Chapter 7: Stability of randomly placed rock mounds

ct5308 Breakwaters and Closure Dams

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Section Hydraulic Engineering

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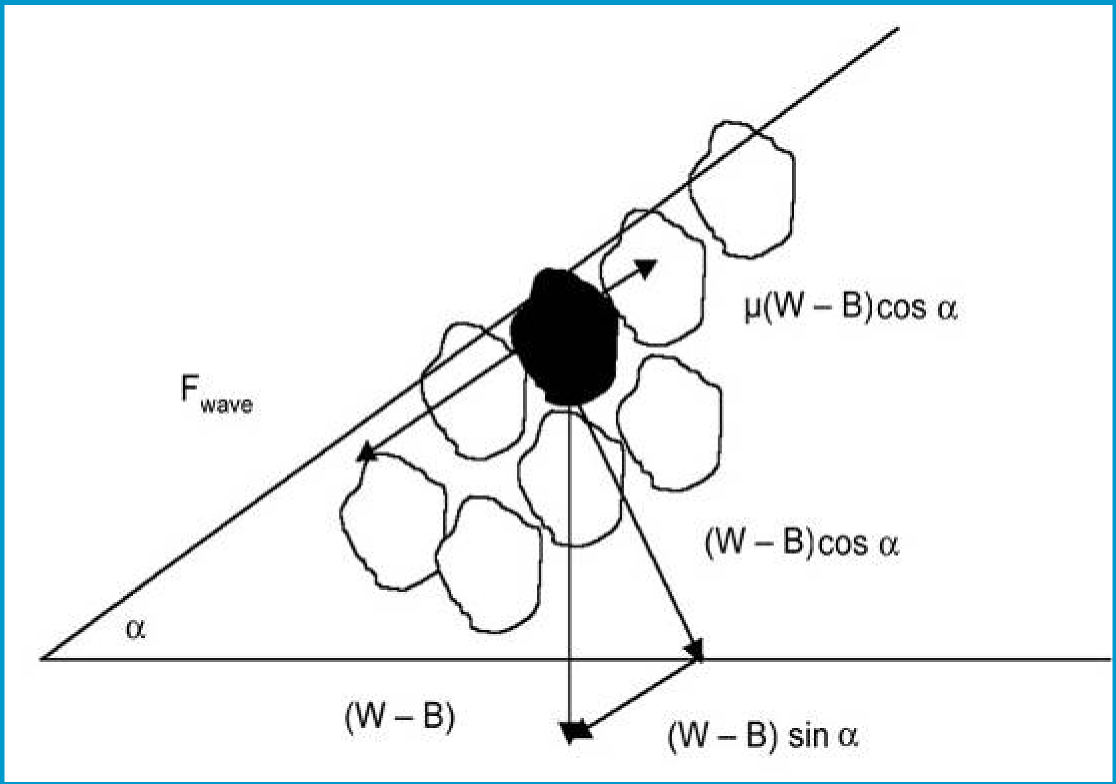
History

- Iribarren * Equilibrium of forces on a block
- Hudson * Experiments and curve fitting
- Van der Meer * More experiments, analysis, curve fitting
- Van Gent * Shallow water conditions

Equilibrium after Iribarren



$$F_{\text{wave}} = \rho_w g\, D_n^{\,2}\, H$$

$$W - B = \left(\rho_r - \rho_w\right) g\, D_n^{\,3}$$

$$W = \rho_r\, g\, D_n^{\,3}$$

Equations for uprush and downrush

$$W \geq \frac{N \rho_r g H^3}{\Delta^3 \left(\mu \cos\alpha + \sin\alpha\right)^3} \qquad W \geq \frac{N \rho_r g H^3}{\Delta^3 \left(\mu \cos\alpha - \sin\alpha\right)^3}$$

type of block	downward stability $(\mu \cos \alpha - \sin \alpha)^3$		upward stability $(\mu \cos \alpha + \sin \alpha)^3$		transition slope between upward and downward stability
	μ	N	μ	N	cot α
rough angular quarry stone	2.38	0.430	2.38	0.849	3.64
cubes	2.84	0.430	2.84	0.918	2.80
tetrapods	3.47	0.656	3.47	1.743	1.77

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Hudson

$$W \geq \frac{\rho_r g H^3}{\Delta^3 K_D \cot\alpha}$$

type of block	number of layers (N)	structure trunk K_D breaking wave	structure trunk K_D non breaking wave	structure head K_D breaking wave	structure head K_D non breaking wave
rough angular quarry stone	1	**	2.9	**	2.3
rough angular quarry stone	2	3.5	4.0	2.5*	2.8*
rough angular quarry stone	3	3.9	4.5	3.7*	4.2*
tetrapod	2	7.2	8.3	5.5*	6.1*
dolos	2	22.0	25.0	15.0	16.5*
cube	2	6.8	7.8		5.0

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spm 1977

H_s

type of block	number of layers (N)	structure trunk K_D breaking wave	structure trunk K_D non breaking wave	structure head K_D breaking wave	structure head K_D non breaking wave
rough angular quarry stone	1	**	2.9	**	2.3
rough angular quarry stone	2	3.5	4.0	2.5*	2.8*
rough angular quarry stone	3	3.9	4.5	3.7*	4.2*
tetrapod	2	7.2	8.3	5.5*	6.1*
dolos	2	22.0	25.0	15.0	16.5*
cube	2	6.8	7.8		5.0

spm 1984

type of block	number of layers (N)	structure trunk K_D breaking wave	structure trunk K_D non breaking wave	structure head K_D breaking wave	structure head K_D non breaking wave
rough angular quarry stone	1	**	2.9	**	2.2
rough angular quarry stone	2	2.0	4.0	1.6*	2.8*
rough angular quarry stone	3	2.2	4.5	2.1*	4.2*
tetrapod	2	7.0	8.0	4.5*	5.5*
dolos	2	15.8	31.8	8.0	16.0*
cube	2	6.5	7.5		5.0
akmon	2	8	9	n.a.	n.a.
Accropod ® (1:1.33)		12	15		

* There is a slight variation of recommended K_D value for different slopes

** Use of single layer is not recommended under breaking waves

$H_{10} = 1.27\ H_s$

Damage multiplier for Hudson

Unit	Damage (D) in %						
	0-5	5-10	10-15	15-20	20-30	30-40	40-50
Quarry stone (smooth)	1.00	1.08	1.14	1.20	1.29	1.41	1.54
Quarry stone (rough)	1.00	1.08	1.19	1.27	1.37	1.47	1.56
Tetrapod	1.00	1.09	1.17	1.24	1.32	1.41	1.50
Dolos	1.00	1.10	1.14	1.17	1.20	1.24	1.27

Damage due to overloading ($H/H_{no\ damage}$)

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comparison of Hudson and Iribarren

$$\frac{H}{\Delta D} = \sqrt[3]{K_D \cot\alpha}$$

$$\frac{H}{\Delta D} = \left(\mu\cos\alpha \pm \sin\alpha\right) N^{-1/3}$$

- shape of block
- layer thickness
- placing manner
- roughness, interlock
- type of wave attack
- head/trunk
- angle of incidence
- size/porosity underlayer
- crest level
- crest type
- wave period
- foreshore shape
- reflection

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application of Hudson

- increase of block density
- increase of block weight
- decrease slope
- grout smaller blocks
- increase K_D by special shaped blocks

$$\frac{H}{\Delta D} = \sqrt[3]{K_D \cot \alpha}$$

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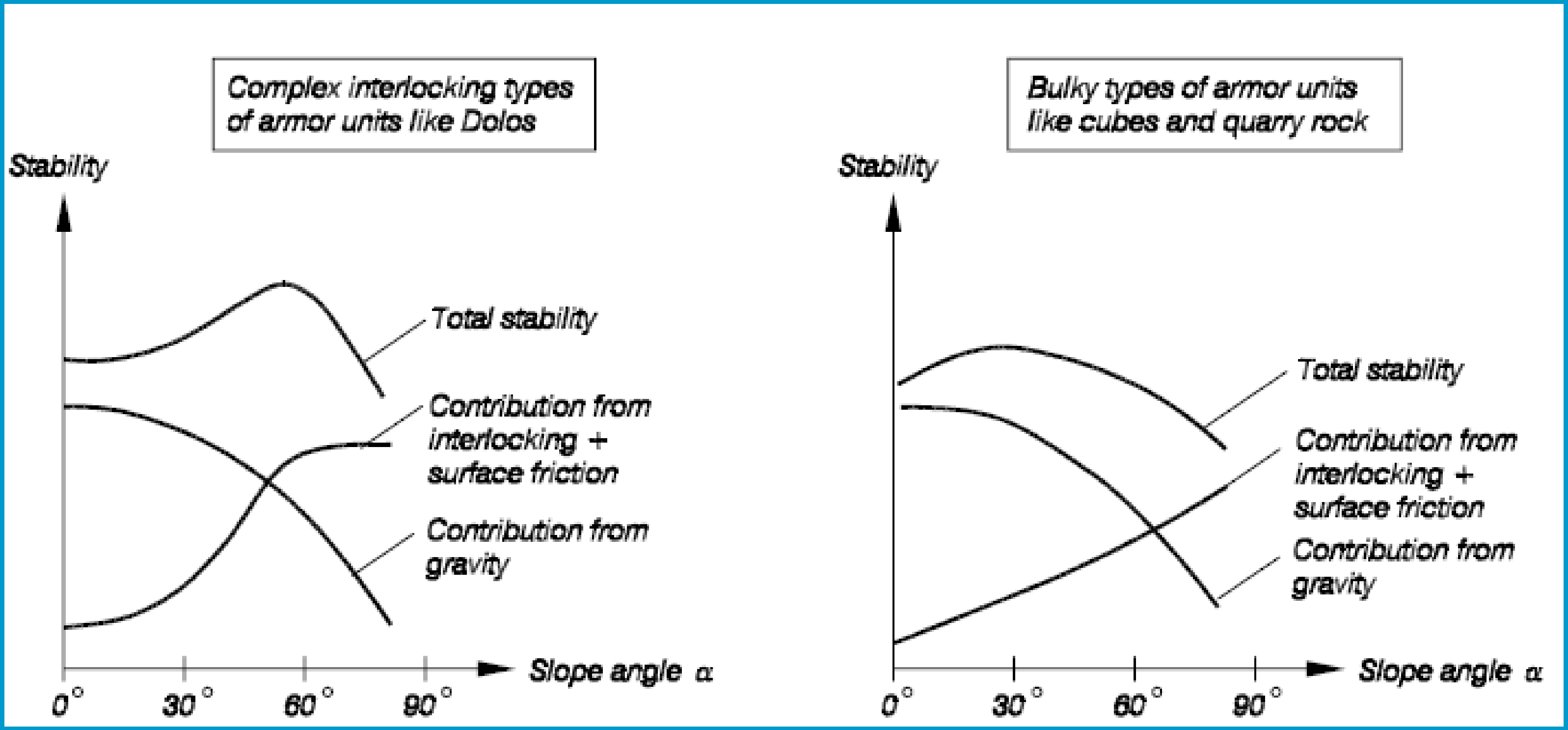
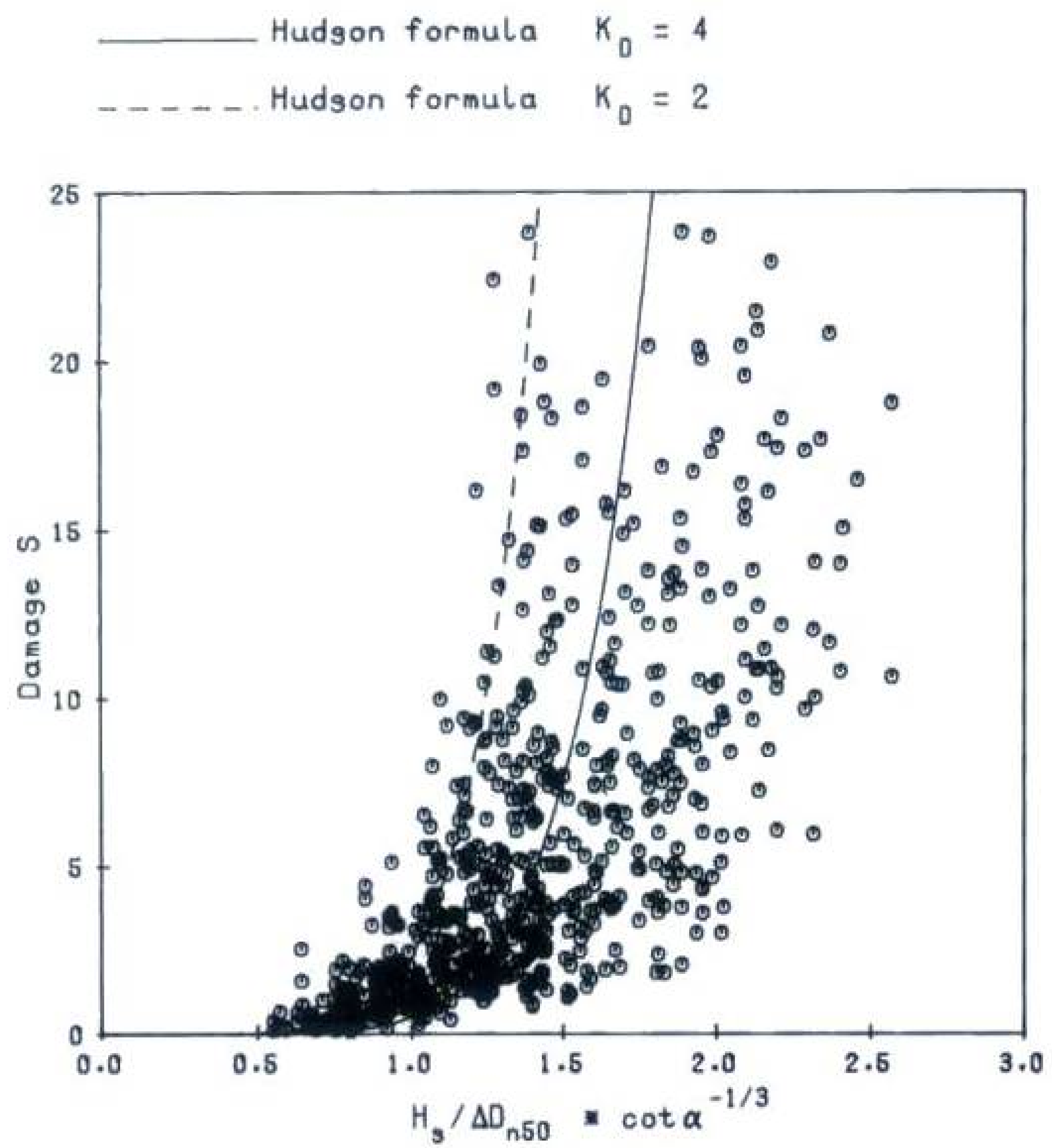
Optimal angle and interlock of blocks



ongoing MSc work by Bart van Zwicht



Hudson and measurements

Damage according to Van der Meer

$$S = \frac{A}{D_{n50}^{\;\;2}}$$

A - erosion area

D_{n50} - nominal diameter (= W_{50} /gρ)$^{1/3}$

W_{50} - “mean” weight of the armour stones

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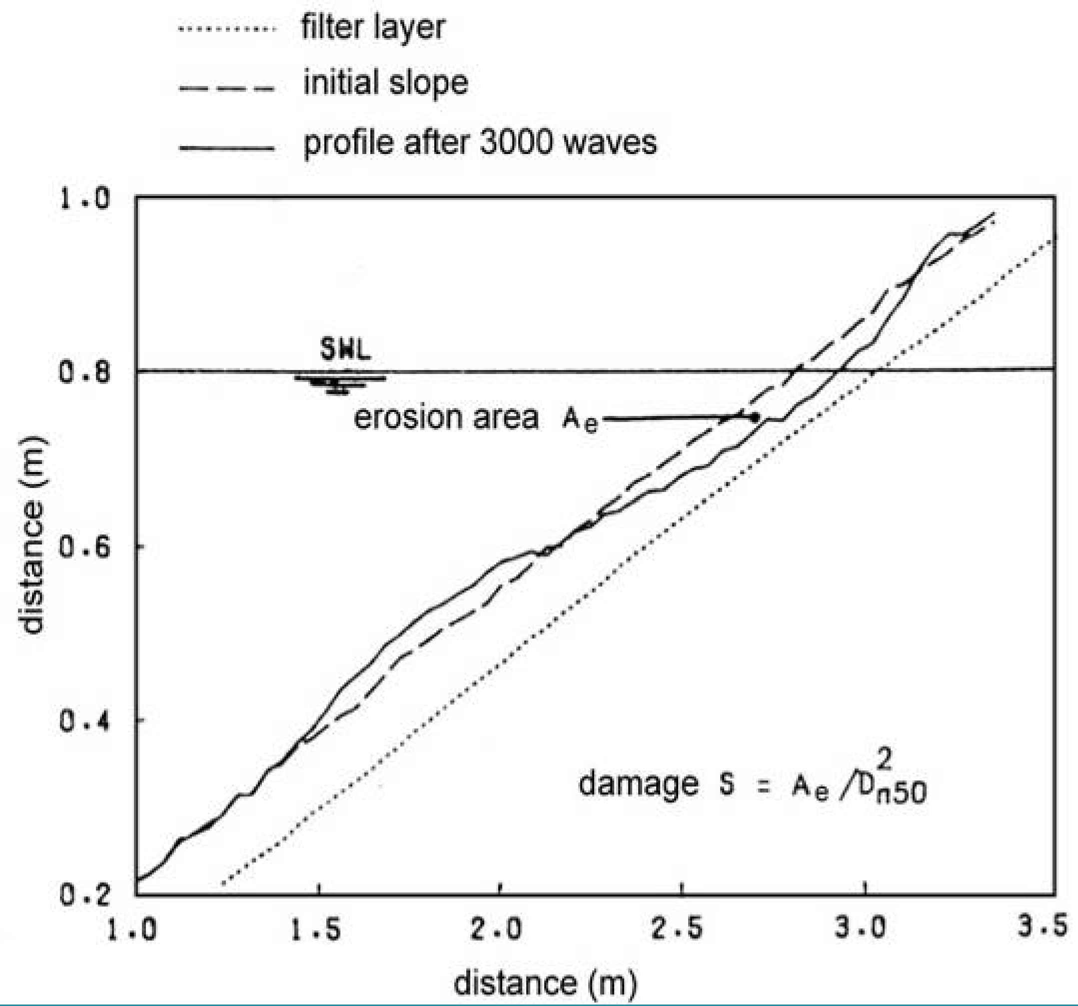
Damage(S) based on erosion area (A)



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classification of S-values

Slope	Initial Damage (needs no repair)	Intermediate Damage (needs repair)	Failure (core exposed)
1:1.5	2	3 – 5	8
1:2	2	4 – 6	8
1:3	2	6 – 9	12
1:4	3	8 – 12	17
1:6	3	8 – 12	17

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wave period

$$\xi = \frac{\tan\alpha}{\sqrt{s}} \qquad s = \frac{2\pi H}{gT^2}$$

Van der Meer uses deep water values:

ξ_{s0m}

thus:

significant wave

deep water

period based on T_m

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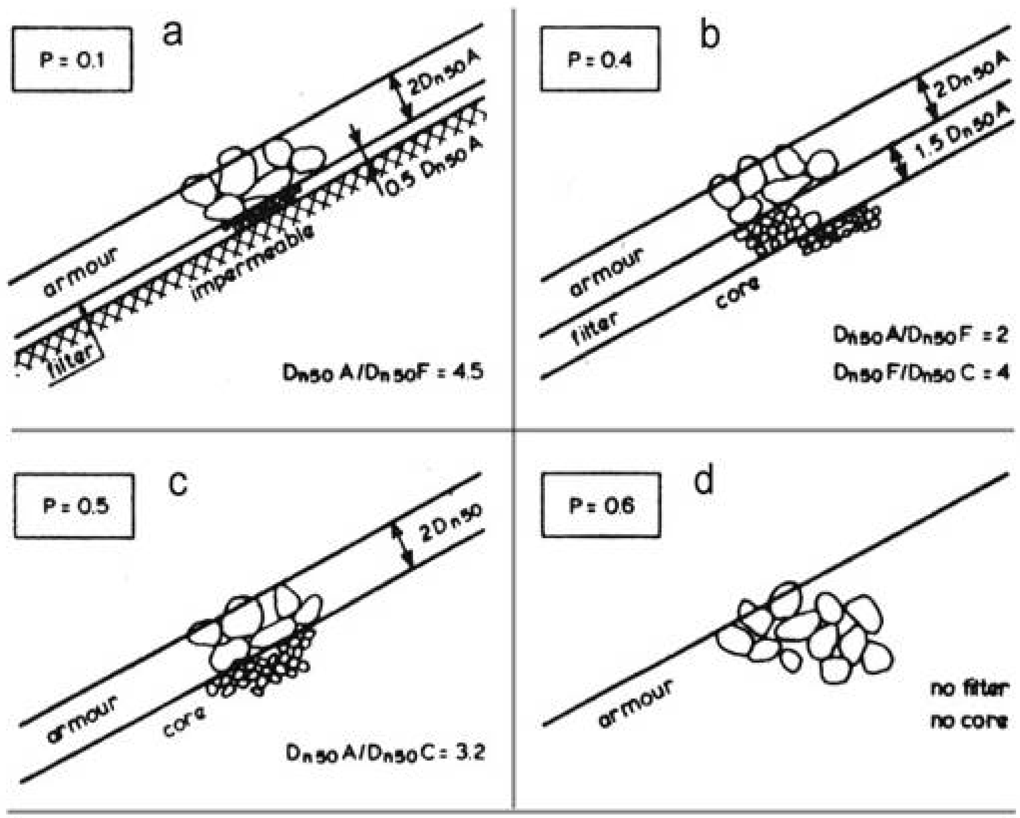
Permeability coefficients



$D_{n50}A$ = nominal diameter of armour stone
$D_{n50}F$ = nominal diameter of filter material
$D_{n50}C$ = nominal diameter of core

Van der Meer

$$\frac{H_{sc}}{\Delta d_{n50}} = 6.2\,P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2}\xi^{-0.5}$$ (plunging breakers)

$$\frac{H_{sc}}{\Delta d_{n50}} = 1.0\,P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2}\xi^{P}\sqrt{\cot\alpha}$$ (surging breakers)

$$\xi_{\text{transition}} = \left[6.2\,P^{0.31}\sqrt{\tan\alpha}\right]^{\left(\frac{1}{P+0.5}\right)}$$

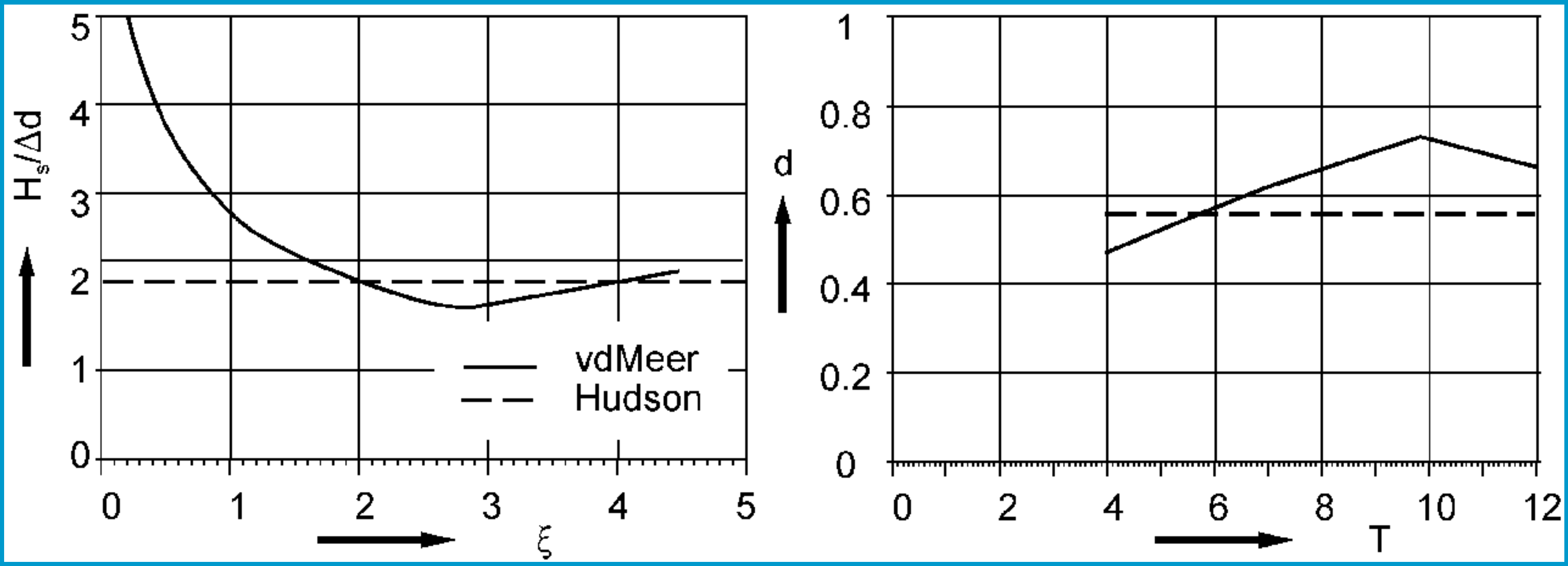
$\xi > \xi_{transition}$ → surging breakers

$\xi < \xi_{transition}$ → plunging breakers

reference case

sign. wave height	H_s	2 m	
slope of revetment	$\cot\alpha$	3	
"Permeability"		P	0.5
mean period	T_m	6 s	
number of waves	N	3000	
rock size	d_{n50}	0.6 m (300-1000 kg)	
relative density		Δ	1.65
damage level	S	2	
Hudson coefficient	K_D	2	

Wave period



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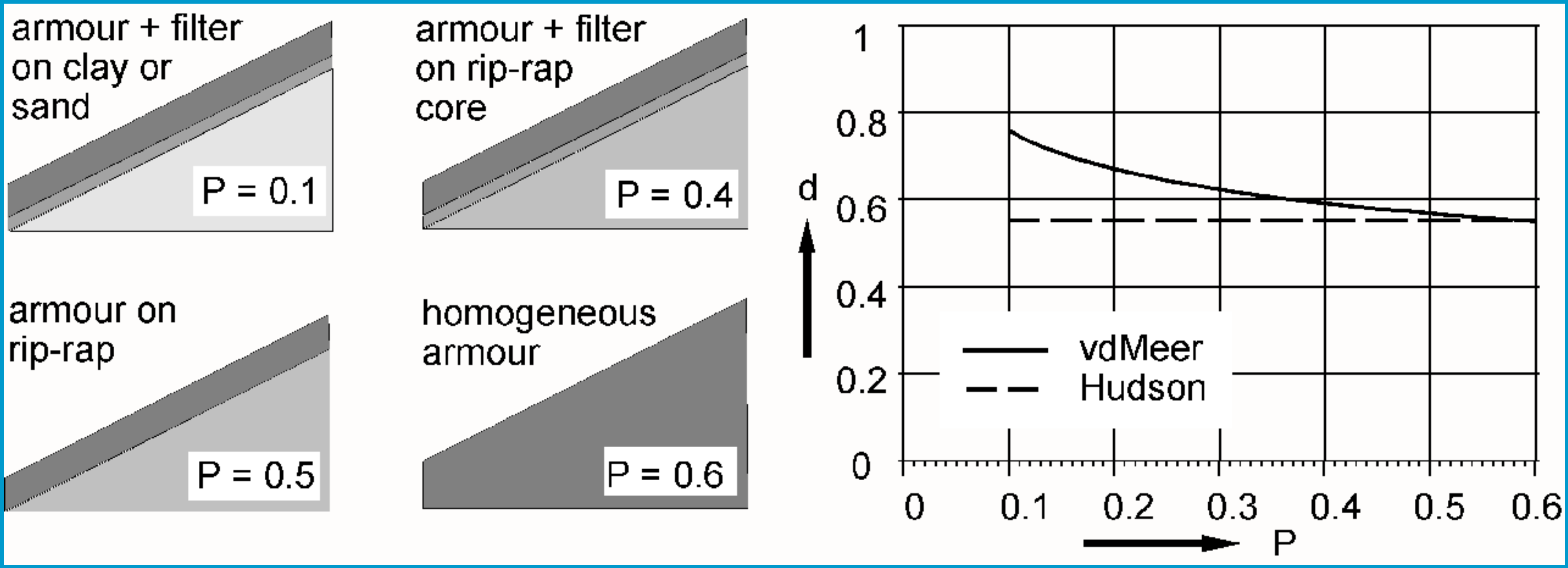
permeability



P = notional permeability factor

notional:
belonging to the realm of ideas, not of experience; existing only in the mind
(*denkbeeldig; begrips-)*

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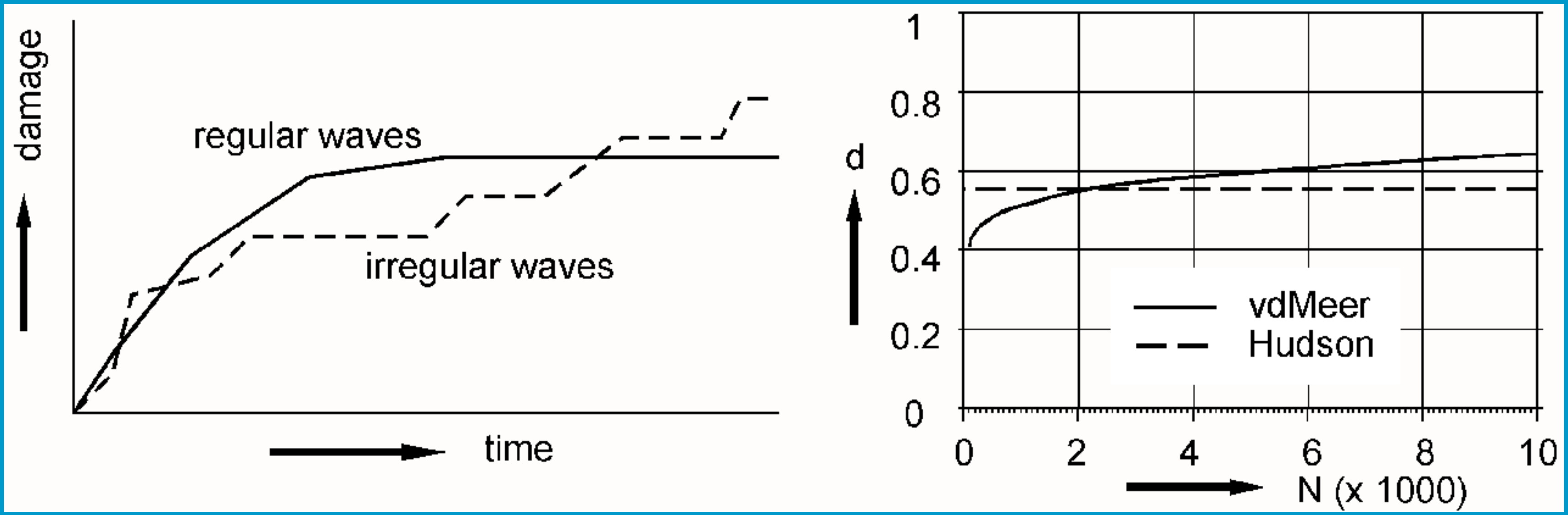
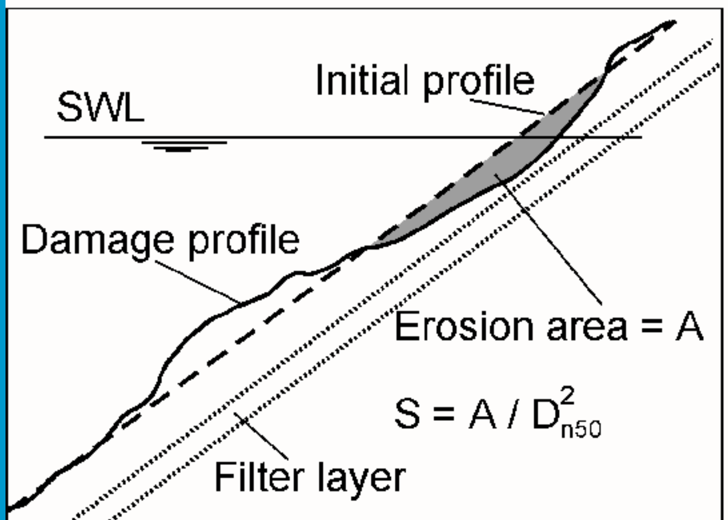
number of waves

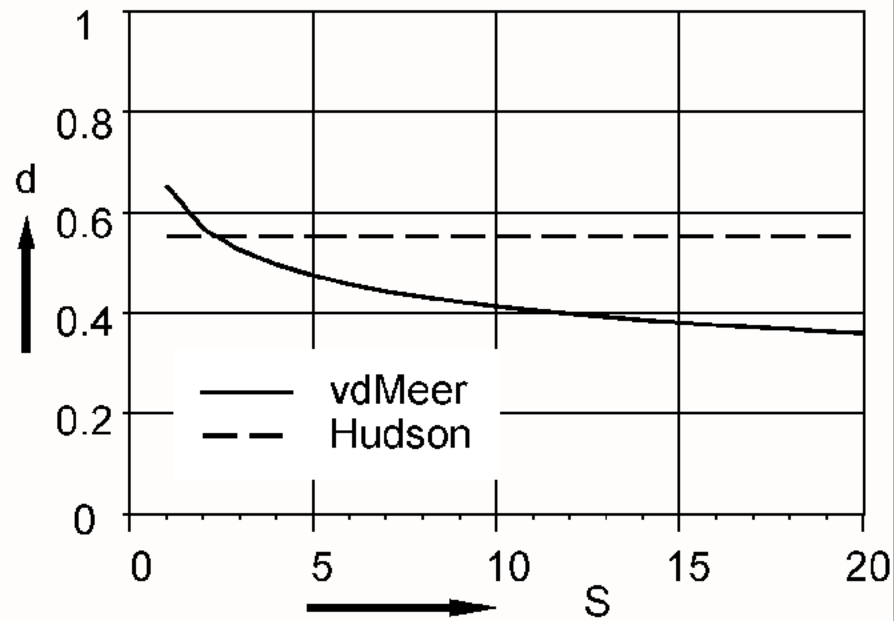


maximum number of waves: 7500

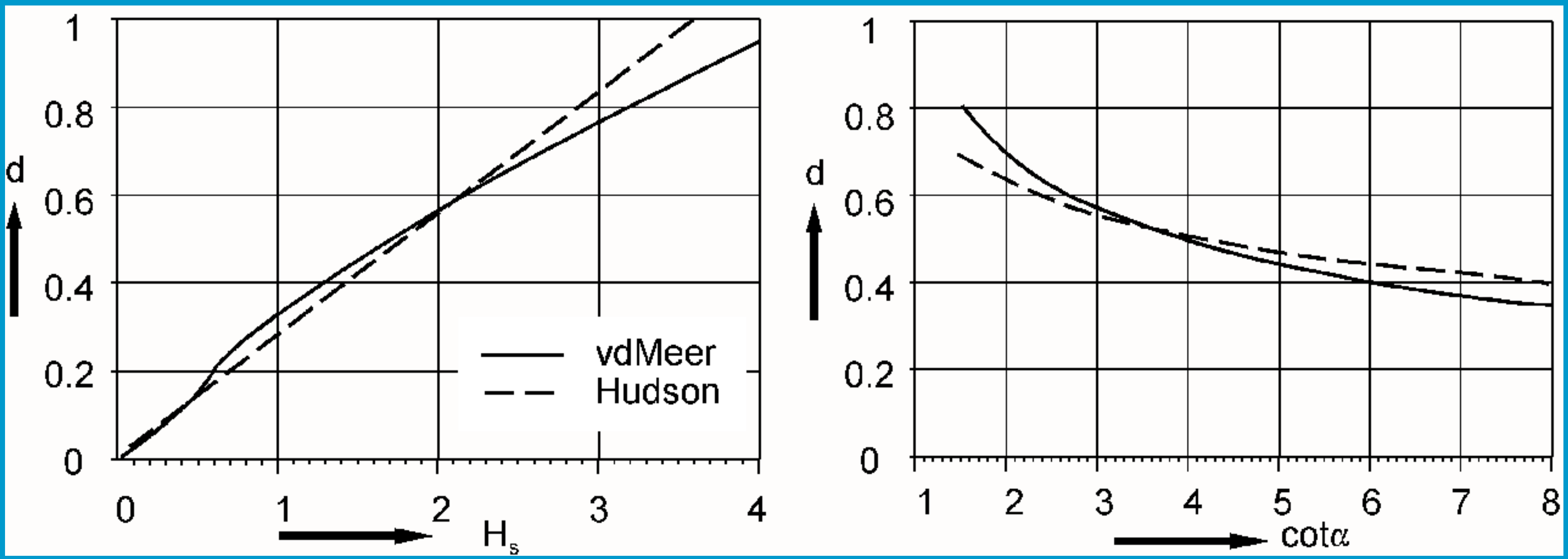
3000 waves of 6 s is 5 hours

damage level

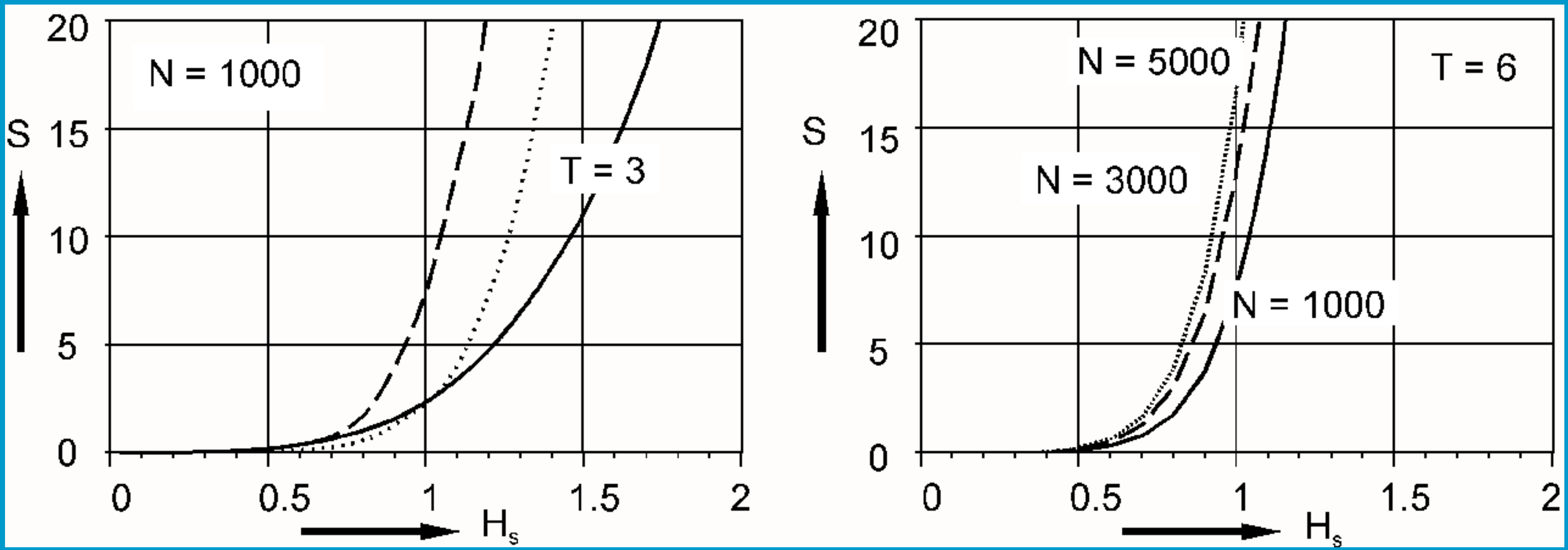




slope angle


1
0.8
0.6
0.4
0.2
0
d
0
1
2
3
4
Hs
vdMeer
Hudson
1
0.8
0.6
0.4
0.2
0
d
1
2
3
4
5
6
7
8
cotα

damage development



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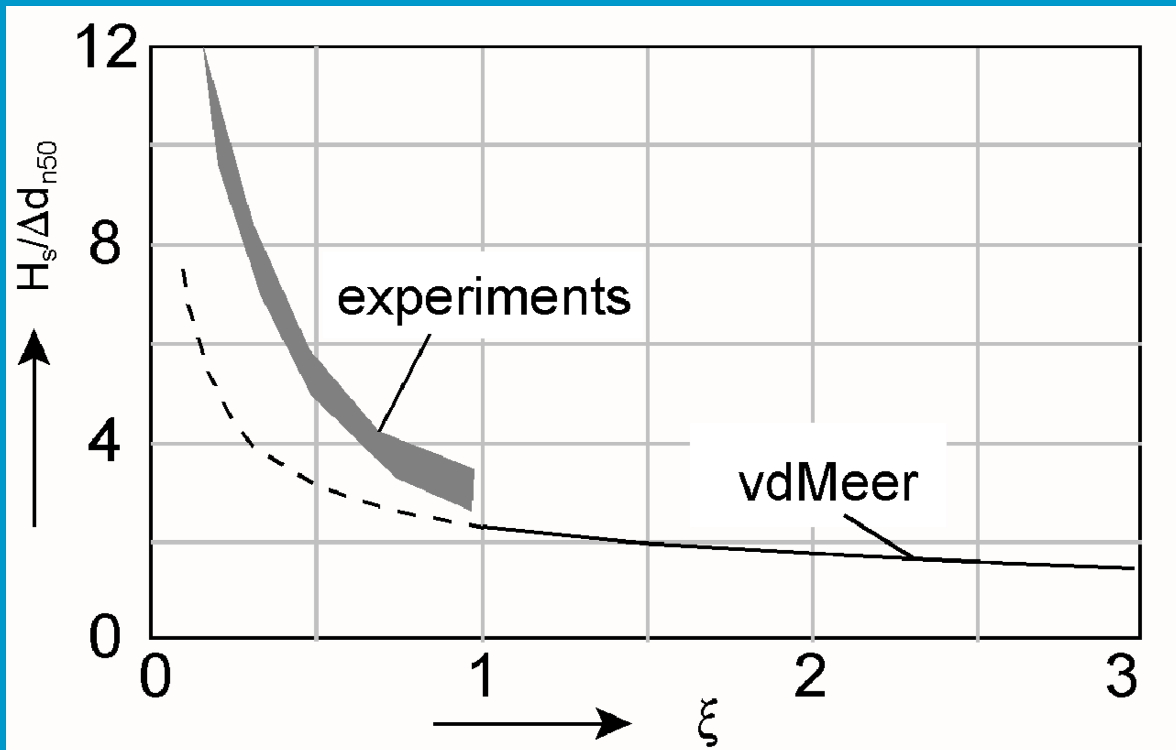
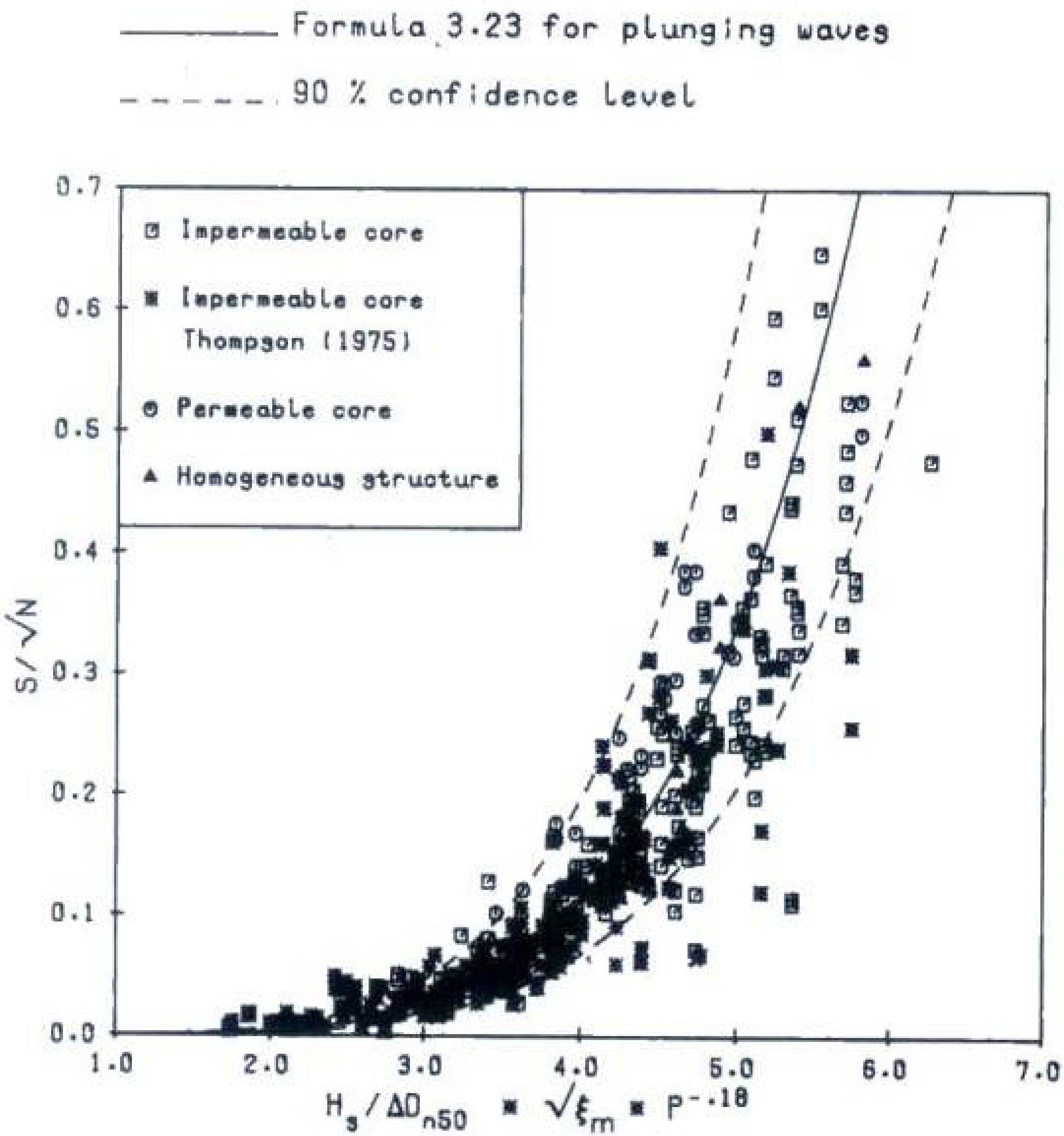
mild slopes

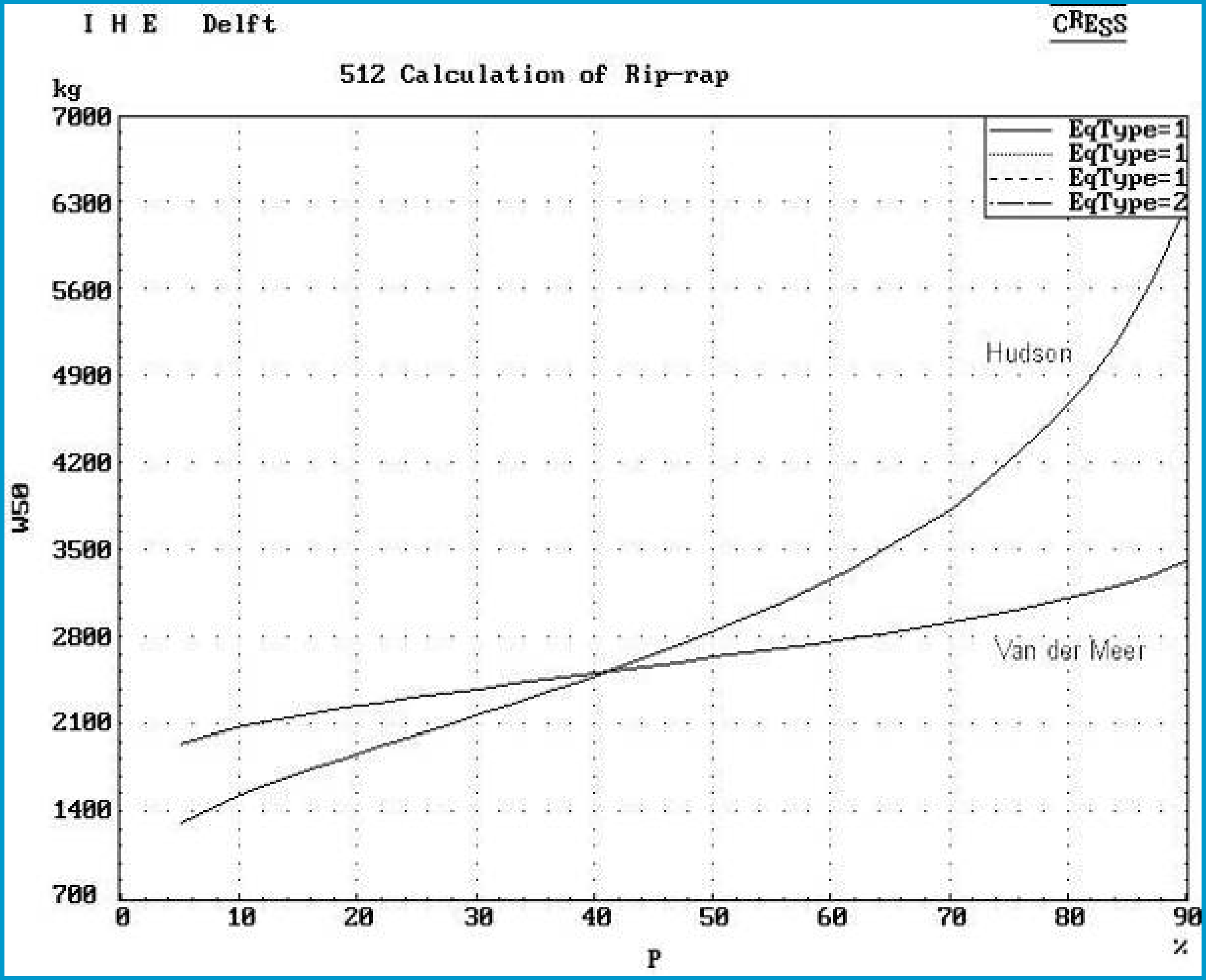




measured values for plunging breakers

coefficients can be considered as stochastic parameters:
$\sigma_{6.2} = 0.5$
$\sigma_{1.0} = 0.08$

Hudson and Van der Meer



shape of quarry stone

Rock shape	Plunging waves	Surging waves
Elongate/Tabular	6.59	1.28
Irregular	6.38	1.16
Equant	6.24	1.08
Standard v.d. Meer	*6.2*	*1.0*
Semi-round	6.10	1.00
Very round	5.75	0.80

coefficients in the Van der Meer equation

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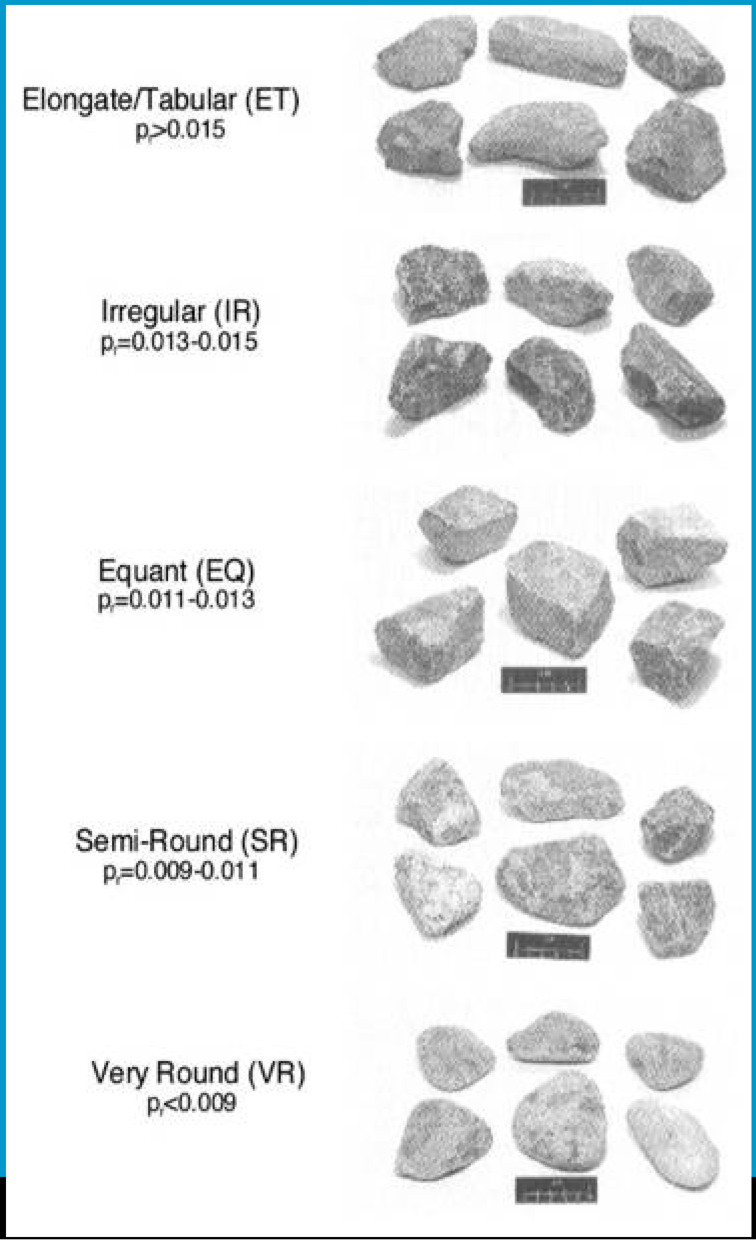
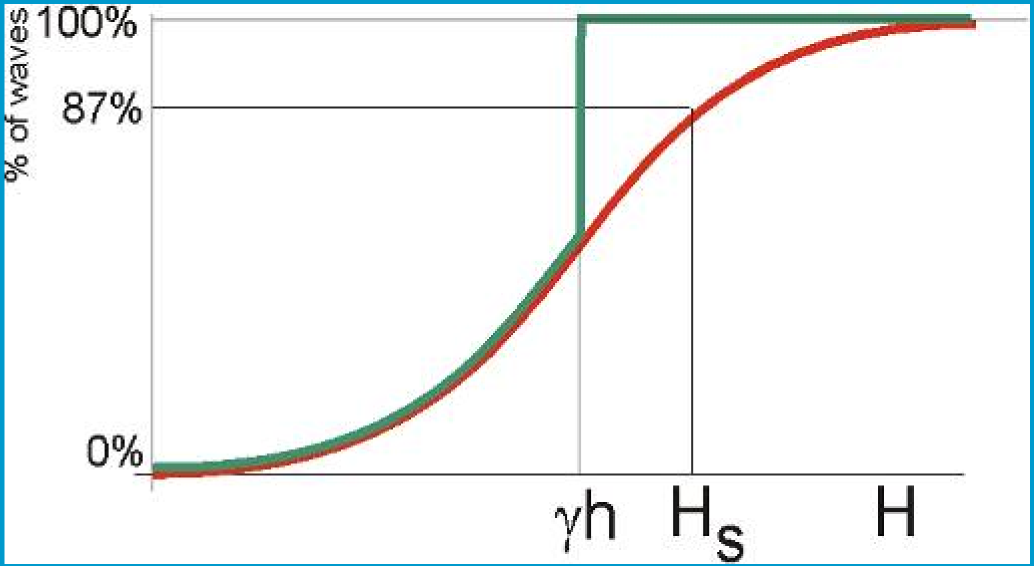


visual comparison of block shapes

Shallow water conditions (wave height)

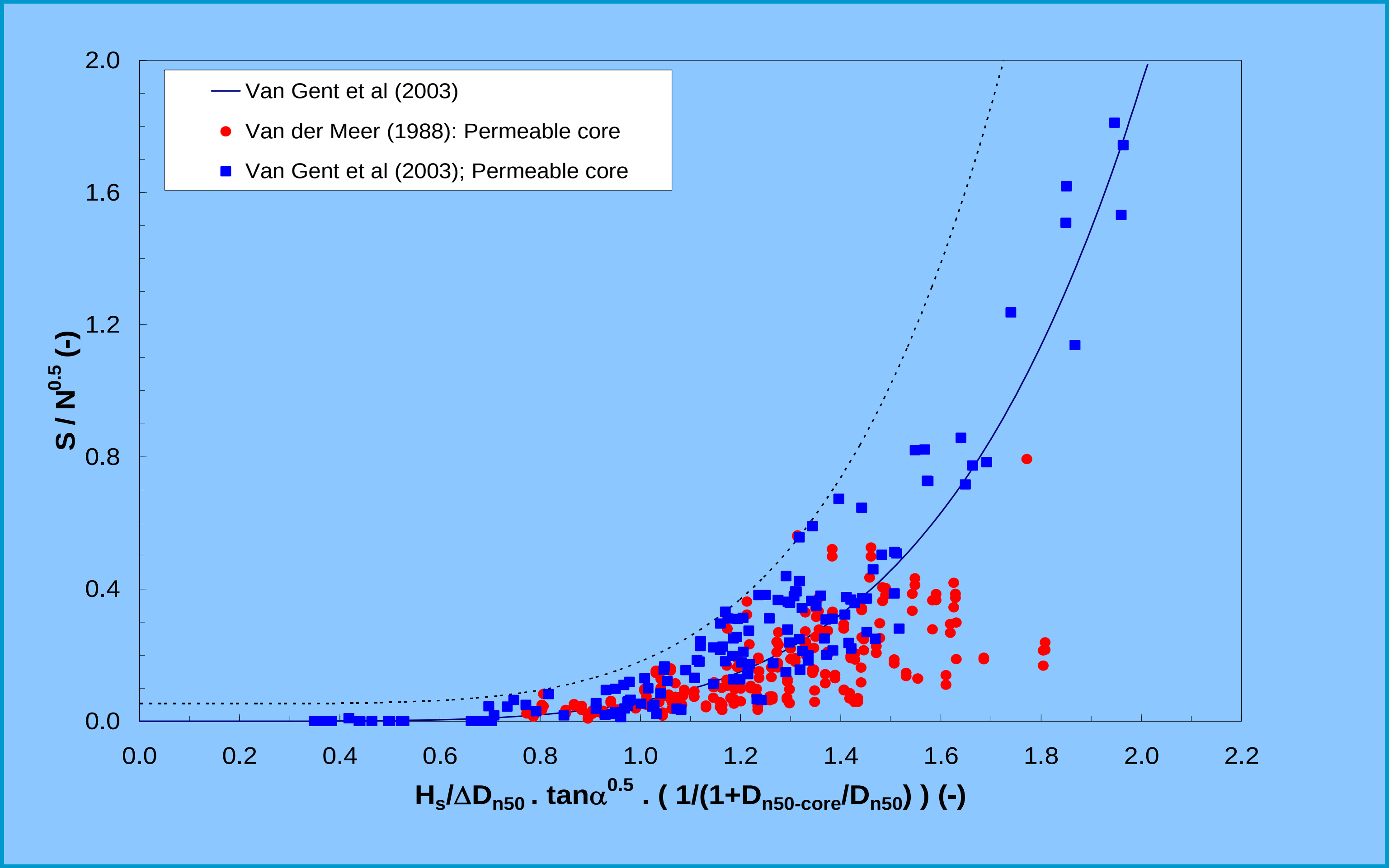
- Rayleigh distribution no longer valid
  - in deep water $H_{2\%} = 1.4\ H_s$
  - in shallow water $H_{2\%} = (1.2 - 1.3)\ \ H_s$
- So, use adapted design formula (you may use $H_{2\%}$ instead of H_s)



Shallow water conditions (wave period)

- When waves come in shallow water, wave spectrum changes
  - in shallow water longer periods are more relevant
  - recommended to use $T_{m-1,0}$

Stone stability (vdMeer vs. vGent)



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The original van der Meer equation

$$\frac{S}{\sqrt{N}} = \left[\frac{1}{c_{pl}} \left(\frac{H_{2\%}}{H_s} \right) \frac{H_s}{\Delta D_{n50}} \xi_m P^{0.18} \right]^5$$

(for plunging breakers)

Values of the coefficient c_{pl}:

Original Van der Meer:	8.68
Transformation to $T_{m-1,0}$:	9.13
Recalibration on data Van Gent:	8.40

For deep water: $H_{2\%}/H_s = 1.4$

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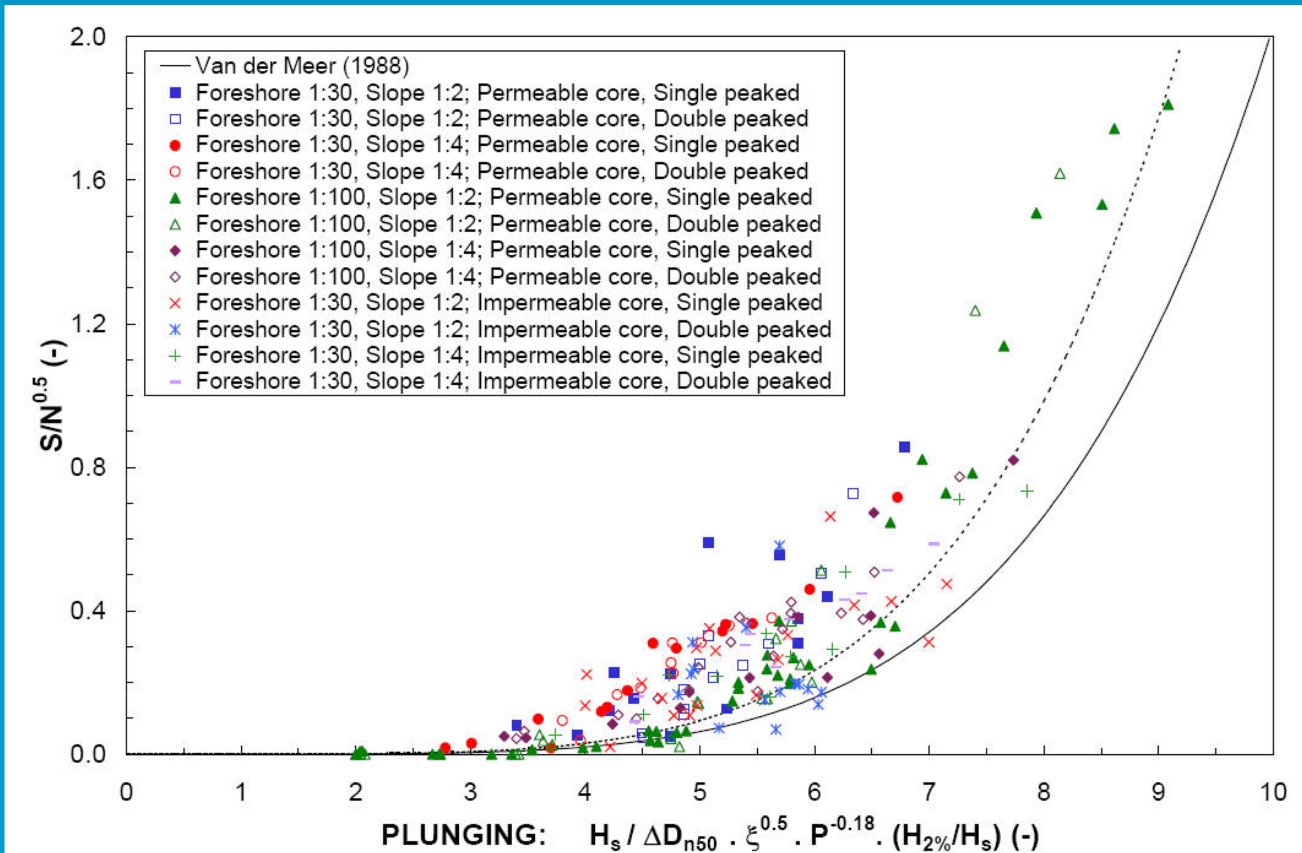
Data of Van Gent and original Van der Meer equation



correct factor $H_{2\%}/H_s$

incorrect conversion from T_m to $T_{m-1,0}$

Van Gent: $T_m = 0.957\ T_{m-1,0}$
Van der Meer: $T_m = 0.904\ T_{m-1,0}$

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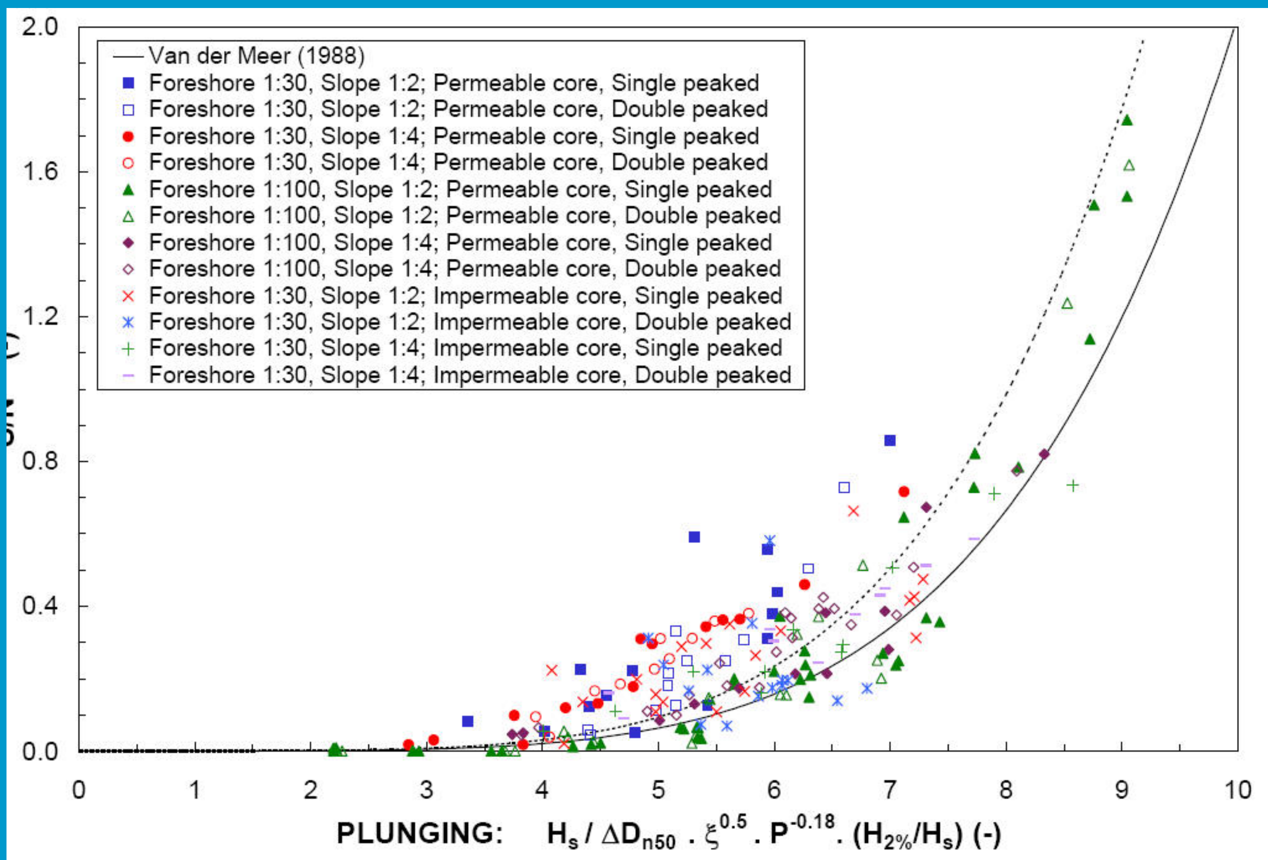
Data of Van Gent and original Van der Meer equation

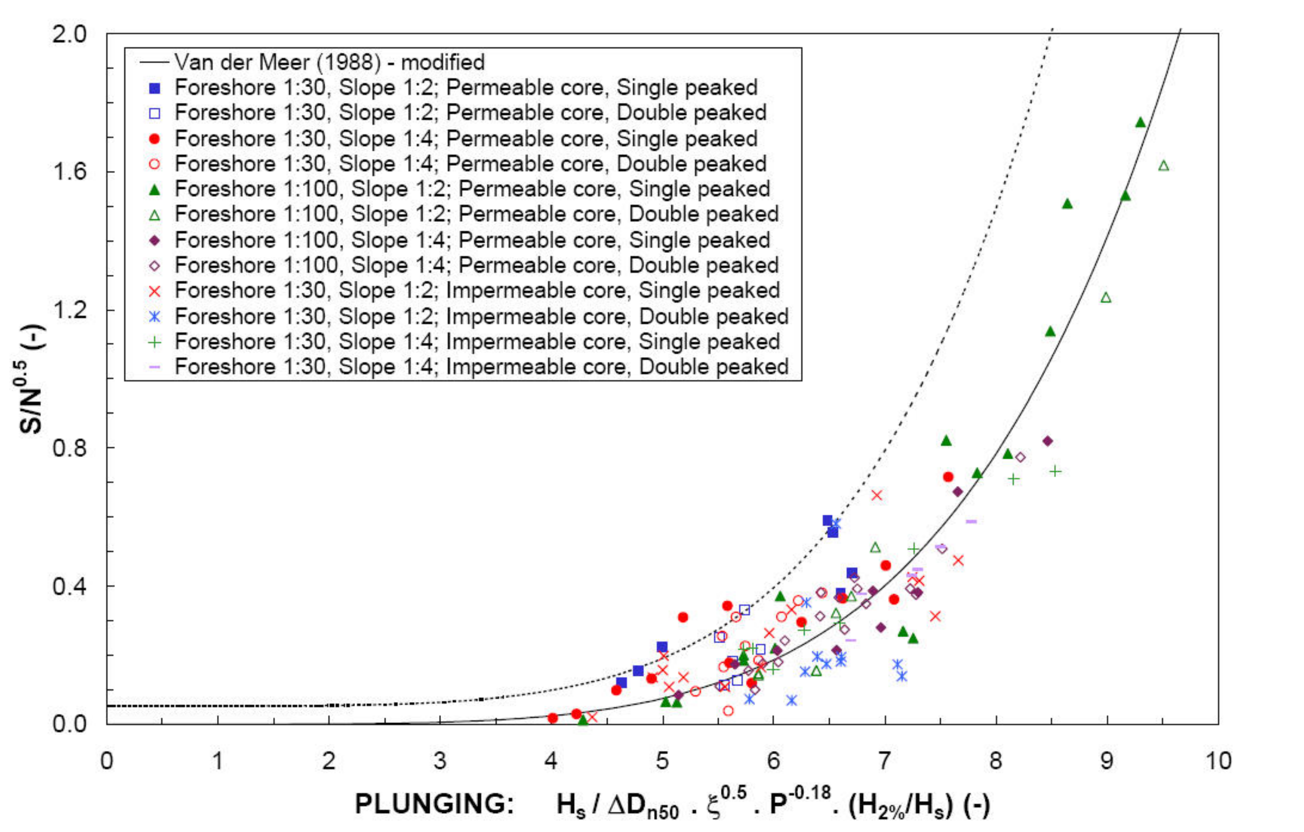


1.4 used as fixed factor for ratio $H_{2\%}/H_s$

incorrect conversion from T_m to $T_{m-1,0}$

Van Gent:
$T_m = 0.957\ T_{m-1,0}$
Van der Meer:
$T_m = 0.904\ T_{m-1,0}$

Data of Van Gent and original Van der Meer equation



Data of Van Gent, recalibrated formula
Plunging waves

c_{pl} changed from 8.68 to 8.4

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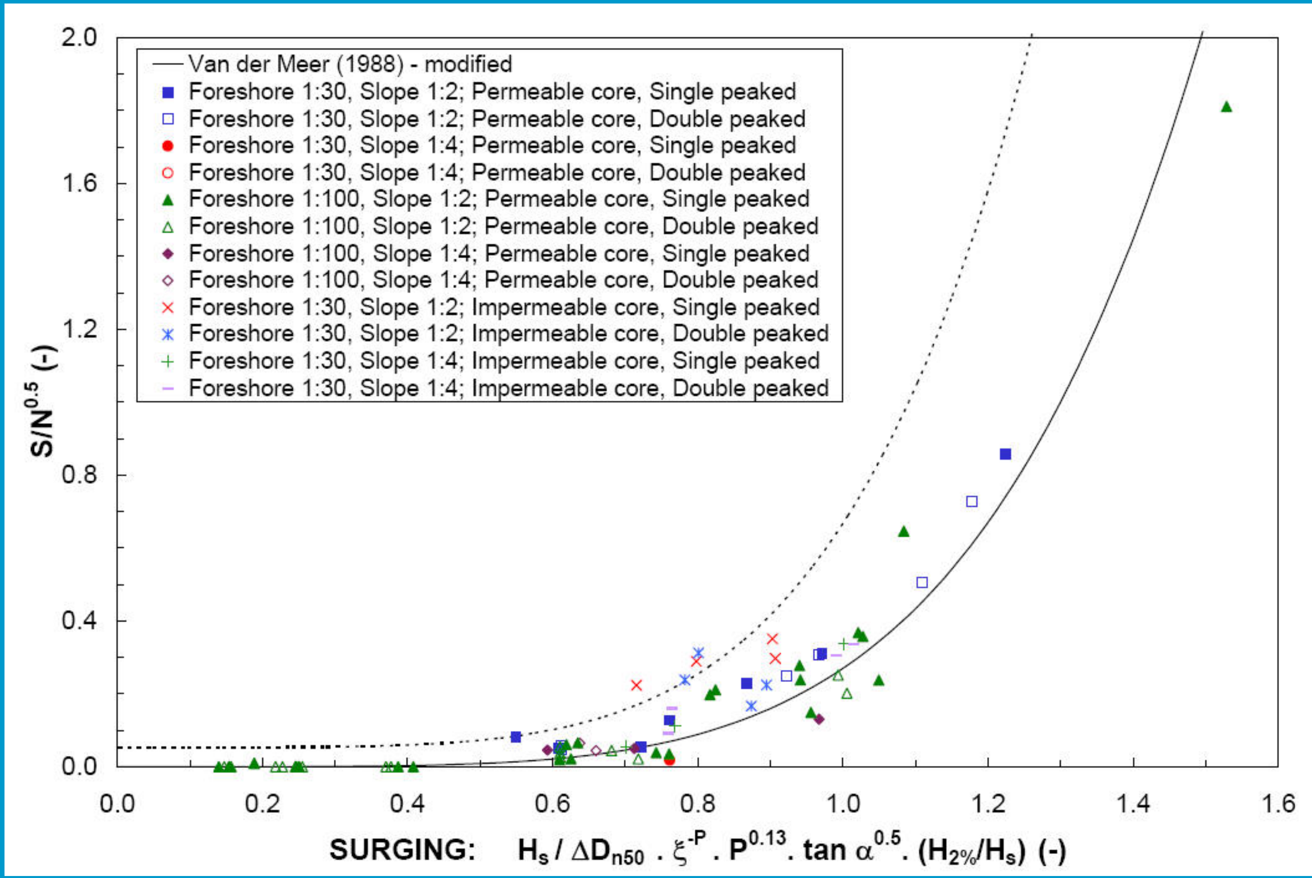
Data of Van Gent and original Van der Meer equation

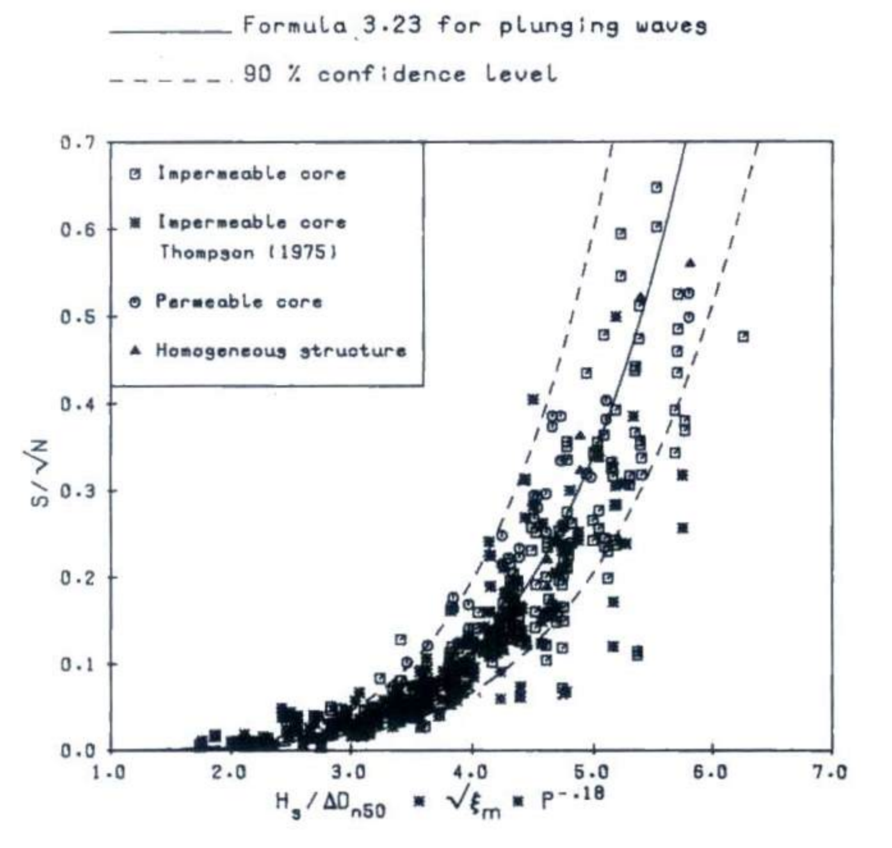


Data of Van Gent, recalibrated formula
Surging waves

c_{su} changed from 1.4 to 1.3

Datasets of Van der Meer

- 309 tests
- slope of foreshore: horizontal (47 tests with 1:30)
- slope of structure: 1:1.5 to 1:6
- core: permeable and impermeable
- ratio H_s/d: 0.12 - 0.26 (deep water)



Datasets of Van Gent

core	# of tests	foreshore	slope	H_s/d
Permeable Permeable Permeable Permeable Permeable Impermeable Impermeable	37 34 31 26 24 34 21	1:100 1:100 1:100 1:30 1:30 1:30 1:30	1:2 1:2 1:4 1:2 1:4 1:2 1:2	0.34-0.51 0.34-0.52 0.31-0.51 0.23-0.78 0.34-0.73 0.15-0.48 0.27-0.53

VdMeer				
Permeable & impermeable	309	mainly horizontal	1:2 to 1:6	0.12-0.26

Observations

- In paper significant difference between results of Van Gent and of Van der Meer
- In paper Van Gent erroneously assumed a conversion factor of 0.957, while it had to be 0.904
  (because Van der Meer did not use in his original test a standard spectrum)
- Largest part of the Van Gent data are different from the original deep water situation of Van der Meer; also the slope of the foreshore was different for most tests

Conclusions

- For the period one should use $T_{m-1,0}$
- In case of standard (deep water) spectrum one may use $T_m = 0.957\ T_{m-1,0}$
- But be careful: the spectrum used in the tests of Van der Meer gave a conversion of $T_m = 0.904\ T_{m-1,0}$
- The recalibration of Van Gent should not be applied for deep water
- For the time being the following coefficients are recommended:

	deep	shallow
c_{pl}	9.13	8.4
c_{su}	1.33-1.39	1.3

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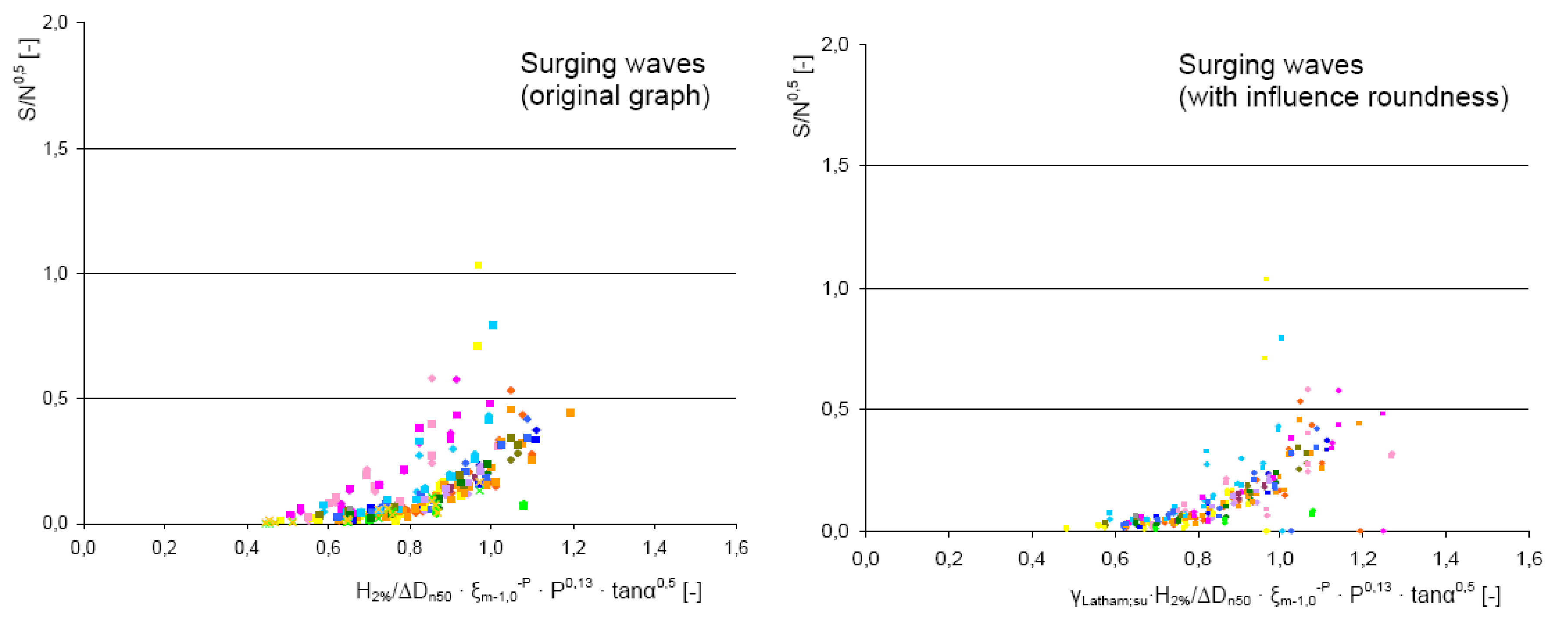
Comparison after all corrections



Marcel Mertens, 2007

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inconsistency

$$\frac{S}{\sqrt{N}} = \left[\frac{1}{c_{pl}} \left(\frac{H_{2\%}}{H_s} \right) \frac{H_s}{\Delta D_{n50}} \xi_{m-1,0} P^{0.18} \right]^5$$

$\xi_{m-1,0}$ is a function of H_s

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General equations (deep & shallow)

$$\frac{H_{2\%}}{\Delta d_{n50}} = c_{pl} P^{0.18} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \left(s_{m-1,0} \right)^{0.25} \sqrt{\cot \alpha}$$ for plunging waves

$$\frac{H_{2\%}}{\Delta d_{n50}} = c_s P^{-0.13} \left(\frac{S}{\sqrt{N}} \right)^{0.2} \left(s_{m-1,0} \right)^{-0.25} \left(\xi_{s-1,0} \right)^{P-0.5}$$ for surging waves

$$\xi_{cr} = \left[\frac{c_{pl}}{c_s} P^{0.31} \sqrt{\tan \alpha} \right]^{\frac{1}{P+0.5}}$$ transition

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A new formula by Van Gent

$$\frac{S}{\sqrt{N}} = \left(0.57 \frac{H_s}{\Delta D_{n50}} \sqrt{\tan\alpha} \frac{1}{1 + {D_{n50core}}/{D_{n50}}} \right)^5$$

Extra in this formula:
$D_{n50core}$

Not in this formula:
P
period or steepness

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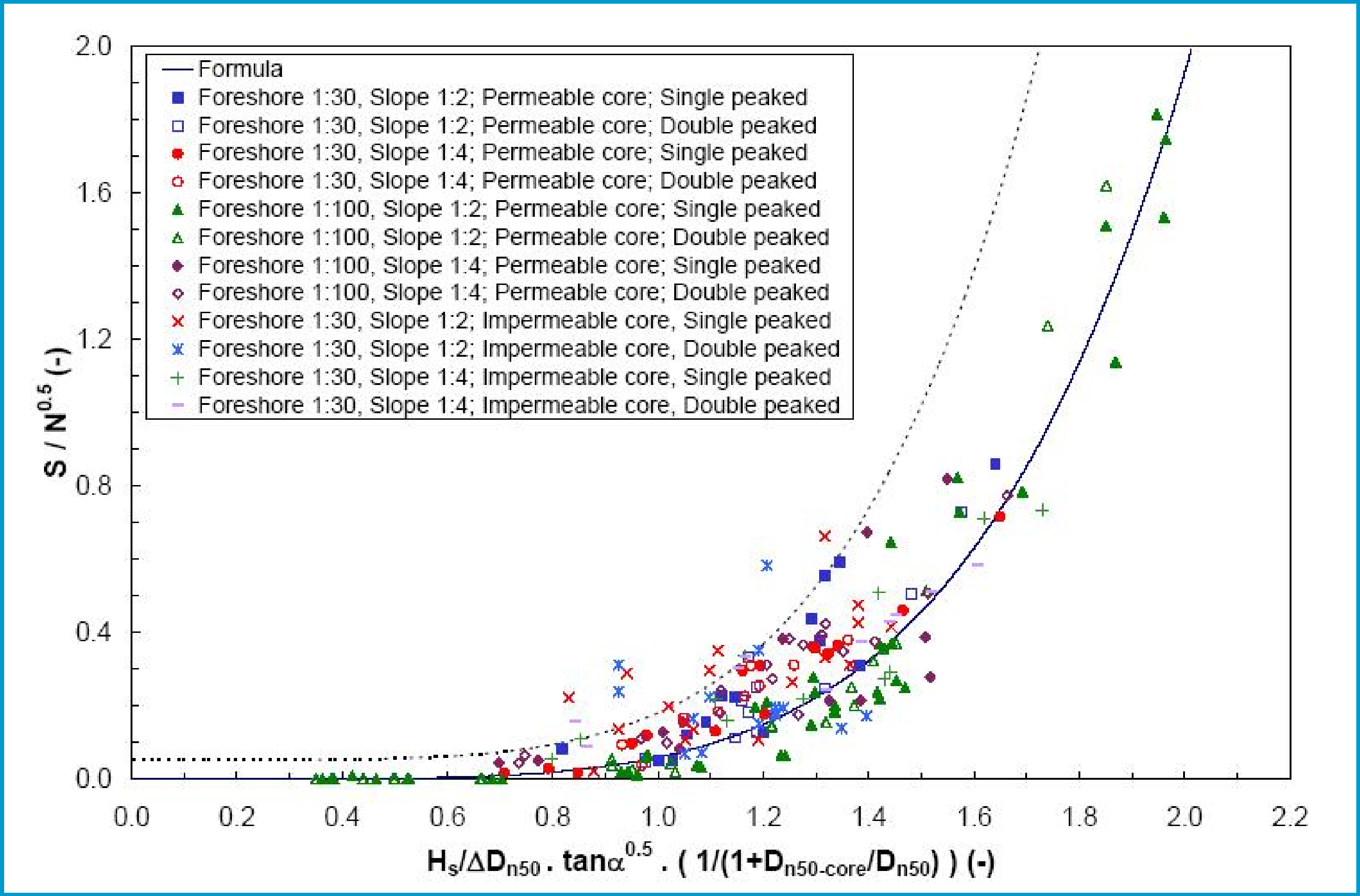
Results of the Van Gent formula



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Reliability of the various equations

Equation	Structure type	σ
Modified vdM Modified vdM	permeable impermeable	0.098 0.133
Modified vdM	all	0.109
Van Gent Van Gent	permeable impermeable	0.103 0.121
Van Gent	all	0.109

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Observations on the Van Gent formula

- Reliability of the Van Gent formula seems as good as the (recalibrated) Van der Meer formula
- Especially for permeable cores results are better
- But Period/Steepness is not included, and is considered as irrelevant
- Reliability is only based on the Van Gent database (shallow water, gentle foreshore)

Conclusions on the Van Gent Formula

- Because on deep water period is relevant (see dataset of Van der Meer) and because spectrum shape is also relevant (introduction of $T_{m-1,0}$) it is not advisable to exclude the period in stability formulas
- The parameter $\dfrac{1}{1+D_{n50core}/D_{n50}}$ is maybe a better parameter for describing the permeability of a structure than the P-value of Van der Meer, because P cannot be determined objectively

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low crested dams (1)

crest above water level

$$\text{Reduction } d_{n50} = \frac{1}{1.25 - 4.8\dfrac{R_c}{H_s}\sqrt{\dfrac{s_{0p}}{2\pi}}}$$

crest below water level

$$\frac{H_s}{\Delta d_{n50}} = -7\ln\left(\frac{1}{2.1+0.1S}\frac{h_c}{h}\right)\sqrt[3]{s_p}$$

R_c	crest height with respect to SWL
s_{0p}	(deep water) wave steepness (from T_p)
h	waterdepth
h_c	height of dam

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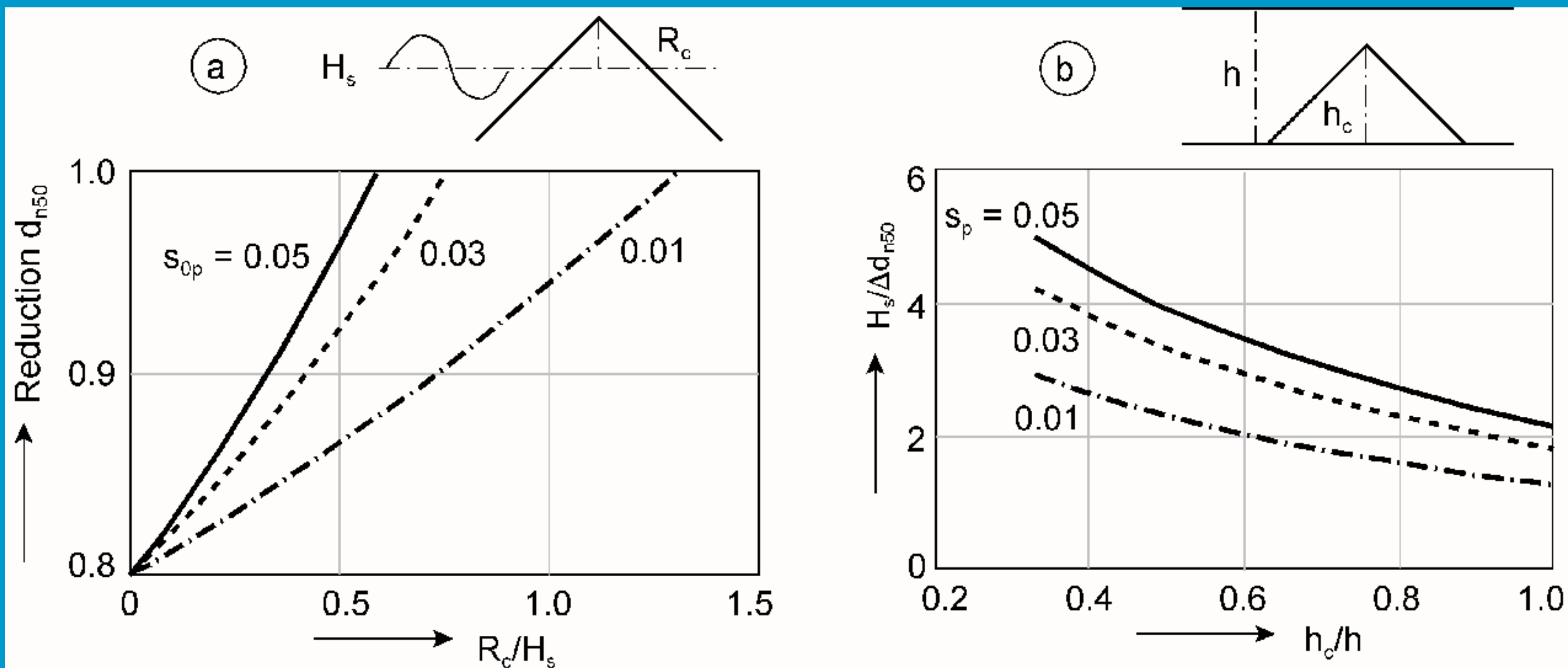
low crested dams (2)



low crested dams (3)

- Given formula are for the front side of the breakwater
- According to Van der Meer: in case of same block size at rear slope, no problems.
- But probably over-dimensioned.
- Tests performed in our lab to find out
  - split research into two steps
    - load of plunge on inner slope
    - dimension of plunge
  - try to understand stability process

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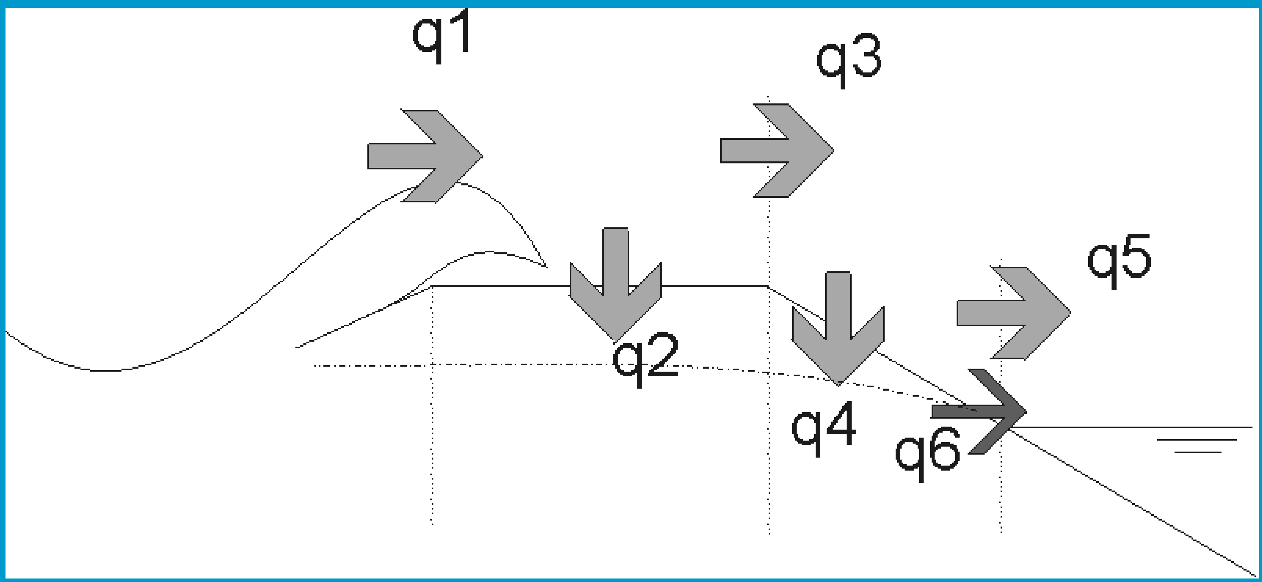
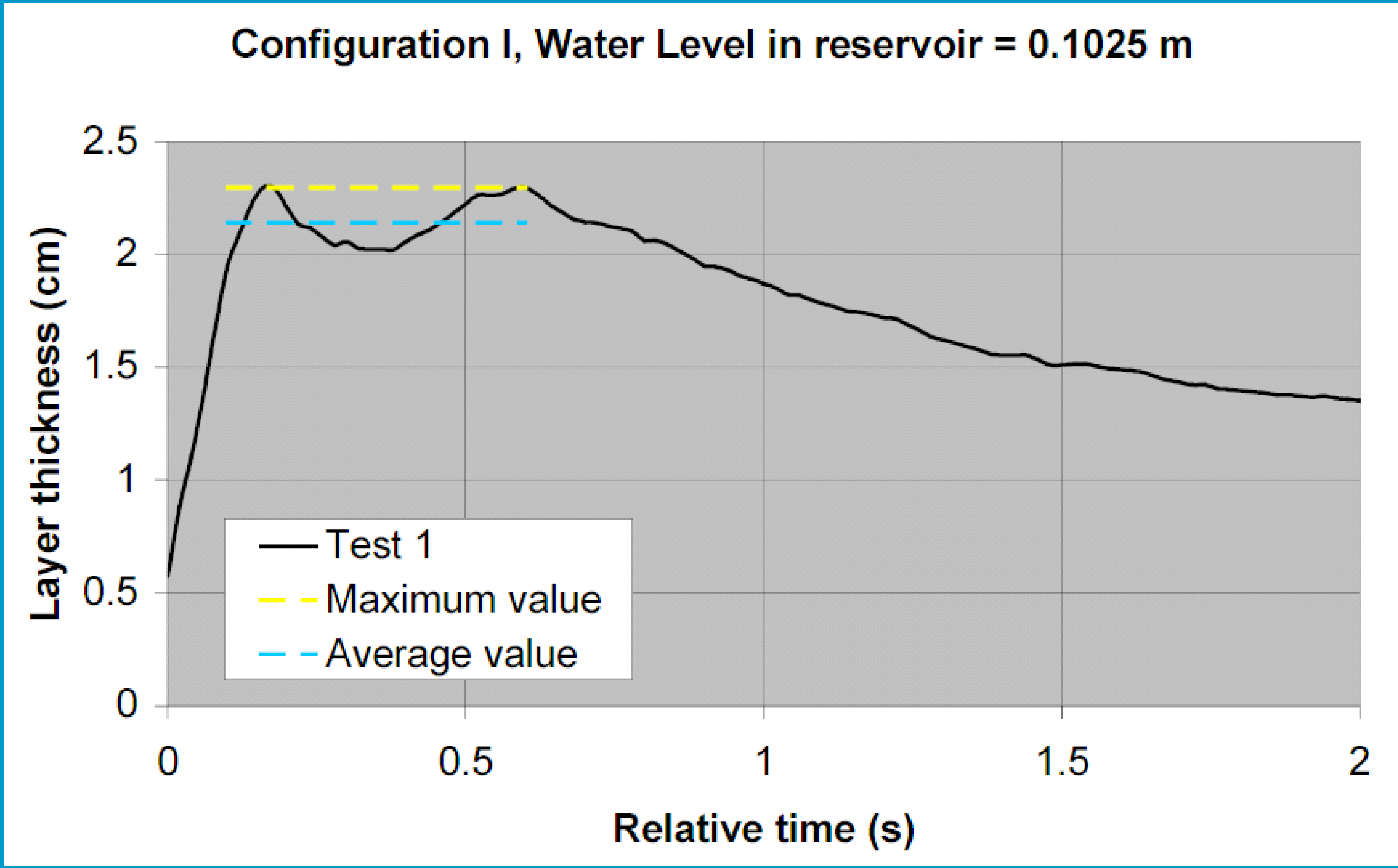
The overtopping process



what happens during a plunge

Layer thickness as function of time



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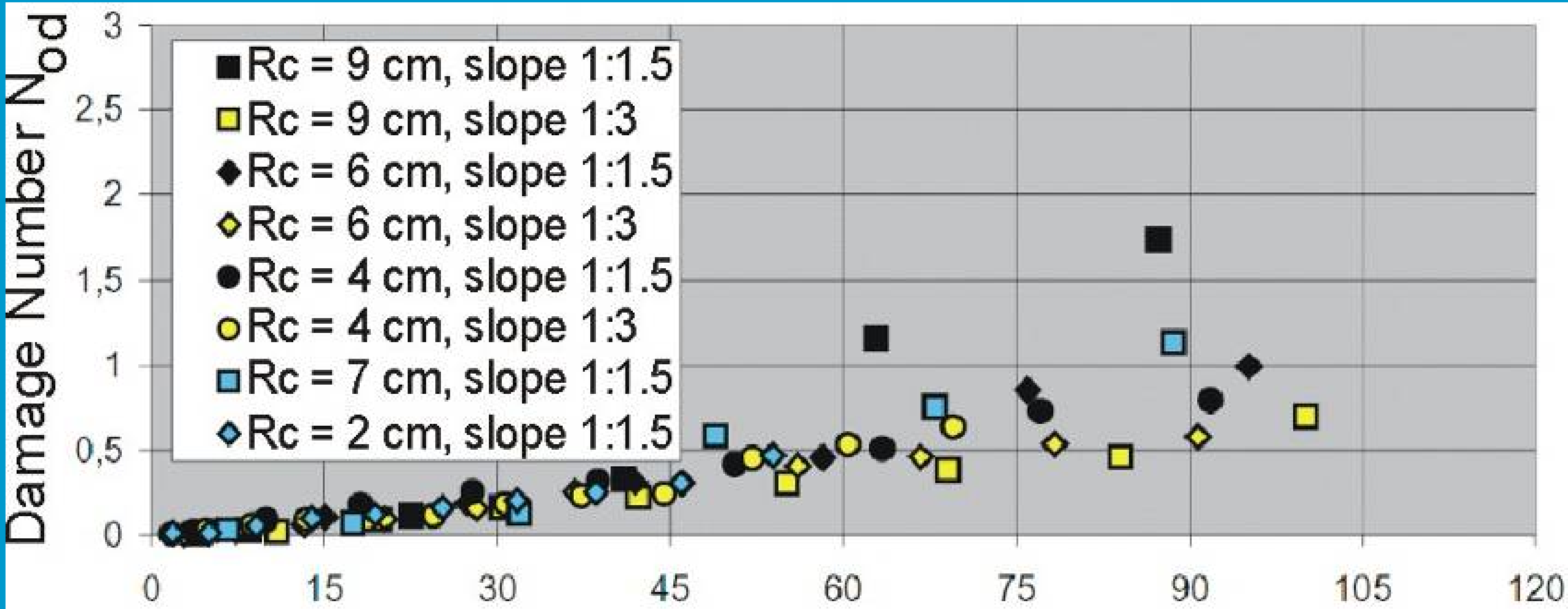
The u_{char} as describing parameter

For velocity use “characteristic velocity”

The characteristic velocity is the maximum discharge divided by maximum layer thickness (and by flume width)

$$\Theta_{u_{char}//,R_c,\alpha,i} = \frac{(u_{char}\cos(\beta-\alpha))^2}{\Delta g D_{n50}} \frac{R_c}{D_{n50}} \sin(\alpha)\sqrt{i}$$

Overall results



$$\Theta_{u_{char}//, R_c, \alpha, i} = \frac{(u_{char}\cos(\beta-\alpha))^2}{\Delta g D_{n50}} \frac{R_c}{D_{n50}} \sin(\alpha)\sqrt{i}$$

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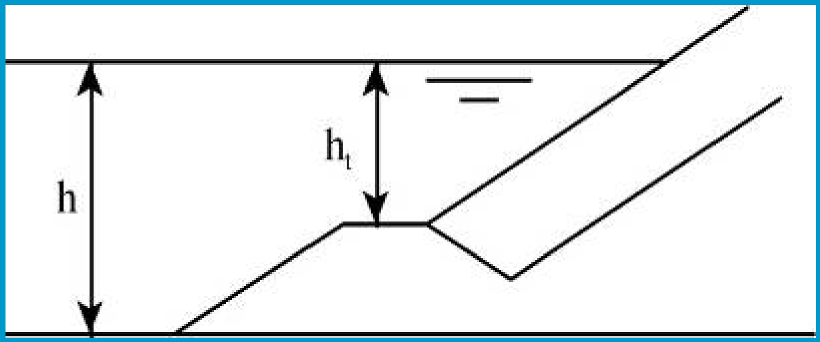
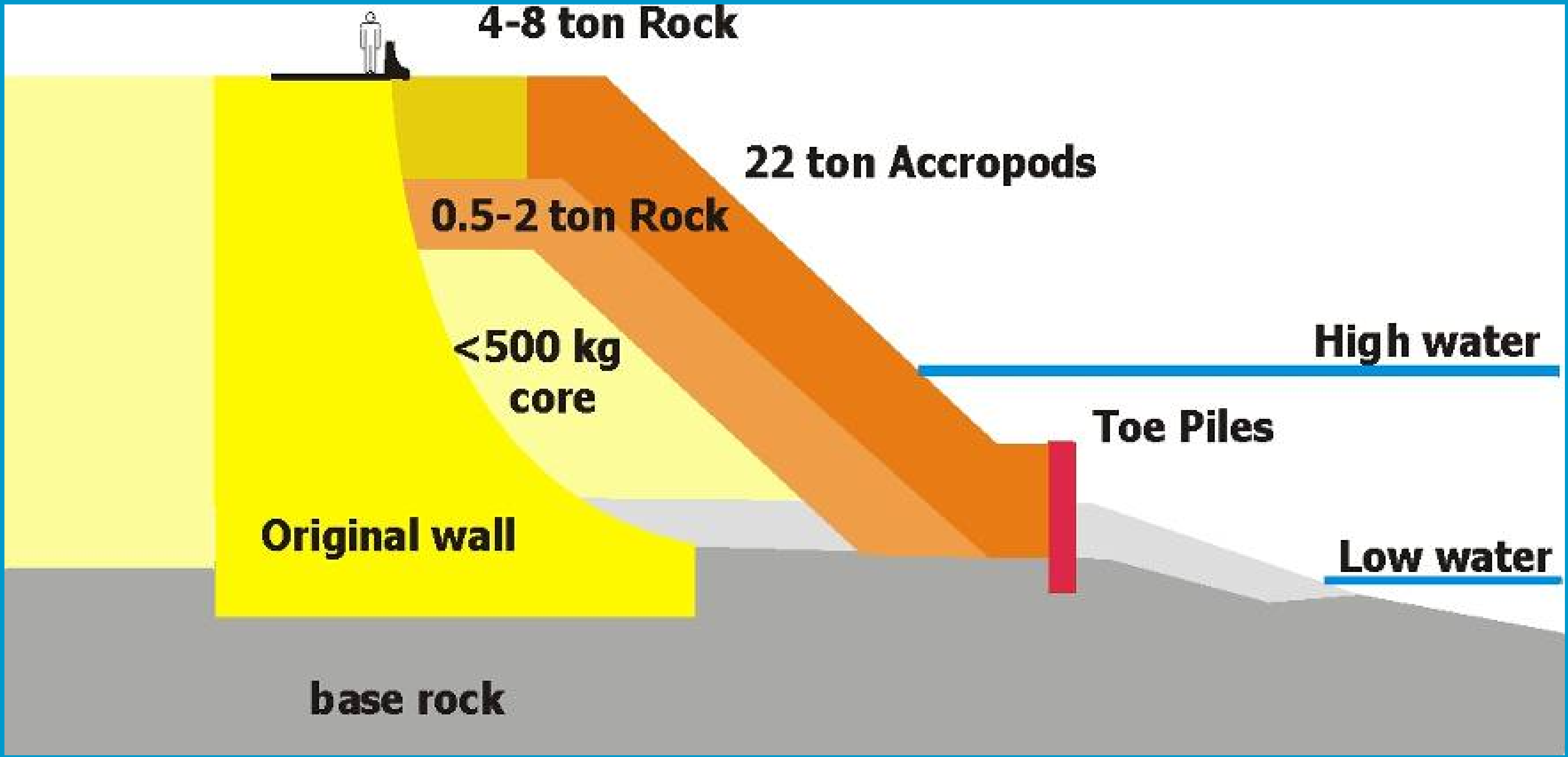
toe stability



TU Delft

Example using toe piles



Scarborough seawall improvement

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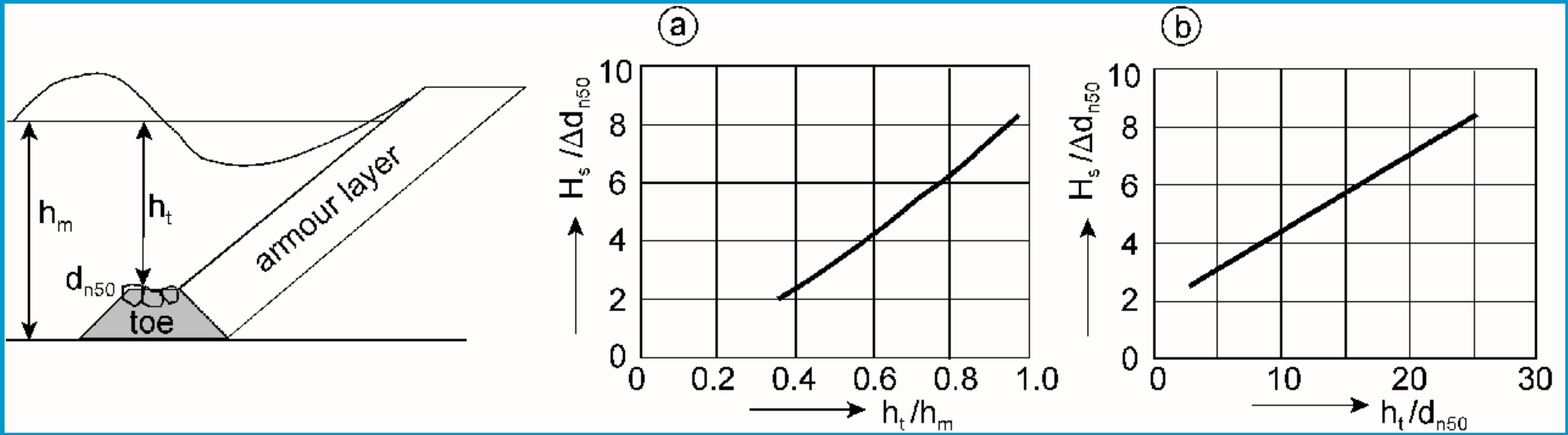
stability of toes



a: deep toes with small damage

$$\frac{H_s}{\Delta d_{n50}} = 8.7 \left(\frac{h_t}{h_m} \right)^{1.4}$$

b: shallow toes

$$\frac{H_s}{\Delta d_{n50}} = 1.1 \left(0.24 \frac{h_t}{d_{n50}} + 1.6 \right)$$

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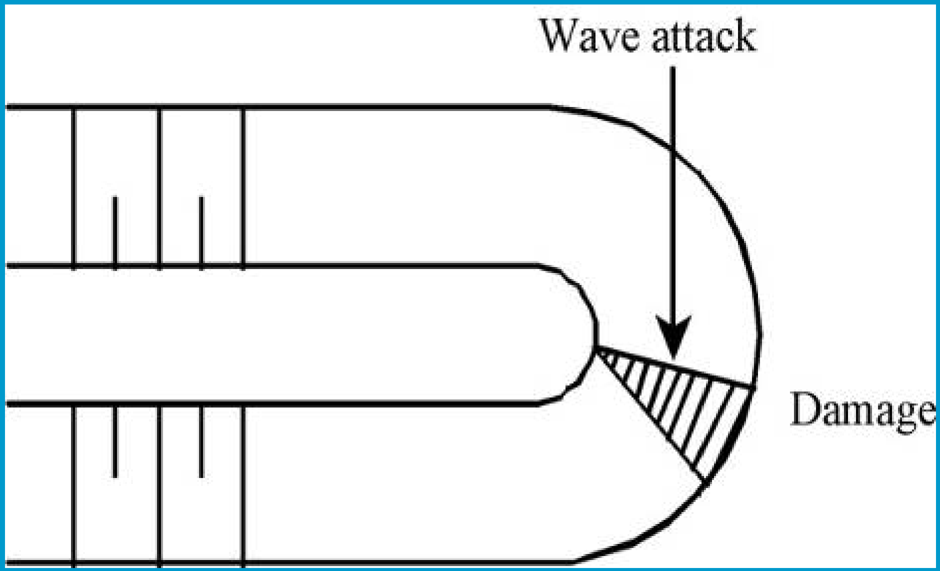
typical damage pattern breakwater head



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