Scour Protection
Rock Dumping

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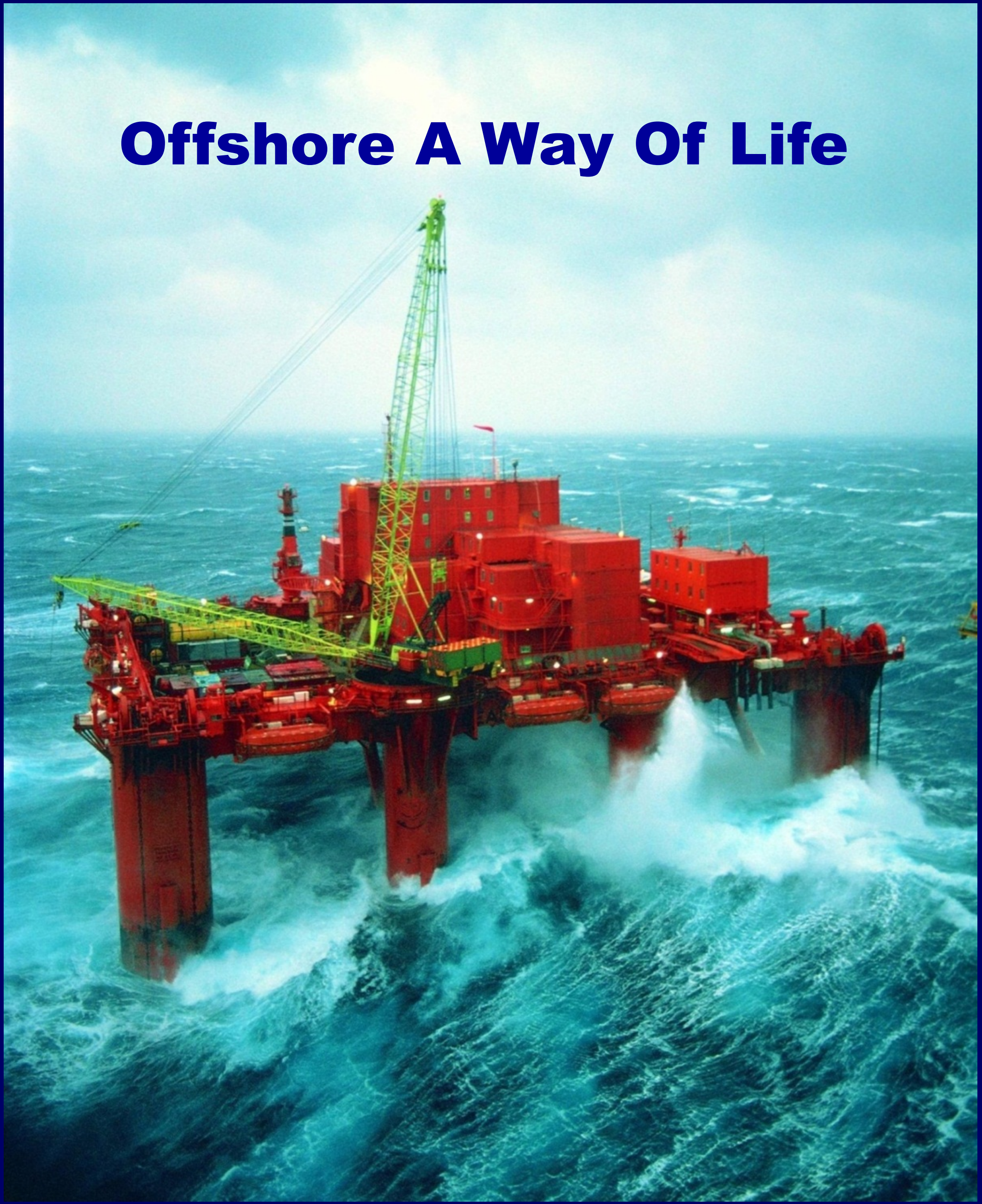

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What is Offshore & Dredging Engineering?

Offshore & Dredging Engineering covers everything at sea that does not have the purpose of transporting goods & people and no fishery.

Problem Statement

During rock dumping to protect monopiles from scour, the pieces of rock will penetrate the seafloor.

- What should be the size of the rock pieces.
- Which volume of rock will penetrate the sea floor.

An Offshore Wind Farm

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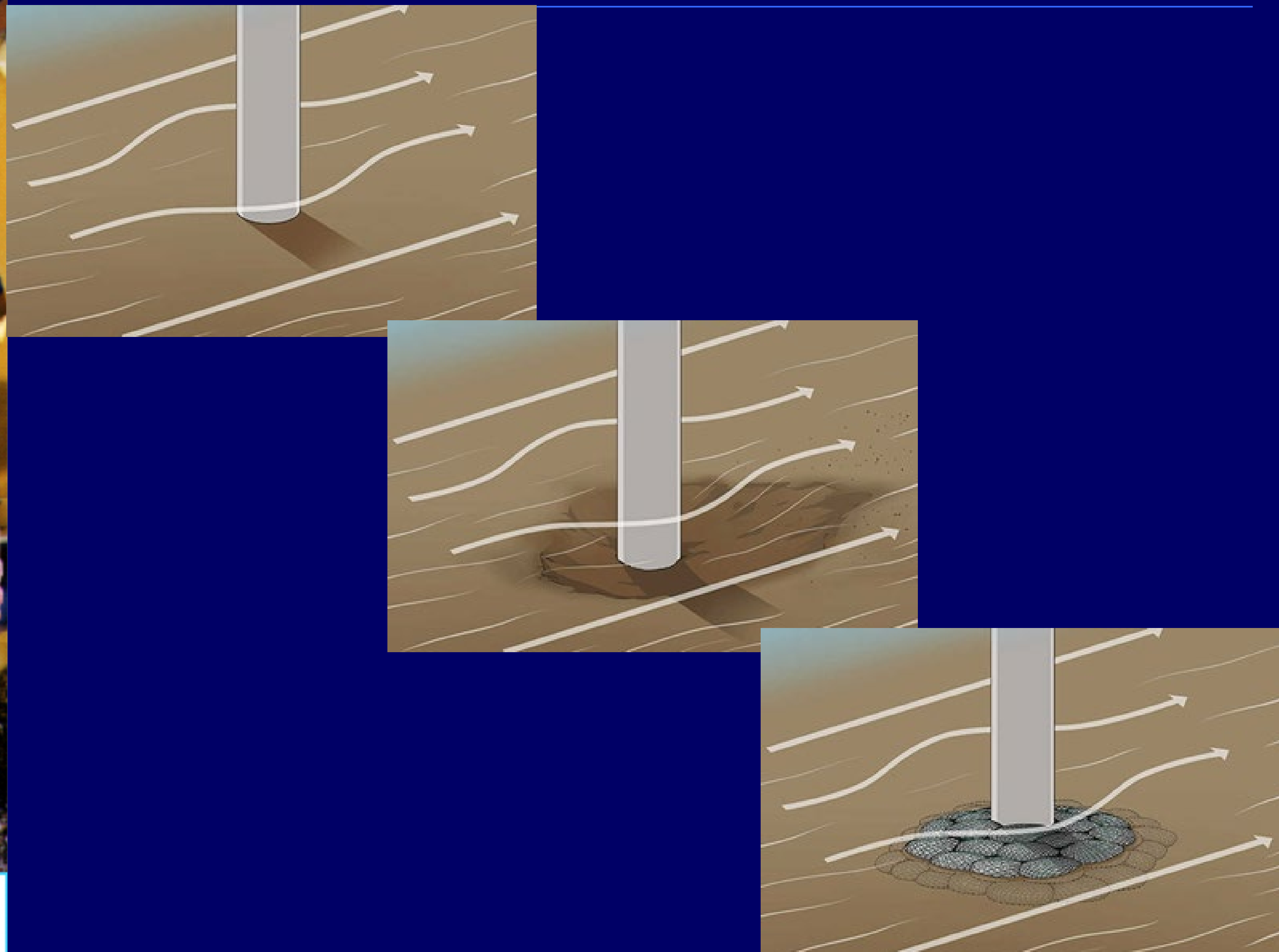
Reference

Beemsterboer, T. N. (2013). *Modelling the immediate penetration of rock particles in soft clay during subsea rock installation, using a flexible fallpipe vessel.* Delft, the Netherlands: Delft University of Technology.

Scour & Scour Protection



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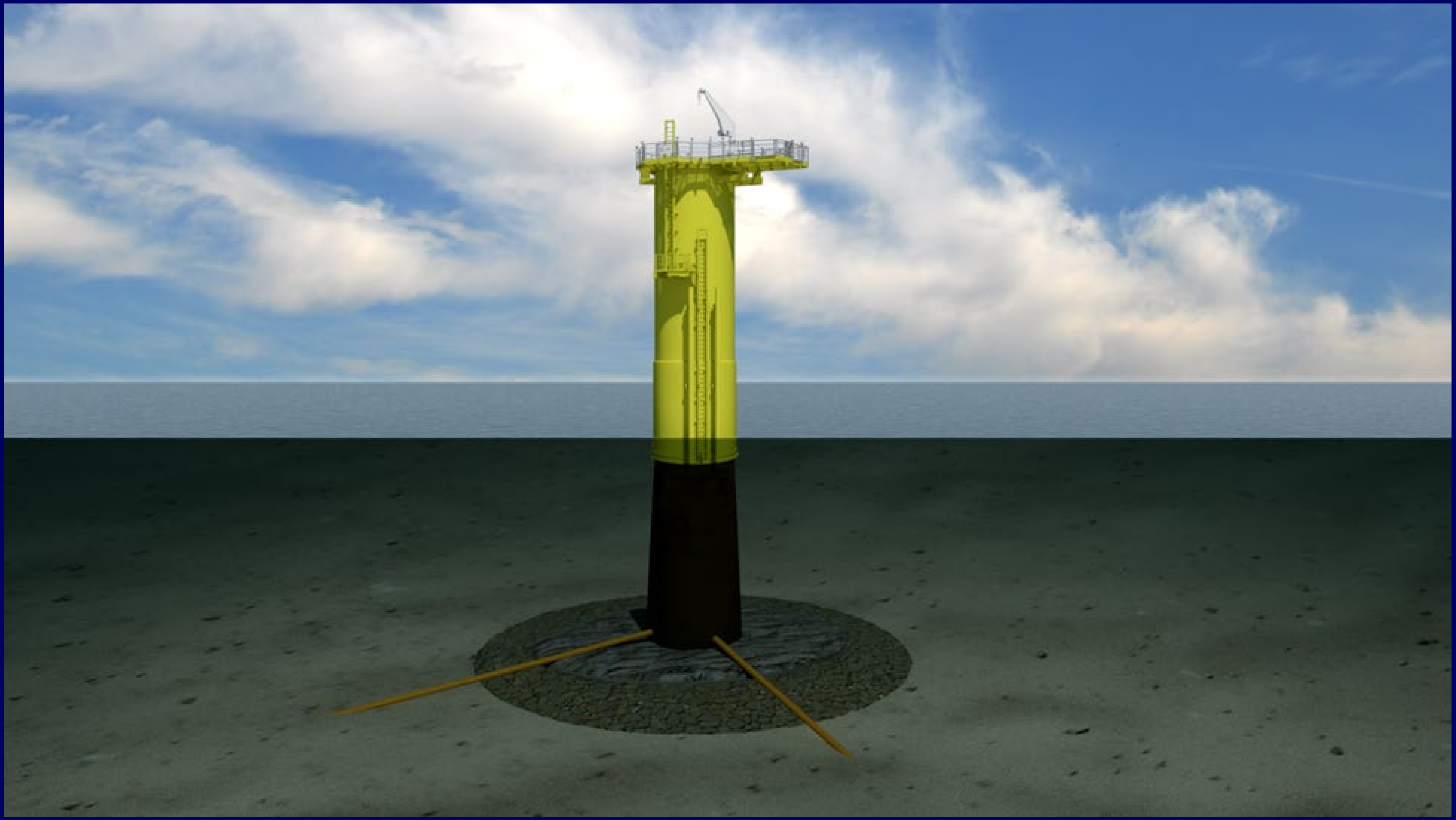
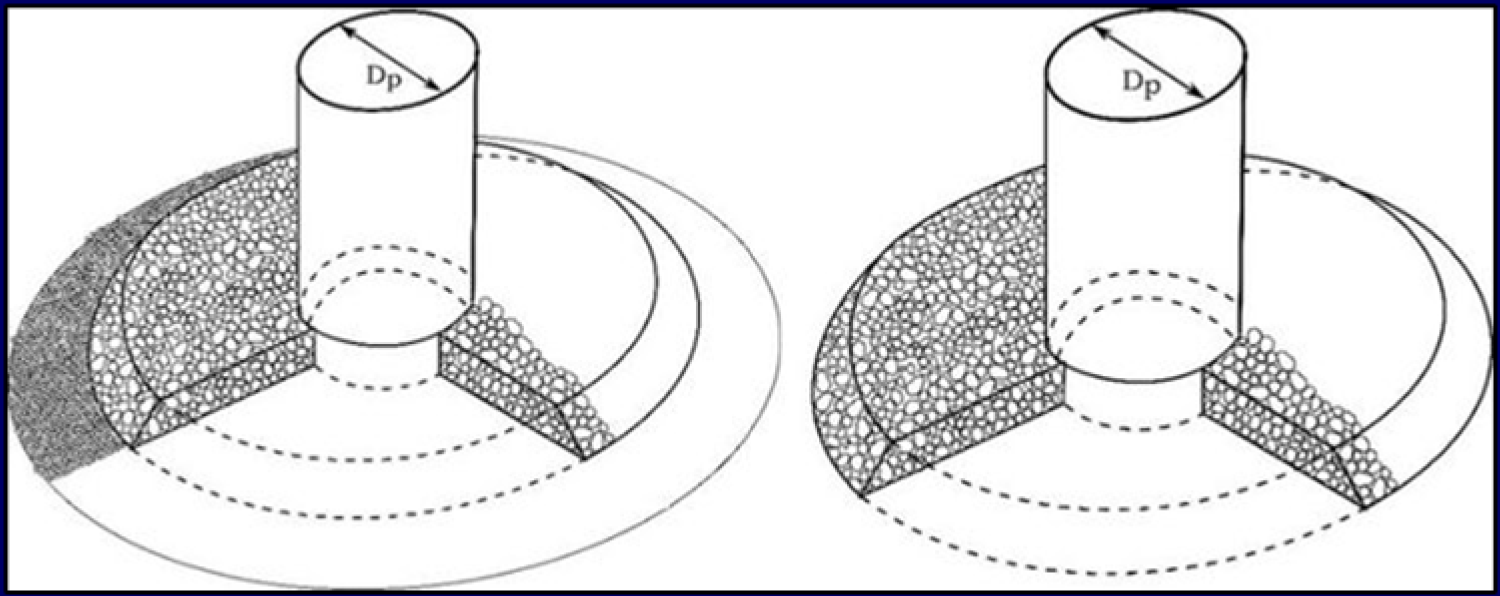
A Monopile with Scour Protection



Scour Protection

With and without filter layer

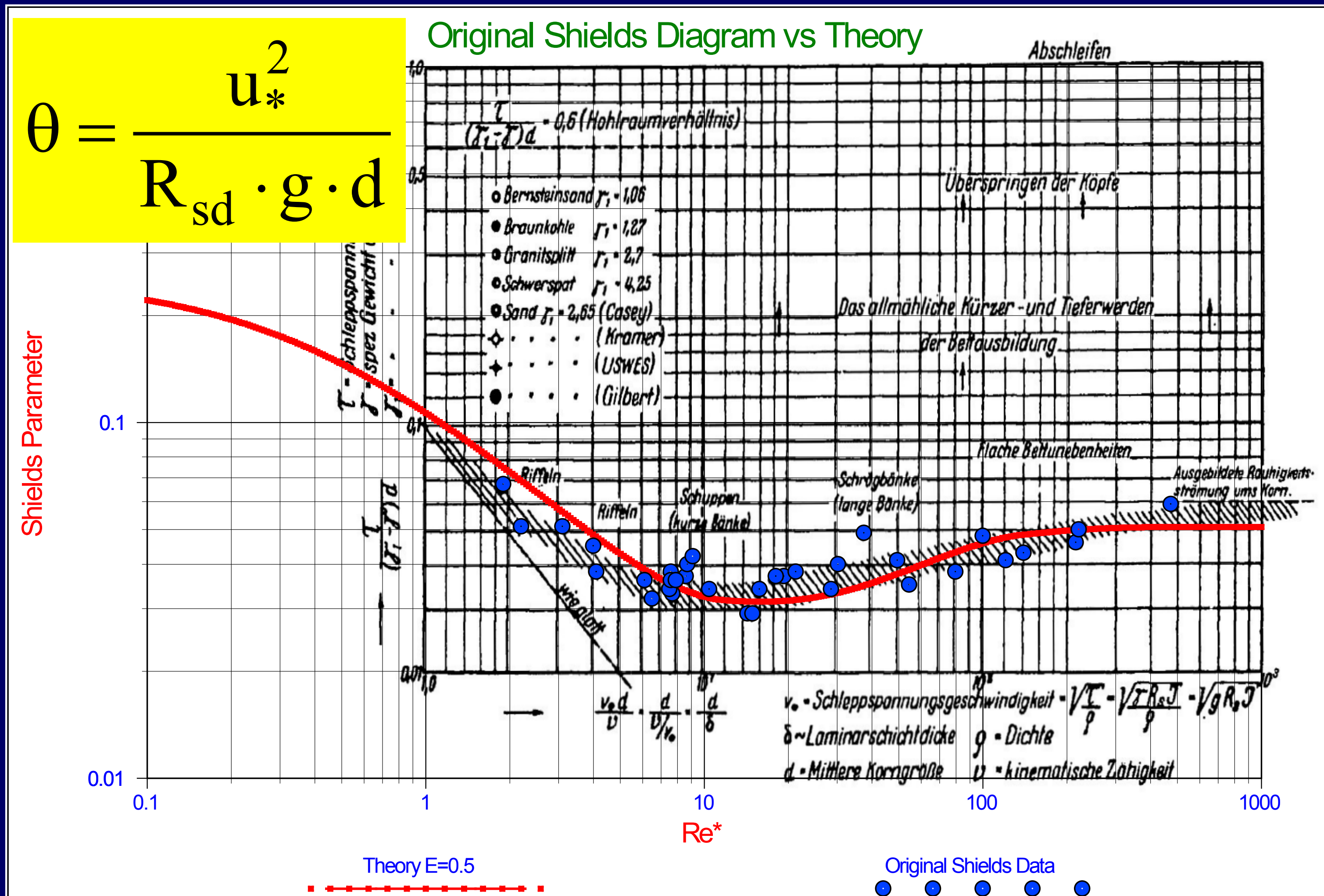


Some Examples

Characteristics	Arklow Bank	Egmond aan Zee	Horns Rev	Princess Amalia	Scroby Sands
Mean sea level (m)	8	20	14	24	12
Foundation diameter (m)	5.0	4.6	4.2	4.0	4.2
Driving length of pile	35	30	34	30	30
Soil type	Sand	Sand	Sand	Sand	Sand
Soil d_{50} (mm)	0.20	0.20	0.15	0.45	0.40
Filter d_{50} (m)	0.05	0.05	0.20	0.17	0.15
Filter thickness (m)	0.60	0.40	1.00	0.90	1.00
Filter layer diameter (m)	45	53	44	52	54
Armor d_{50} (m)	0.42	0.40	0.55	0.50	0..45
Armor thickness (m)	1.20	1.80	1.80	1.50	1.300
Armor layer diameter (m)	35	41	34	40	34
Significant wave height (m)	5.6	3.6	5.2	7.7	3.2
Wave peak period (s)	9	8	6.3	9.7	8.1
Current velocity (m/s)	2.0	0.6	1.2	1.3	1.7
Orbital velocity bottom (m/s)	2.7	0.7	1.2	1.6	1.1
Relative roughness (-)	0.05	0.02	0.04	0.02	0.04

The original Shields diagram

$$\theta = \frac{u_*^2}{R_{sd} \cdot g \cdot d}$$



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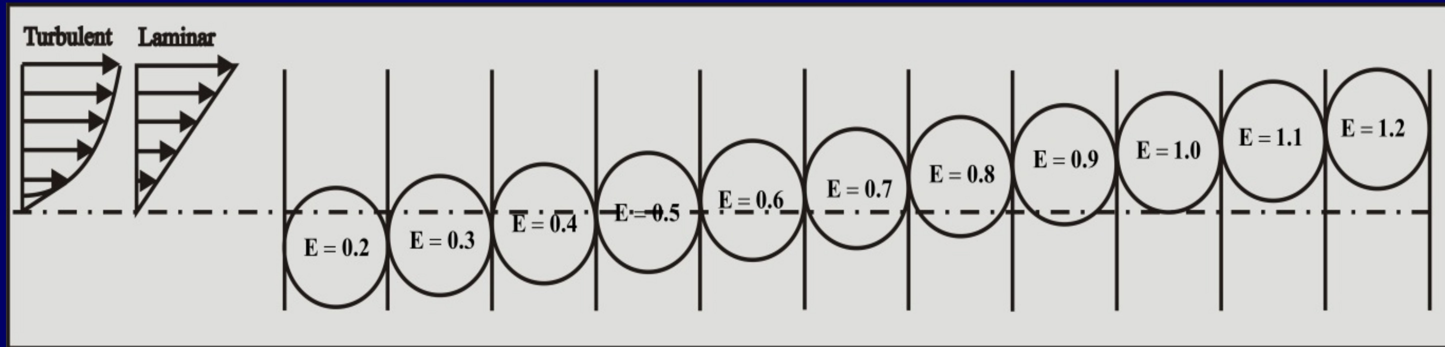
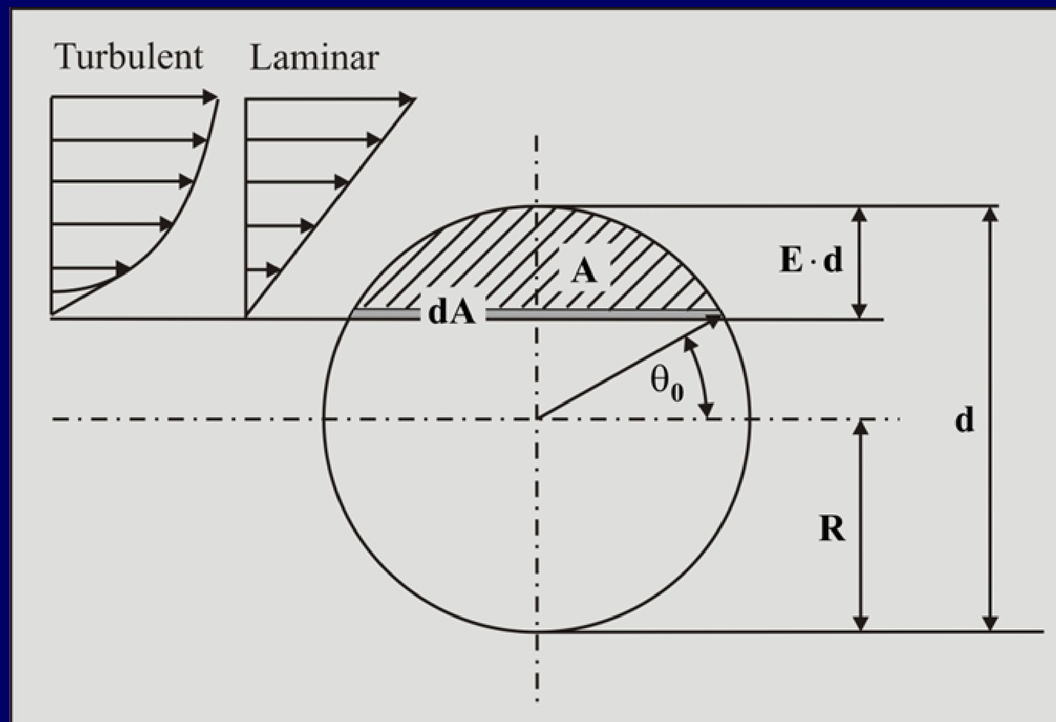
Exposure Levels - Protrusion Levels





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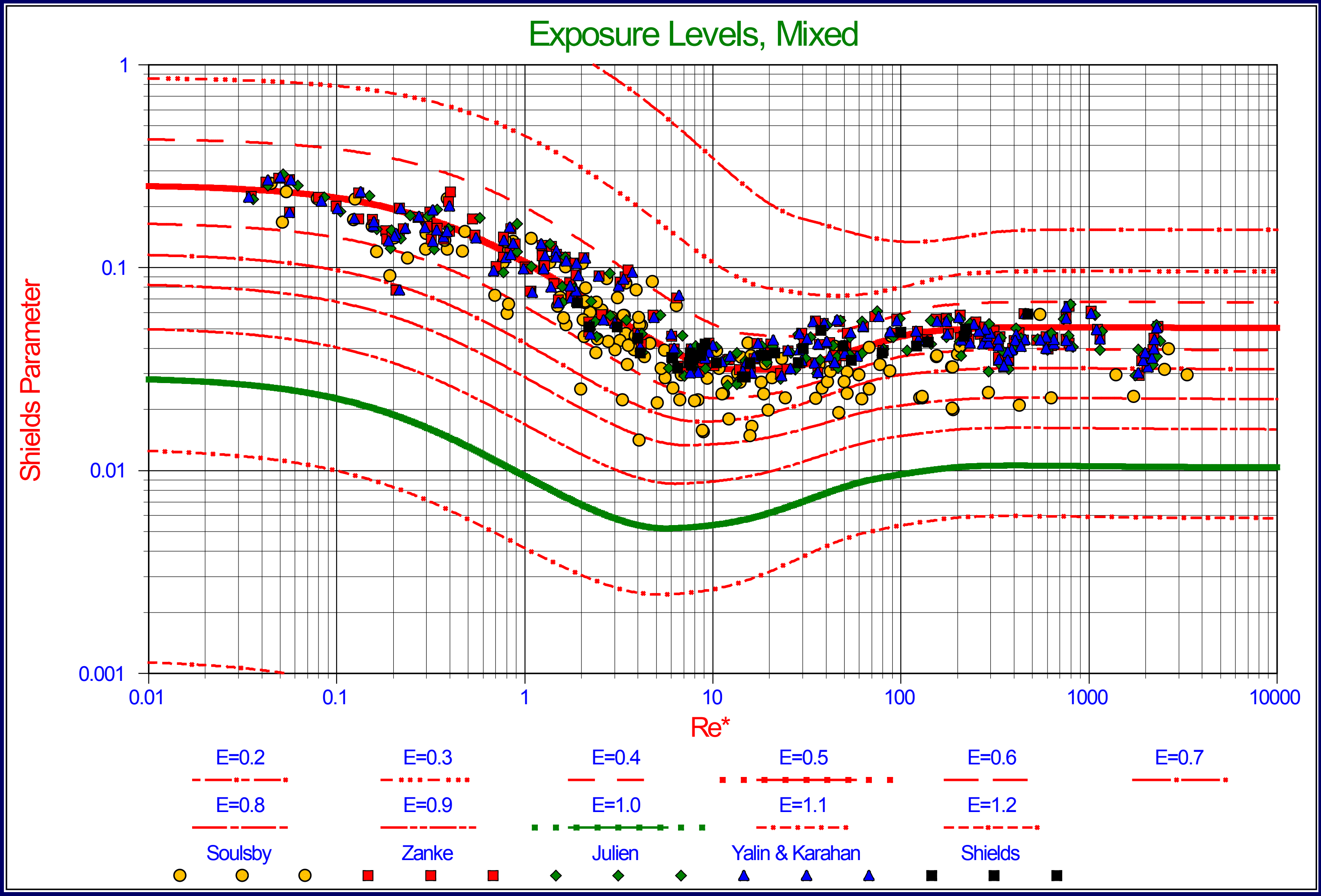
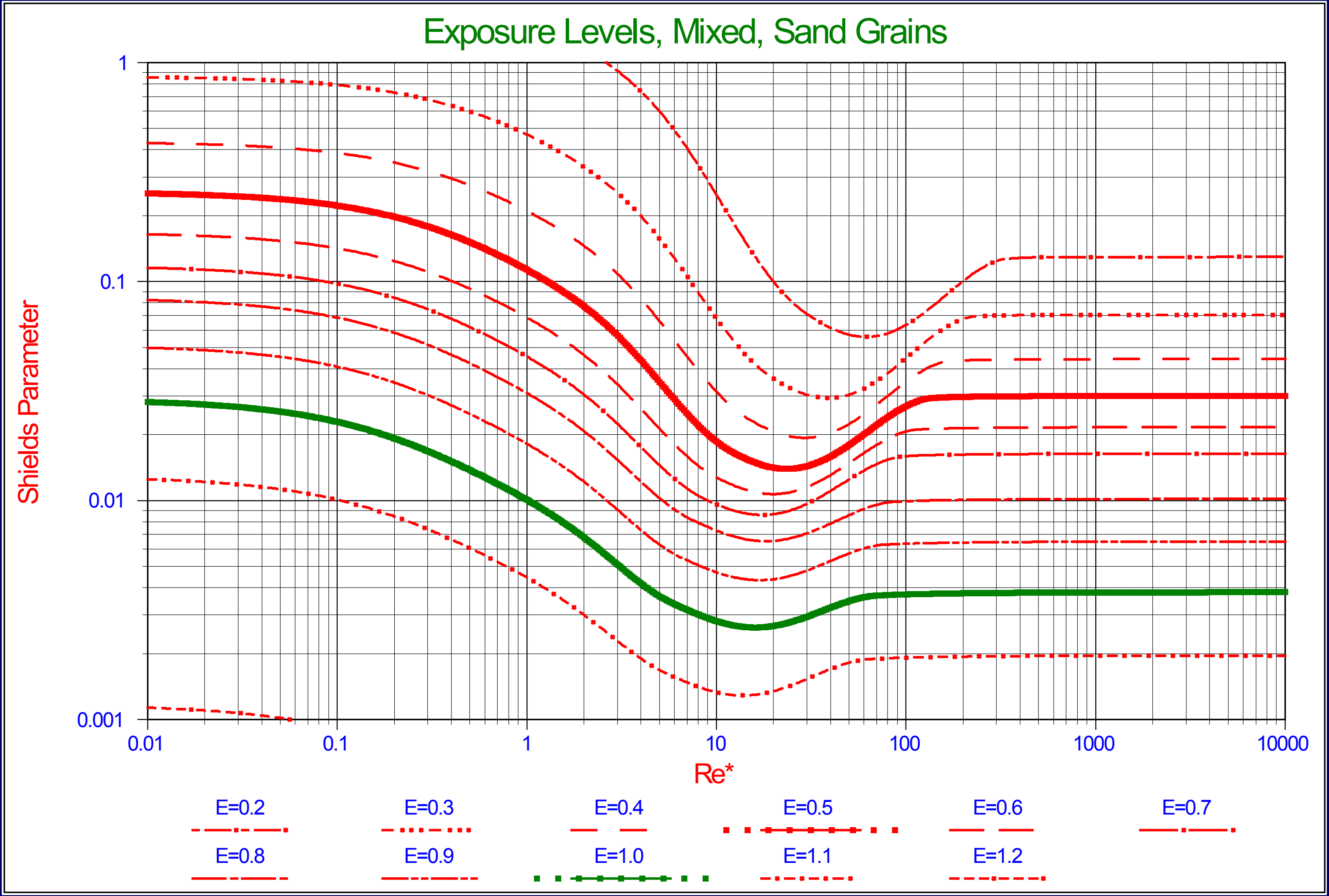
Exposure Levels Both (Spheres)



Different protrusion levels (sand)



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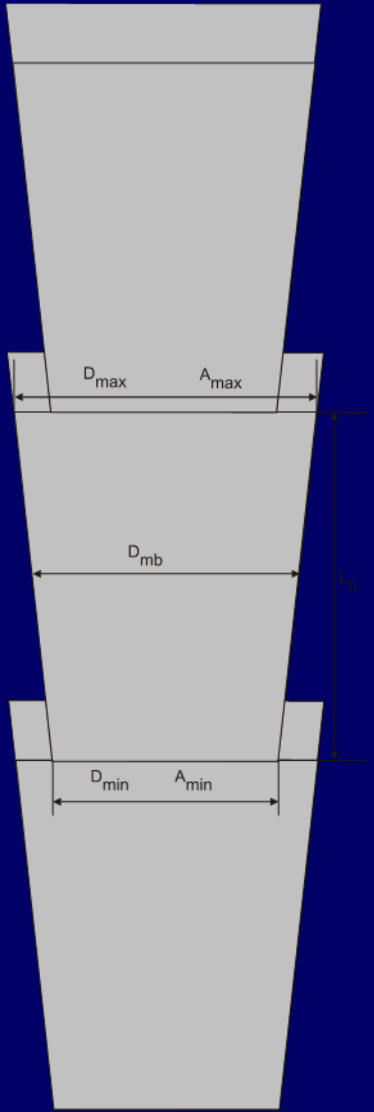
Stone Size versus Flow Velocity

$$\theta = \frac{u_*^2}{R_{sd} \cdot g \cdot d}$$

$$d = \frac{\frac{\lambda_b}{8} \cdot v_b^2}{R_{sd} \cdot g \cdot \theta} = \frac{\frac{0.06}{8} \cdot v_b^2}{1.65 \cdot 9.81 \cdot 0.01} = 0.044 \cdot v_b^2$$

v_b (m/s)	d (m)
1	0.044
2	0.176
3	0.395
4	0.703
5	1.098
6	1.580

The Fall Pipe with Buckets



The Velocity in the Fall Pipe

$$\Delta p_g = \Delta p_{tot}$$

$$\left(\rho_m - \rho_l\right) \cdot g \cdot L_b = \left(\lambda_{DW} + \lambda_C\right) \cdot \frac{L_b}{D_{mb}} \cdot \frac{1}{2} \cdot \rho_l \cdot v_{mm}^2$$

$$v_{mm} = \sqrt{\frac{\left(\rho_m - \rho_l\right)}{\rho_l} \cdot \frac{2 \cdot g \cdot D_{mb}}{\left(\lambda_{DW} + \lambda_C\right)}}$$

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Kinetic Energy Stone 1

$$v_{exit} = v_{mm} \cdot \left(\frac{D_{mb}}{D_{min}} \right)^2$$

$$v_t = \frac{10 \cdot \nu_l}{d} \cdot \left(\sqrt{1 + \frac{R_{sd} \cdot g \cdot d^3}{100 \cdot \nu_l^2}} - 1 \right)$$

$$v_{th} = v_t \cdot \left(1 - C_{vs}\right)^{2.4} \cdot e^{-\frac{d}{D_{mb}}}$$

Kinetic Energy Stone 2

$$\text{if } SOD < 6.3 \cdot D_{min} \text{ then } v_{sf} = v_{exit}$$

$$\text{if } SOD > 6.3 \cdot D_{min} \text{ then } v_{sf} = \frac{6.3 \cdot D_{min}}{SOD} \cdot v_{exit}$$

$$v_{stone} = v_{sf} + v_{th}$$

$$E_{kin} = \frac{1}{2} \cdot m \cdot v_{stone}^2 = \frac{1}{2} \cdot \rho_q \cdot \frac{\pi}{6} \cdot d^3 \cdot v_{stone}^2$$

Terzaghi Equation, Bearing Capacity

Stone footing:

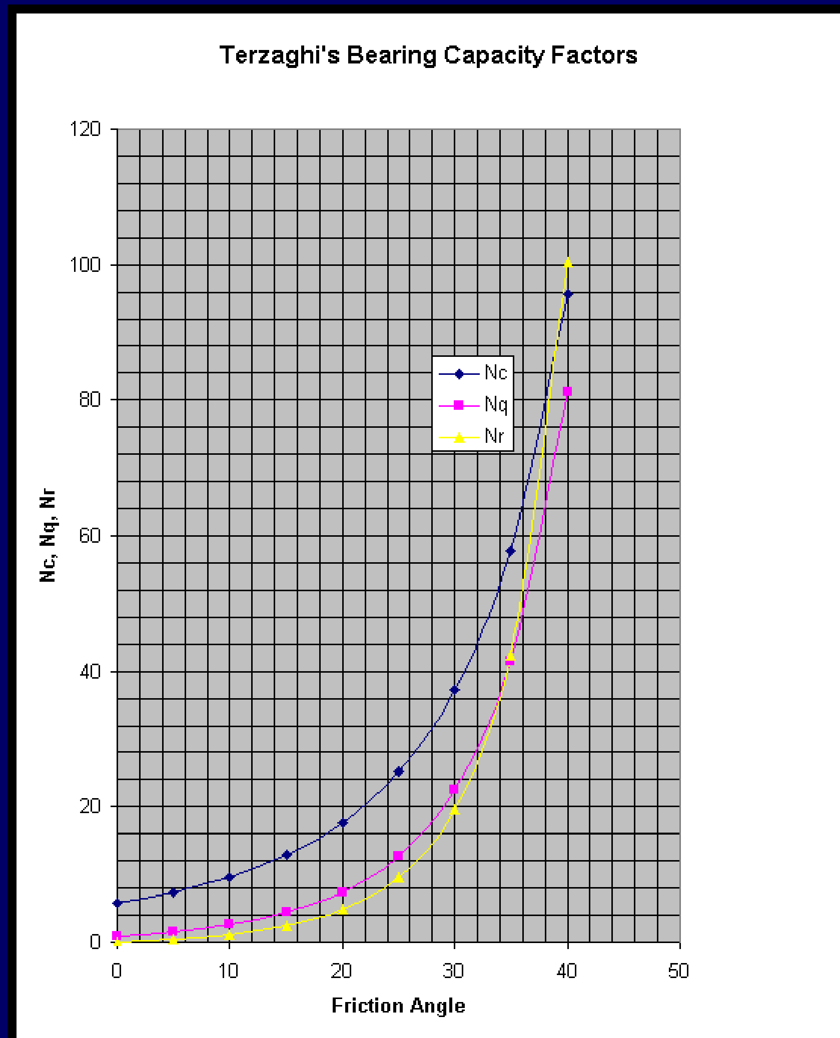
$$F_{BC} = A_{stone} \cdot \left(1.2 \cdot c \cdot N_c + \gamma \cdot p_d \cdot N_q + 0.4 \cdot \gamma \cdot W \cdot N_\gamma\right)$$

$$N_q = \frac{\left(e^{(3\cdot\pi/4-\varphi/2)\cdot\tan(\varphi)}\right)^2}{2 \cdot \cos^2\left(\pi/4+\varphi/2\right)}$$

$$N_c = \frac{\left(N_q - 1\right)}{\tan\left(\varphi\right)}$$

$$N_\gamma = 1.5 \cdot \left(N_q - 1\right) \cdot \tan\left(\varphi\right)$$

Terzaghi Values



φ	N_c	N_q	N_γ
0	5.7	1	0
5	7.3	1.6	0.5
10	9.6	2.7	1.2
15	12.9	4.4	2.5
20	17.7	7.4	5
25	25.1	12.7	9.7
30	37.2	22.5	19.7
35	57.8	41.4	42.4
40	95.7	81.3	100.4
45	172.3	173.3	297.5
48	258.3	287.9	780.1

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Kinetic Energy = Work

$$p_d \cdot \left(F_{BC} + F_g - F_b \right) = E_{kin} = \frac{1}{2} \cdot \rho_q \cdot \frac{\pi}{6} \cdot d^3 \cdot v_{stone}^2$$

$$p_d = \frac{E_{kin}}{F_{BC} + F_g - F_b}$$

Conclusions

- The Shields approach for real sands and gravels is a good approach to determine the size of the rock pieces in the armor layer.
- For the penetration of the rock pieces in the sea floor a modified Terzaghi equation is used.
- The assumption that the kinetic energy of the rock pieces equals the work carried out while penetrating the sea floor, seems to be a good assumption.

Questions?