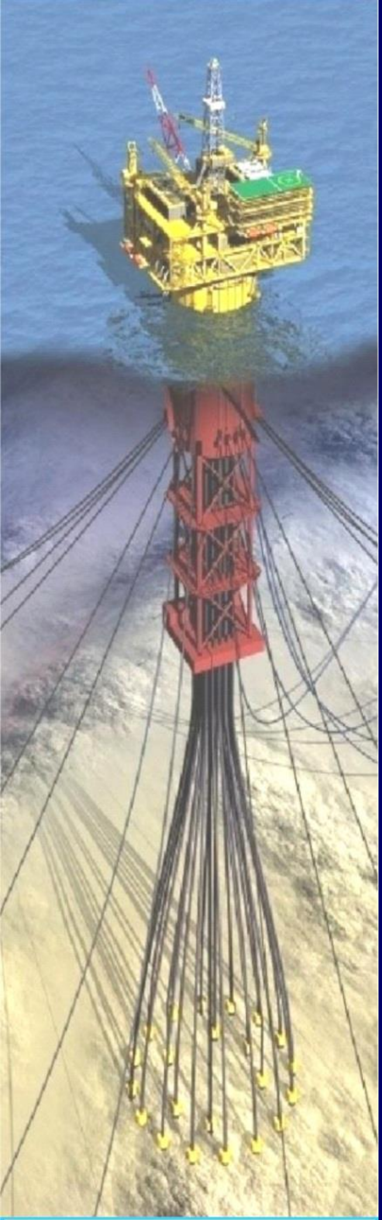

DSCRC Model Production Estimating based on Specific Energy

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Head of Studies
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& Marine Technology
&
Associate Professor of
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Dredging A Way Of Life

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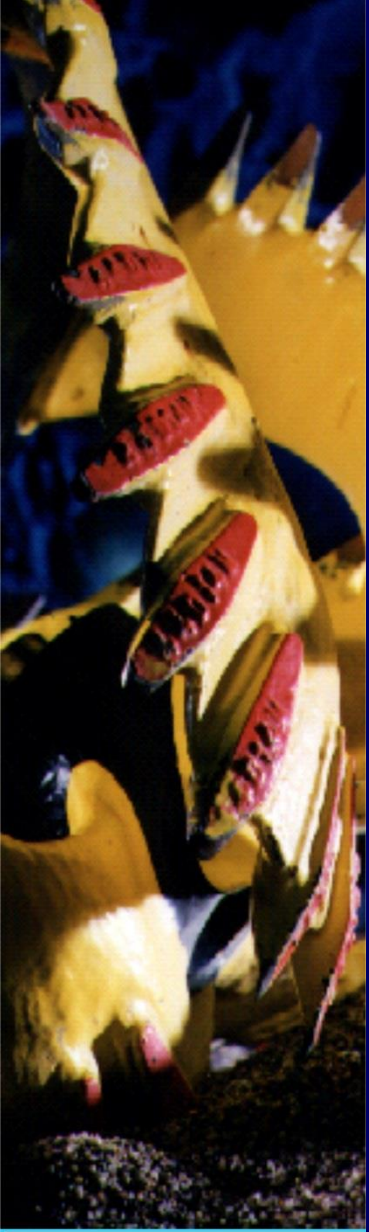

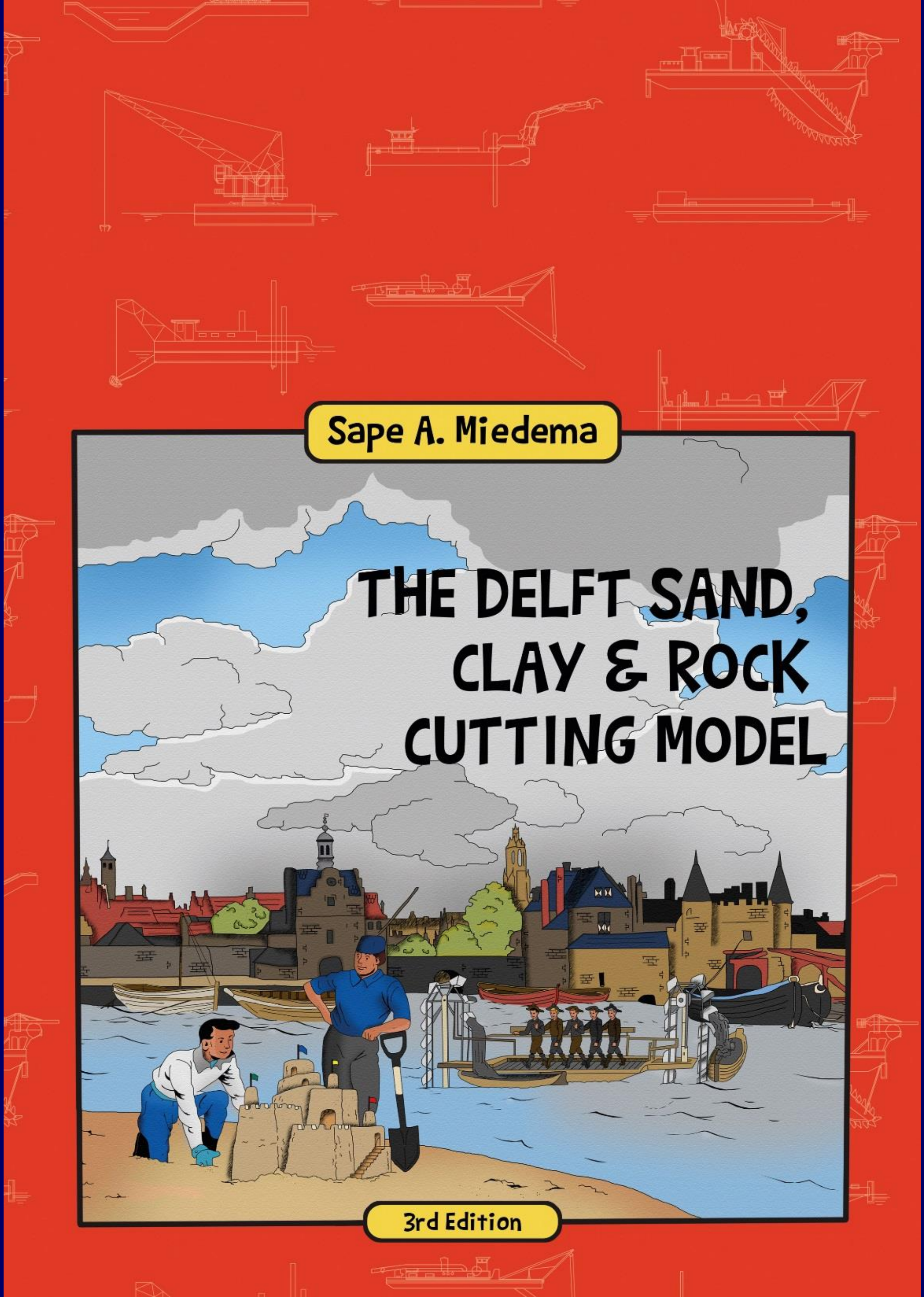

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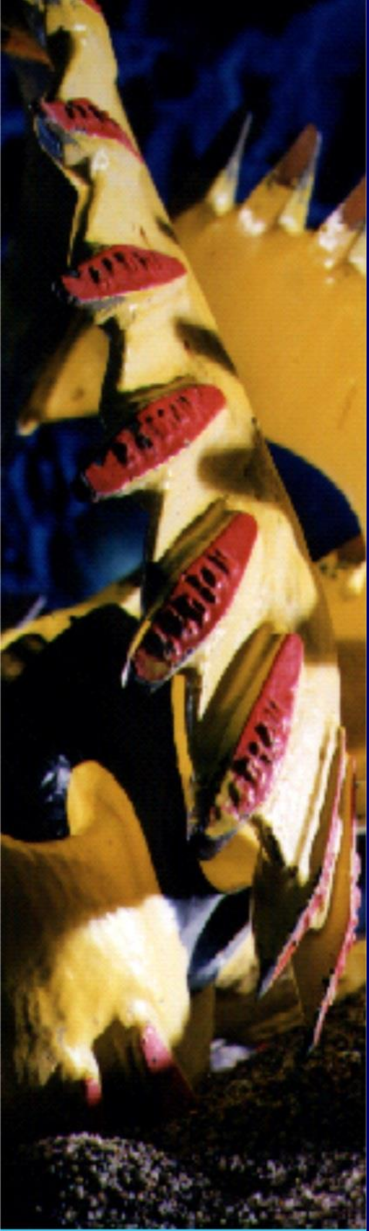
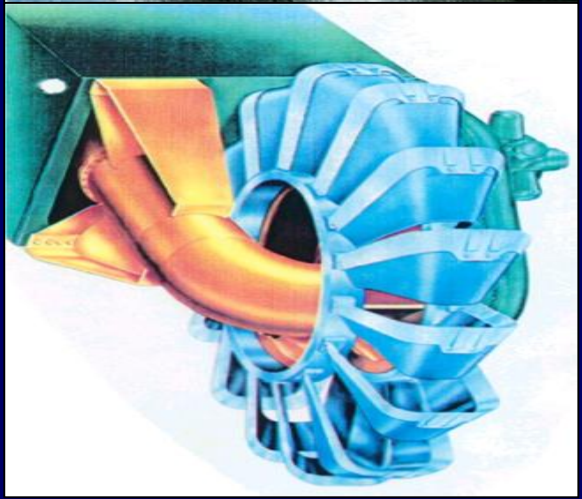
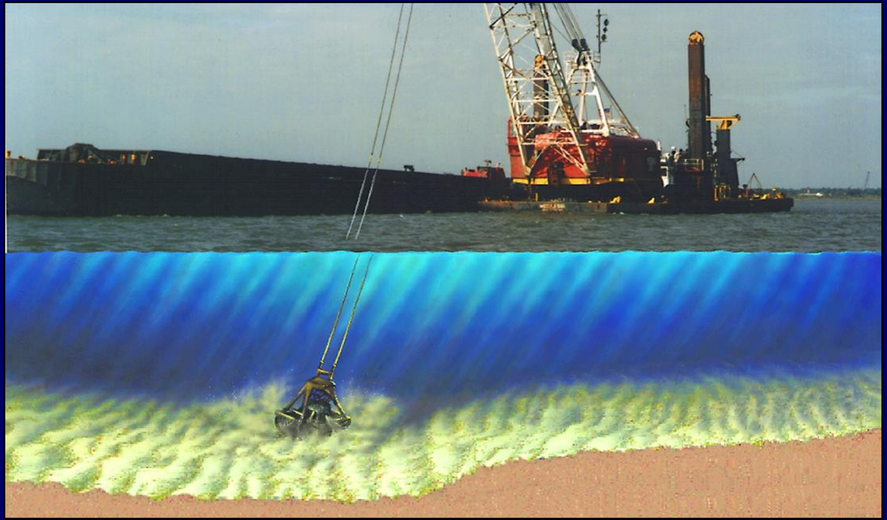
Cutting of Soil in Dredging







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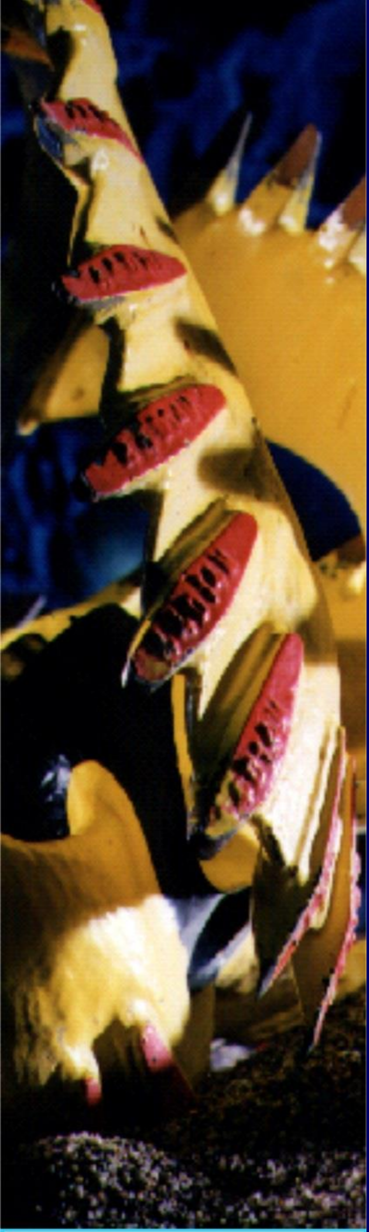

Problem Definition:

How to determine the production of dredging and other excavating equipment.

Solution:

Based on the installed excavating/cutting power and the specific energy of the soil the production can be determined.

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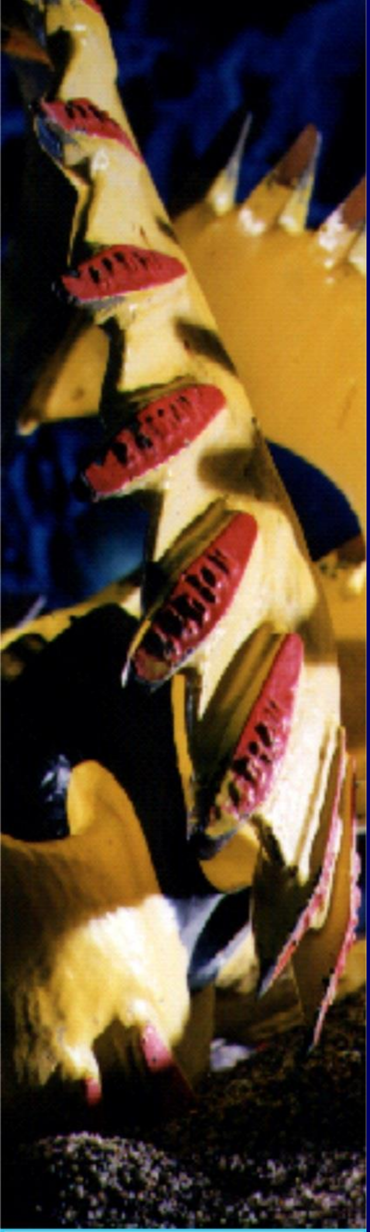

Specific Energy

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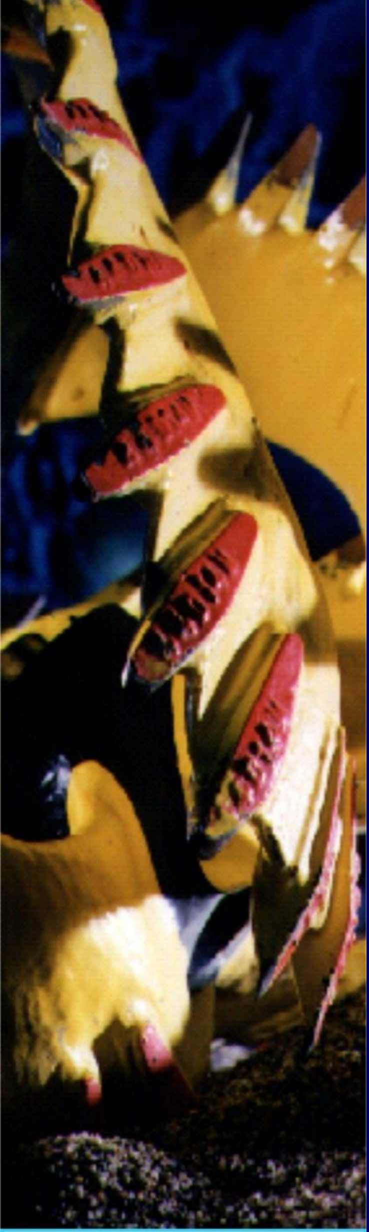
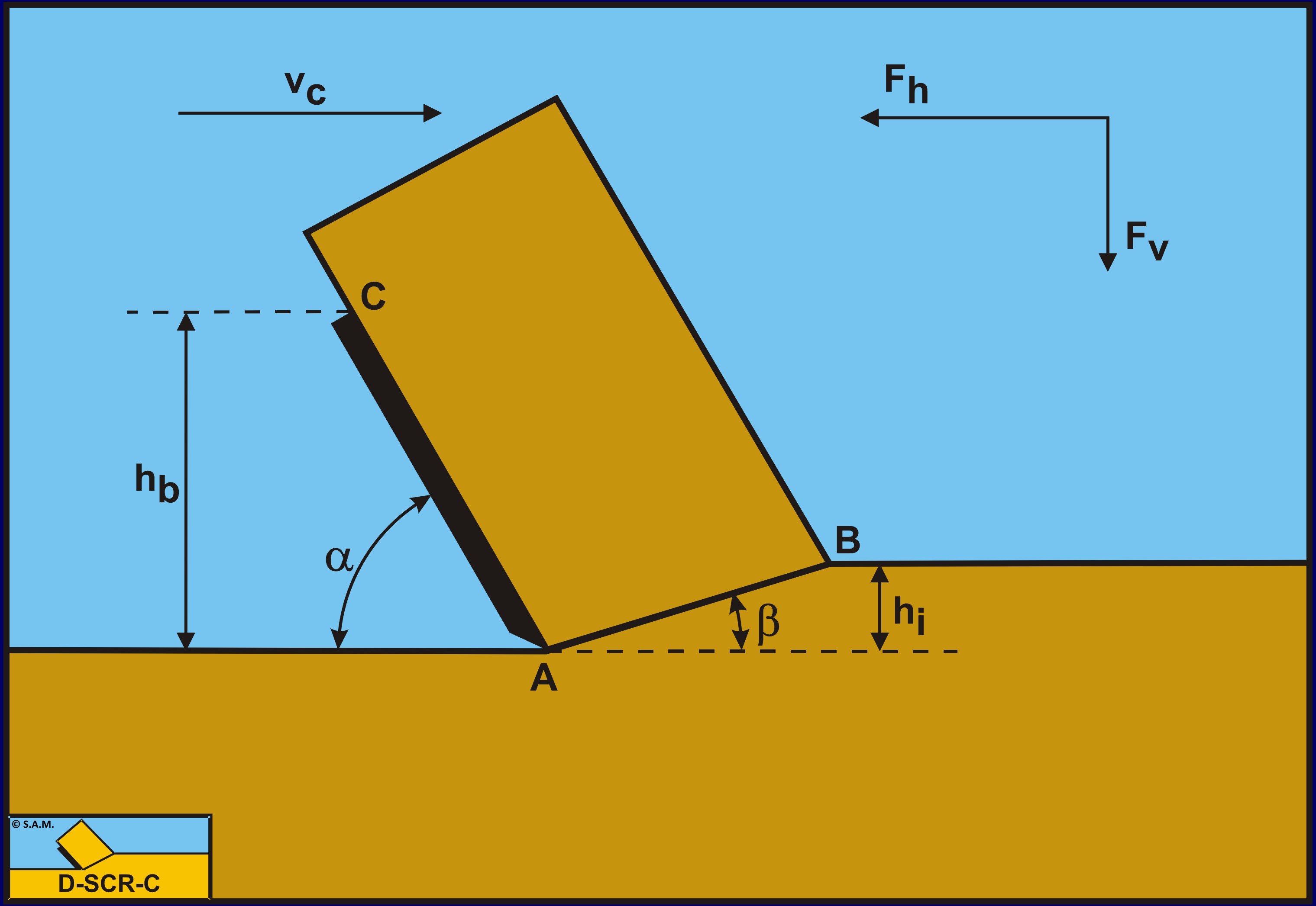


Definitions 2D Cutting Process



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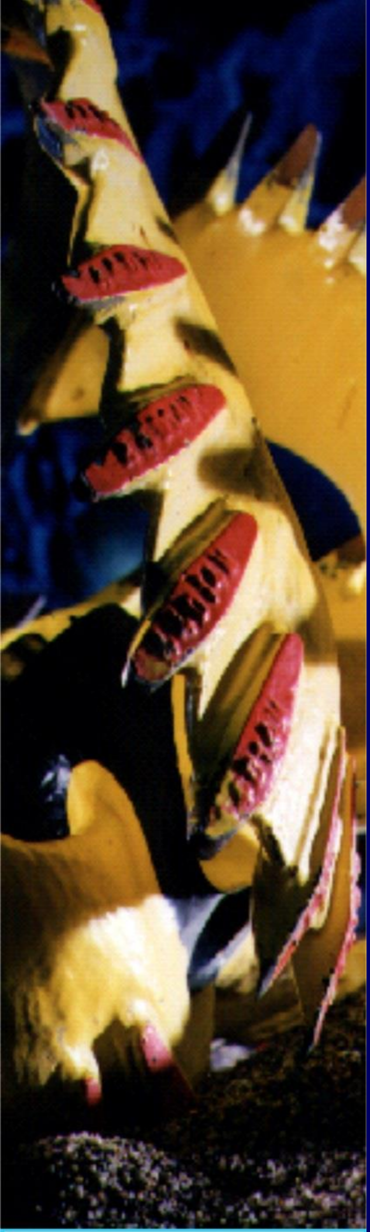
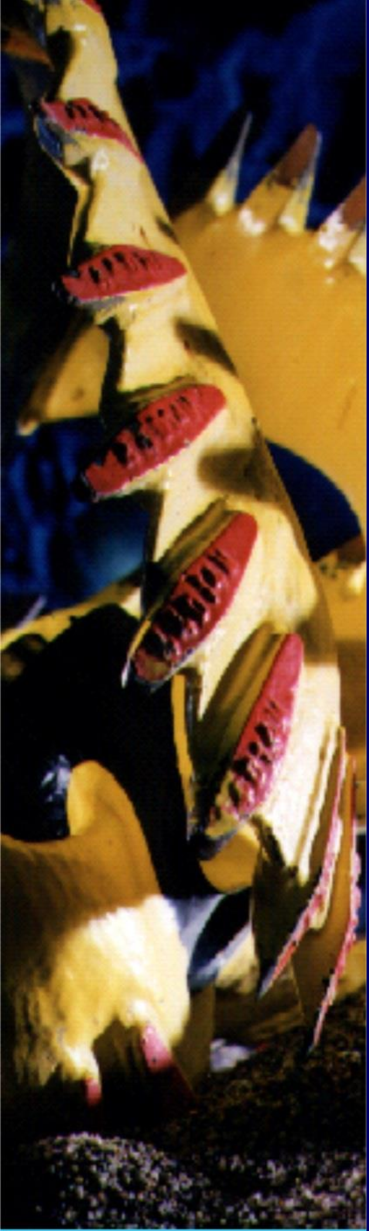


Specific Energy Work Based

$$E_{sp} = \frac{Work}{Volume} = \frac{Force \cdot Distance}{Volume}$$

$$= \frac{F_h \cdot x}{h_i \cdot w \cdot x} = \frac{F_h}{h_i \cdot w} = \frac{kN}{m \cdot m}$$

$$= \frac{kJ}{m^3} = \frac{kN \cdot m}{m^3} = \frac{kN}{m^2} = kPa$$

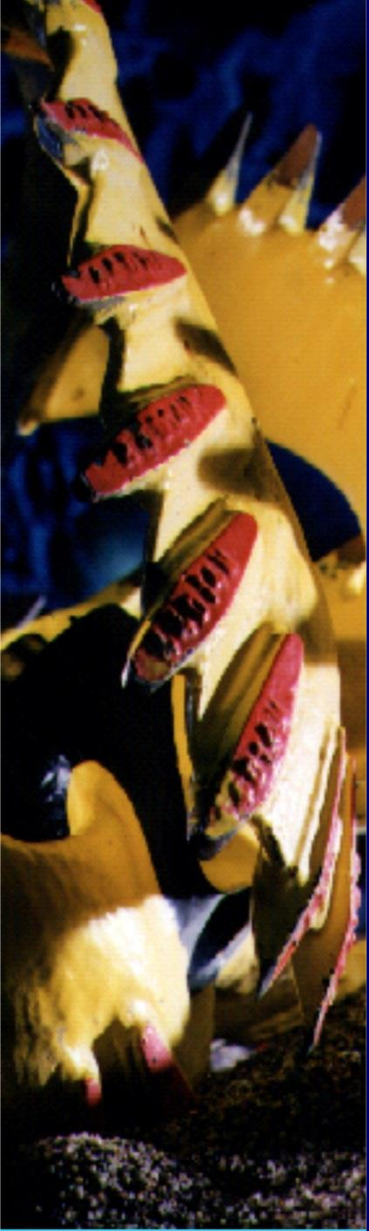


Specific Energy Power Based

$$E_{sp} = \frac{\text{Work / Unit of Time}}{\text{Volume / Unit of Time}} = \frac{\text{Cutting Power}}{\text{Volume Flow}}$$

$$= \frac{\text{Force} \cdot \text{Velocity}}{\text{Volume Flow}} = \frac{F_h \cdot v_c}{h_i \cdot w \cdot v_c} = \frac{F_h}{h_i \cdot w}$$

$$= \frac{kJ/s}{m^3/s} = \frac{kW}{m^3/s} = \frac{kN \cdot m/s}{m^3/s} = \frac{kN}{m^2} = kPa$$



Production Specific Energy Based

$$\text{Production} = \frac{\text{Available Cutting Power}}{\text{Specific Cutting Energy}}$$

$$Q_c = \frac{P_c}{E_{sp}} = \frac{kW}{kPa} = \frac{kN \cdot m/s}{kN/m^2} = \frac{m^3}{s}$$

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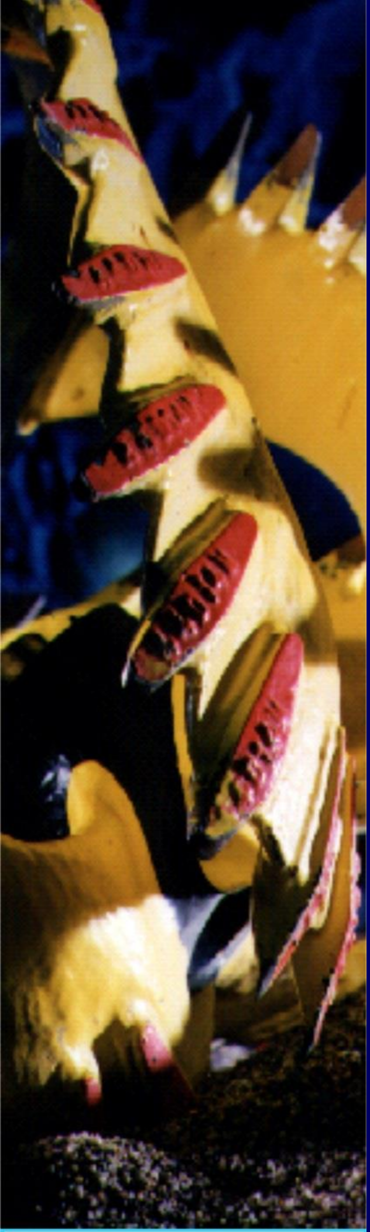

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Introduction Soil Mechanics

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Sand

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Sand, Gobi Dessert

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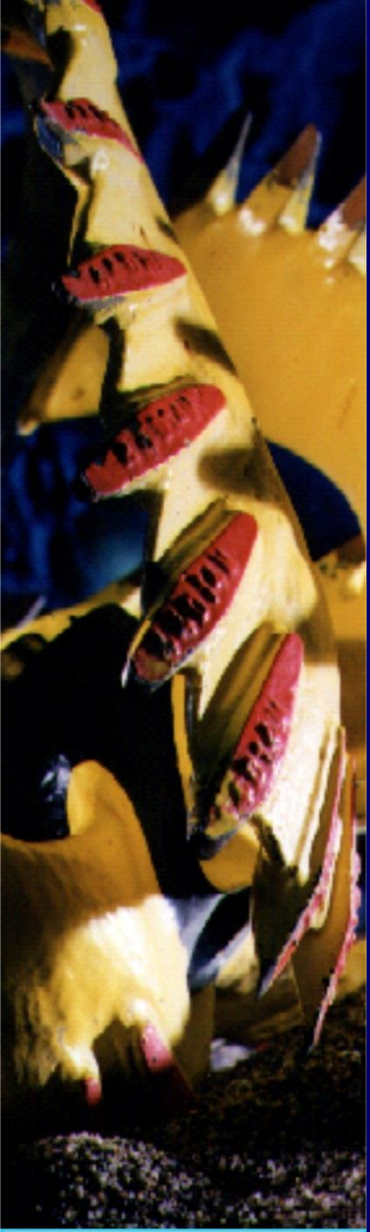
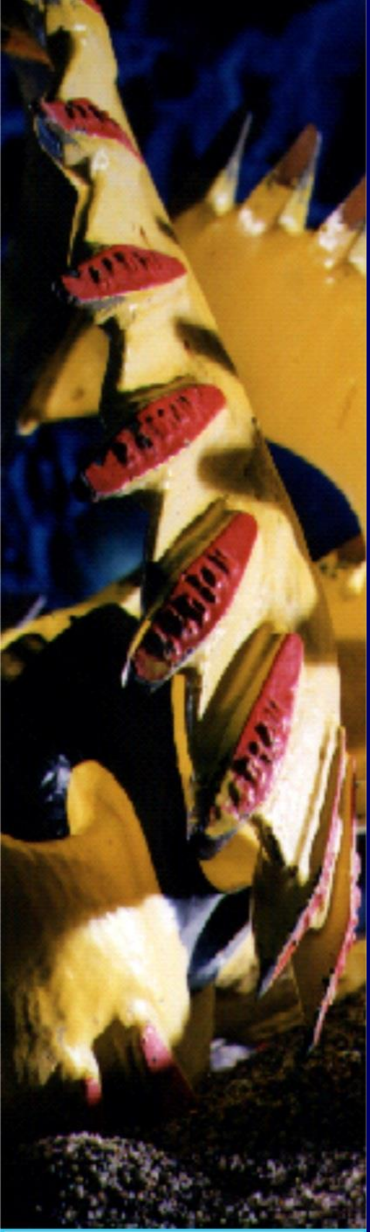
Clay

Quaternary Clay in Estonia





Rock

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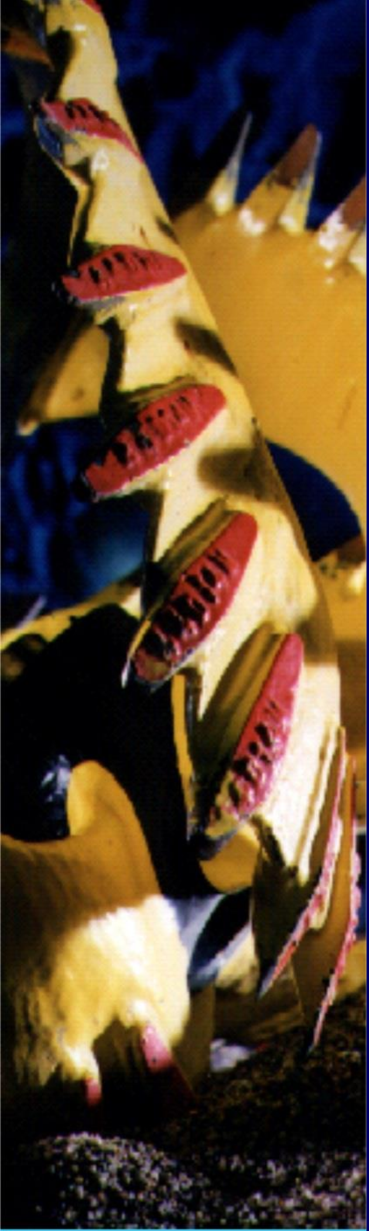

Utica Shale, Fort Plain, New York

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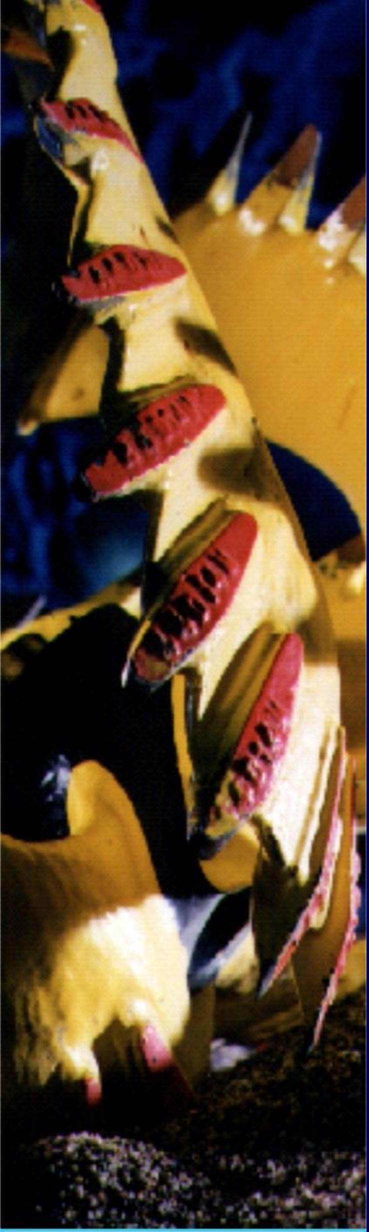

Soil Mechanical Parameters

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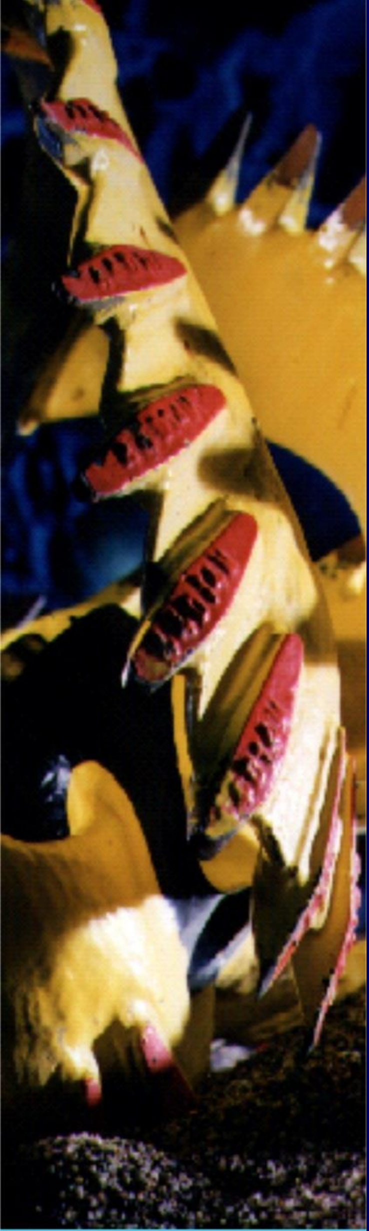
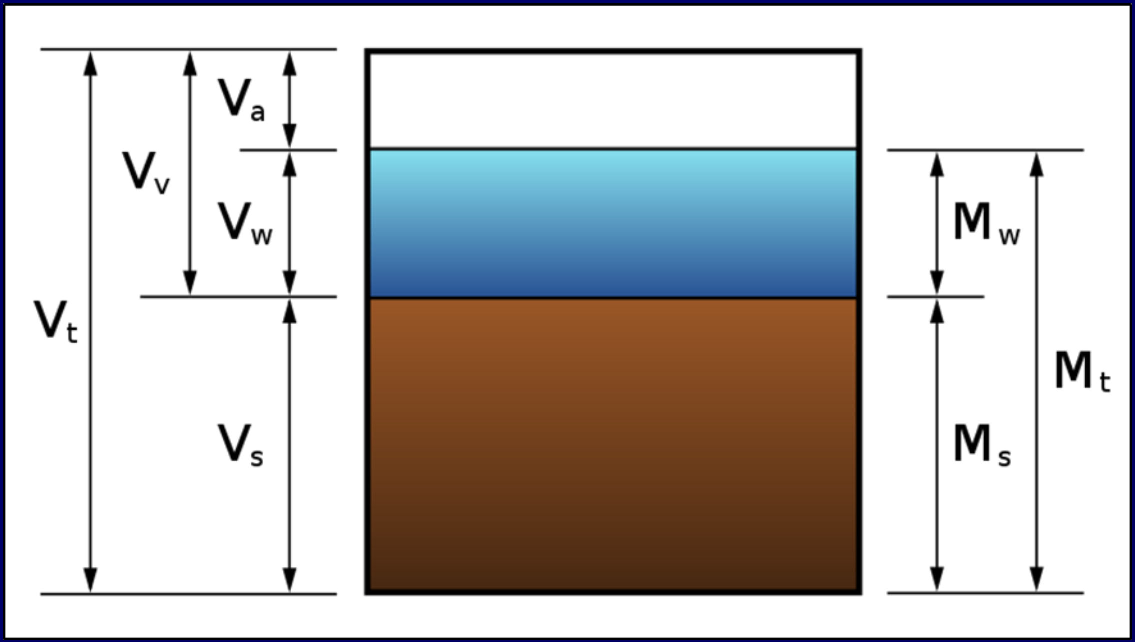


Mass Volume Relations



Density Solids
Porosity
Bulk Density

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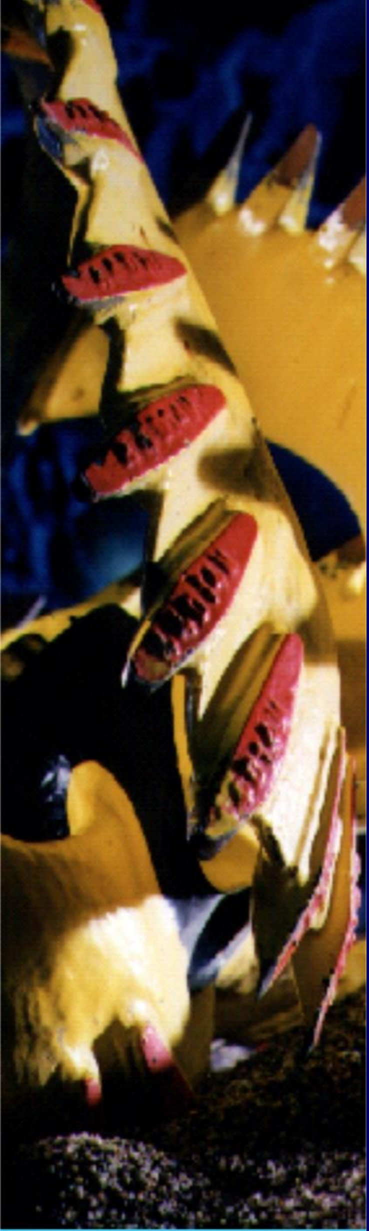
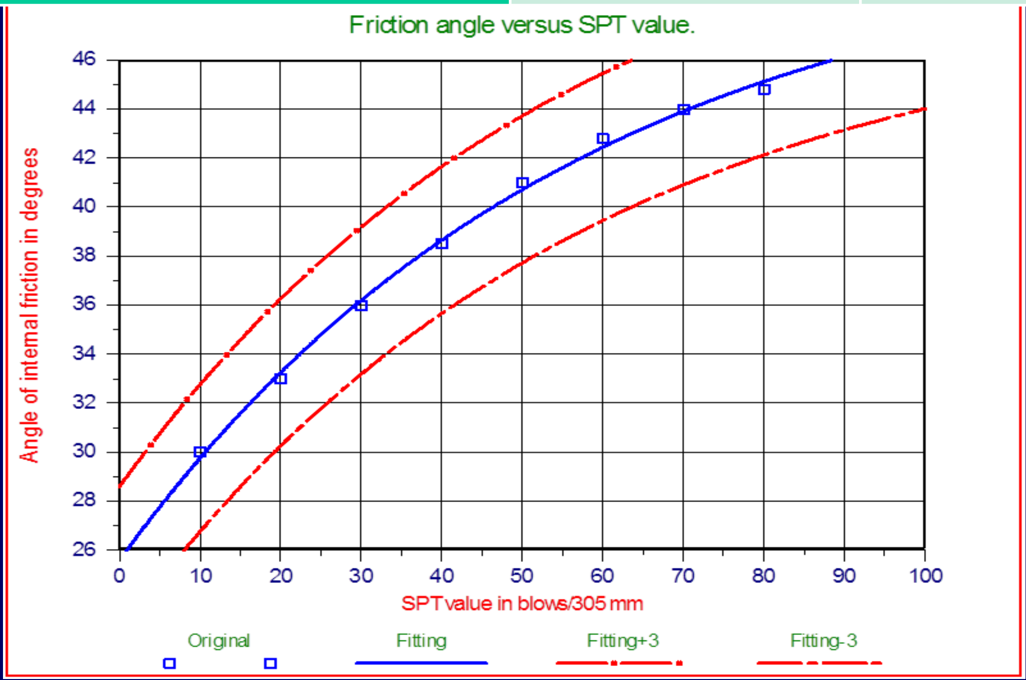


Angle of Internal Friction

SPT Penetration, N-Value (blows/ foot)	Density of Sand	φ (degrees)
<4	Very loose	<29
4 - 10	Loose	29 - 30
10 - 30	Medium	30 - 36
30 - 50	Dense	36 - 41
>50	Very dense	>41



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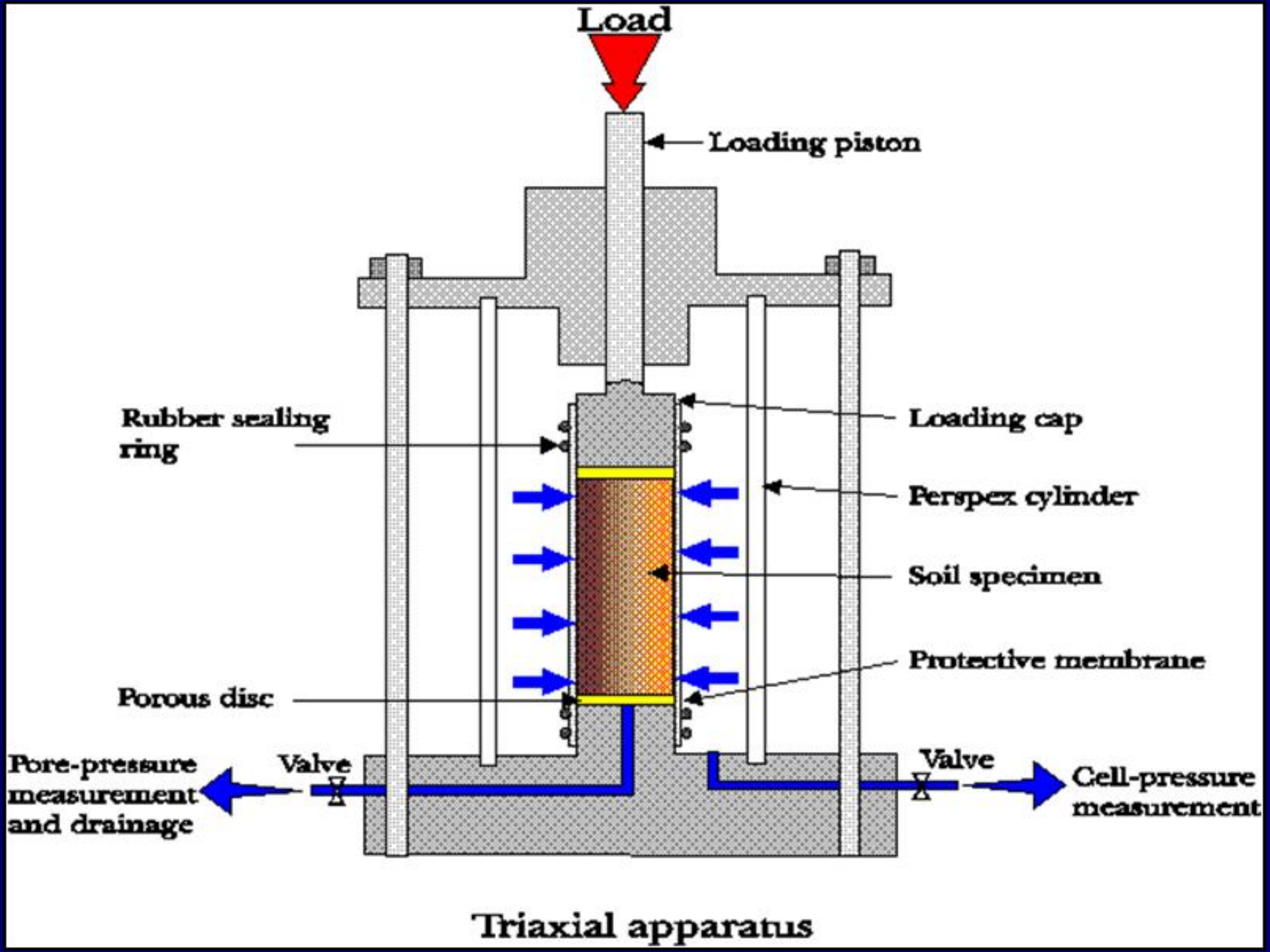
Tri-axial Test



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Angle of External Friction

20°	steel piles (NAVFAC)
$0.67 \cdot \varphi - 0.83 \cdot \varphi$	USACE
20°	steel (Broms)
$\frac{3}{4} \cdot \varphi$	concrete (Broms)
$\frac{2}{3} \cdot \varphi$	timber (Broms)
$0.67 \cdot \varphi$	Lindeburg
$\frac{2}{3} \cdot \varphi$	for concrete walls (Coulomb)

Cohesion/Adhesion

SPT Penetration (blows/ foot)	Estimated Consistency	U.C.S.(kPa)
<2	Very Soft	<24
2 - 4	Soft	24 - 48
4 - 8	Medium	48 - 96
8 - 15	Stiff	96 – 192
15 - 30	Very Stiff	192 – 388
>30	Hard	>388

Permeability

k (cm/s)	10^2	10^1	$10^0=1$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
k (ft/day)	10^5	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}
Relative Permeability	Pervious				Semi-Pervious				Impervious				
Aquifer	Good					Poor				None			
Unconsolidated Sand & Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam							
Unconsolidated Clay & Organic					Peat		Layered Clay			Fat / Unweathered Clay			
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	

Permeability	Pervious				Semi-Pervious				Impervious				
Unconsolidated Sand & Gravel	Well Sorted Gravel		Well Sorted Sand or Sand & Gravel			Very Fine Sand, Silt, Loess, Loam							
Unconsolidated Clay & Organic					Peat		Layered Clay			Unweathered Clay			
Consolidated Rocks	Highly Fractured Rocks				Oil Reservoir Rocks			Fresh Sandstone		Fresh Limestone, Dolomite		Fresh Granite	
K (cm^2)	0.001	0.0001	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}	10^{-13}	10^{-14}	10^{-15}
K (millidarcy)	10^{+8}	10^{+7}	10^{+6}	10^{+5}	10,000	1,000	100	10	1	0.1	0.01	0.001	0.0001

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Unconfined Compressive Stress

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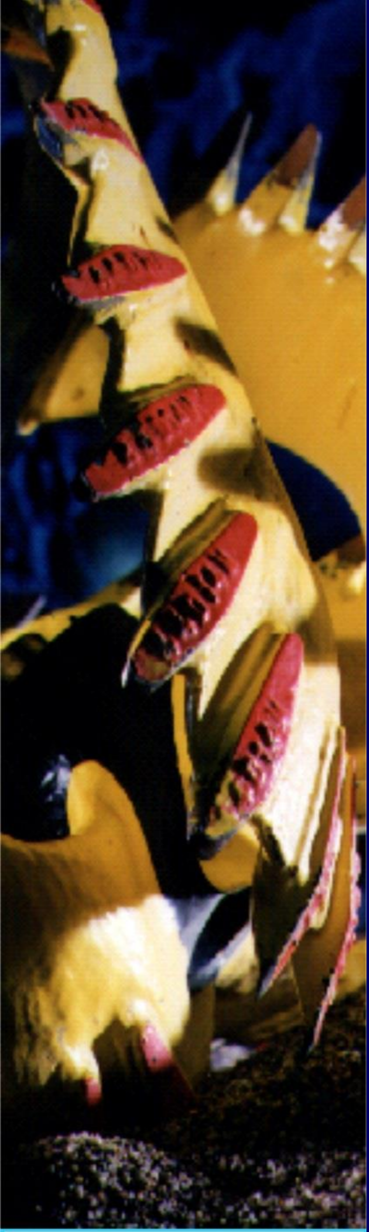
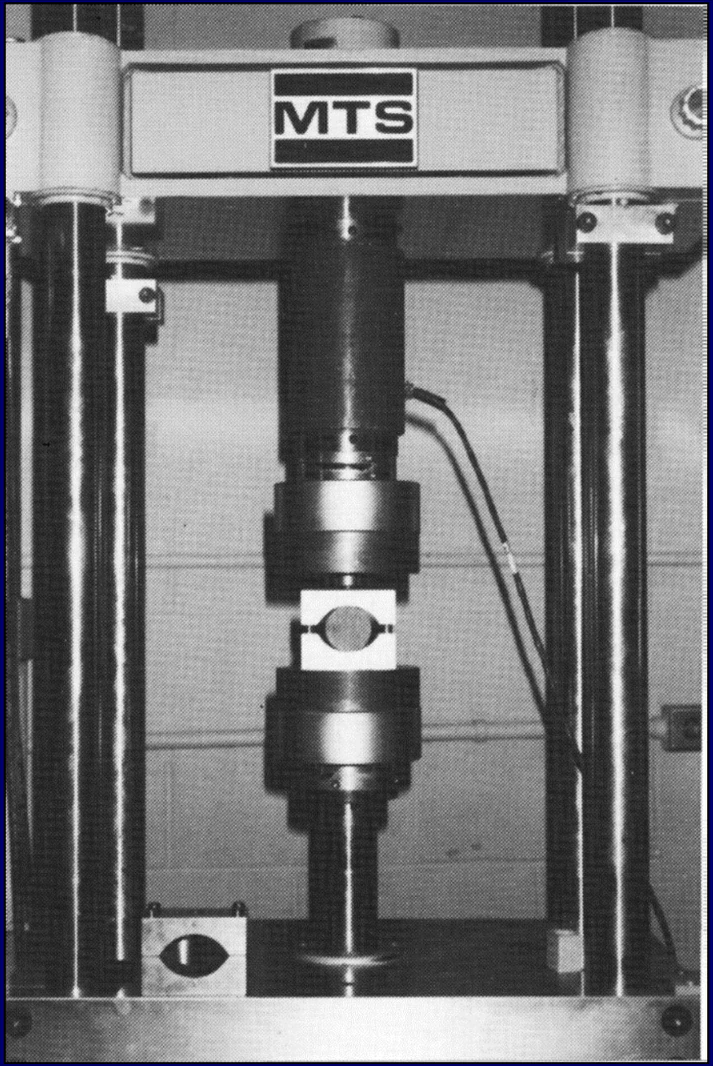
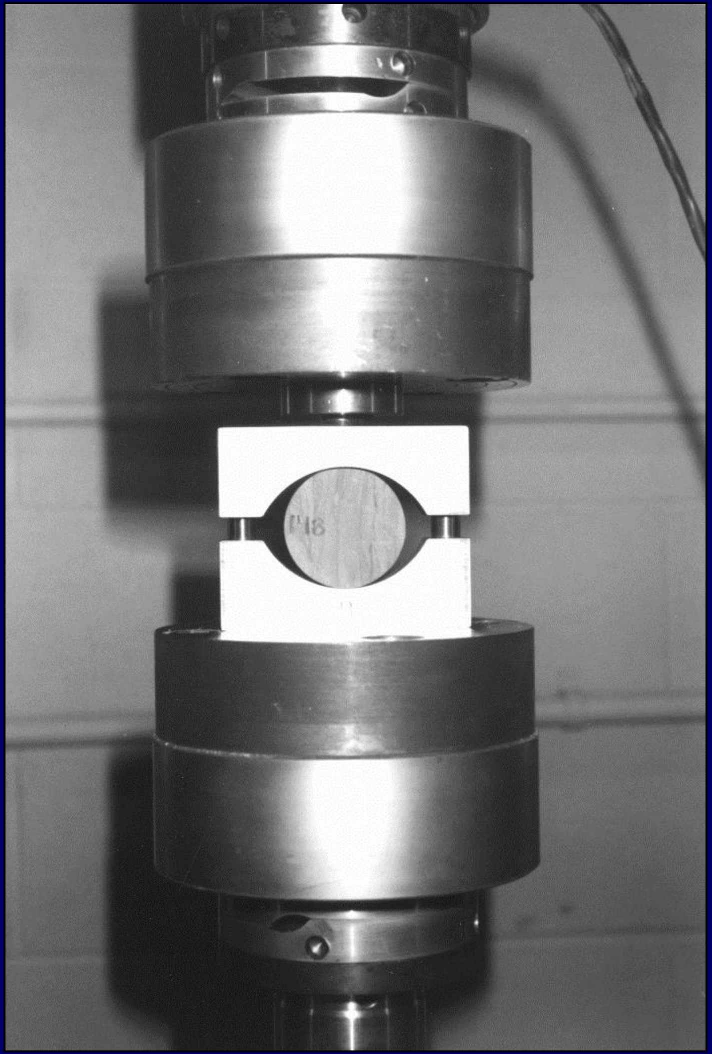
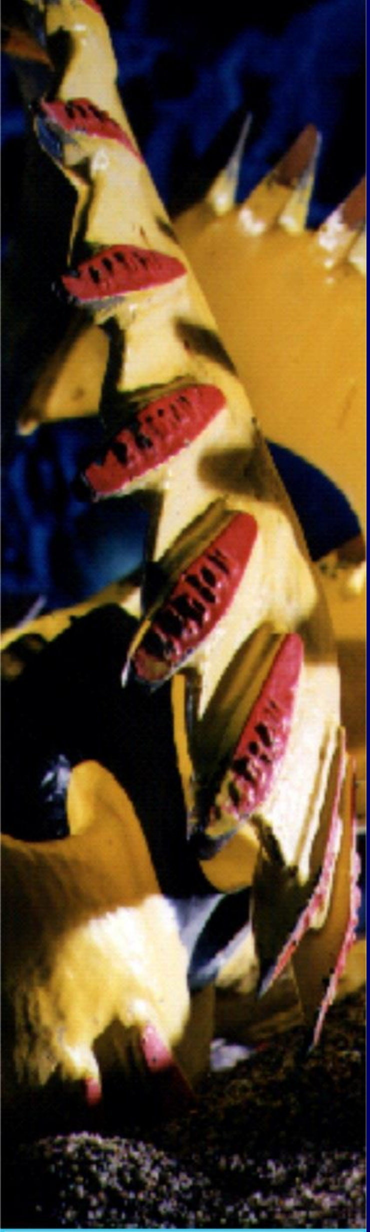


The BTS Test







Cutting Forces
Generic Model

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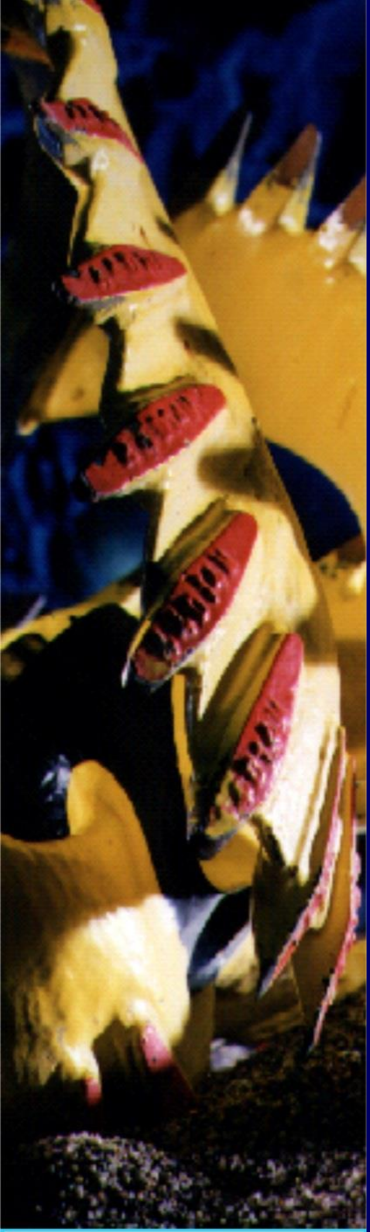
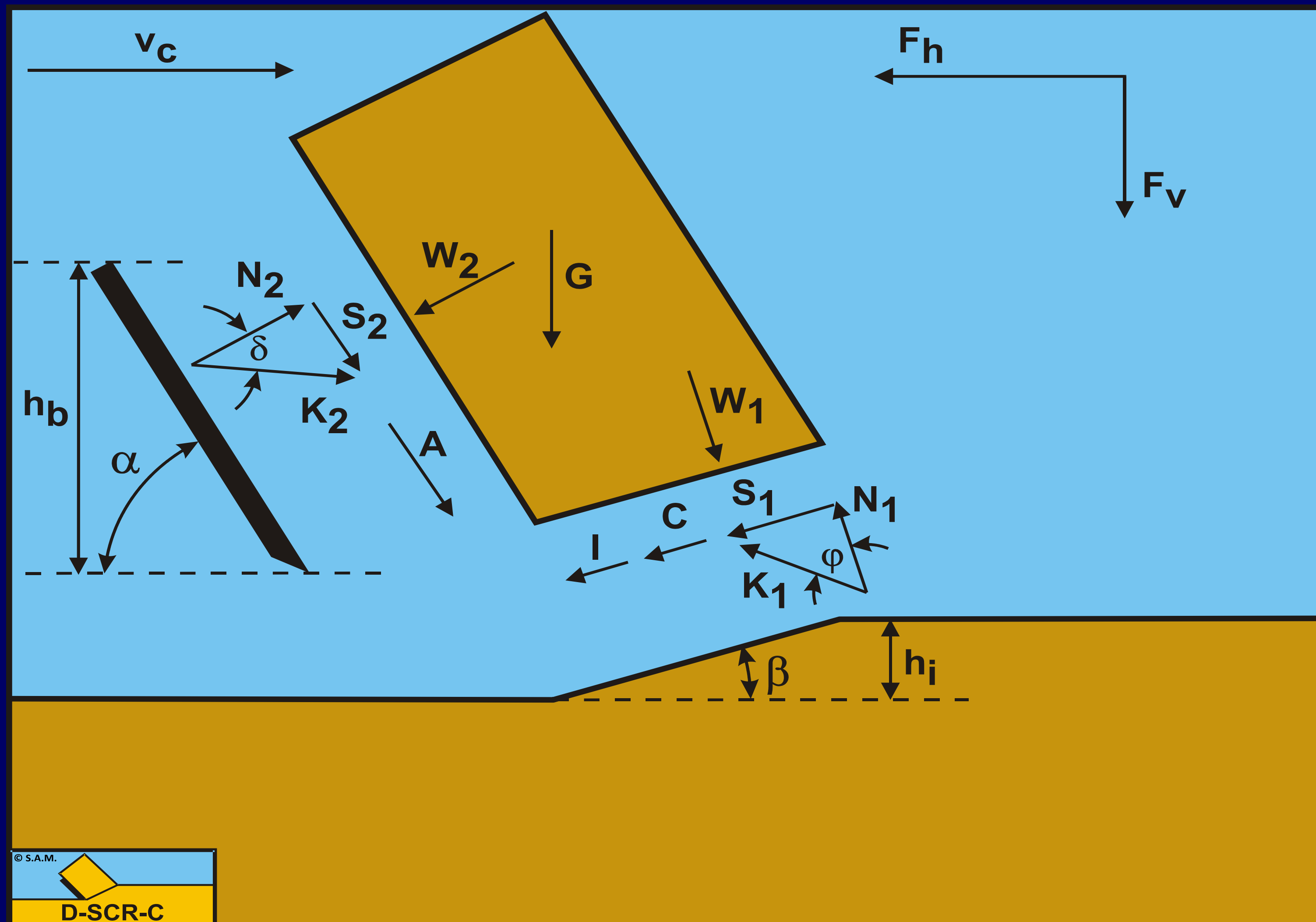


Forces on the Layer Cut

- G: Gravity Force – Weight of the Soil Cut
- I: Inertial Force – Acceleration Force
- N: Normal Force Resulting from Normal Stress
- S: Friction Force Resulting from Frictional Stress
- K: Vectorial Sum Normal Force + Friction Force
- C: Cohesive Force Resulting from Shear Strength
- A: Adhesive Force Resulting from Sticky Effect
- W: Pore Pressure Force Resulting from Pore Pressures

Forces on the Layer Cut



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Resulting Equations

$$K_2 = \frac{W_2 \cdot \sin(\alpha + \beta + \varphi) + W_1 \cdot \sin(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$+ \frac{G \cdot \sin(\beta + \varphi) + I \cdot \cos(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$+ \frac{C \cdot \cos(\varphi) - A \cdot \cos(\alpha + \beta + \varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$F_h = -W_2 \cdot \sin(\alpha) + K_2 \cdot \sin(\alpha + \delta) + A \cdot \cos(\alpha)$$

$$F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta) - A \cdot \sin(\alpha)$$

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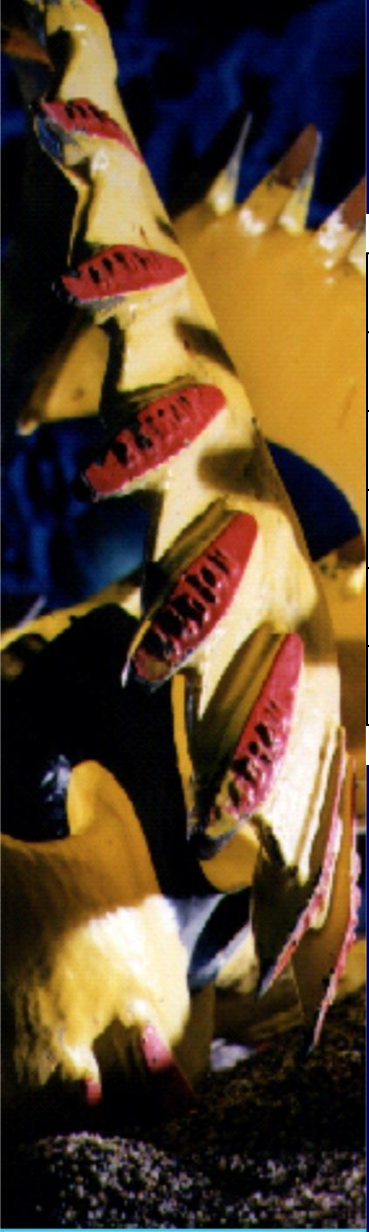
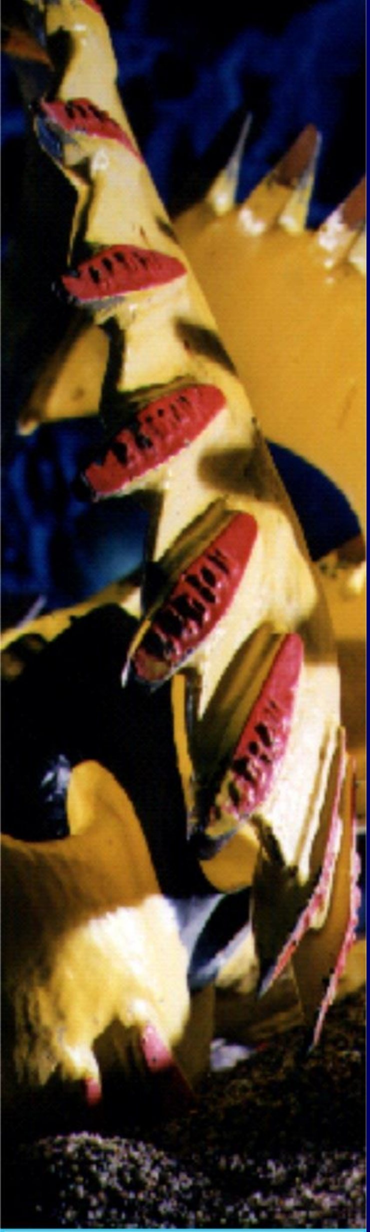


Which Terms in Which Soil

	Gravity	Inertia	Pore Pressure	Cohesion	Adhesion	Friction
Dry sand						
Saturated sand						
Clay						
Atmospheric rock						
Hyperbaric rock						



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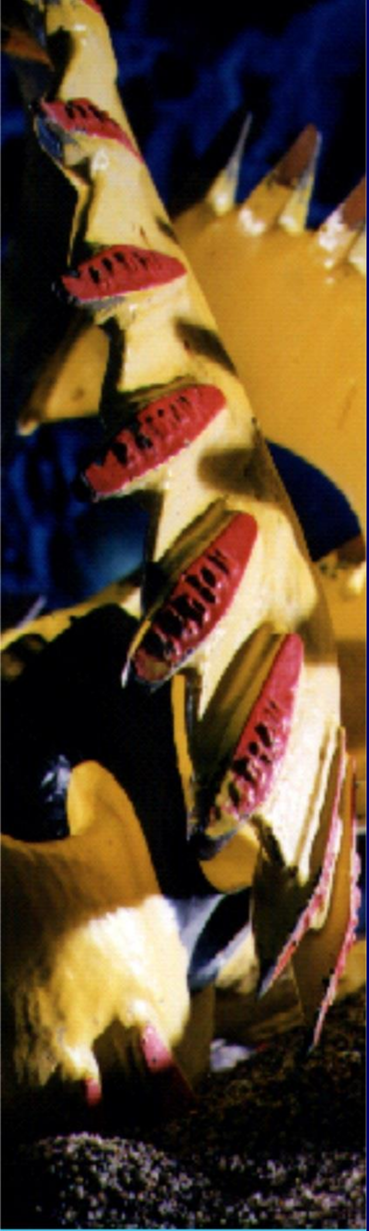
Saturated Sand



Saturated Sand Resulting Equations

$$K_2 = \frac{W_2 \cdot \sin(\alpha + \beta + \varphi) + W_1 \cdot \sin(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$F_h = -W_2 \cdot \sin(\alpha) + K_2 \cdot \sin(\alpha + \delta)$$

$$F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta)$$

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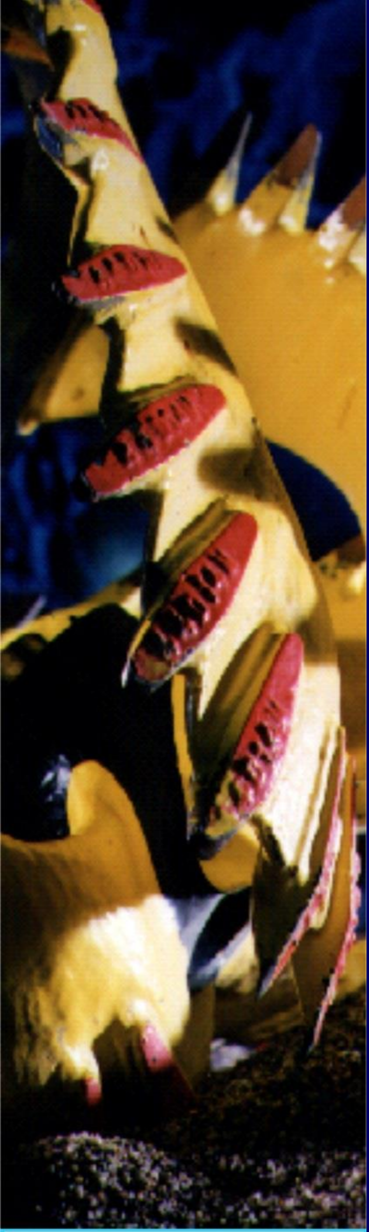
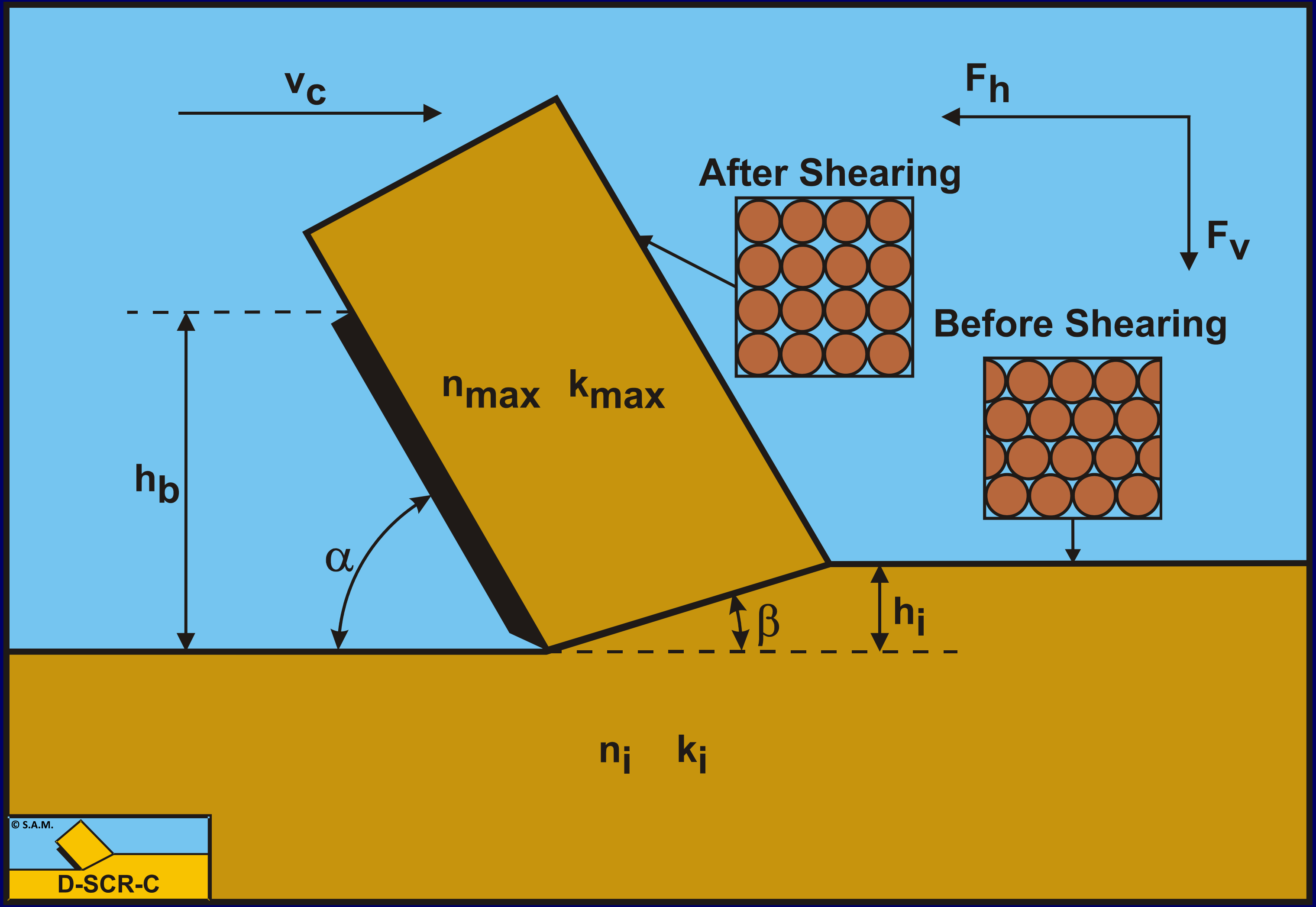
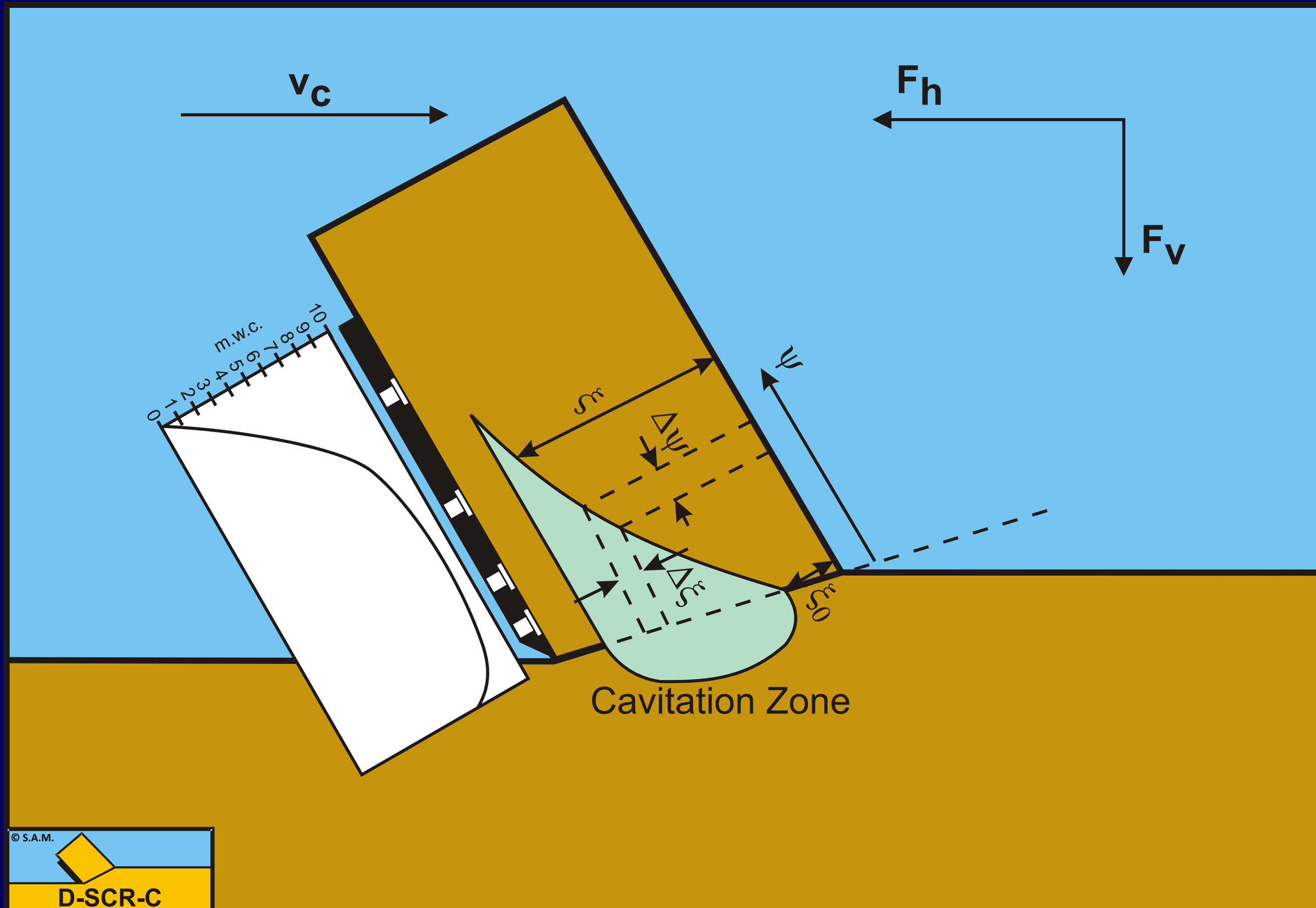
Saturated Sand Dilatation

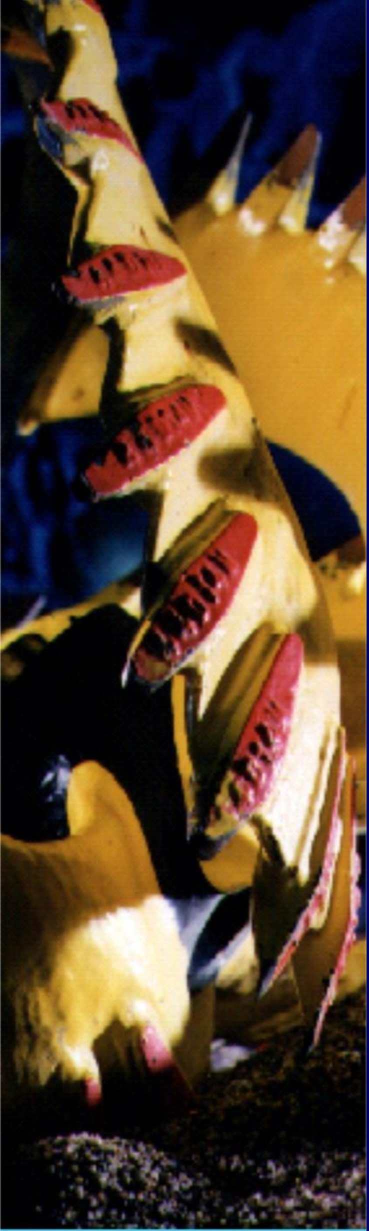




Cavitation



v_c
F_h
F_v
m.w.c.
0 1 2 3 4 5 6 7 8 9 10
ε
Δψ
ψ
Δε
$ε_0$
Cavitation Zone
© S.A.M.
D-SCR-C



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Saturated Sand Cutting Equations

Non-Cavitating Equations

$$F_h = \frac{c_1 \cdot \rho_w \cdot g \cdot v_c \cdot h_i^2 \cdot w \cdot \varepsilon}{k_m}$$

$$F_v = \frac{c_2 \cdot \rho_w \cdot g \cdot v_c \cdot h_i^2 \cdot w \cdot \varepsilon}{k_m}$$

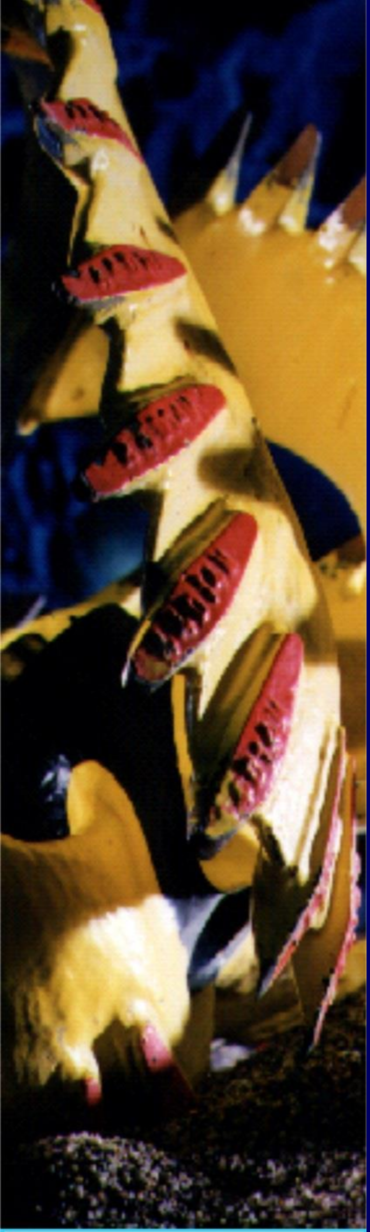
Cavitating Equations

$$F_h = d_1 \cdot \rho_w \cdot g \cdot (z + 10) \cdot h_i \cdot w$$

$$F_v = d_2 \cdot \rho_w \cdot g \cdot (z + 10) \cdot h_i \cdot w$$

Cavitation Transition

$$v_c > \frac{d_1 \cdot (z + 10) \cdot k_m}{c_1 \cdot h_i \cdot \varepsilon} \quad \text{gives cavitation}$$

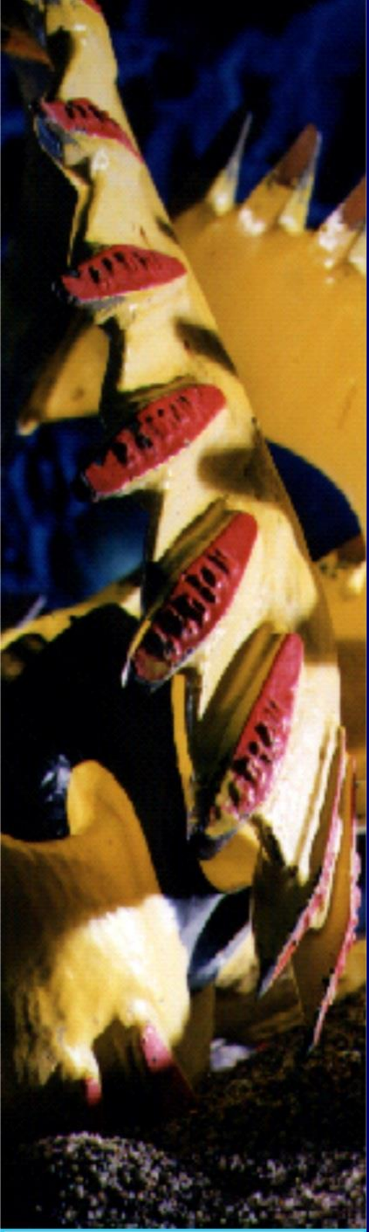


Saturated Sand Specific Energy

$$E_{sp} = \frac{P_c}{Q_c} = \frac{F_h \cdot v_c}{h_i \cdot w \cdot v_c} = d_1 \cdot \rho_w \cdot g \cdot (z + 10)$$

$$Q_c = \frac{P_c}{E_{sp}} = \frac{P_c}{d_1 \cdot \rho_w \cdot g \cdot (z + 10)}$$

Saturated Sand, the Factors c_1, c_2, d_1, d_2



Assuming: $\delta = \frac{2}{3} \cdot \varphi$ and $h_b / h_i = 3$

$$SPT_{10} = \frac{1}{(0.646 + 0.0354 \cdot z)} \cdot SPT_z$$

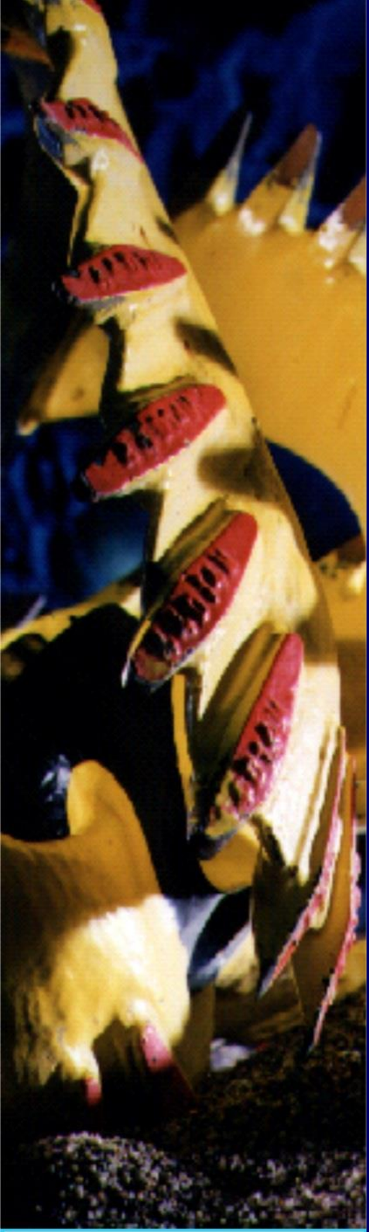
$$\varphi = 51.5 - 25.9 \cdot e^{-0.01753 \cdot SPT_{10}}$$

$$c_1 = 0.0593 \cdot e^{0.0692 \cdot \varphi}$$

$$c_2 = -0.3785 + 0.0250 \cdot \varphi - 0.000445 \cdot \varphi^2$$

$$d_1 = 0.3889 \cdot e^{0.0680 \cdot \varphi}$$

$$d_2 = +1.4708 - 0.0685 \cdot \varphi$$



Example Saturated Sand Cutting

$$d_1 = 0.3889 \cdot e^{0.0680 \cdot \varphi}$$

Suppose $\varphi = 40^\circ \quad \Rightarrow \quad d_1 = 5.9$

$$E_{sp} = 5.9 \cdot \rho_w \cdot g \cdot (z + 10) = 59 \cdot (z + 10)$$

Suppose installed cutter power 2 MW

$$\text{Production at 10 m water depth} = \frac{2000}{59 \cdot (10 + 10)} = 1.69 \ m^3/s$$

$$\text{Production at 30 m water depth} = \frac{2000}{59 \cdot (30 + 10)} = 0.85 \ m^3/s$$

Clay Cutting

Resulting Equations, Clay Cutting

$$K_2 = \frac{C - A \cdot \cos(\alpha + \beta)}{\sin(\alpha + \beta)}$$

$$F_h = K_2 \cdot \sin(\alpha) + A \cdot \cos(\alpha)$$

$$F_v = K_2 \cdot \cos(\alpha) - A \cdot \sin(\alpha)$$

$$C = \frac{c \cdot h_i \cdot w}{\sin(\beta)}$$

$$A = \frac{a \cdot h_b \cdot w}{\sin(\alpha)}$$

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Resulting Equations, Clay Cutting

$$F_h = \left\{ \frac{c_d \cdot h_i}{\sin(\beta) \cdot \sin(\alpha + \beta)} + \frac{a \cdot h_b \cdot \sin(\beta)}{\sin(\alpha) \cdot \sin(\alpha + \beta)} \right\} \cdot w$$

$$k_a = \frac{a_d \cdot h_b}{c_d \cdot h_i}$$

$$F_h = \left\{ \frac{1}{\sin(\beta) \cdot \sin(\alpha + \beta)} + \frac{k_a \cdot \sin(\beta)}{\sin(\alpha) \cdot \sin(\alpha + \beta)} \right\} \cdot c_d \cdot h_i \cdot w$$

Forces in Clay, SPT Relation

$$c_d = c_y + c_0 \cdot \ln\left(1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \approx 2 \cdot c_y$$

$$c_y \approx 6 \cdot SPT \quad \Rightarrow \quad c_d \approx 12 \cdot SPT$$

$$E_{sp} = \frac{F_h \cdot v_c}{h_i \cdot w \cdot v_c}$$

$$Q = \frac{P}{E_{sp}}$$

$$E_{sp} = \left\{ \frac{1}{\sin(\beta) \cdot \sin(\alpha + \beta)} + \frac{k_a \cdot \sin(\beta)}{\sin(\alpha) \cdot \sin(\alpha + \beta)} \right\} \cdot 12 \cdot SPT$$

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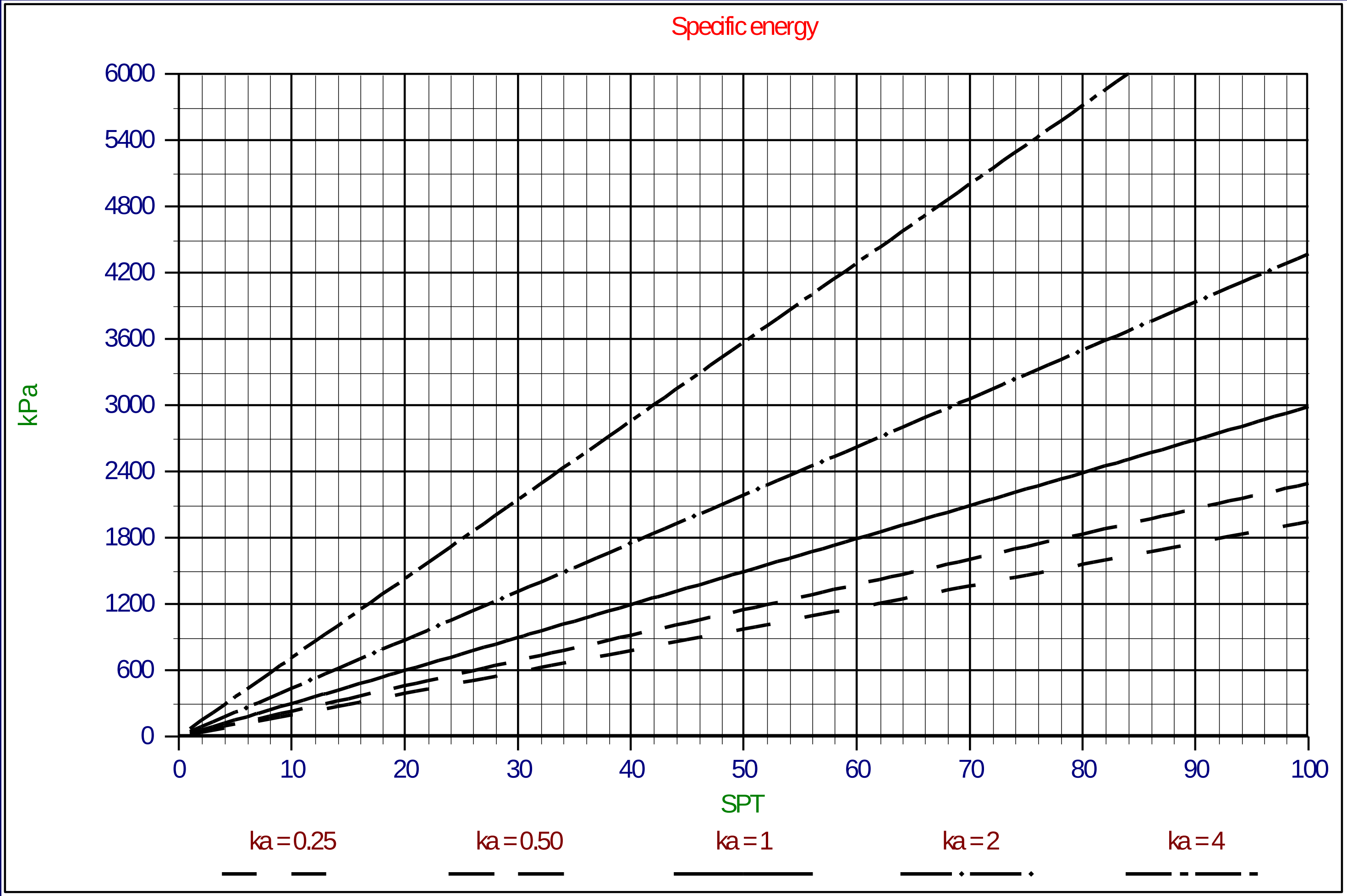
Specific Energy in Clay, 60 Degree Blade



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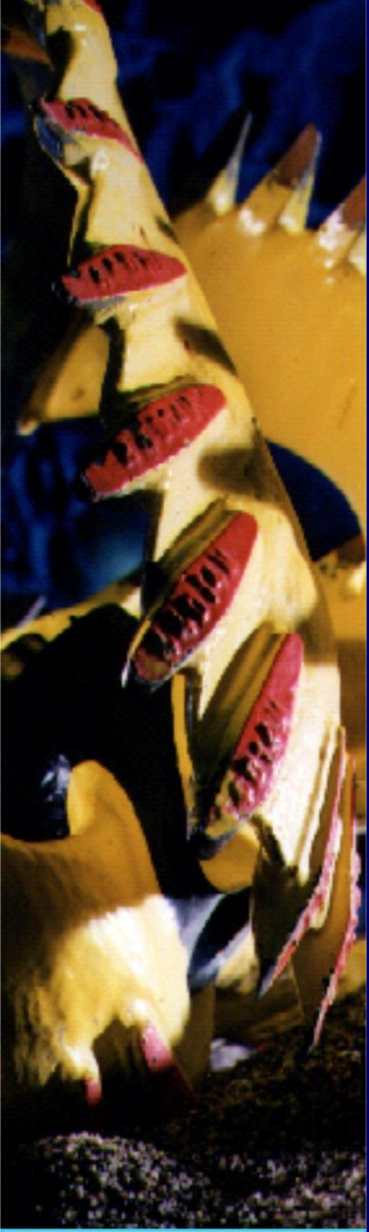

Example Clay Cutting

Suppose cohesion c=60 kPa and adhesion a=40 kPa.

This gives a dynamic cohesion c_d=120 kPa and adhesion a_d=80 kPa.

The blade height h_b and layer thickness h_i are the same.

The k_a factor is 80/120=0.67.

The SPT value is the cohesion divided by 6 giving SPT=10.

Reading from the graph gives a specific energy of about 300 kPa.

This gives a production of 3.33 m^3/s per MW installed power.

Suppose cohesion c=300 kPa and adhesion a=30 kPa.

This gives a dynamic cohesion c_d=600 kPa and adhesion a_d=60 kPa.

The blade height h_b is 2.5 times the layer thickness h_i.

The k_a factor is $60 \cdot 2.5/600=0.25$.

The SPT value is the cohesion divided by 6 giving SPT=50.

Reading from the graph gives a specific energy of about 900 kPa.

This gives a production of 1.11 m^3/s per MW installed power.

Rock Cutting

Resulting Equations

$$K_2 = \frac{C \cdot \cos(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$F_h = K_2 \cdot \sin(\alpha + \delta)$$

$$F_v = K_2 \cdot \cos(\alpha + \delta)$$

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Hyperbaric Rock Cutting

Resulting Equations

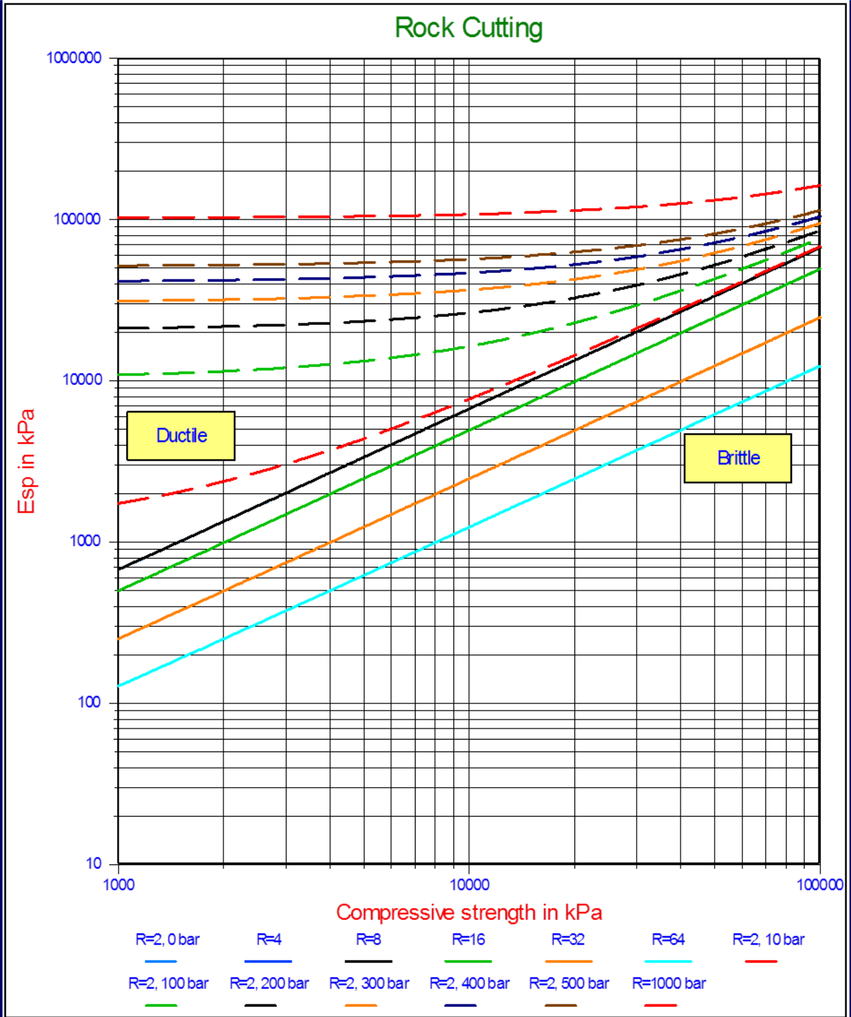
$$K_2 = \frac{W_2 \cdot \sin(\alpha + \beta + \varphi) + W_1 \cdot \sin(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$+ \frac{C \cdot \cos(\varphi)}{\sin(\alpha + \beta + \delta + \varphi)}$$

$$F_h = -W_2 \cdot \sin(\alpha) + K_2 \cdot \sin(\alpha + \delta)$$

$$F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta)$$

Specific Energy 60 Degrees



The specific energy Esp as a function of the compressive strength of rock, for different ratio's between the compressive strength and the tensile strength. For a 60 degree blade.

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Example Rock Cutting

Suppose a rock with UCS=20 MPa.

Atmospheric rock cutting:

If the BTS (tensile strength) is small, for example 1 MPa

the cutting process is brittle tensile giving a specific energy of 2.5-5 MPa.

This gives a production of 0.2-0.4 m^3/s per MW installed cutter power.

If the tensile strength is high, for example 5 MPa

the cutting process is brittle shear giving a specific energy of 10 MPa.

This gives a production of 0.1 m^3/s per MW installed cutter power.

Hyperbaric rock cutting:

The tensile strength does not play a role, only the water depth.

At a waterdepth of 1000 m the specific energy is about 20 MPa.

This gives a production of 0.05 m^3/s per MW installed cutter power.

At a waterdepth of 2000 m the specific energy is about 30 MPa.

This gives a production of 0.033 m^3/s per MW installed cutter power.

Limitations

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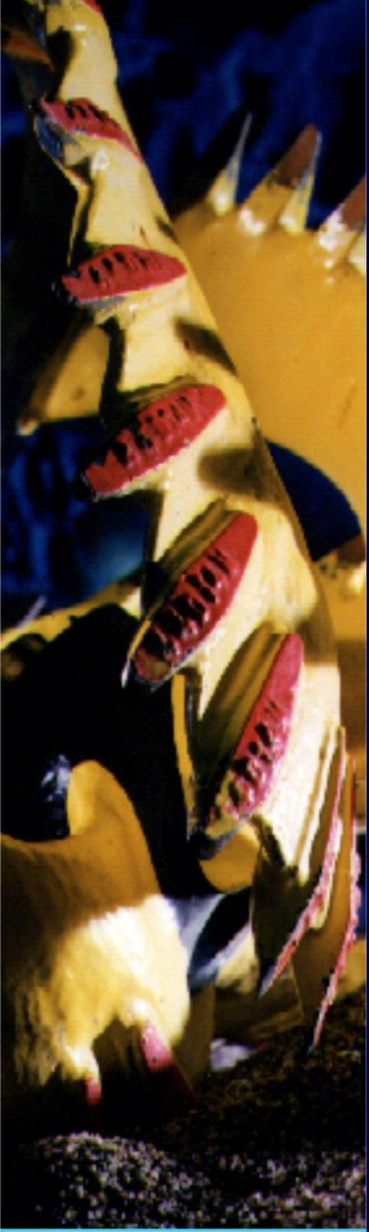

Limitations of the Method

- The production determined is only based on the available cutting power.

- The production has to fit through/in the cutting device, for example the cutterhead, the draghead, the clamshell, the backhoe, etc.
- The required forces/power have/has to be available, for example the swing winch forces/power (CSD) or the propulsion power (TSHD).
- The production determined has to match the slurry transport in case of a CSD or TSHD.

Conclusions

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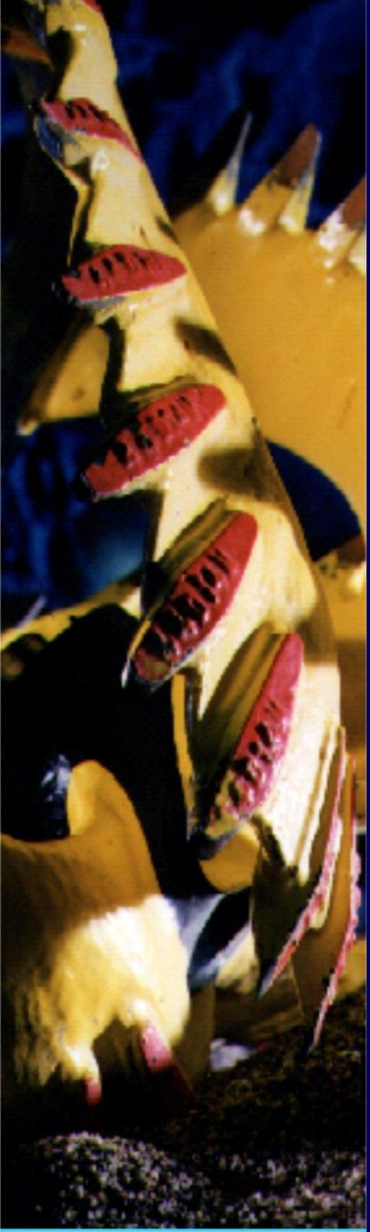
Conclusions

- The specific energy is a convinient tool to determine the dredging production.
- However there are some limitations to this method.
- If there is a limitation to the production because of other reasons, this limitation should be applied.



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Questions?