DSCRC Model Production Estimating based on Specific Energy

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

Delft University of Technology
Dredging A Way Of Life

Delft University of Technology – Offshore & Dredging Engineering
Sape A. Miedema

THE DELFT SAND, CLAY & ROCK CUTTING MODEL

3rd Edition
Cutting of Soil in Dredging
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
Definitions 2D Cutting Process

- $v_c$
- $F_h$
- $F_v$
- $h_b$
- $h_i$
- $\alpha$
- $\beta$
Specific Energy Work Based

\[ E_{sp} = \frac{\text{Work}}{\text{Volume}} = \frac{\text{Force} \cdot \text{Distance}}{\text{Volume}} \]

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

\[ = \frac{kJ}{m^3} = \frac{kN \cdot m}{m^3} = \frac{kN}{m^2} = kPa \]
Specific Energy Power Based

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

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

\[
= \frac{kJ}{s} = \frac{KW}{m^3/s} = \frac{kN \cdot m}{s} = \frac{kN}{m^2} = kPa
\]
Production Specific Energy Based

Production = \frac{Available\ Cutting\ Power}{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}
Introduction

Soil Mechanics

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Sand
Sand, Gobi Dessert
Quaternary Clay in Estonia

Faculty of 3mE - Dredging Engineering
Rock
Utica Shale, Fort Plain, New York
Soil Mechanical Parameters
Mass Volume Relations

Density Solids
Porosity
Bulk Density

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# Angle of Internal Friction

<table>
<thead>
<tr>
<th>SPT Penetration, N-Value (blows/foot)</th>
<th>Density of Sand</th>
<th>$\phi$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>Very loose</td>
<td>&lt;29</td>
</tr>
<tr>
<td>4 - 10</td>
<td>Loose</td>
<td>29 - 30</td>
</tr>
<tr>
<td>10 - 30</td>
<td>Medium</td>
<td>30 - 36</td>
</tr>
<tr>
<td>30 - 50</td>
<td>Dense</td>
<td>36 - 41</td>
</tr>
<tr>
<td>&gt;50</td>
<td>Very dense</td>
<td>&gt;41</td>
</tr>
</tbody>
</table>

![Friction angle versus SPT value graph](image-url)

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Tri-axial Test

Triaxial apparatus

- Loading piston
- Loading cap
- Perspex cylinder
- Soil specimen
- Protective membrane
- Rubber sealing ring
- Porous disc
- Pore-pressure measurement and drainage
- Valve
- Cell-pressure measurement
## Angle of External Friction

<table>
<thead>
<tr>
<th>Angle</th>
<th>Material Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$20^\circ$</td>
<td>steel piles (NAVFAC)</td>
<td>USACE</td>
</tr>
<tr>
<td>$0.67 \cdot \phi - 0.83 \cdot \phi$</td>
<td>USACE</td>
<td>steel (Broms)</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>steel (Broms)</td>
<td>concrete (Broms)</td>
</tr>
<tr>
<td>$\frac{3}{4} \cdot \phi$</td>
<td>concrete (Broms)</td>
<td>timber (Broms)</td>
</tr>
<tr>
<td>$\frac{2}{3} \cdot \phi$</td>
<td>Lindeburg</td>
<td></td>
</tr>
<tr>
<td>$0.67 \cdot \phi$</td>
<td>Lindeburg</td>
<td></td>
</tr>
<tr>
<td>$\frac{2}{3} \cdot \phi$</td>
<td>for concrete walls (Coulomb)</td>
<td></td>
</tr>
</tbody>
</table>
# Cohesion/Adhesion

<table>
<thead>
<tr>
<th>SPT Penetration (blows/foot)</th>
<th>Estimated Consistency</th>
<th>U.C.S. (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;2</td>
<td>Very Soft</td>
<td>&lt;24</td>
</tr>
<tr>
<td>2 - 4</td>
<td>Soft</td>
<td>24 - 48</td>
</tr>
<tr>
<td>4 - 8</td>
<td>Medium</td>
<td>48 - 96</td>
</tr>
<tr>
<td>8 - 15</td>
<td>Stiff</td>
<td>96 – 192</td>
</tr>
<tr>
<td>15 - 30</td>
<td>Very Stiff</td>
<td>192 – 388</td>
</tr>
<tr>
<td>&gt;30</td>
<td>Hard</td>
<td>&gt;388</td>
</tr>
</tbody>
</table>
# Permeability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pervious</th>
<th>Semi-Pervious</th>
<th>Impervious</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ (cm/s)</td>
<td>$10^2$ $10^1$</td>
<td>$10^0-1$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>$k$ (ft/day)</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Relative Permeability</td>
<td>Good</td>
<td>Semi-Pervious</td>
<td>Impervious</td>
</tr>
<tr>
<td>Aquifer</td>
<td>Well Sorted Gravel</td>
<td>Well Sorted Sand or Sand &amp; Gravel</td>
<td>Very Fine Sand, Silt, Loess, Loam</td>
</tr>
<tr>
<td>Unconsolidated Sand &amp; Gravel</td>
<td>Peat</td>
<td>Layered Clay</td>
<td>Fat / Unweathered Clay</td>
</tr>
<tr>
<td>Unconsolidated Clay &amp; Organic</td>
<td>Fresh Sandstone</td>
<td>Fresh Limestone, Dolomite</td>
<td>Fresh Granite</td>
</tr>
<tr>
<td>Consolidated Rocks</td>
<td>Highly Fractured Rocks</td>
<td>Oil Reservoir Rocks</td>
<td>Impervious</td>
</tr>
</tbody>
</table>

## Permeability

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pervious</th>
<th>Semi-Pervious</th>
<th>Impervious</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$ (cm$^2$)</td>
<td>$0.001$ $0.0001$</td>
<td>$10^{-5}$ $10^{-6}$</td>
<td>$10^{-7}$ $10^{-8}$</td>
</tr>
<tr>
<td>$K$ (millidarcy)</td>
<td>$10^{-8}$ $10^{-7}$</td>
<td>$10^{-6}$ $10^{-5}$</td>
<td>$10^{-4}$ $10^{-5}$</td>
</tr>
</tbody>
</table>
Unconfined Compressive Stress

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Cutting Forces
Generic Model
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

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

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

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

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

\[
F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta) - A \cdot \sin(\alpha)
\]
## Which Terms in Which Soil

<table>
<thead>
<tr>
<th></th>
<th>Gravity</th>
<th>Inertia</th>
<th>Pore Pressure</th>
<th>Cohesion</th>
<th>Adhesion</th>
<th>Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturated sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperbaric rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Saturated Sand
Saturated Sand Resulting Equations

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

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

\[
F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta)
\]
Saturated Sand Dilatation

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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 \( \varphi = 40^\circ \) \( \Rightarrow \) \( d_1 = 5.9 \)

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

Suppose installed cutter power 2 MW

Production at 10 m water depth = \( \frac{2000}{59 \cdot (10 + 10)} \) = 1.69 m³ / s

Production at 30 m water depth = \( \frac{2000}{59 \cdot (30 + 10)} \) = 0.85 m³ / s
Clay Cutting
Resulting Equations, Clay Cutting

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

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

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

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

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

\[ c_d = c_y + c_0 \cdot \ln \left( 1 + \frac{\varepsilon}{\varepsilon_0} \right) \approx 2 \cdot c_y \]

\[ c_y \approx 6 \cdot \text{SPT} \quad \Rightarrow \quad c_d \approx 12 \cdot \text{SPT} \]

\[ E_{sp} = \frac{F_h \cdot v_c}{h_i \cdot w \cdot v_c} \quad \quad \quad Q = \frac{P}{E_{sp}} \]

\[ E_{sp} = \left\{ \frac{1}{\sin (\beta) \cdot \sin (\alpha + \beta)} + \frac{k_a \cdot \sin (\beta)}{\sin (\alpha) \cdot \sin (\alpha + \beta)} \right\} \cdot 12 \cdot \text{SPT} \]
Specific Energy in Clay, 60 Degree Blade

![Graph showing specific energy in clay with different ka values](image-url)

- ka = 0.25
- ka = 0.50
- ka = 1
- ka = 2
- ka = 4

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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 $3.33 \text{ m}^3 / \text{s per MW installed power}$.

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 $1.11 \text{ m}^3 / \text{s per MW installed power}$.
Rock Cutting
Resulting Equations

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

\[ F_h = K_2 \cdot \sin(\alpha + \delta) \]

\[ F_v = K_2 \cdot \cos(\alpha + \delta) \]
Hyperbaric Rock Cutting
Resulting Equations

\[ K_2 = \frac{W_2 \cdot \sin(\alpha + \beta + \phi) + W_1 \cdot \sin(\phi)}{\sin(\alpha + \beta + \delta + \phi)} \]

\[ + \frac{C \cdot \cos(\phi)}{\sin(\alpha + \beta + \delta + \phi)} \]

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

\[ F_v = -W_2 \cdot \cos(\alpha) + K_2 \cdot \cos(\alpha + \delta) \]
Specific Energy 60 Degrees

The specific energy $E_{sp}$ as a function of the compressive strength of rock, for different ratios between the compressive strength and the tensile strength. For a 60 degree blade.
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 m³/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 m³/s per MW installed cutter power.

Hyperbaric rock cutting:
The tensile strength does not play a role, only the water depth. At a water depth of 1000 m the specific energy is about 20 MPa. This gives a production of 0.05 m³/s per MW installed cutter power. At a water depth of 2000 m the specific energy is about 30 MPa. This gives a production of 0.033 m³/s per MW installed cutter power.
Limitations
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
Conclusions

- The specific energy is a convenient 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.
Questions?