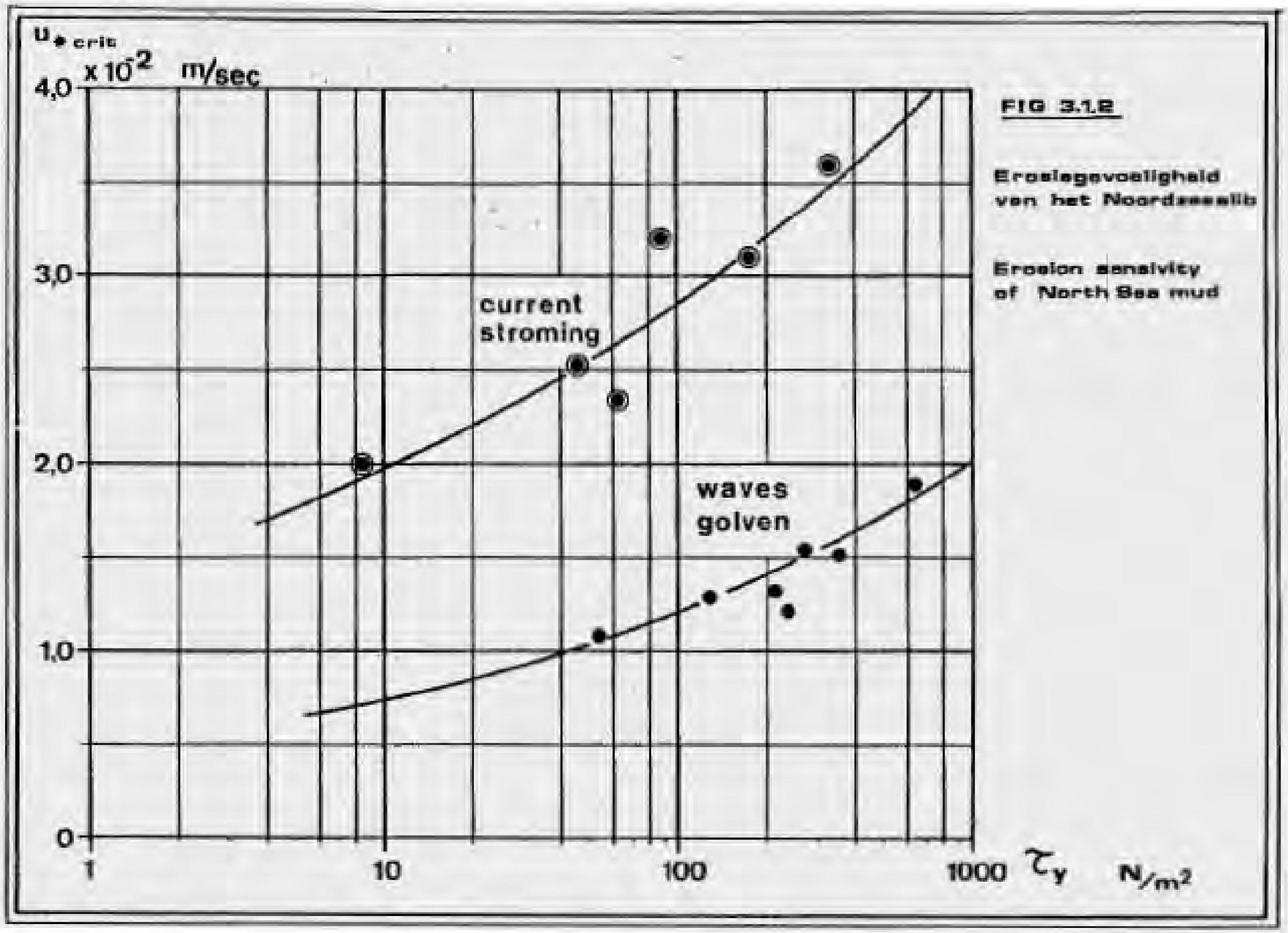
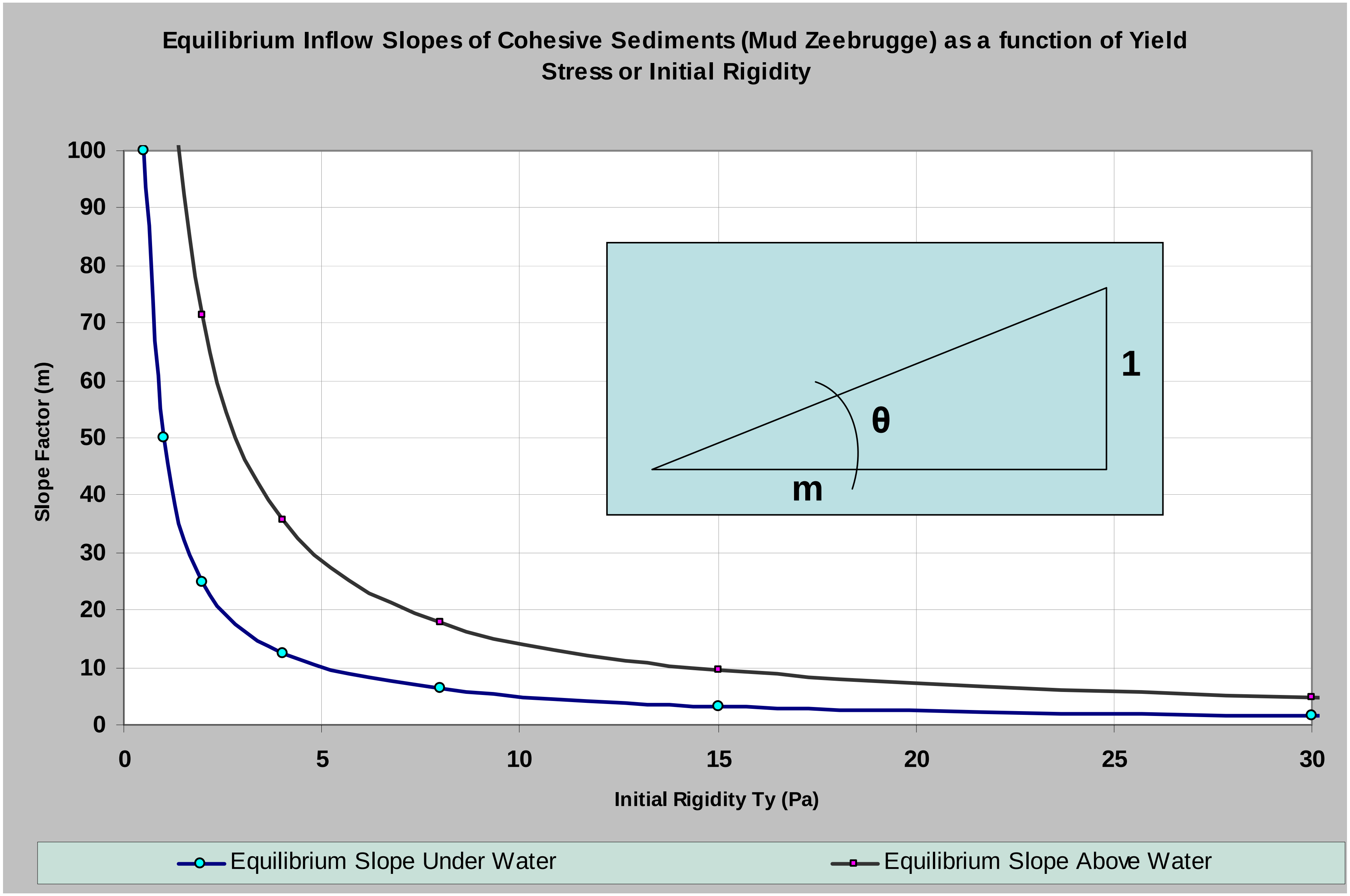
Rheology will determine erosion-sensitivity (expressed as u*crit) for cohesive sediments (B Malherbe PhD thesis)



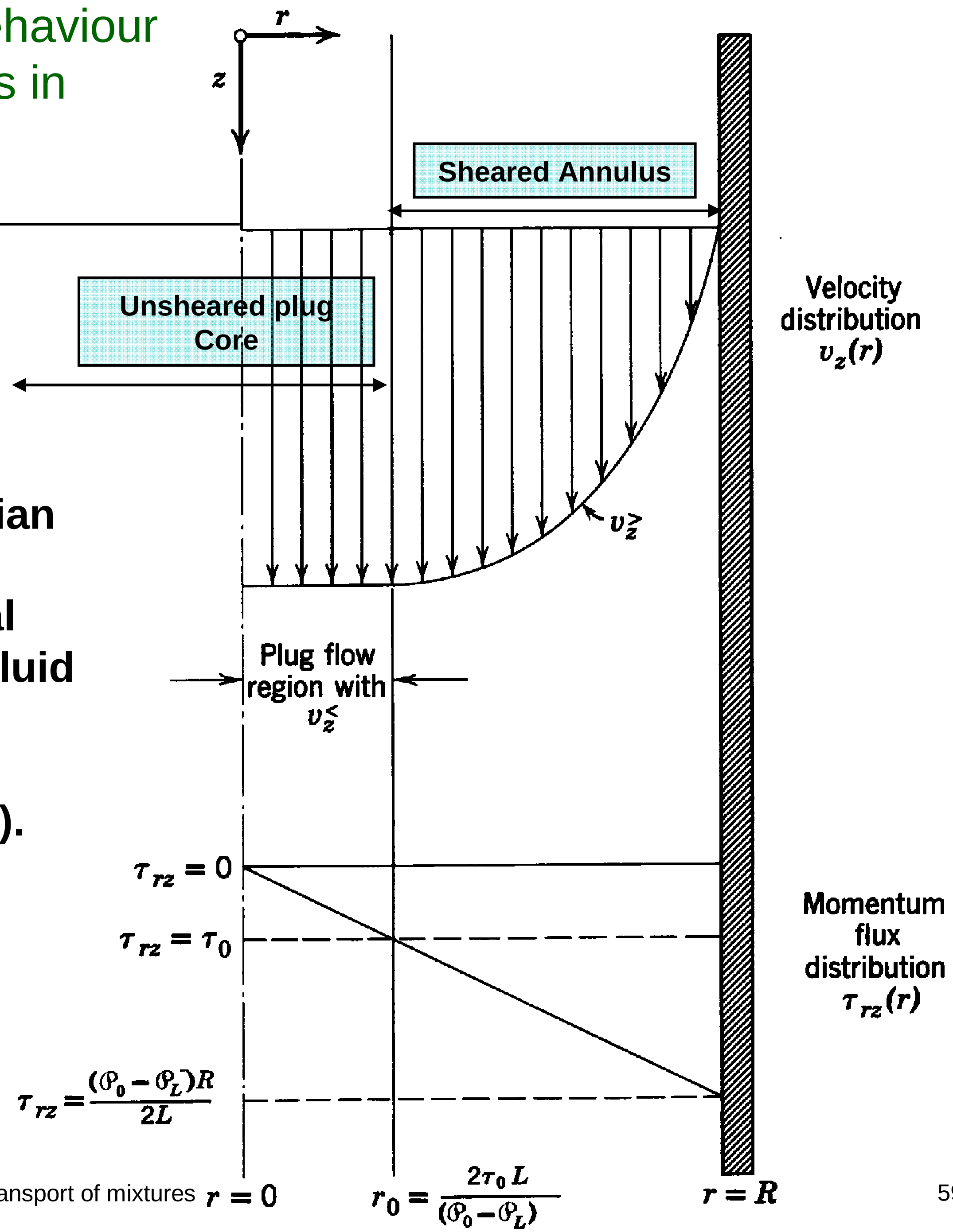
Rheology determines the equilibrium inflow slope of cohesive sediments



Rheology determines the Flow behaviour of Non-Newtonian Bingham Fluids in pipes

Bingham fluids exhibit Newtonian behavior after the shear stress exceeds τ_o or τy. In the central region a "plug" of unsheared fluid or suspension occurs.

(ref University of Texas, Austin).



Flow behaviour of Non-Newtonian Bingham Fluids

Unsheared Core

$$r \le r_c \qquad u_z = u_c = \frac{\tau_0}{2\mu_\infty r_c}\left(R - r_c\right)^2$$

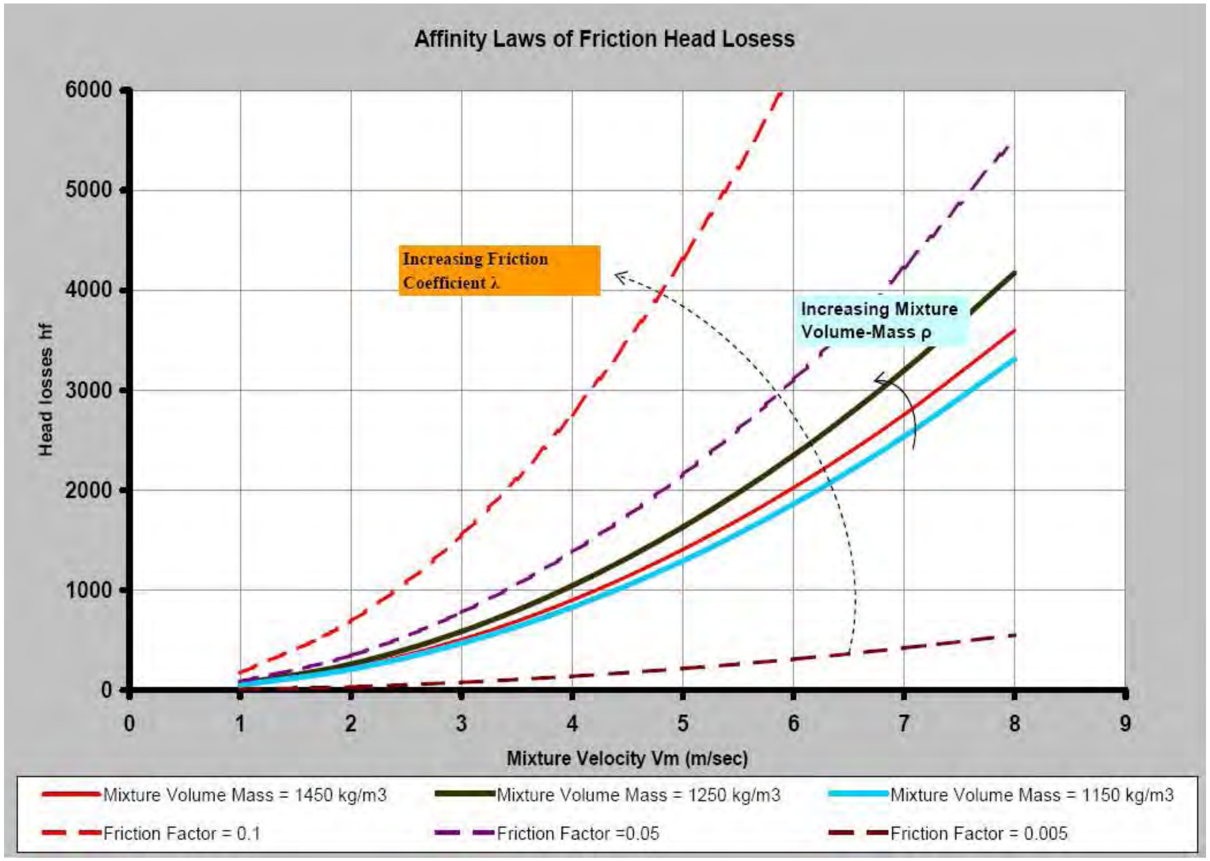
Sheared Annular Region

$$r > r_c \qquad u_z = \frac{\left(R - r\right)}{\mu_\infty}\left[\frac{\tau_{rz}}{2}\left(1 + \frac{r}{R}\right) - \tau_0\right]$$

Frictional losses of fluids in pipelines: affinities with Friction Cfct & Volume-Mass

General equation describing frictional head losses of fluids/suspensions in pipes

$$\Delta p_f = \lambda.\rho.\frac{L}{D}\frac{\overline{V}^2}{2}$$



Applies to any type of fluid – Newtonian, Pseudo-Plastic, Bingham, Dilatant,…- under any flow conditions

Laminar Bingham Fluid Flow: determination of friction factor

$$\lambda = \frac{16}{\mathrm{Re}_{BP}} . \left[1 + \frac{He}{6.\mathrm{Re}_{BP}} - \frac{He^4}{3.\lambda^3.(\mathrm{Re}_{BP})^7} \right]$$ (Non-linear)

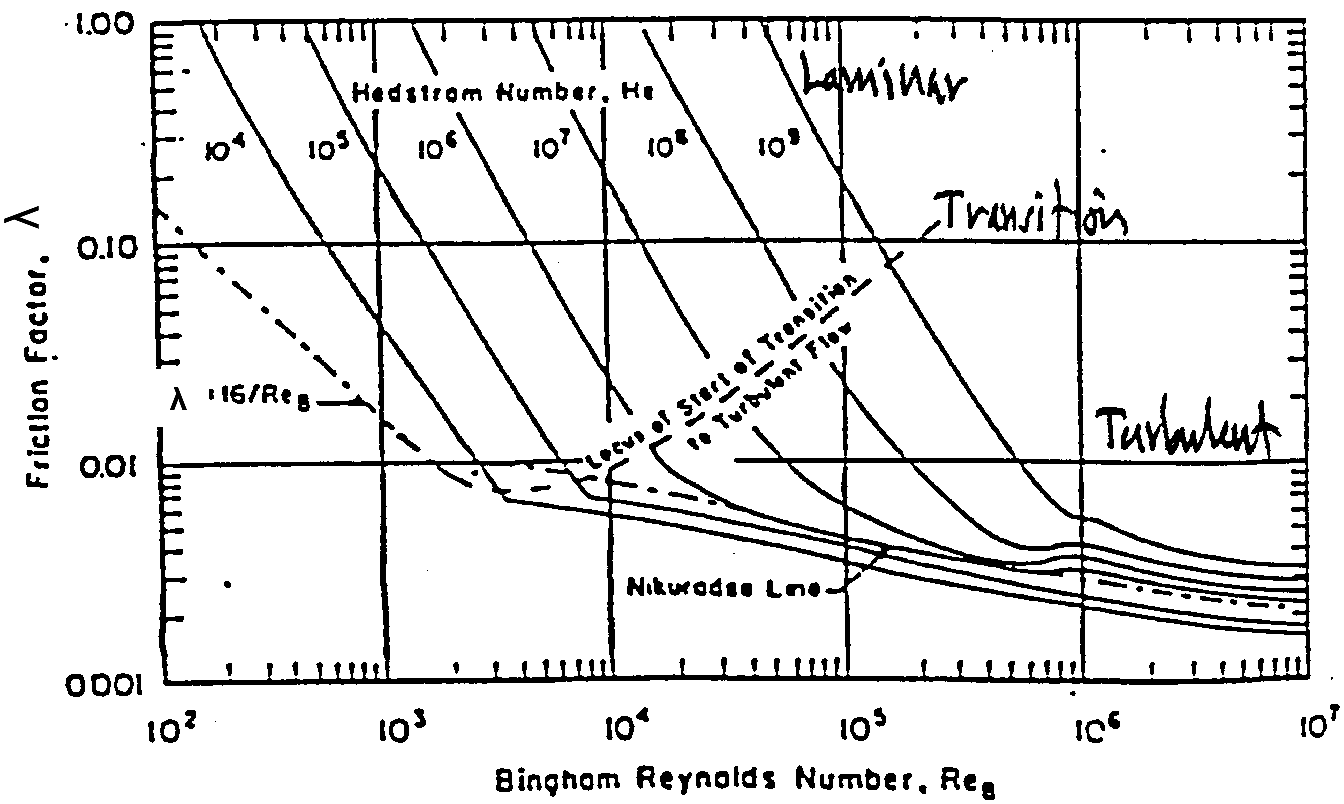
$$He = \frac{D^2.\rho.\tau_0}{\mu_\infty^2}$$ Hedström Number

$$\mathrm{Re}_{BP} = \frac{D.\rho.\overline{V}}{\mu_\infty}$$ Reynolds Number

Turbulent Bingham Fluid Flow: determination of friction factor

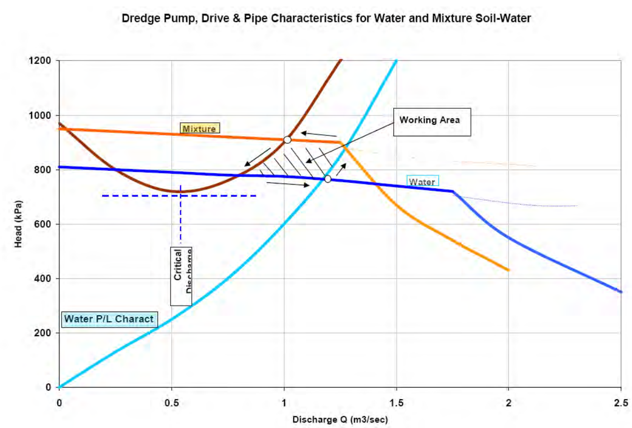
$$\lambda = 10^{a}\,\mathrm{Re}_{BP}^{-0.193}$$

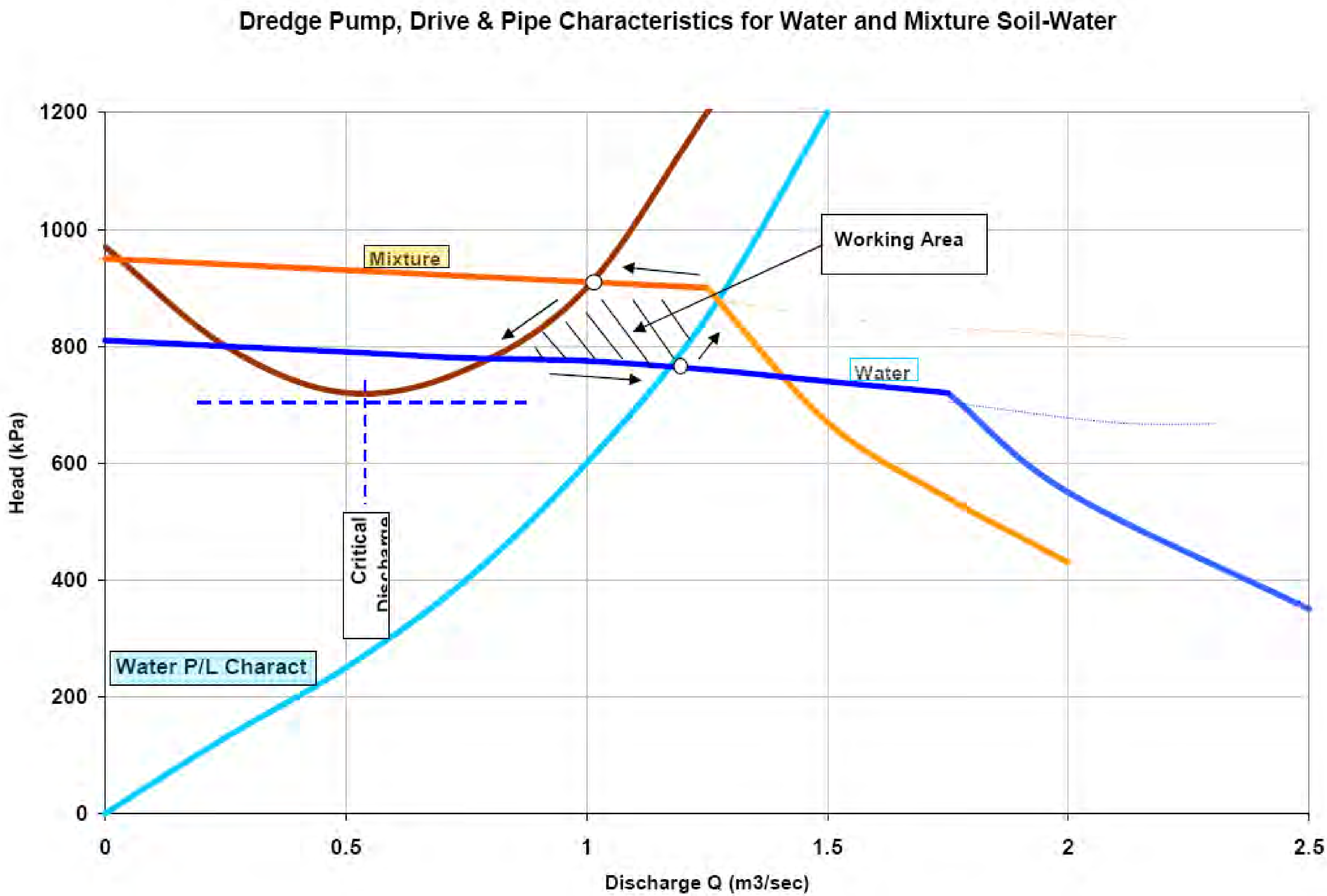
$$a = -1{,}378.\left(1 + 0.146.e^{-2.9x10^{-5}.\,\mathrm{He}}\right)$$



Hydraulic Transport: physics of the system

1. **Pipeline characteristic (Discharge (Q)/Head (H) relationship)**
   - **homogeneous fluid in straight pipe**
   - **Soil-water mixtures in straight pipes**
   - **special head-losses: bends, narrowings,…**
   - **vertical and inclined pipes**
2. **Pump-characteristic (Discharge (Q)/ Head (H) relationship)**
   - **Pumptypes**
   - **Characteristic for homogeneous fluids**
   - **Characteristic for soil-water mixtures**
3. **Driving system**
   - **Modification of pump-characteristic**
   - **for diesel-elec, direct diesel,… driving**
4. **Working area of whole system: driving system, pump, pipeline and mixture**

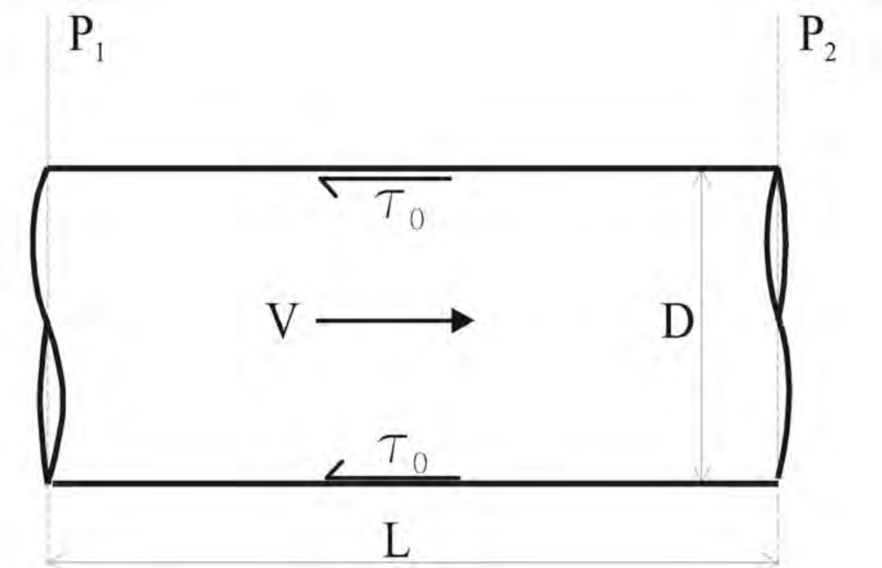



Dredge Pump, Drive & Pipe Characteristics for Water and Mixture Soil-Water
Head (kPa)
1200
1000
800
600
400
200
0
0
0.5
1
1.5
2
2.5
Discharge Q (m3/sec)
Mixture
Working Area
Water
Critical Discharge
Water P/L Charact

Hydraulic Transport: Pipeline Hydraulic Characteristic

Basic Assumptions:

- **Horizontal cylindric pipeline: no bends, valves,…**
- **Homogeneous incompressible fluid: perfect suspension, no segregation, no gases,…**
- **Newtonian fluid: (almost) linear realationship between shear stress and strain**
- **Uniform flow: no velocity profiles between wall and center-line**
- **Constant flow velocity**



Hydraulisch Transport: Pipeline characteristic

- **Law of mass-conservation:**

$$\rho.Vm_{in}.A_{in} = \rho.Vm_{out}.A_{out}$$

- **Law of momentum-conservation:**

$\Delta p/L = 4.\tau_0 / D$ (Navier-Stokes)
$\Delta p\ f = (\alpha.\rho.v^2/2 + \lambda.L/D.\rho.v^2/2 + \xi.\rho.v^2/2)$ (Darcy-Weisbach)
with λ =f (Re, He, k/D) (head-loss coefficient due to friction: see previous slides)

$$p_{in} = p_{out} + \Delta p_f$$

Hydraulic Transport: Pipeline characteristic

- **Law of energy-conservation: Law of Bernouilli**

$$p + \frac{1}{2}\rho v^2 + \rho g h = Cst$$

Pressure Energy (p)

Kinetic Energy ($\frac{1}{2}\rho v^2$)

Potential Energy ($\rho g h$)

This physical law expresses the whole process: the pump-drive plant adds energy to the mixture by increasing velocity: this Kinetic Energy is then oscillating constantly within the system between Kinetic Energy (mixture velocity), Pressure energy (pressure) and Potential energy (elevation). Velocity, pressure and elevation are thus the main parameters of the dredging process.

Hydraulic Transport: Pipeline characteristic

Integration of the 3 physical Laws yields:

$$p_{in} + \cancel{\frac{1}{2}\rho v^2} + \rho g h_{in} = p_{out} + \cancel{\frac{1}{2}\rho v^2} + \lambda \frac{L}{D}.\frac{1}{2}\rho v^2 + \rho g h_{out}$$

Applied to:

- Succession of pipes with various diameters:

$$p_{in} + \frac{1}{2}\rho v_{in}^2 + \rho g h_1 = p_{out} + \frac{1}{2}\rho v_{out}^2 + \sum \lambda_i \frac{L}{D}.\frac{1}{2}\rho v_i^2 + \rho g h_2$$

- Special losses with dedicated ξ coefficient for bends, valves, etc..:

$$p_{in} + \frac{1}{2}\rho v_{in}^2 + \rho g h_1 = p_{out} + \frac{1}{2}\rho v_{out}^2 + \alpha.\frac{1}{2}.\rho.v_i^2 + \sum \lambda_i \frac{L}{D}.\frac{1}{2}\rho v_i^2 + \sum \xi \frac{1}{2}\rho v_i^2 + \rho g h_2$$

Hydraulic Transport: pipeline characteristic

In the dredging process the geometry/elevation of the pipeline is generally fixed and known, i.e. not variable during the process. Kinetic Energy and Pressure Energy are the components that can be controlled. They can be transformed into pressure, by dividing the terms by ρ.g.

dynamic pressure and the static pressure (manometric head)

$$p_{in} + \frac{1}{2}\rho v_{in}^2 + \rho g h_1 = p_{out} + \frac{1}{2}\rho v_{out}^2 + \alpha.\frac{1}{2}.\rho.v_i^2 + \sum \lambda_i \frac{L}{D}.\frac{1}{2}\rho v_i^2 + \sum \xi \frac{1}{2}\rho v_i^2 + \rho g h_2$$

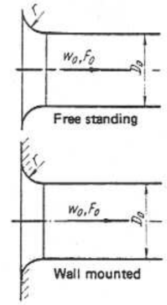
Entry-losses | **Straight pipe friction-losses** | **Bend, valve,..friction-losses**

These terms together express the Head Losses,ΔH, due to friction in the pipeline and in special pipe-components: note the same character as a dynamic pressure!

Special resistances for specific pipeline components:

Circular bellmouth inlet (collector) without baffle; $Re = w_0 D_h / \nu > 10^4$ [6, 8]

Diagram 3-4

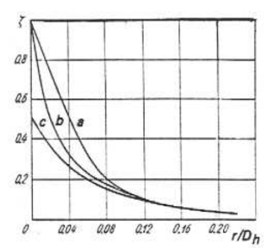


$$D_h = \frac{4F_0}{\Pi_0}$$

$$\zeta = \frac{\Delta p}{\rho w_0^2/2}$$, see curves a, b, and c as a function of $\frac{r}{D_h}$

Values of ζ

Bellmouth (collector) characteristics	$\frac{r}{D_h}$: 0	0.01	0.02	0.03	0.04	0.05	0.06	0.08	0.12	0.16	≥0.20
a) Free standing (not sharp-edged)	1.0	0.87	0.74	0.61	0.51	0.40	0.32	0.20	0.10	0.06	0.03
b) Free standing (sharp-edged)	1.0	0.65	0.49	0.39	0.32	0.27	0.22	0.18	0.10	0.06	0.03
c) Wall-mounted (not sharp-edged)	0.5	0.44	0.37	0.31	0.26	0.22	0.20	0.15	0.09	0.06	0.03



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Hydraulic Transport: Pressure Equations

Pressure Line:

$$p_{in} + \frac{1}{2}\rho v_{in}^2 + \rho g h_1 = p_{out} + \frac{1}{2}\rho v_{out}^2 + \alpha.\frac{1}{2}.\rho.v^2 + \sum \lambda_i \frac{L}{D}.\frac{1}{2}\rho v_i^2 + \sum \xi \frac{1}{2}\rho v_i^2 + \rho g h_{out}$$

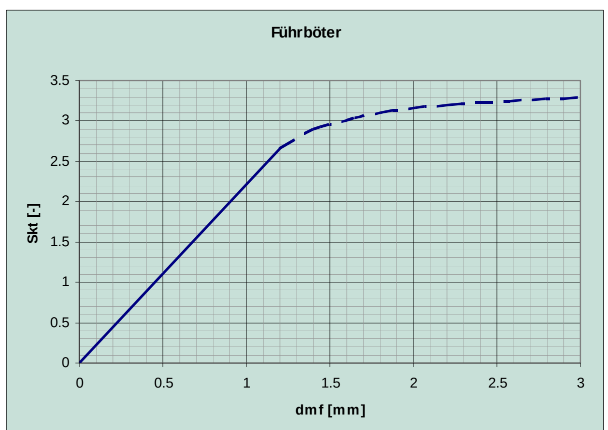
Entry-losses

Straight pipe friction-losses

Bend, valve,..friction-losses

Suction Line:

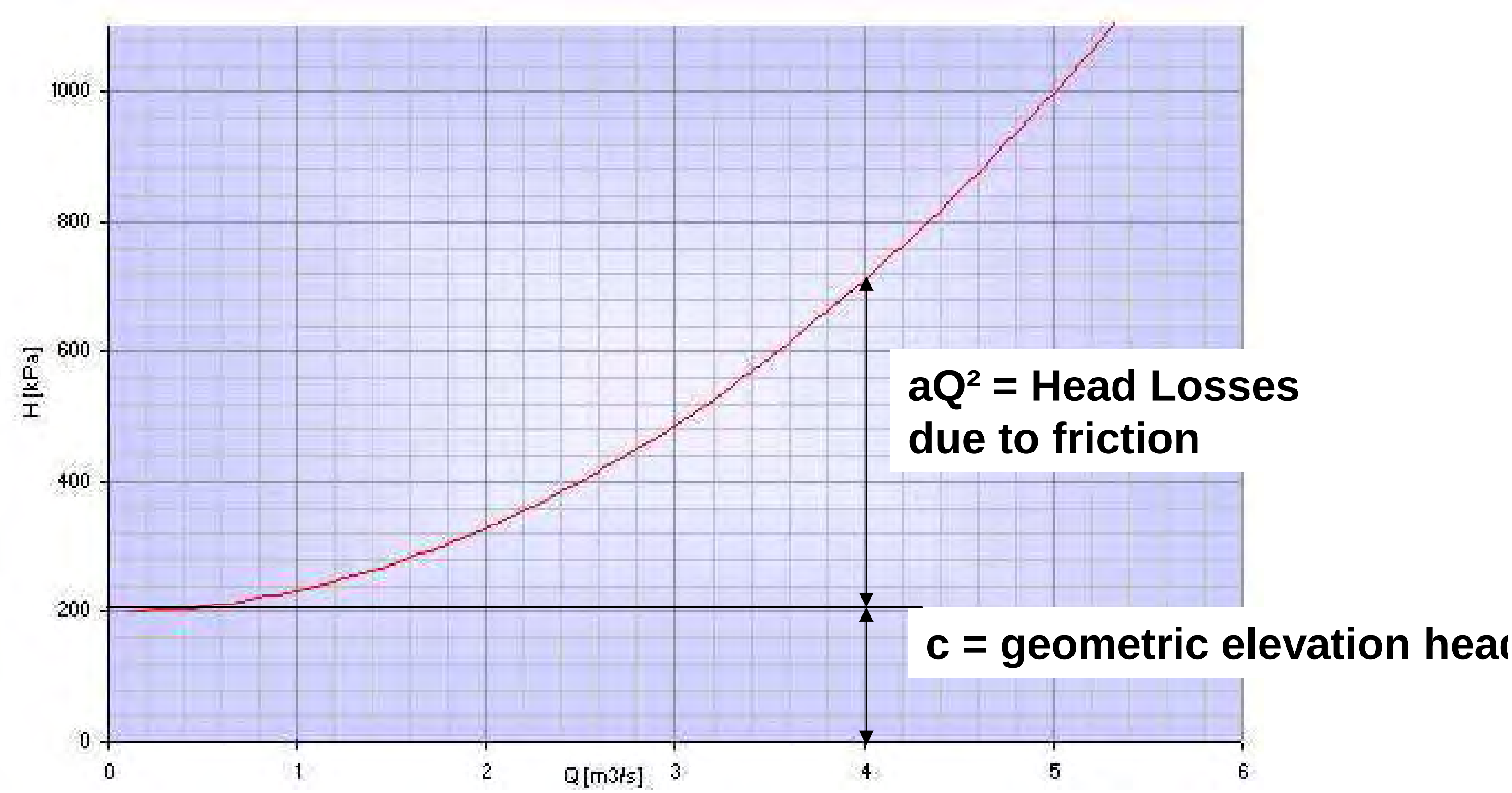
$$p_{vac} = \rho g h_z - \rho_m.g.(h_z - h_{pump}) - \frac{1}{2}\rho_m.v^2 - \alpha.\frac{1}{2}.\rho_m.v_i^2 - \sum \lambda_i \frac{L}{D}.\frac{1}{2}\rho_m.v_i^2 - \sum \xi \frac{1}{2}\rho_m.v_i^2 - \rho_w.g.Skt.Li.(\rho_m - \rho_w)/((\rho_s - \rho_w).v_m)$$



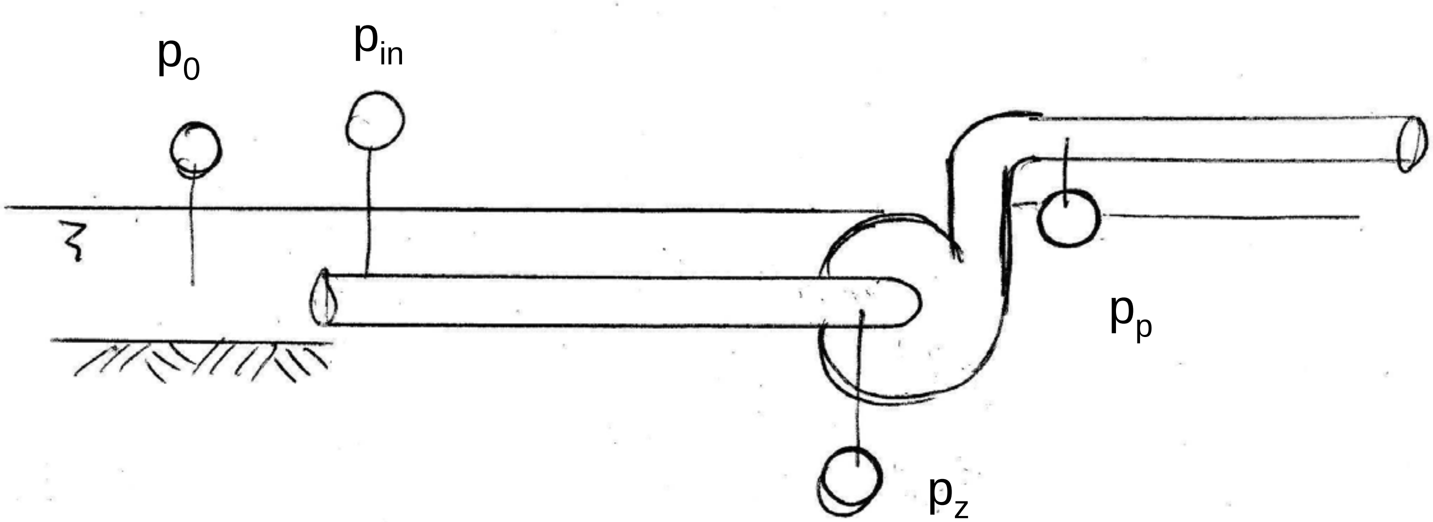
Special losses for non-cohesive particles (cfr Führböter)

Hydraulic Transport: Graphical representation of pipeline-characteristic

- **Relationship is of the following kind**: $H = aQ^2 + c$



Suction characteristic for a horizontal pipeline



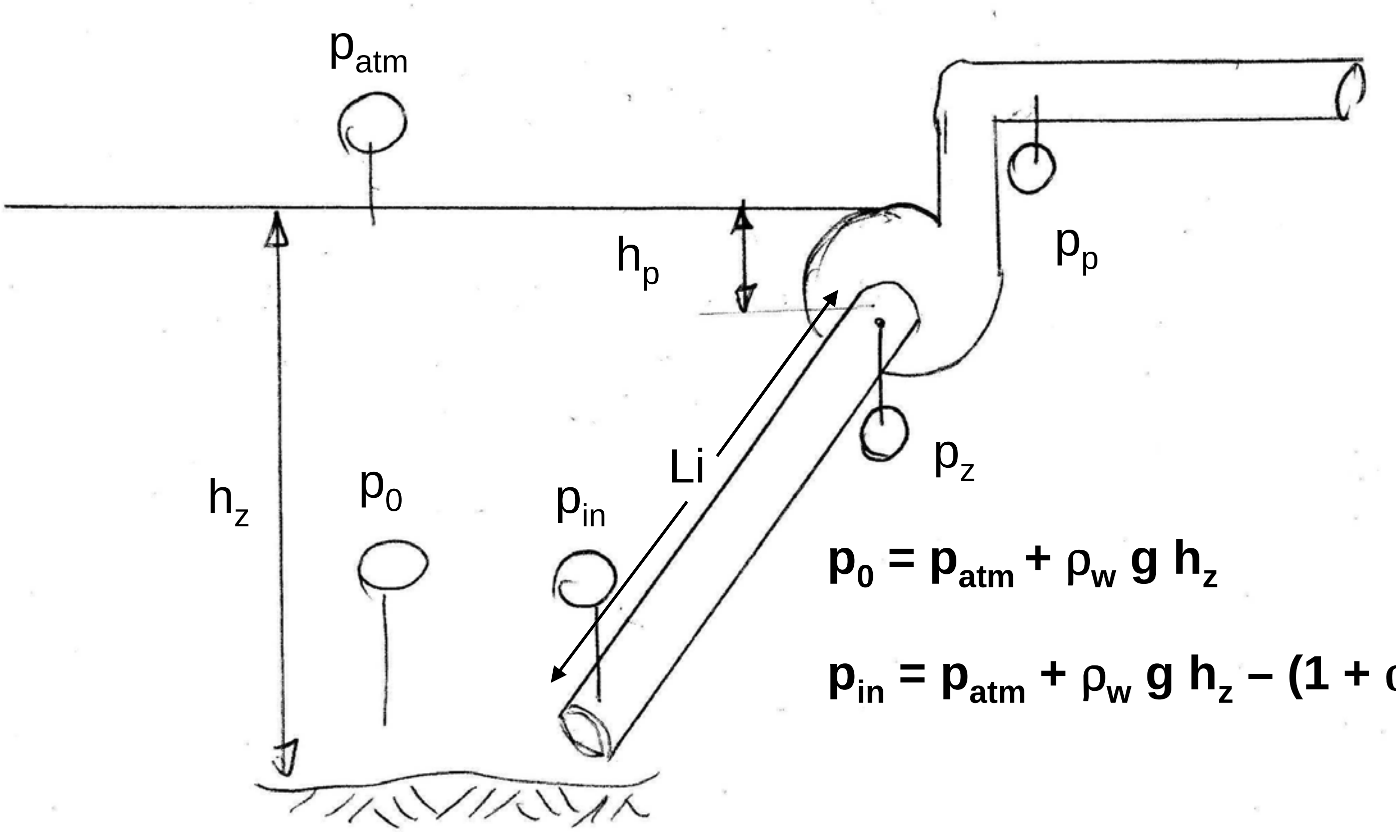
$$p_0 = p_{atm}$$

$$p_{in} = p_{atm} - (1 + \alpha)0.5\ \rho_m\ v^2$$

$$P_z = p_{atm} - (1 + \alpha + \lambda\ L/D)0.5\ \rho_m\ v^2$$

$$P_p = p_{atm} - (1 + \alpha + \lambda\ L/D)0.5\ \rho_m\ v^2 + \Delta p$$

Suction characteristic for a dredge pipeline in operation:



$$p_0 = p_{atm} + \rho_w\, g\, h_z$$

$$p_{in} = p_{atm} + \rho_w\, g\, h_z - (1 + \alpha)0.5\, \rho_m\, v^2$$

$$p_z = p_{atm} + \rho_w\, g\, h_z - \rho_m\, g\, (h_z - h_p) - (1 + \alpha + \xi + \lambda\, Li/D).\ 0.5.\ \rho_m\ .v^2 - \rho_w.g.Skt.Li.(\rho_m - \rho_w)/((\rho_s - \rho_w).v)$$

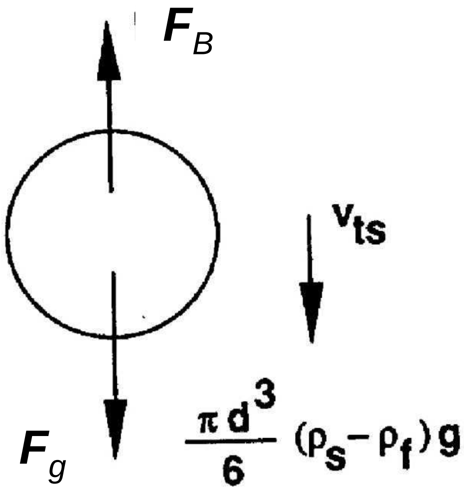
$$p_p = p_{atm} + \rho_w\, g\, h_z - \rho_m\, g\, (h_z - h_p) - (1 + \alpha + \xi + \lambda\, Li/D)0.5\, \rho_m\, v^2 - \rho w.g.Skt.Li.(\rho m - \rho w)/((\rho s - \rho w).v) + \Delta p$$

Hydraulic Transport: Forces on particles in water

Forces exterted on particle:

1. **Gravitational force**

$$F_g = \rho_s V_s g$$

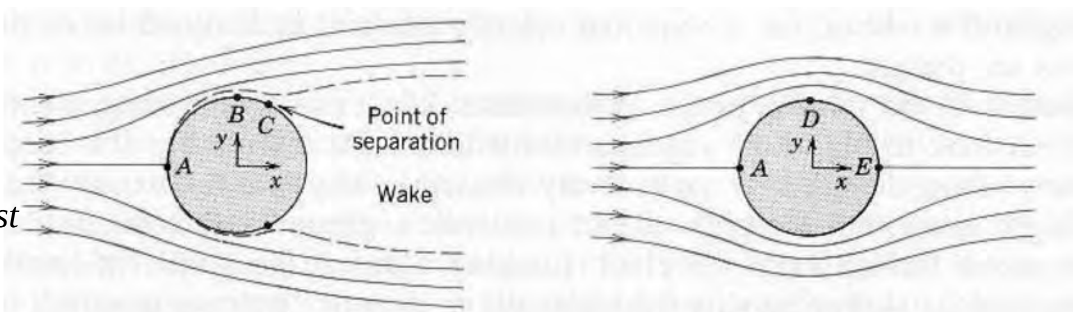


2. **Buoyancy force (Archimedes)**

$$F_B = \rho_w V_s g$$

3. **Flow-resistance forces**
   - **Wall-friction**
   - **Drag-resistance**

$$F_D = \frac{1}{2} C_D \rho_w v^2 A_{st}$$

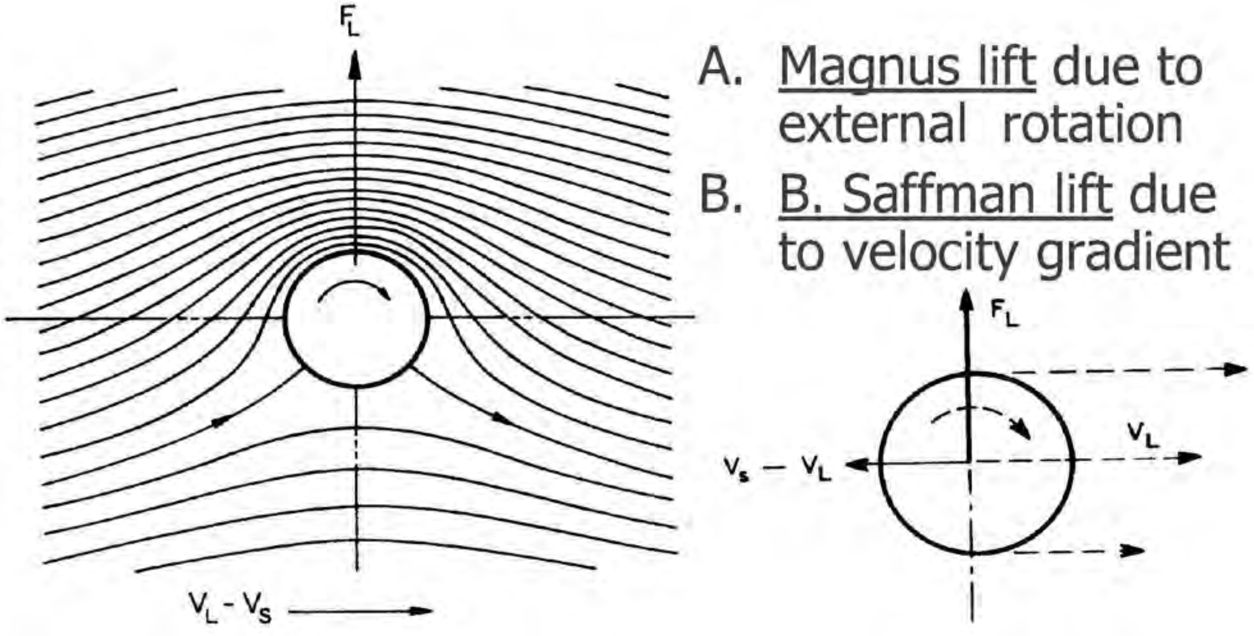


(a) Viscous flow (b) Inviscid flow

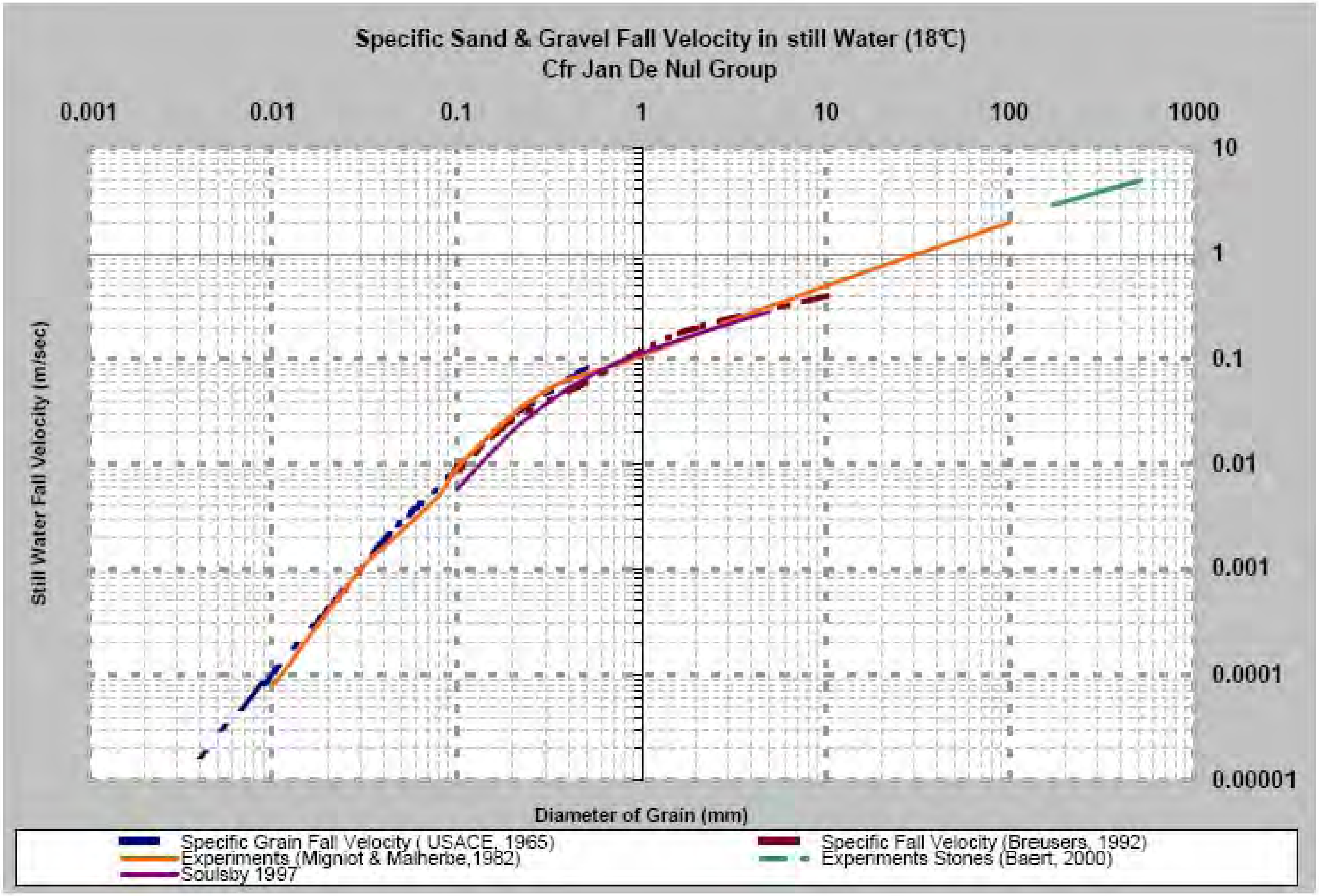
Hydraulic Transport: Forces on particles in water

4. Lift-forces due to velocity gradients, particle geometry,….

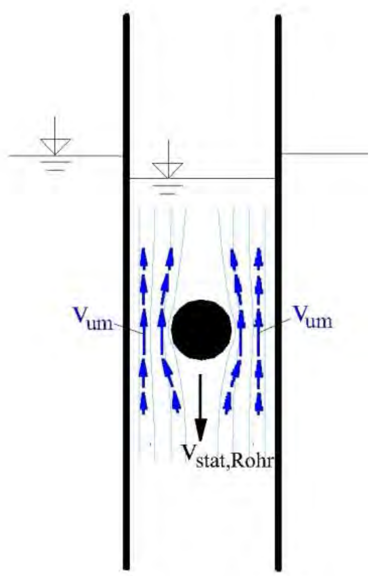
$$F_L = \frac{1}{2} C_L \rho_w v^2 A_{st}$$

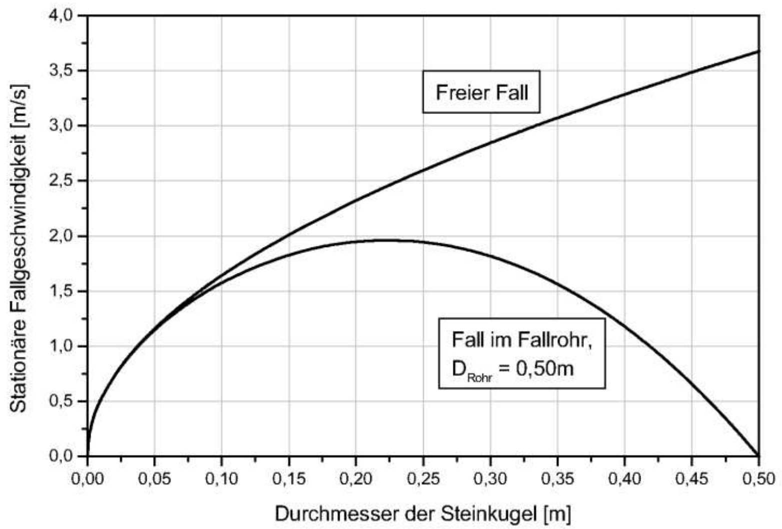


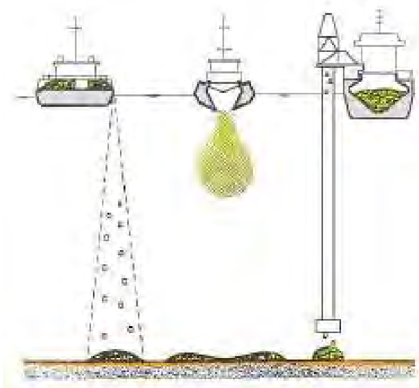
Hydraulic Transport: free-fall velocity of particles in water



Practical application: dumping of particles trough a vertical pipe







Non-visquous fluids: only local water-displacement around the particle compensates for the volumetric passage of the particle. The total Head remains constant

Visquous fluids : the particle drags an added mass of water during its fall and the upward compensating current gets resistance from the wall of the pipe and the stone. The water-head decreases in the pipe.

Multipurpose valpijpschip '*Simon Stevin*'

Multipurpose valpijpschip '*Simon Stevin*',

Jan De Nul,

DP Class 2 (dynamic positioning),

max. werk diepte:	1.700 m
max. stort capaciteit:	2.000 t/hr
diameter valpijp:	1.000 mm
breuksteengrootte D100:	max. 400 mm

lopende banden vormen het interne transport-systeem, dit maakt storten over boord mogelijk

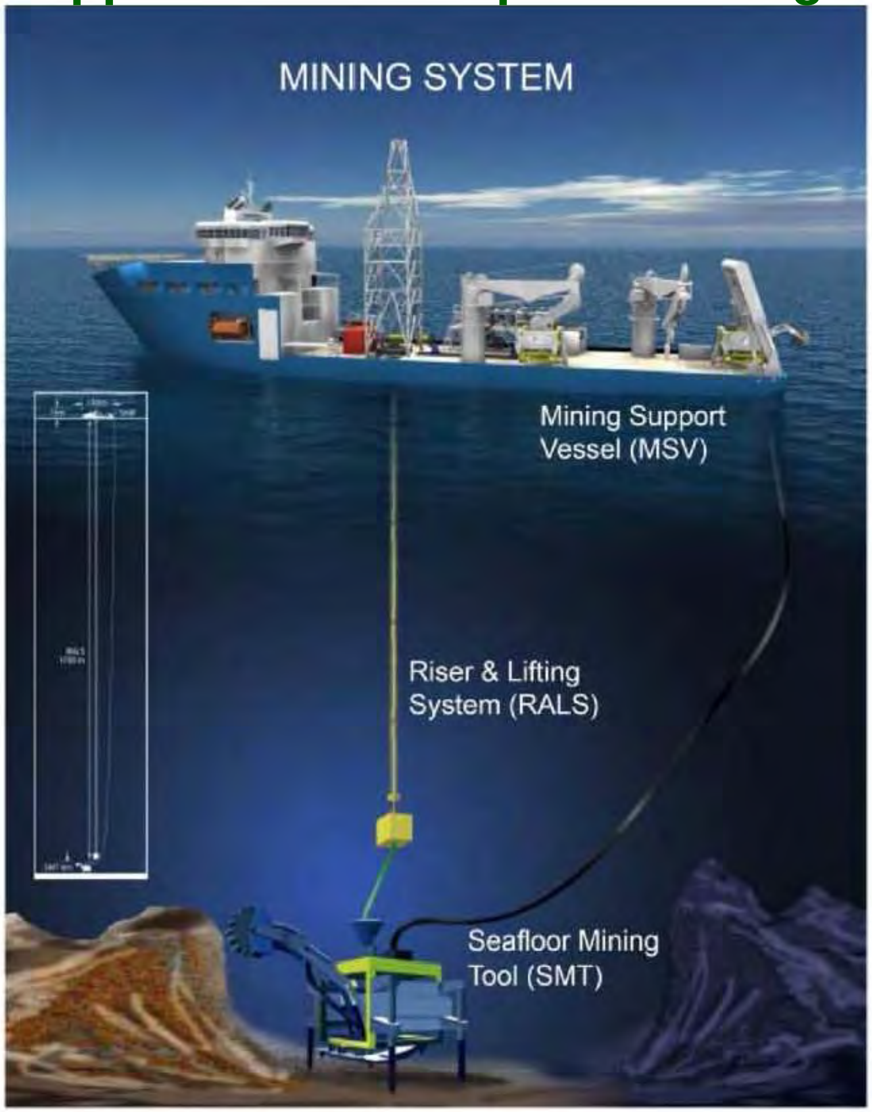
hydraulische excavateurs in de hoppers (elk met een capaciteit van 1000 ton/uur)

moonpool:	10 x 10 m (soort beun)

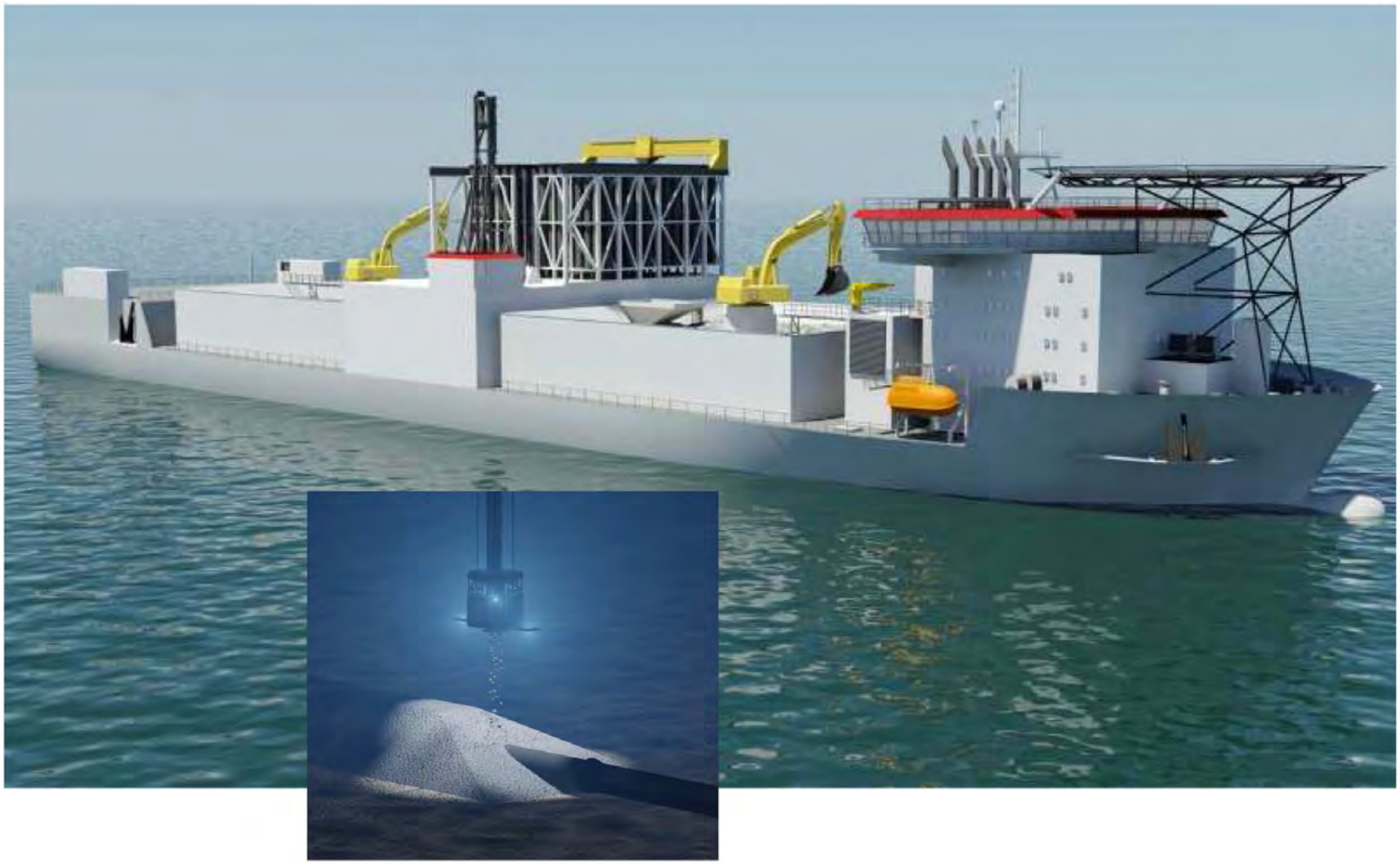
2 dekkranen, helicopter platform

afmetingen:	191,5 x 40 x 13,2 m
diepgang:	7,5 m (26.000 dwt)
diepgang:	8,5 m (32.500 dwt)
laadvolume:	19.500 m^3
vaarsnelheid:	15,5 knopen
hoofd motoren:	5 x 4.500 kW
(boeg) schroeven:	in totaal 8
accommodatie:	70 personen
oplevering:	2009

Hydraulic Transport: Application in Deep Sea Mining



Hydraulic Transport: Application in rock-dumping



Hydraulic Transport: Application in rock-transport, ballasting of GBS

Hydraulic Transport: Particles in flowing water inside a dredge pipe

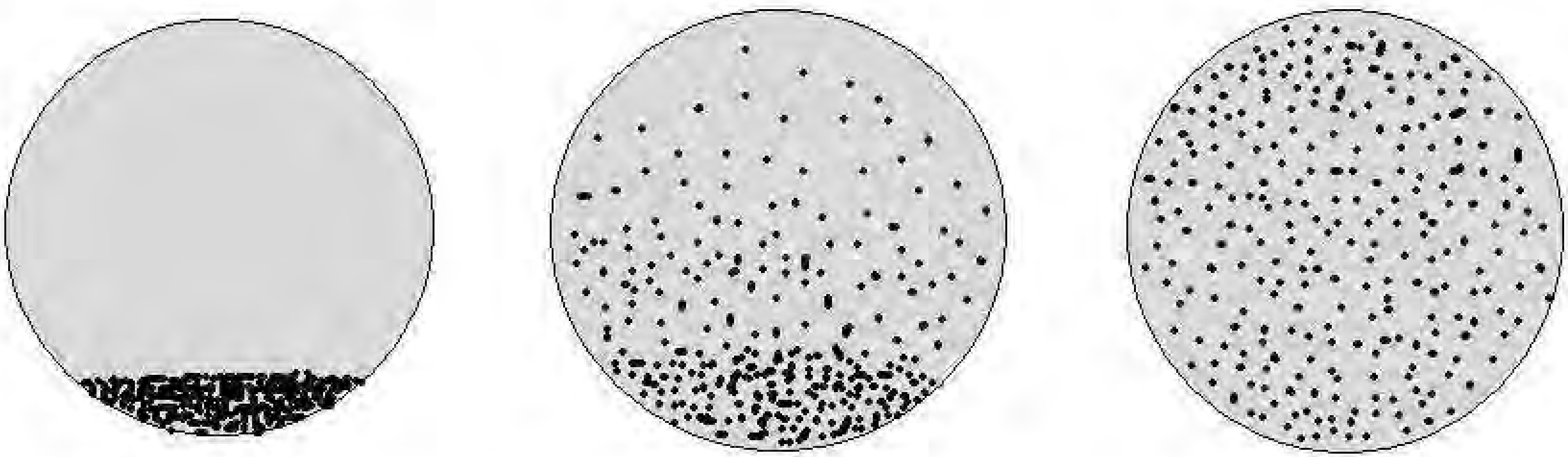
During the hydraulic transport-process of a dredger:

- the dredge-pump & drive plant, adds energy to the fluid by increasing its Kinetic Energy, which is soon transformed into a combination of Kinetic energy (fluid velocity) and into Potential energy (pressure)
- By increasing the velocity, the turbulence within the fluid will increase, hence facilitating the keeping of particles in suspension
- Energy will not really be transmitted to the sand-particles, but
    - Particles are kept into suspension by turbulences and (omnidirectional) turbulent forces
    - They will be dragged by dragforces (actual friction resistance) caused by the moving fluid
    - The velocity of sand-particles is lower than the one of the moving fluid: this phenomenon is called “slip” and depends upon the size of the particles, the concentration of solids inside the suspension, the viscosity, etc…

Hydraulic Transport: Hydraulic regimes of particles in flowing water

Mainly, 4 flow-regimes:

Stationary bed | **Sliding bed with partial suspension** | **Homogeneous suspension**

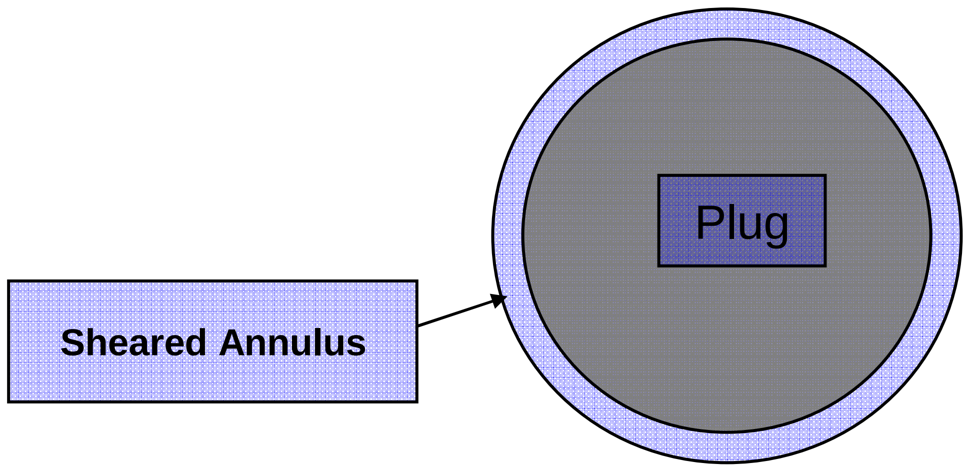


Governing factors

- **Increasing velocity: more drag, more turbulence**
- **Increasing viscosity (increasing concentration): more drag**
- **Decreasing grain-size: smaller fall velocity**
- **Decreasing pipe-diameter: higher velocity**

Hydraulic Transport: Hydraulic regimes of particles in flowing water

Particular Case: Plug flow occurring mainly with cohesive sediments (mud-type) with high concentrations , viscosities and/or yield stress



Hydraulic Transport: Phenomenon and physics of Slip

$$v_s = v_w - v_{slîp} \qquad f_S = \frac{v_s}{v_m}$$

Slip-velocity is dependent upon hydraulic regime

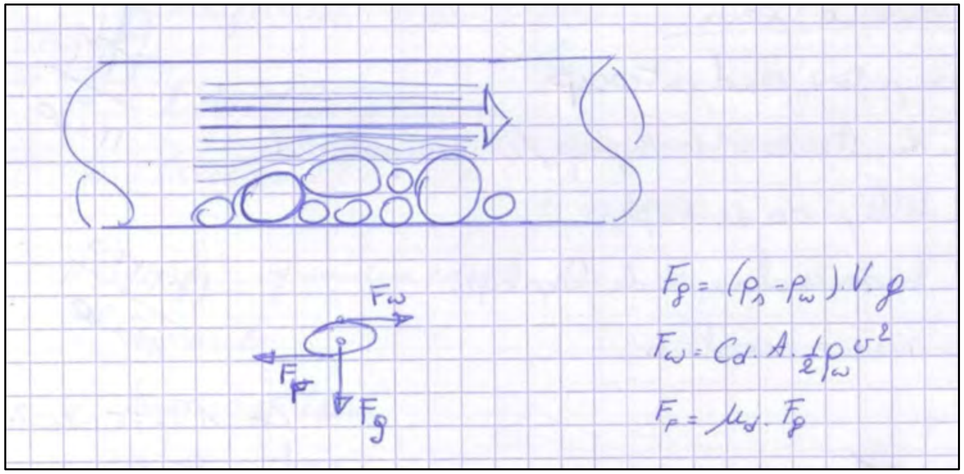
- **Particle in suspension:** $v_{slip} \approx 0$
- **Particle in sliding bed:** $0 < v_{slip} < v_w$
- **Particle in vertical flow:** $v_{slip} \approx 0$

Factors governing slip:

- **Contact-surface between particle and fluid**
- **Specific density of particles wrt fluid**
- **Grain-size diameter**

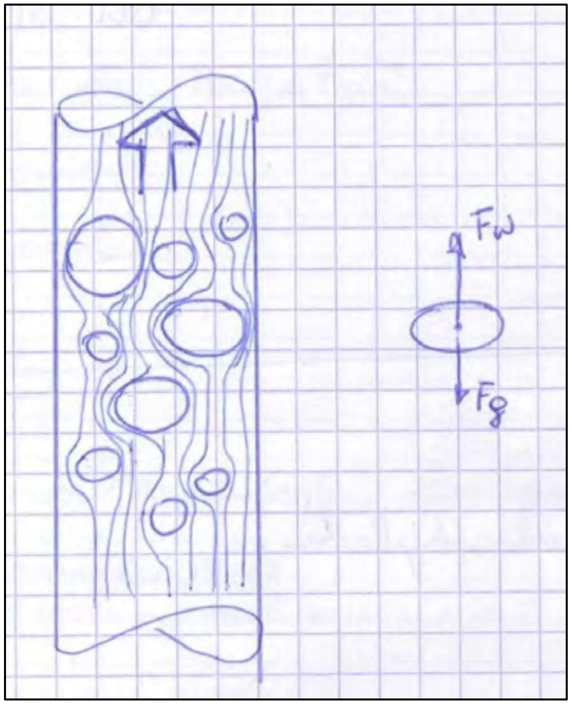
Sediment/soil	Slipfactor fs
Silt and Clay	0,9 - 1
Fine Sand	0.8-1
Coarse Sand	0.7-0.9
Gravel	0.65-0.85
Boulders	0.4-0.65

Hydraulic Transport: Effect of Inclination of dredge-pipe on Slip

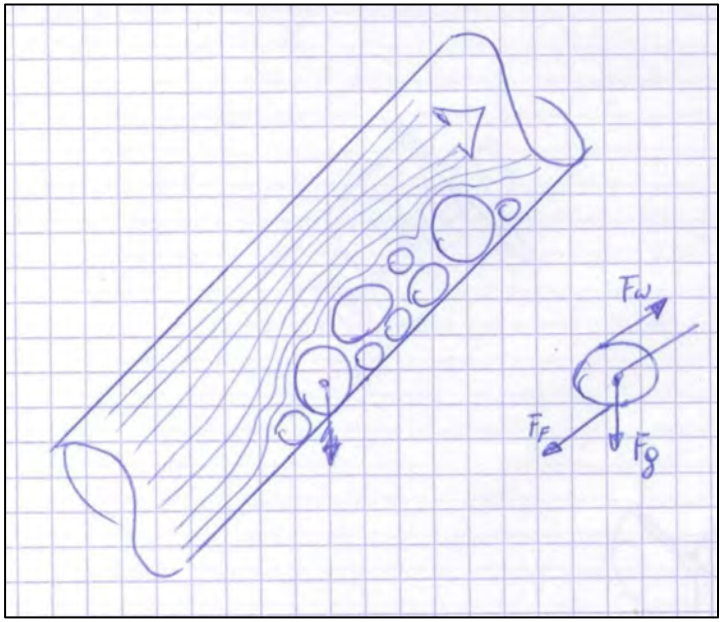


Horizontal pipe:

Intermediate Slip-factor, see prev tabe



Inclined pipe: large Slip-factor



Vertical pipe: small Slip-factor

Volume-Mass and Density: Concepts and Definitions

Volume-mass ρ is the mass of a soil (kg) per volume-unit (m3). The unit of volume-mass is kg/m3.

The mass of a saturated soil is determined by:

- **The solid constituents - grains, rock-fragments, shells, organic matter…- and their specific volume-mass**
- **The liquid or gaseous constituents in the voids between the solids**
- **The proportion (%) of these 3 different phase-constituents in 1 m3, determined by void-ratio, compaction-degree,… and the gas-content in the fluid**

Density is the volume-mass of a soil referred to the reference volume-mass (fresh water at ρ_w = 1.000 kg/m3). Density is hence dimensionless.

Facts and Figures about volume-mass

- **Dry solid volume mass**
  - **Void-content n = volume of voids / total volume**
    typically is n = 40 – 60% for granular soils
  - **Specific volume-mass of solids: Quartz, Feldspars, Carbonate**

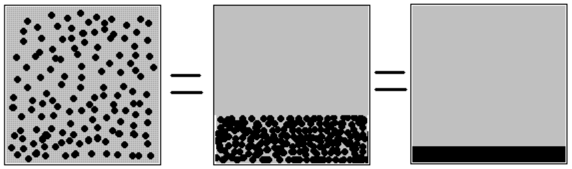
$$\rho_s = 2.65 - 2.7 t / m^3$$

  - **Typical values for sand are 1.100 – 1.500 kgds/m³**

$$\rho_d = (1-n)\rho_s + n\rho_{air} \cong (1-n)\rho_s$$

- **Volume-mass of (water) saturated mixture**

$$\rho_{sat} = (1-n)\rho_s + n\rho_w$$



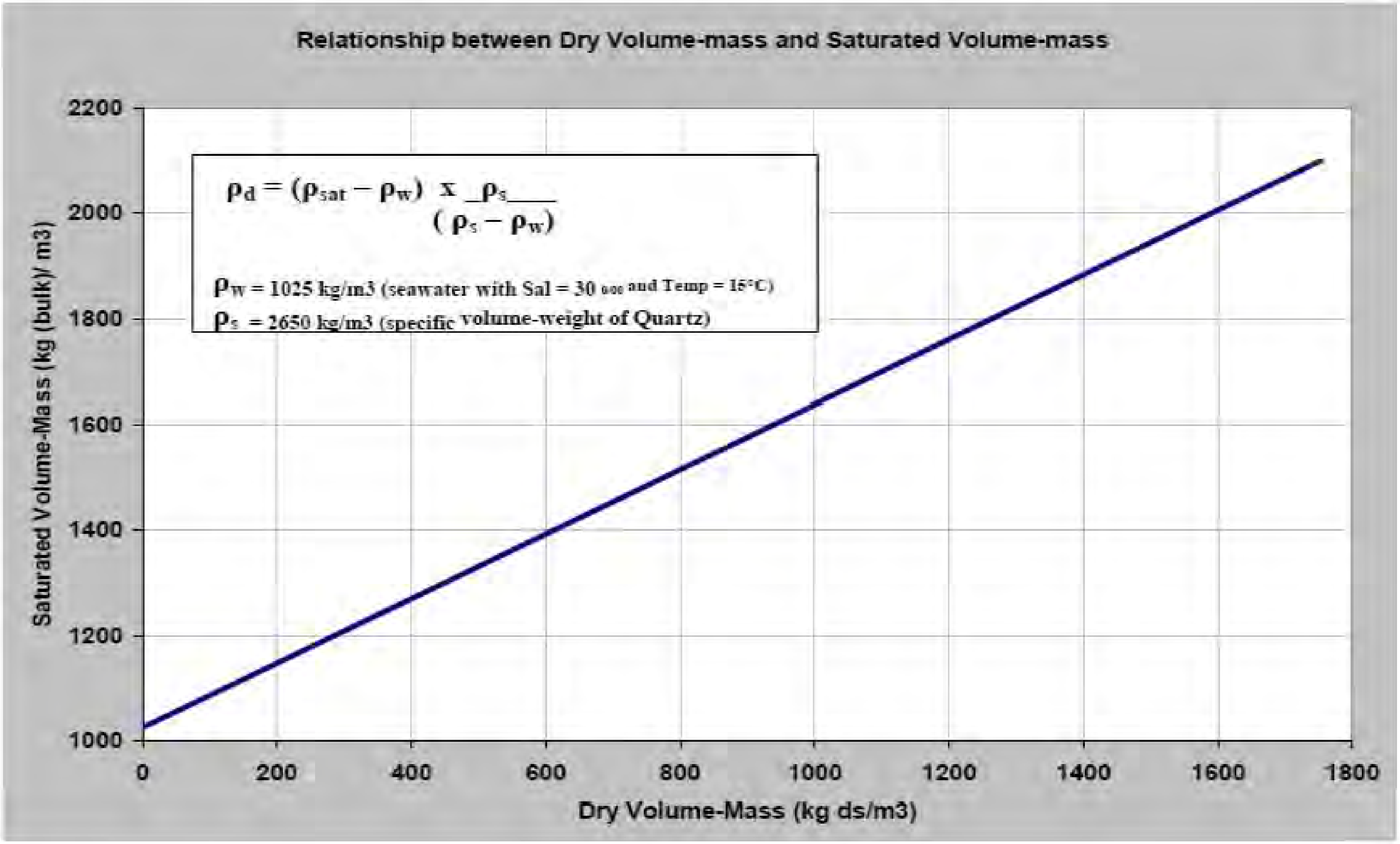
Typical values for sand are 1.800 – 2.000 kg/m³
(variable according to shell-content, grain-size distribution, grain-shape, compaction-characteristics,..)

Volume-mass and sediment-soil properties

Volume-mass of a sediment or soil expresses the packing of grains and will determine:

- **Cohesion and shear- resistance**
- **Relative compaction degree (granular soils)**
- **Degree of consolidation (cohesive soil)**
- **Void ratio**

The first most important geotechnical equation in Dredging



The second most important geotechnical equation in Dredging: the mechanisms of dilution and concentration

Principle of Continuity of solids = during the whole process of dredging – between in-situ, via dredged mixture to discharge and ultimately consolidation/compaction – the mass of solids does not change. The only changes occurring are related to the proportion of water & gases vs. solids.

Two exceptions:

- **During overflow: overflow losses induce the loss of fines to the natural system.**
- **During disposal: fines are dispersed (aquatic disposal) or evacuated as fines over the weir**

Continuity of mass of dry solids (cont)

$M\ ds_x$ = mass of dry soils/mixture-solids in stage x

V = bulk volume of soil/mixture

$$\rho d = (\rho sat - \rho w) \times \frac{\rho s}{(\rho s - \rho w)}$$

- **ρw = 1025 kg/m3 (seawater with Sal = 30 0/00 and Temp = 15°C)**
- **ρs = 2650 kg/m3 (specific volume-weight of Quartz)**

$$M\ ds_1 \cdot V_1 = M\ ds_2 \cdot V_2 \quad >> \quad (\rho\ sat_1 - \rho\ w) \cdot V_1 = (\rho\ sat_2 - \rho\ w) \cdot V_2$$

$$Cf = \frac{V_1}{V_2} = \frac{(\rho\ sat_2 - \rho\ w)}{(\rho\ sat_1 - \rho\ w)}.$$

This simple formula transforms any soil-volume in any other volume, just on the basis of the bulk saturated volume-mass.

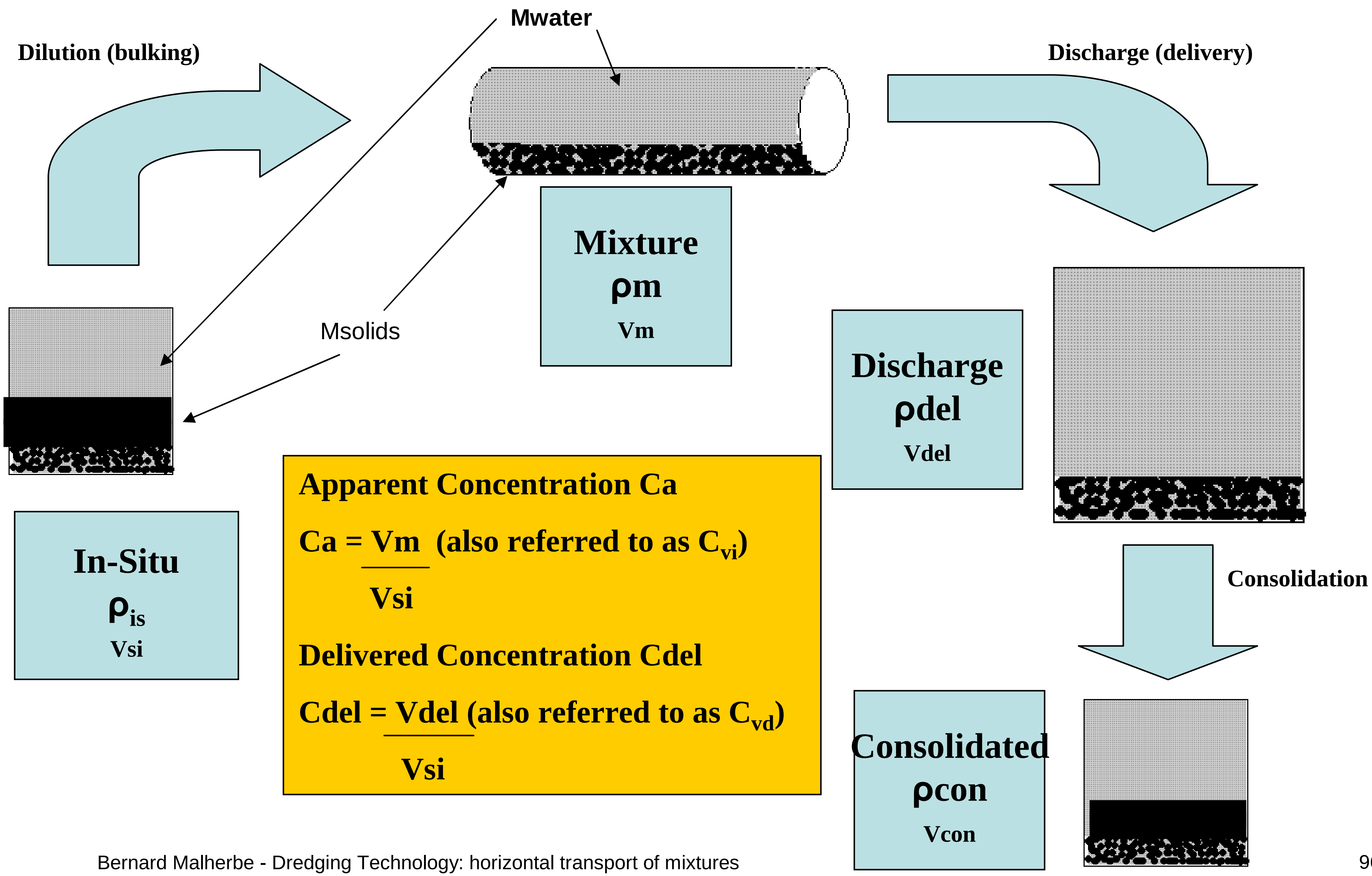
Cf is often called the 'Concentration Factor'.

Dredging Volumes Control: what is measured ? And where ?

Production control can only rely on (online) measurements !!.

Site	Volume-mass (kg/m3)	Velocity (m/sec)	Pressure Heads (kPa)	Volume (m3)
In-situ (pre-dredging)	Geotechnical survey $\rho_{in\text{-}situ}$			Bathy Survey $V_{in\text{-}situ\ in}$
Onboard dredger	Suction tube $\rho_{mixture}$	Suction tube $V_{mixture}$	Suction & discharge tubes	In hopper V_{del}
On disposal	Geotechnical survey ρ_{del}			Topo survey V_{del}
In-situ (post dredging)				Bathy Survey $V_{del} = V_{in\text{-}situ\ in} - V_{in\text{-}situ\ out}$

Hydraulic Dredging Volumes during Transport: Notions of Apparent Concentration and Delivered concentration



Apparent Concentration Ca

$$Ca = \frac{Vm}{Vsi}$$ (also referred to as C_{vi})

Delivered Concentration Cdel

$$Cdel = \frac{Vdel}{Vsi}$$ (also referred to as C_{vd})

Hydraulic Discharges during Transport

The mixture- discharge, Qm, is defined as the sum of the (transport-) Water-Discharge, Qw, plus the Solids-Discharge , Qs. Discharge introduces the notion of unit-time: xx m3/sec.

However, the measuring gauges, monitor 2 parameters:

- **ρ_{sat} or ρ_{bulk} (radio-active transmission probe, measuring the attenuation of γ-rays, interacting with large atoms)**
- **v_w or the velocity of the electrolytic fluid water (electro-magnetic gauge)**

Hence, no direct measurement is achieved of the Solids-Discharge, Qs,…which is ultimately what a dredger is only interested in. Sediment-particles in a moving fluid are known to "slip", which means they are moving with a velocity slower or equal to that of the fluid (see Slide 47). That's why the Ca is called 'apparent'.

Therefore, there is little other choice for the dredger than to assume a slip-factor , *ƒ*s, for the transported sediment, and to calculate the Solids-Discharge from the Mixture-Discharge.

$$Q_{del} = f_s \,.\, Q_m = f_s .\, v_m . A \,.\, C_a$$

A = section of dredging tube at the gauge

Hydraulic Discharges during Transport

$$Q_{del} = f_s \, . \, Q_m = f_s . \, v_m . A . \, C_a$$

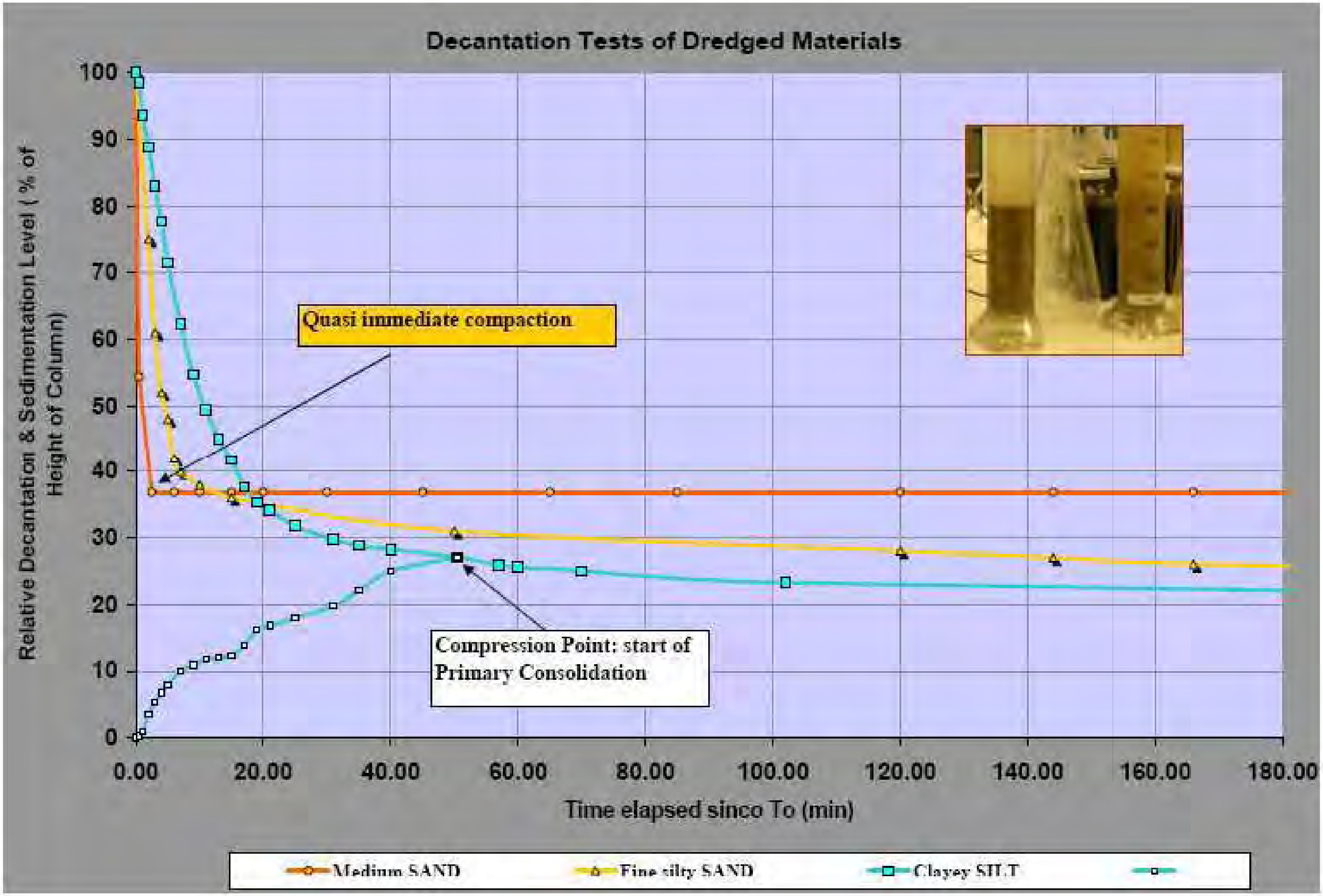
In the equation above, all parameters are measured or known , except the slip-factor, fs.

But fs can , in some circumstances, be measured by feedback:
when comparing the total integrated mixture volume, Vm over a given period, with the (topographical) measured Vdel (e.g. via Digital Terrain Modelling of an upland confined disposal facility) over that same working period, one gets a better approximation of the fs factor.

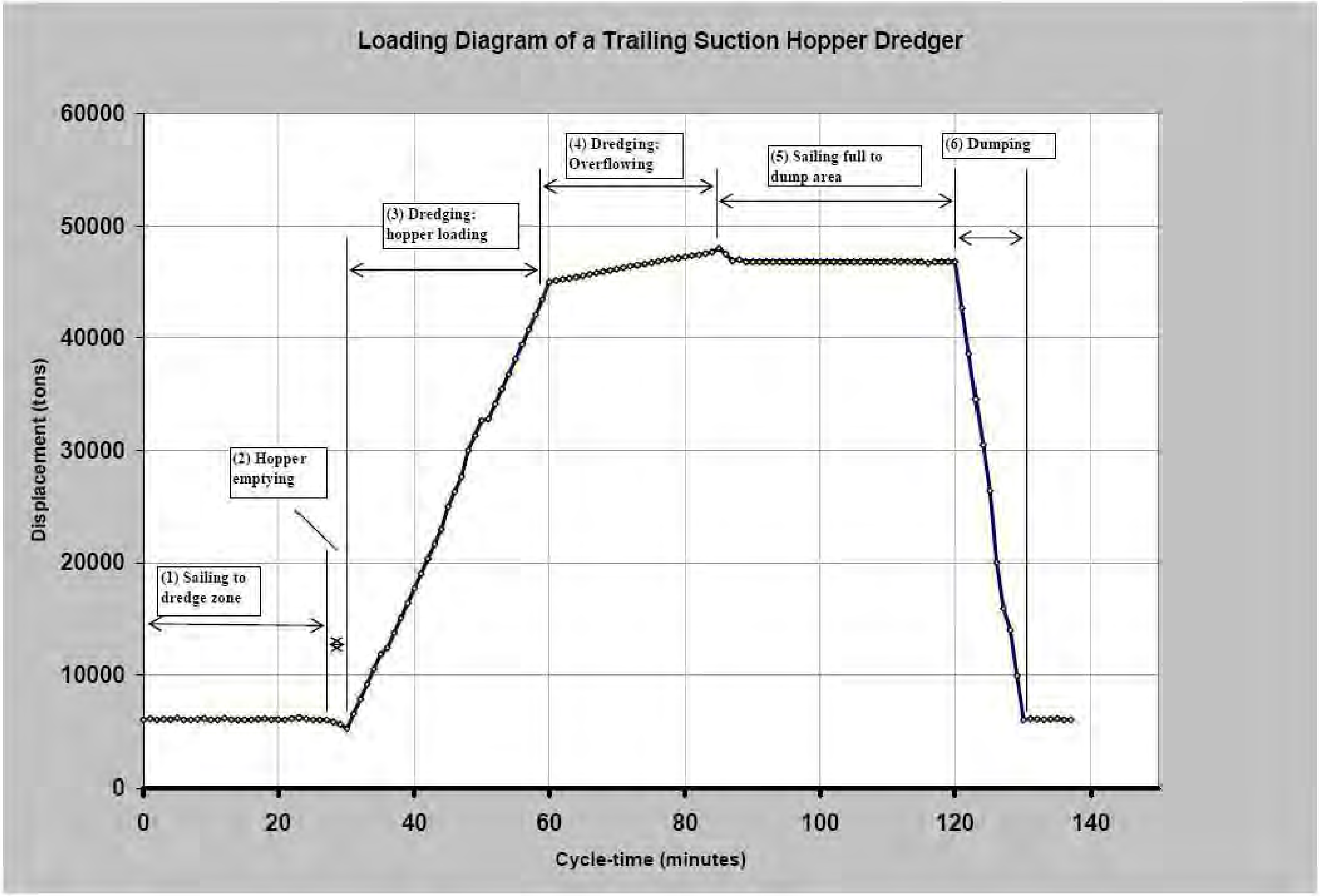
This is, of course, only valid for (almost) instanteneous compacting/consolidating sediments like sands and gravels. Granular sediments/soils bulk more during hydraulic transport, but get back rapidly to their (more or less) original (in-situ) compaction degree. (FYI: the fs is quite different from 1 for granular sediments).

Cohesive and/or fine-grained sediments/soils will bulk less, will need time to consolidate to a constant value and will generally keep a residual bulking (within a project-period of months or years). Unless, accelerated consolidation by dewatering is done. (FYI: the fs is generally close to 1 for cohesive sediments)

Application of concentration-equation: Compaction and Consolidation of Dredged & Delivered Materials

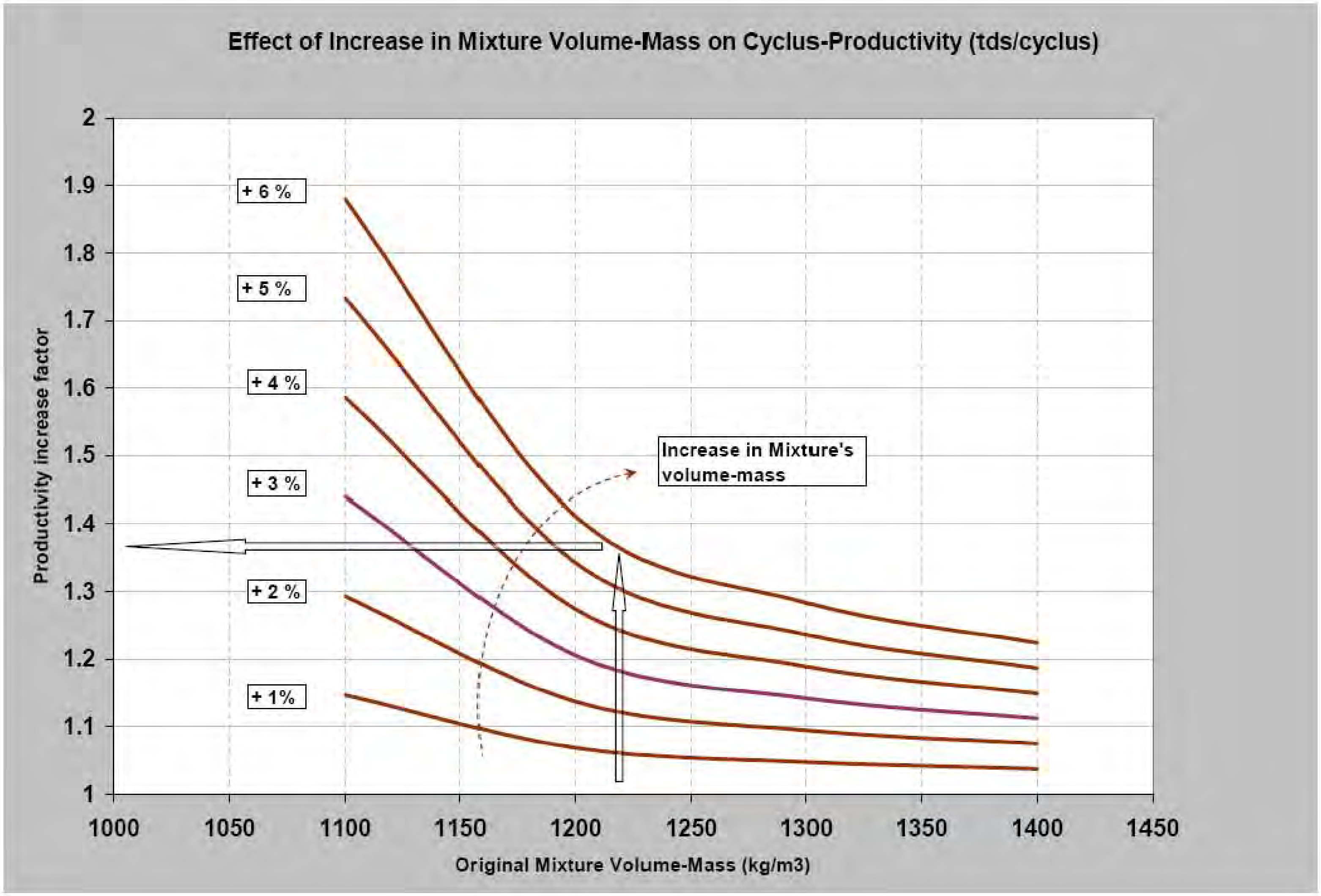


Application of concentration-equation: Production-Control and Cyclus-Management

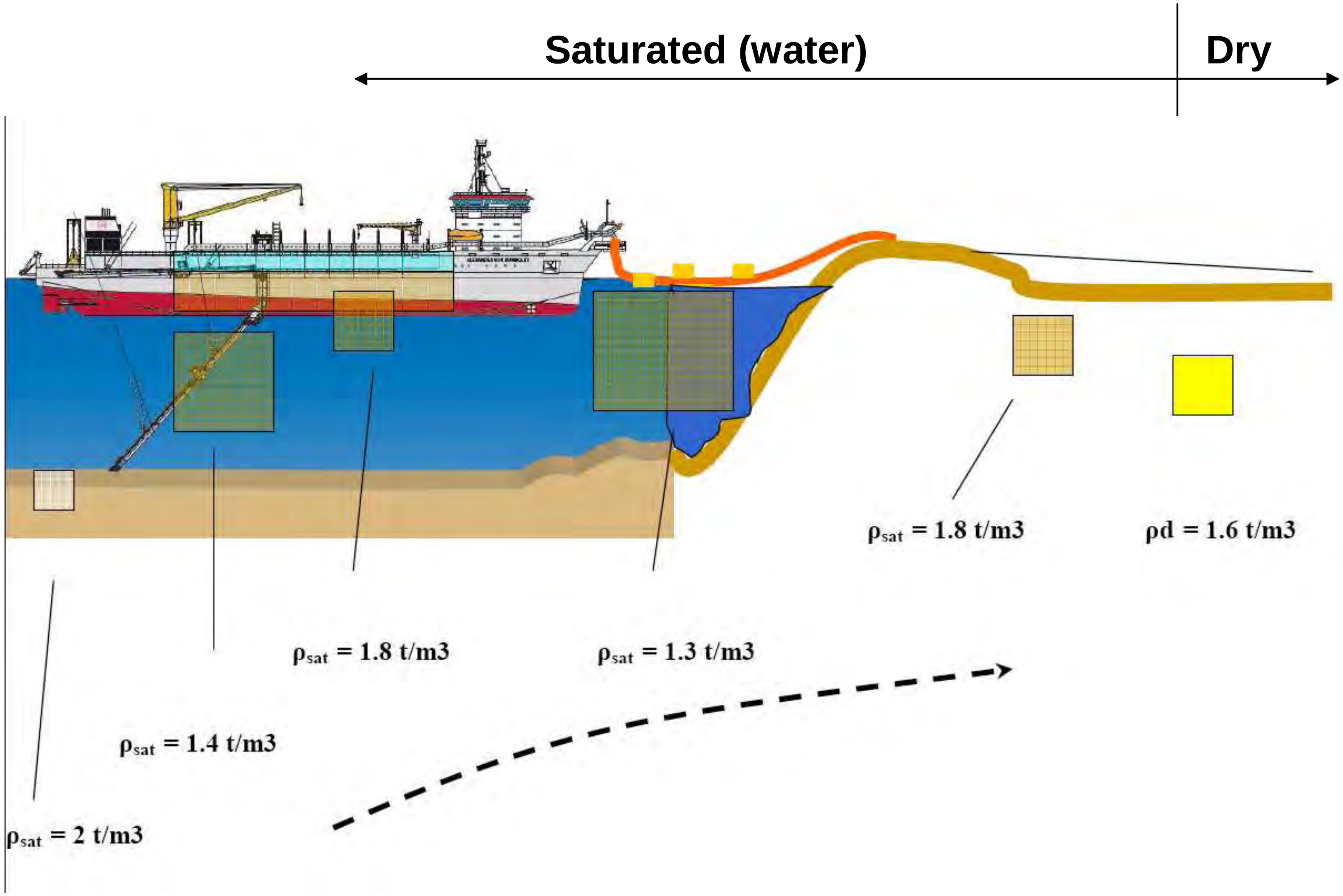



Double Transformed Loading Diagram of a TSHD
Displacement (tons) and Payload (tons of dry solids)
Cycle time (minutes)
60000
50000
40000
30000
20000
10000
0
-10000
0
20
40
60
80
100
120
140
Productive times
Non-Productive times (sailing, dumping,…)
Displacement aaf time
Loss of supernatant sheet

Application of concentration-equation: optimization of productivity by increase of mixture-density



Hydraulic Transport: Examples of sequence of Volume-Masses and volumes in a dredging & reclamation project



Hydraulic Transport: Hydraulic Process description

The hydraulic transport of sand-water mixtures is (for the time being) too complex and too poorly understood to be described analytically. Therefore, engineers have to rely on empirical relationships and formulae

The most relevant empirical formulae are based on closed-loop laboratory tests:

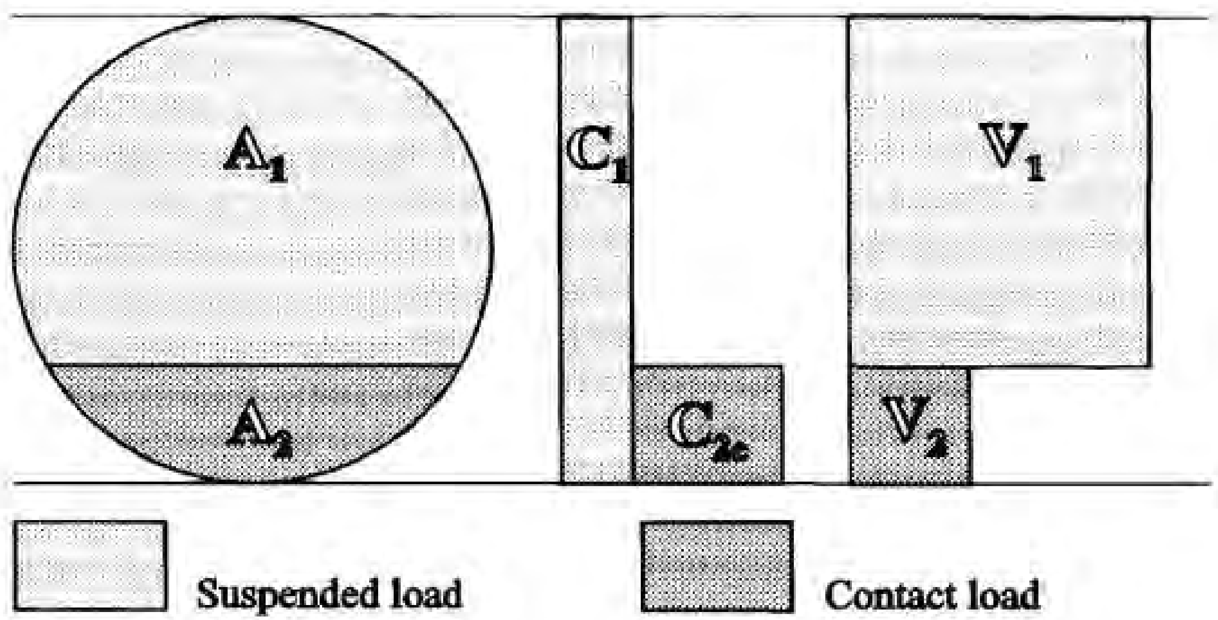
- **PhD's theses uit '50-ies en '60-ies**
  - **R. Durand & E. Condolios (1952) – R. Gibert (1960)**
  - **Alfred Führböter (1961)**
  - **Jufin-Lopatin (1966)**
  - **Wilson (1972-1996)**

But the lab-tests had drawbacks:

- **.too small diameters of pipes (excepted Durand and Wilson)**
- **too limited concentration ranges**
- **selected (near ideal) dredged materials (excepted Durand)**

Hydraulic Transport: Two-layered Model cfr Wilson

Wilson (1992-1996)



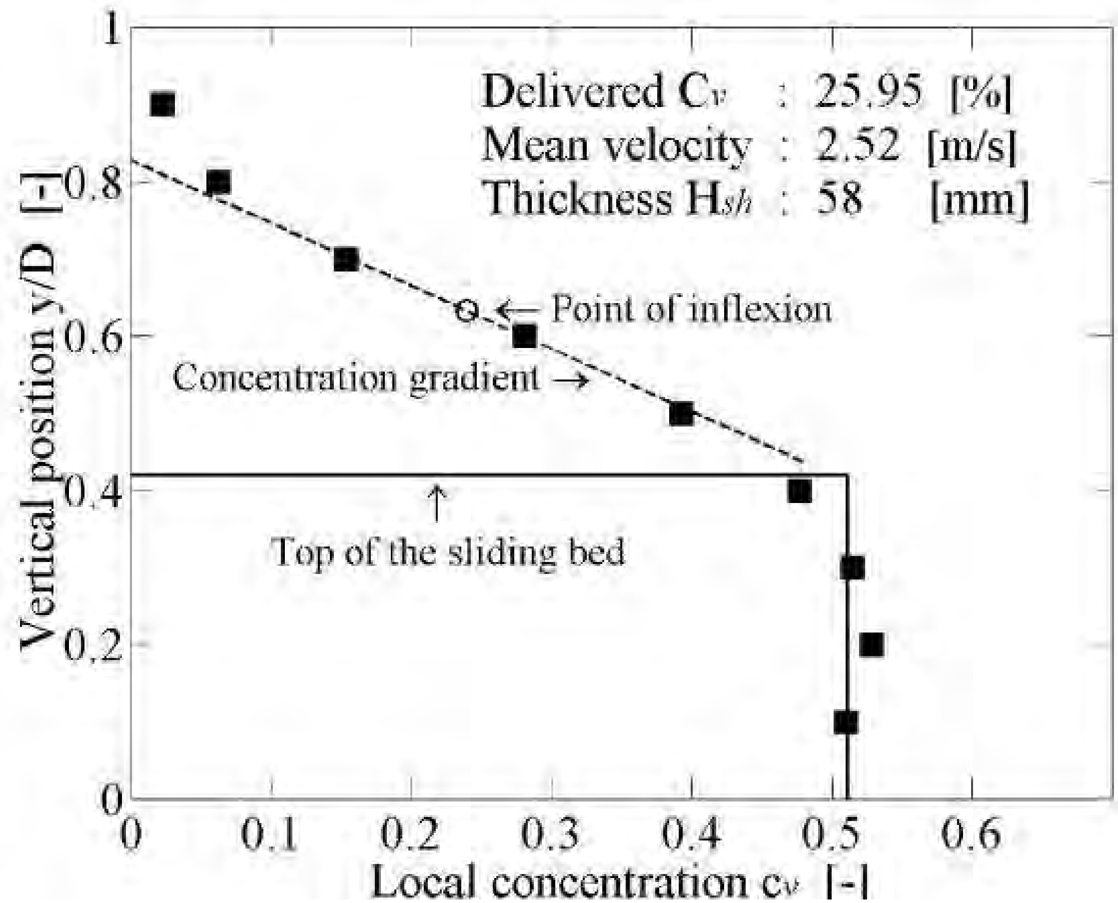
A = Wet Surface

C = Concentration

V = Volume

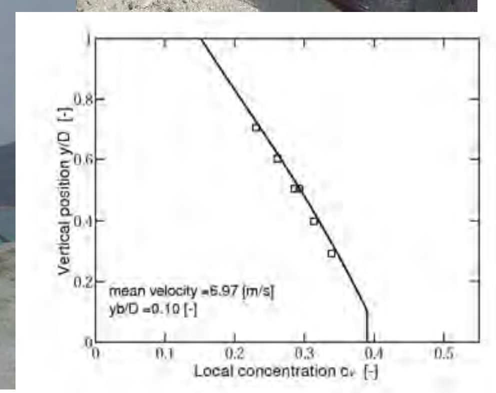
Hydraulic Transport: Two-layered Model further elaborated

Václav Matousek – TU Delft (1997)



Hydraulic Transport: Real-scale tests on Two-Layered Model

Via verification on real-scale reclamation works, the Two-Layered model was transformed into a practical engineering tool –
Pusan Port Development (South-Korea, anno 2002) 0,300 mm sand



Hydraulic Transport: Practical engineering State of the Art

Concluding:

- **Only empirical formulae are used**
- **Parameters are calibrated with site-specific measurements or experience-data**
- **Corrections to be applied for different pipe-diameters, cutter dredgers or hopper dredgers,…**

Careful:

- **Input-data are generally not precise (too little soil and soil-variability data)**

  - median grain-size is not easy to determine

  - effect of coarse materials (boulders,…) is huge : stones > 5 cm diameter are removed from lab-tests

  - effect of fines on dynamic viscosity

  - effect of variations in grain-size distribution

- **Type of dredging is important**

  TSHD: Segregation of material in hopper: coarser under discharge pipe

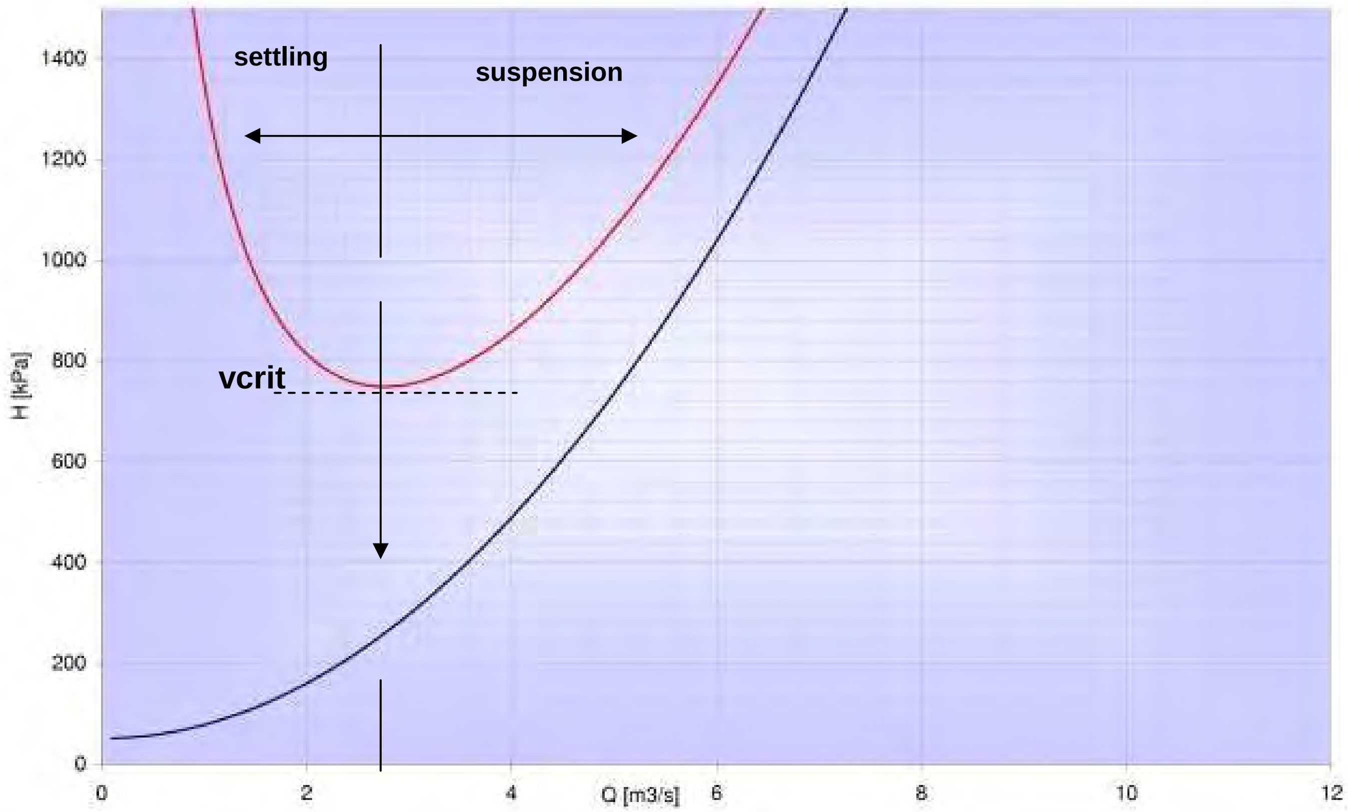
  CSD: undercutting vs overcutting

- **Variations in process-parameters are not smoothed out over long discharge-pipes**

Hydraulic Transport: Hydraulic characteristic of sand-water mixture

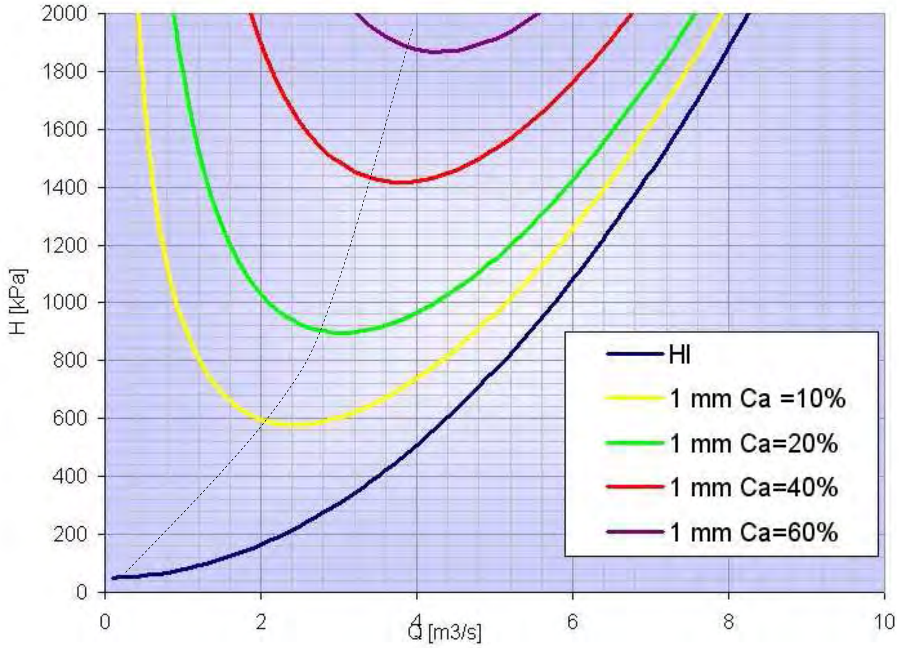
- **Relationship is of the following type:** $$H = aQ^2 + \frac{b}{Q} + c$$

- **Minimum of curve: critical velocity/discharge**

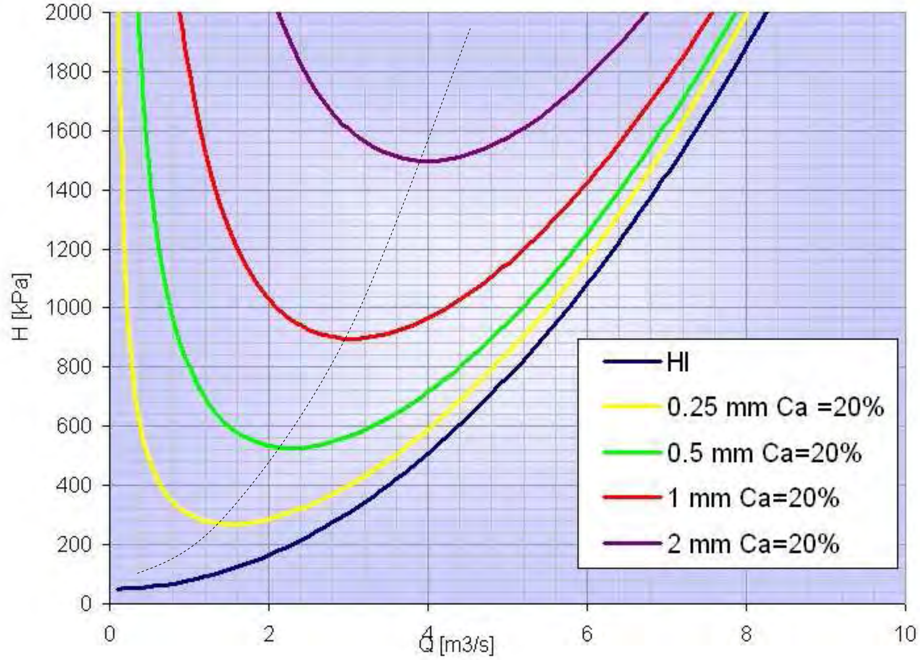


Hydraulic Transport: Influence of variable concentrations and grain-sizes (Führböter)

Effect of increasing concentration

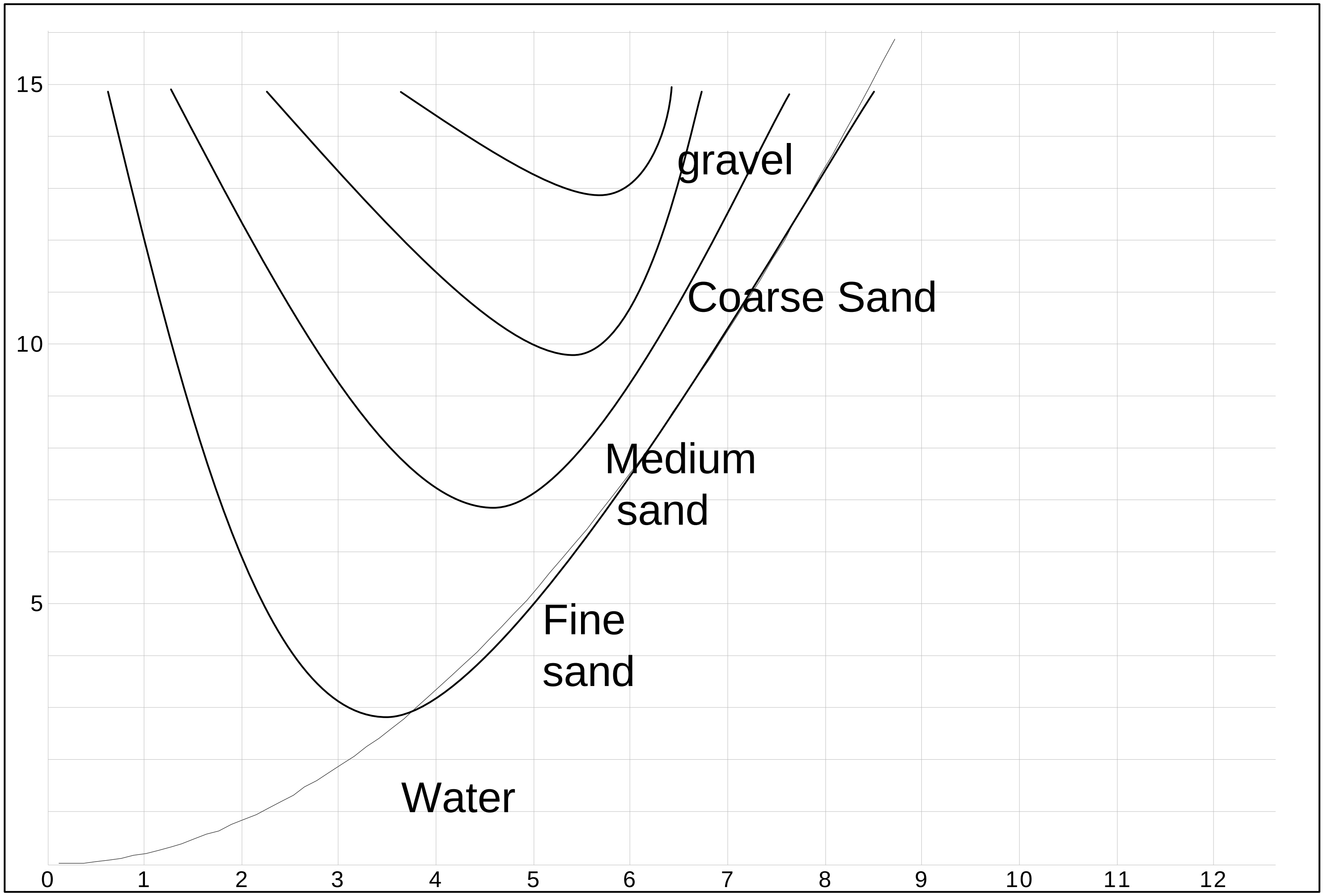


Effect of increasing median-grain-size



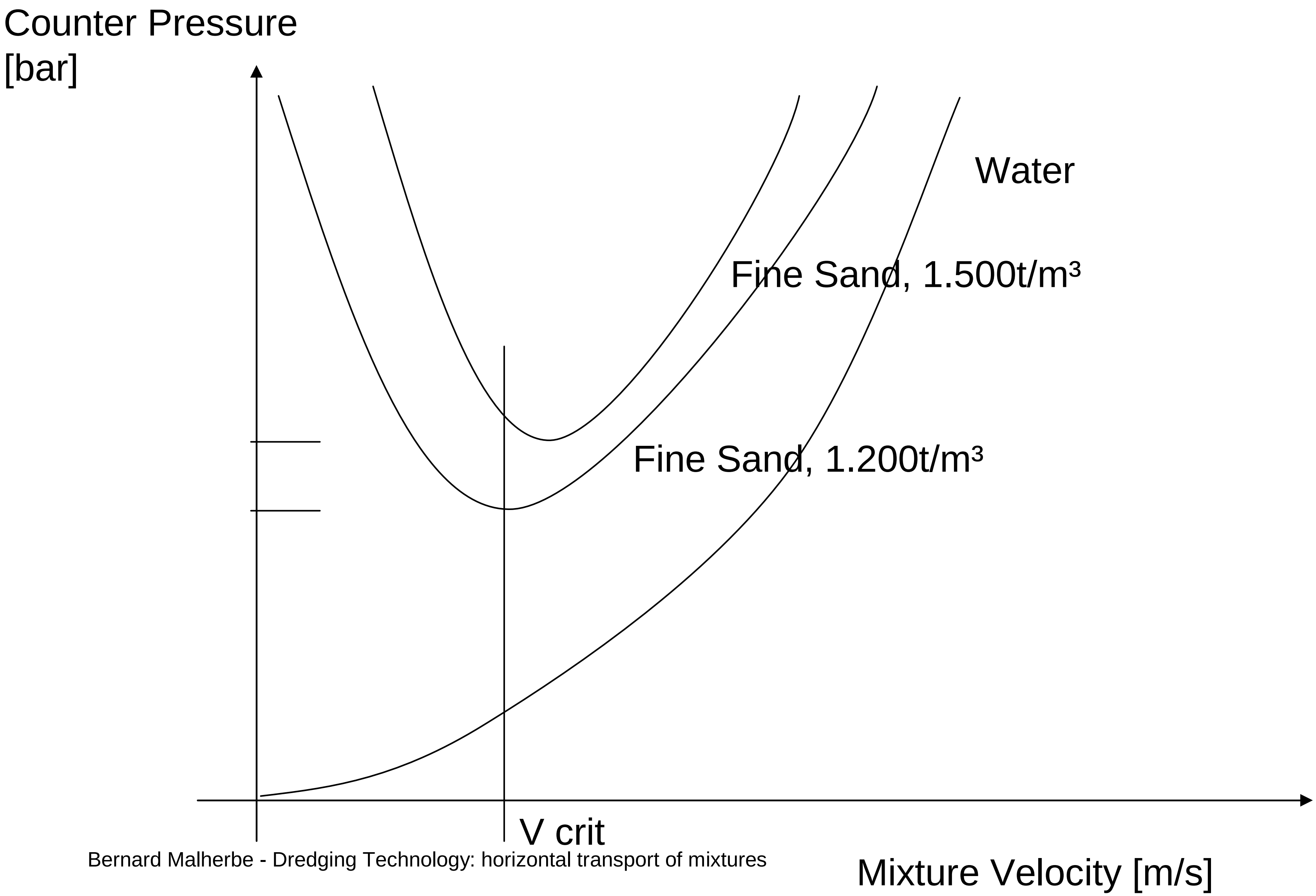
Hydraulic Transport in Pipelines: Affinities with Grain-Size

Counter-Pressures (bar)

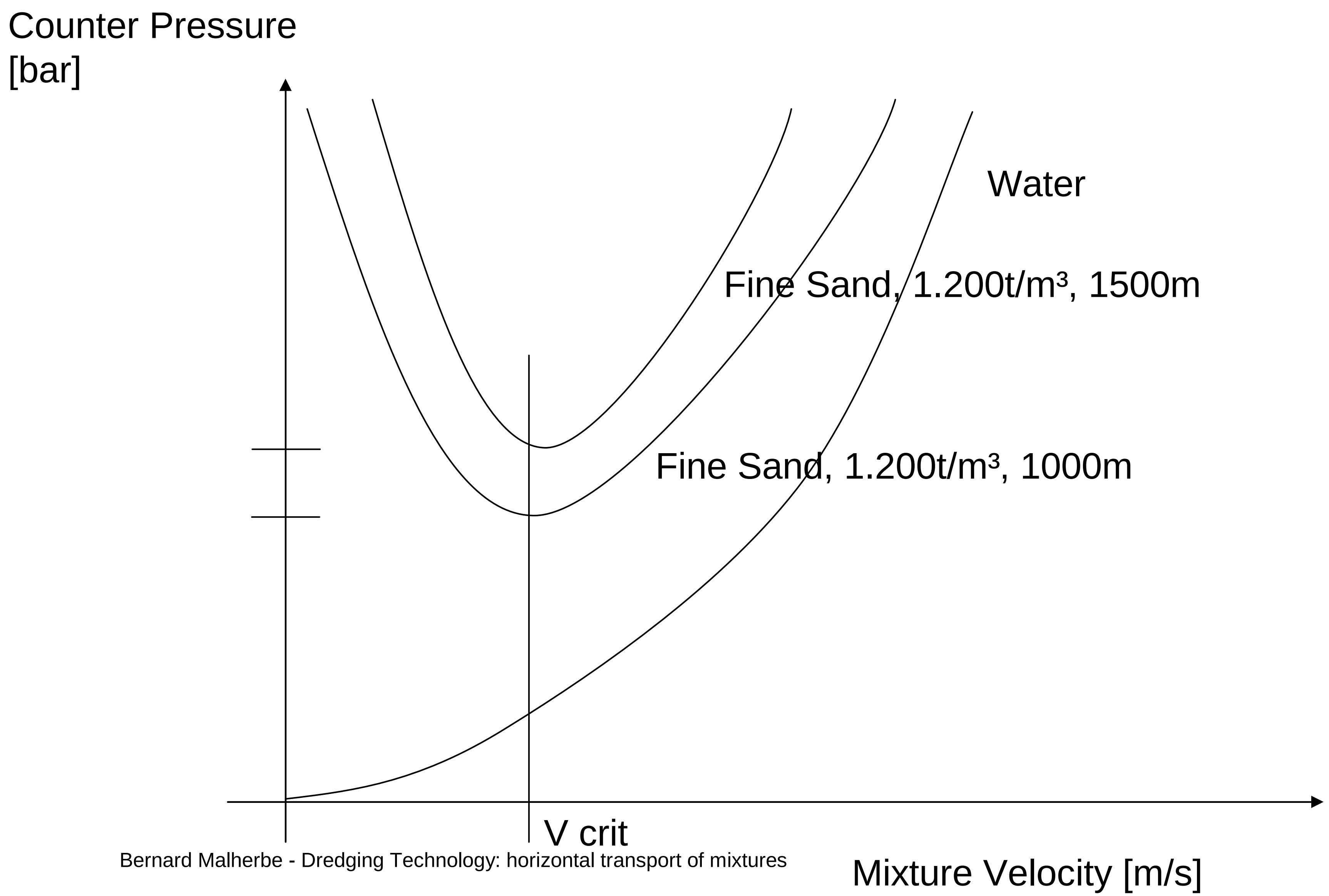


Mixture Velocity [m/s]

Hydraulic Transport in Pipelines: Affinities to Volume-Mass



Hydraulic Transport in Pipelines: Affinities with Pipeline-Length



Hydraulic Transport:

END of PART 1

Hydraulic Transport: Exercise about Concentration

Input: **Dredged Material : Silty Sand**
In-Situ Volume-Mass :ρ sat = 1.500 kg/m3
Measured Volume-Mass in Pressure Tube: ρm = 1.300 kg/m3
Measured velocity in Pressure Tube : v = 5 m/sec

ρ_s=2.65 t/m³
ρ_W=1.025 t/m³

Calculate :

- **What is the bulking factor due to hydraulic dredging ?**
- **What is the apparent Concentration ?**
- **What is the Delivered Solids Discharge (estimated)?**