Coastal **R**esearch **C**entre (**FZK**)
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Offshore-wind turbines – Large-scale investigations on scour protection for monopile foundations under sea state conditions

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Offshore - Windpark OSB Butendiek

34 km North-West of Sylt, water depth: d = 21 m

Monopile foundation, pile diameter: D = 5.5 m

Scour protection design by IMS Hamburg:

Shields approach

Design wave: H = 12.5 m ; T = 14.0 s

- Protection with geotextile sand containers

- Protection with rock material

Aim: Verification and optimization by GWK investigations in model scale 1:10

	Large-scale tests in the GWK
Part 1	Basic Tests on Optimization of the Model Set-up (Optimization of Scale)
Part 2	Tests on Scour Protection with Geotextile Sand Containers
Part 3	Tests on Scour Protection with Rock Material
Part 4	Tests on Scour Evolution without Scour Protection

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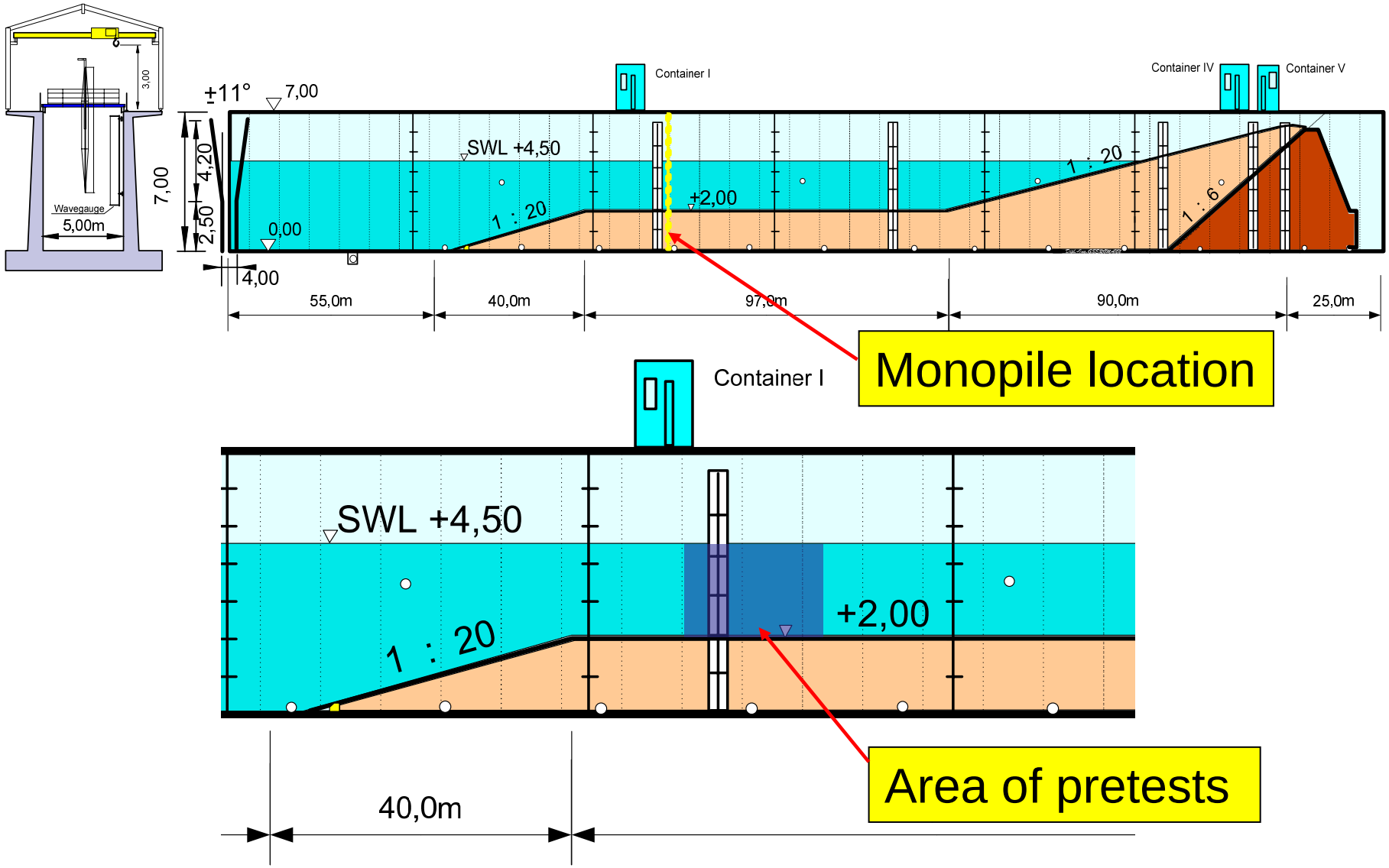

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Stability pretests of single containers and container groups

Geotextile Container Size (unfilled) l x w [cm]	Percentage of Filling [%]											
	56				80				100			
	Weight G [kg]	Dimension [cm]			Weight G [kg]	Dimension [cm]			Weight G [kg]	Dimension [cm]		
		l	w	h		l	w	h		l	w	h
29.5 x 14.5	1.71	28.2	14.4	3.3	2.45	27.2	13.6	5.0	3.06	27.3	13.3	6.6
36.0 x 18.5	3.34	35.6	17.7	3.9	4.78	34.2	17.2	6.0	5.97	35.4	16.9	7.5
47.0 x 23.0	7.24	45.2	22.8	5.2	10.33	44.0	22.1	7.8	12.91	43.9	22.3	10.2
48.0 x 26.0	10.25	51.3	24.8	6.9	14.64	51.3	25.3	9.0	18.31	48.7	25.2	11.8

Jonswap-Spectra N = 120 Waves

Water depth [m]	Tp [s]	$H_{1/3}$ generated [m]			
2.50	5.00	0.60	0.80	1.00	1.20

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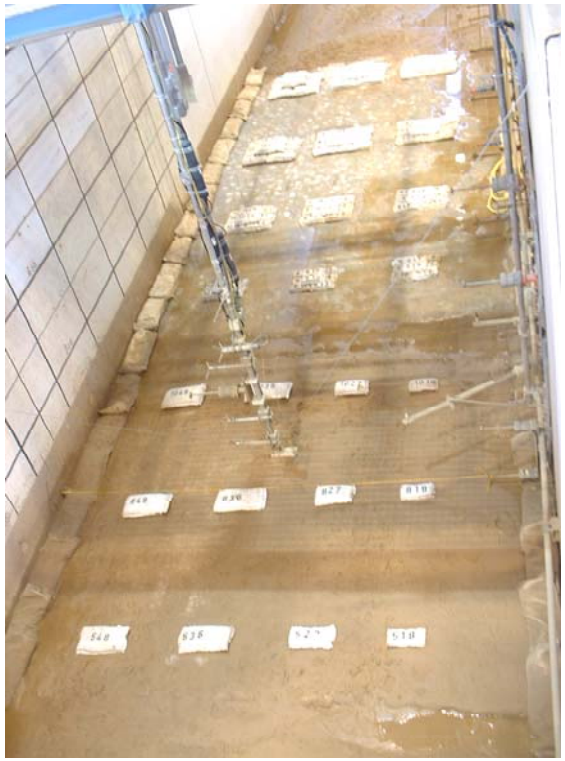
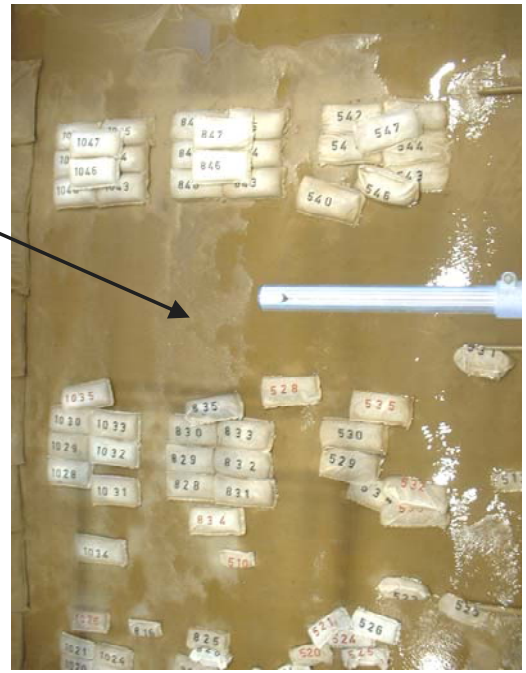
Pretest series with 108 geotextile sand containers placed inline and transverse to wave approach direction

Single sand containers and sand container groups (4 container sizes, 3 filling grades, 12 weights)

Before pretest **After pretest**



Sand containers placed transverse before tests



Detail for the container groups

Displacements of sand containers after a test with $H_{1/3}$ = 1.0 m, T_p = 5 s

Pretest configuration: Transverse placing

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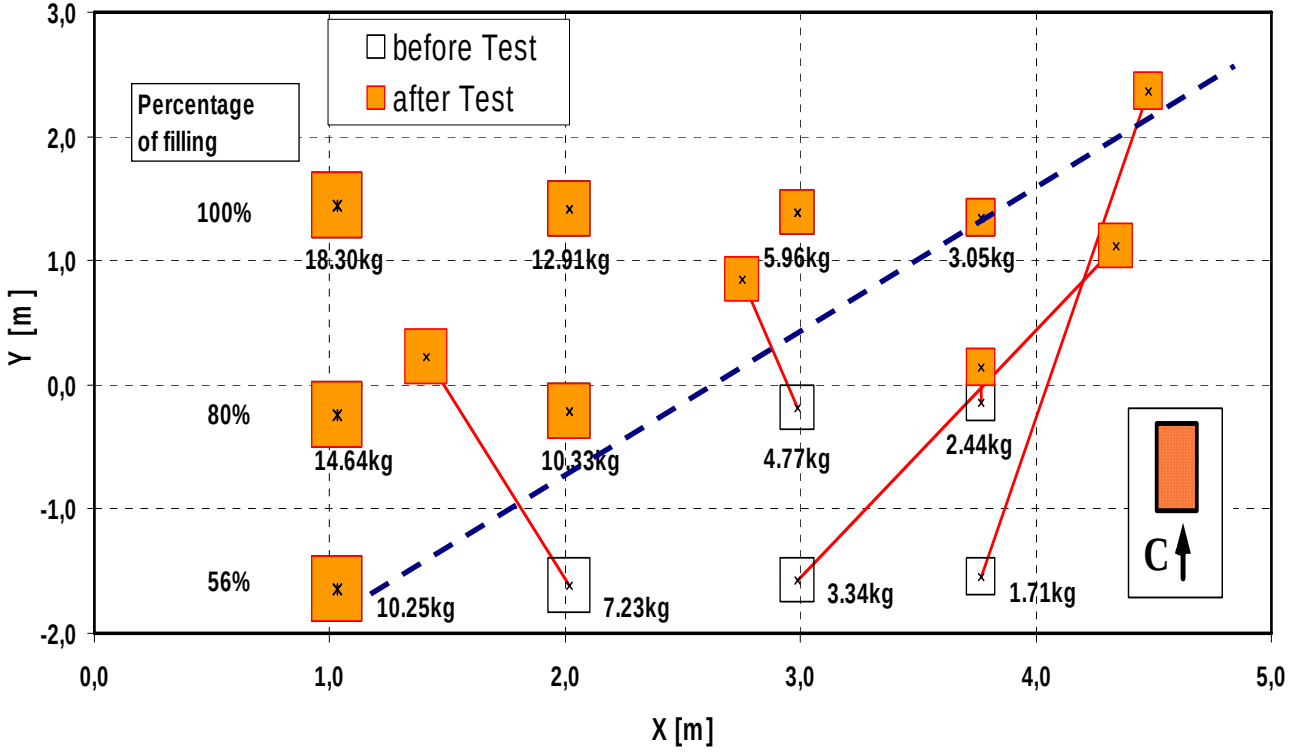
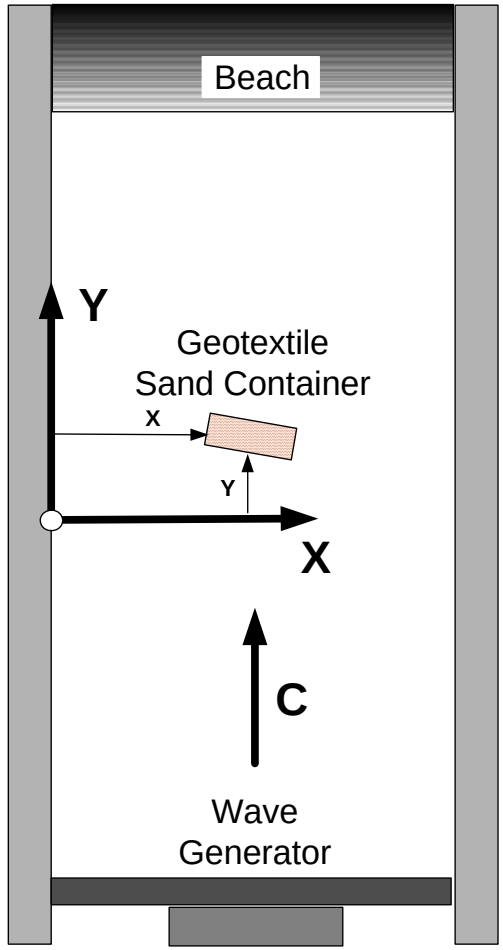
Displacements measured after a pretest with wave attack inline to single sand containers





($H_{1/3\ generated}$ = 1.20 m)

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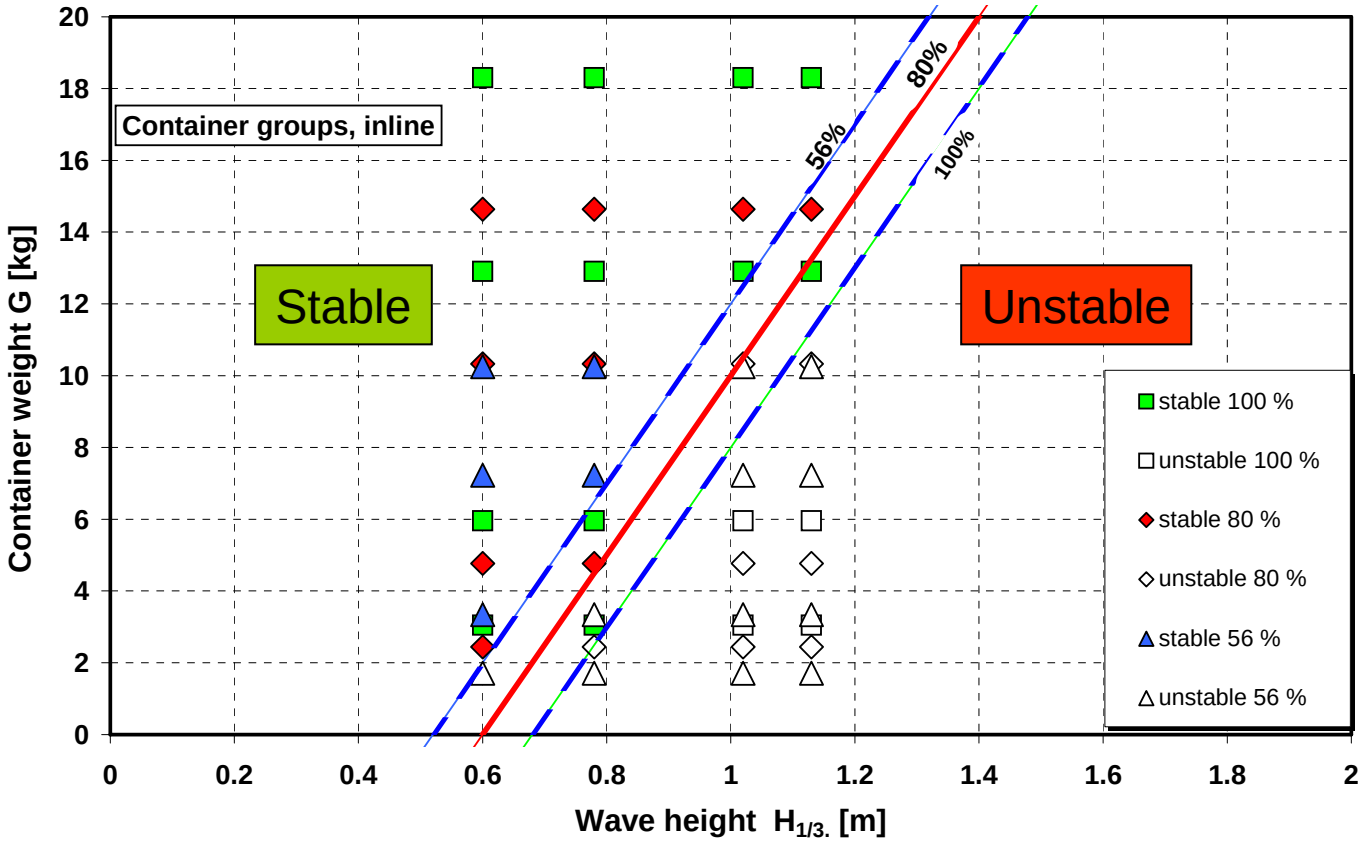
Stability results recorded from pretests with sand container groups inline wave attack



$H_{1/3}$ = 0.6 – 1.2 m; Tp = 5 s

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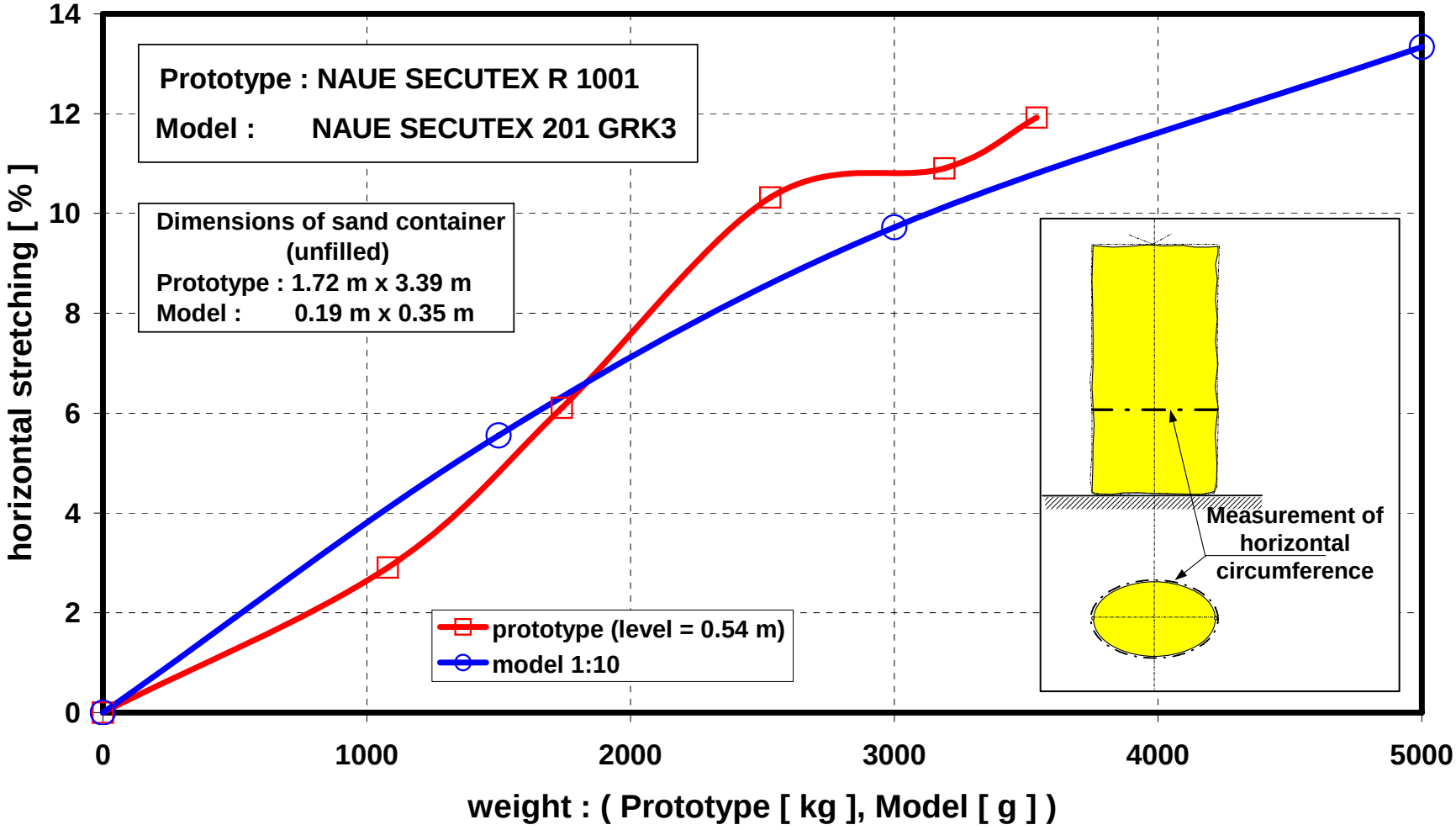
Stretching test for scaling the geotextile material



Geotextile material: Polypropylen (PP), needle-punched non-woven

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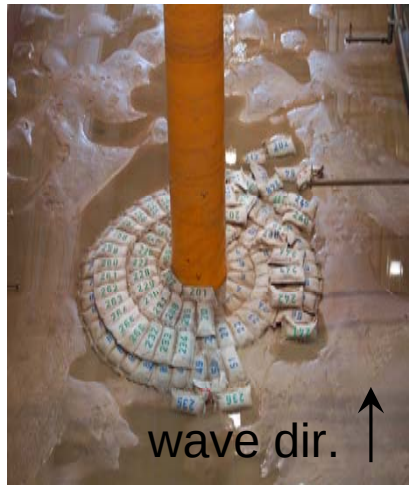
Testseries with sand containers performed in the GWK

Testseries 4.5 kg 85 % filling	Layers	Number of sand containers			Placing conditions	
		Lower layer	Upper layer	Total		Waterdepth [m]
I	2	87	66	153	regular	0 (dry)
II	2	97	92	189	irregular	0 (dry)
III	2	95	94	189	irregular	0.5
IV	2	100	96	196	irregular	2.1



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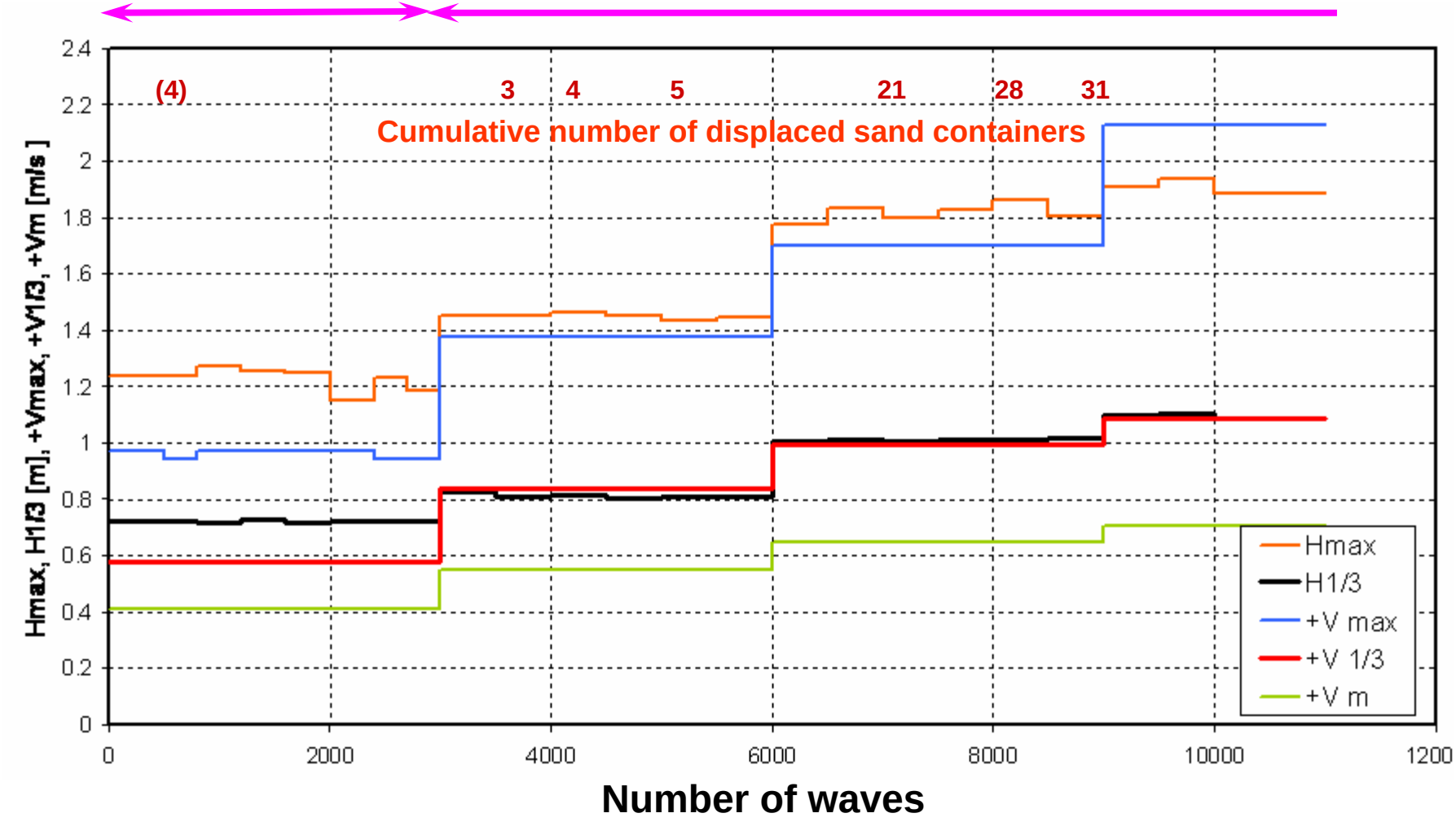
Testseries II Irregularly placed (dry) sand containers

Design Wave H 1/3 = 0.75 m

Displacements



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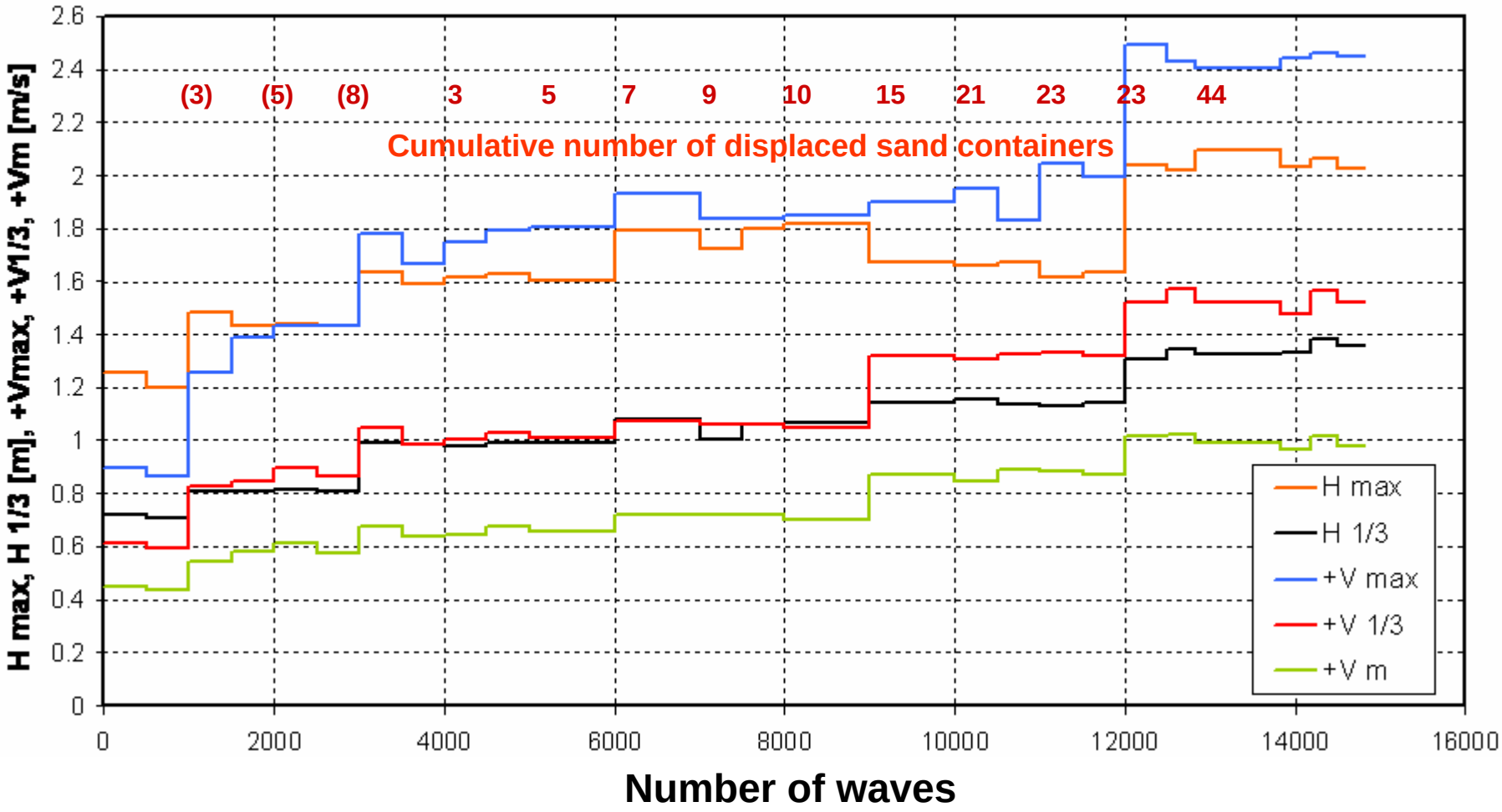
Testseries IV Irregularly placed (under water) sand containers

Design Wave
H 1/3 = 0.75 m

Displacements



Pretests with rock material for scour protection

Comparison of different design approaches

1. After Soulsby without wave current amplification:
   >> critical diameter of the stones 1.40 m
2. After Izbash and Khaldre without wave current amplification:
   >> critical diameter of the stones 0.38 m
3. After Izbash and Khaldre with 70 % wave current amplification:
   >> critical diameter of the stones 1.10 m

Conclusion: Pretests with different stones are necessary!

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Pretests with rock material – Parameters and fotos

	H1/3 [m]	Tp [s]	Tm [s]	Hmax [m]	V+max [m/s]	Stable	Unstable
Single stones	0.59	4.7	4.68	0.79	0.85	all	-
	0.80	5.00	4.54	1.20	1.05	all	-
	0.96	5.36	4.82	1.34	1.19	all	-
	1.34	5.00	4.54	1.92	1.36	residual	2 / 3 kg
	0.98	6.19	5.30	1.32	1.51	residual	1 / 2 / 3 kg
	1.16	5.97	5.39	1.42	1.37	residual	1 / 2 / 3 kg
	1.15	7.12	6.21	1.58	1.65	residual	1 / 2 / 3 kg
Stone groups	0.59	4.69	4.71	0.81	0.78	all	-
	0.80	5.00	4.53	1.21	1.04	3 kg	0.5 / 1 / 2 kg
	0.96	5.36	4.75	1.42	1.19	3 kg	0.5 / 1 / 2 kg
	1.09	5.00	4.50	1.46	1.31	2 kg	0.5 / 1 / 3 kg

single stones 1.0 to 18.9 kg

groups of stones 0.5 to 3.0 kg

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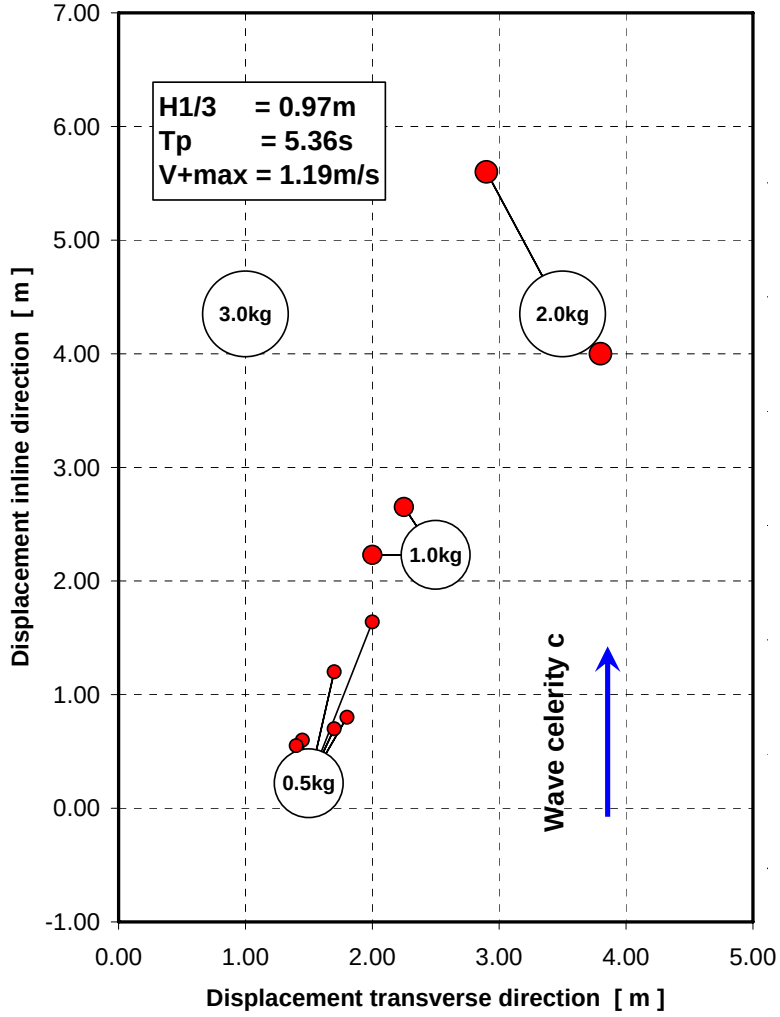
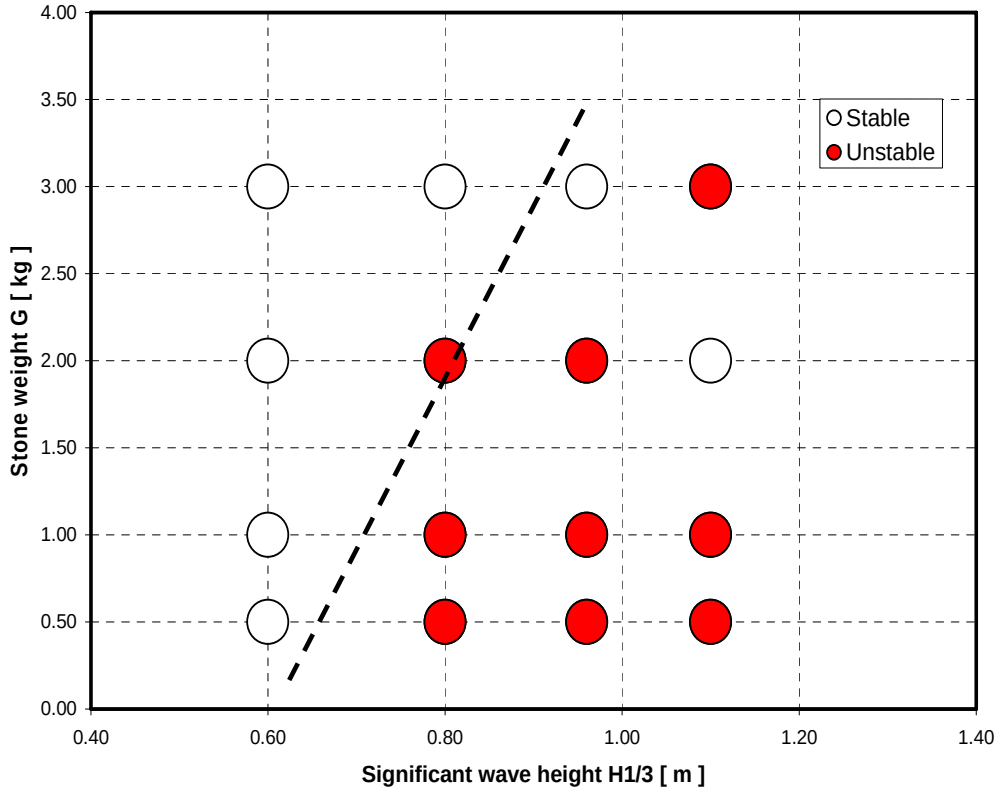
Results of the pretests with groups of rock material





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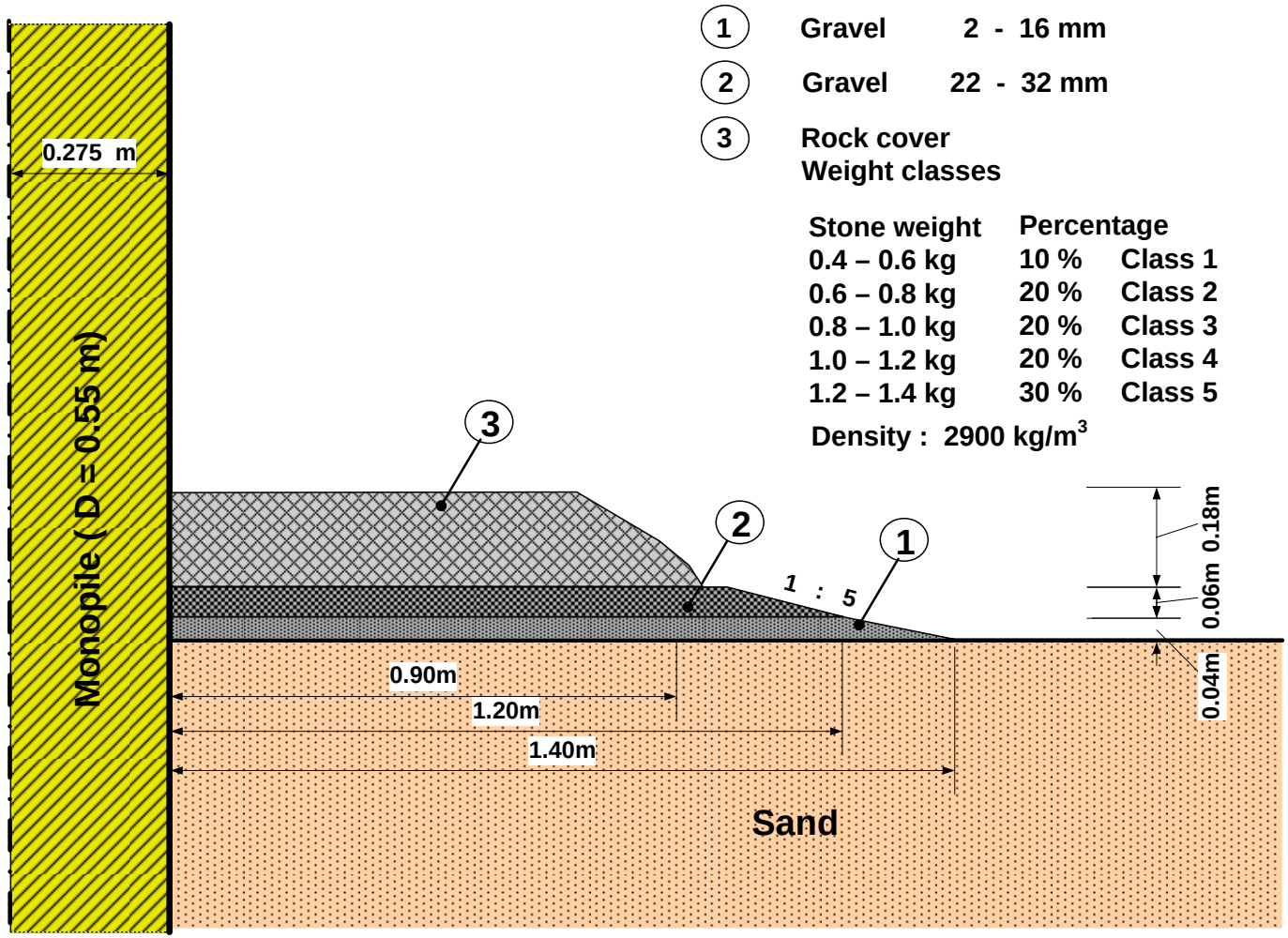
Testseries with scour protection of rock material - Model scale 1 : 10



Axially symmetrical cross section

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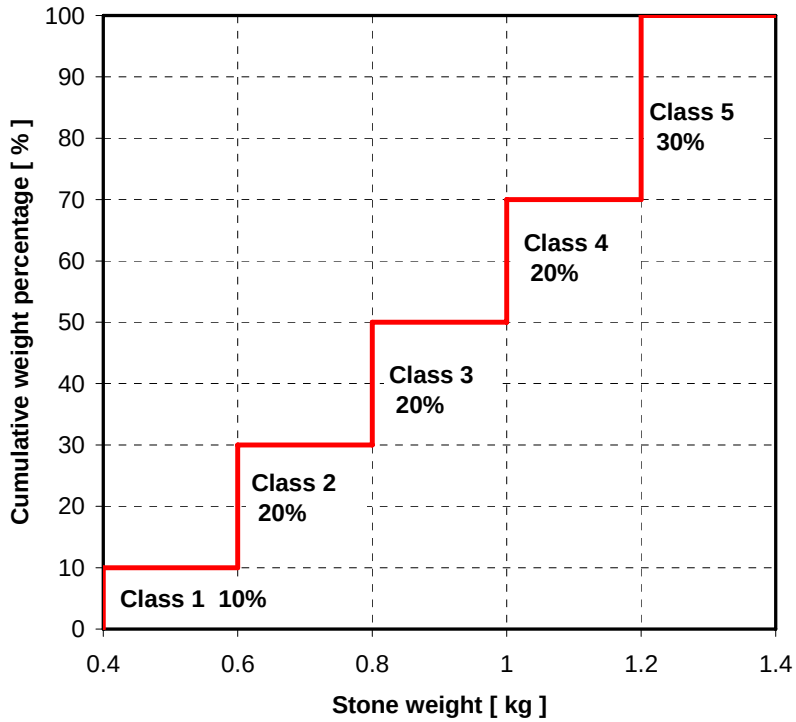
C

Scour protection of rock material

in the Large Wave Channel (GWK)

Model scale 1 : 10

Rock cover layer



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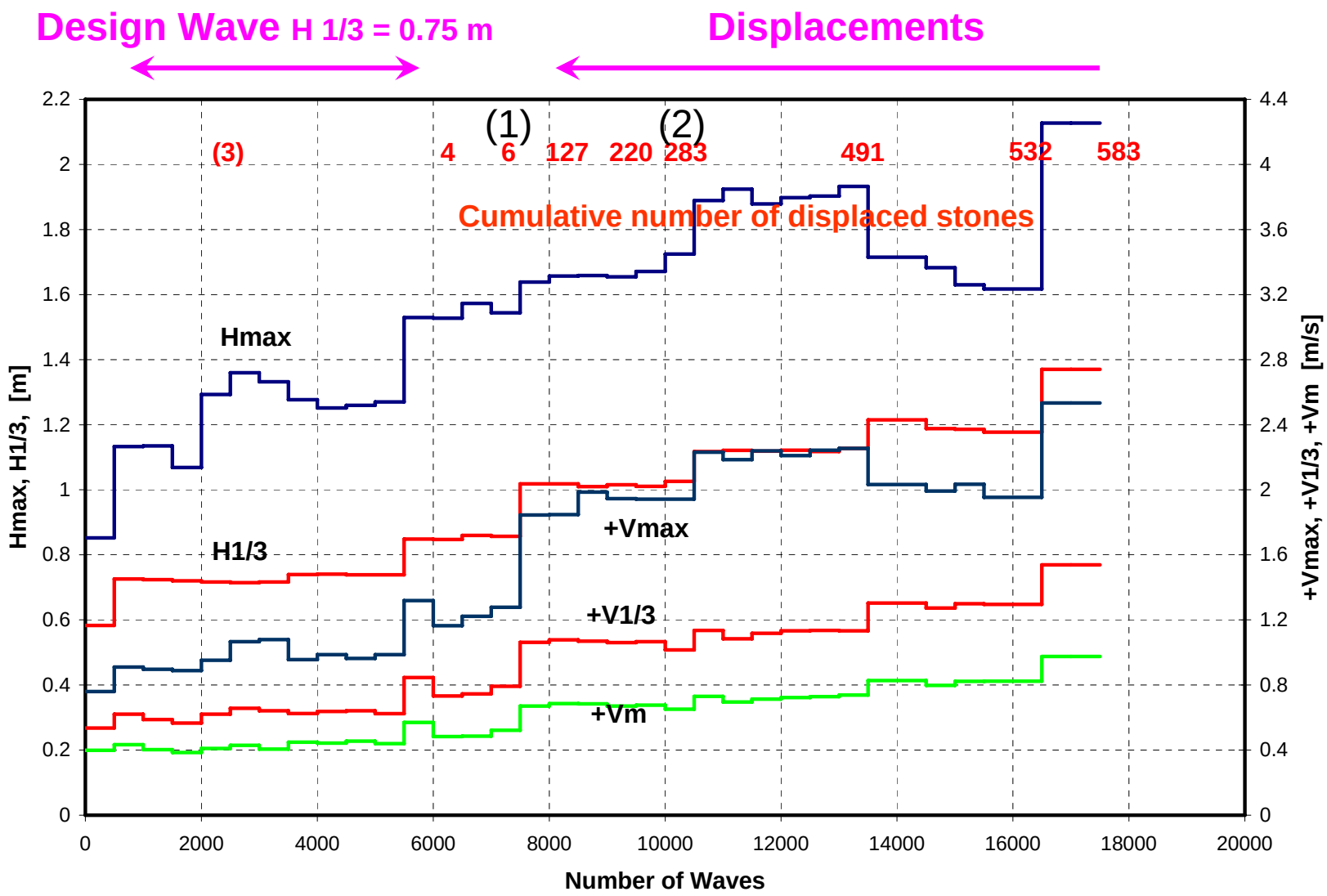
Testseries with scour protection of rock material



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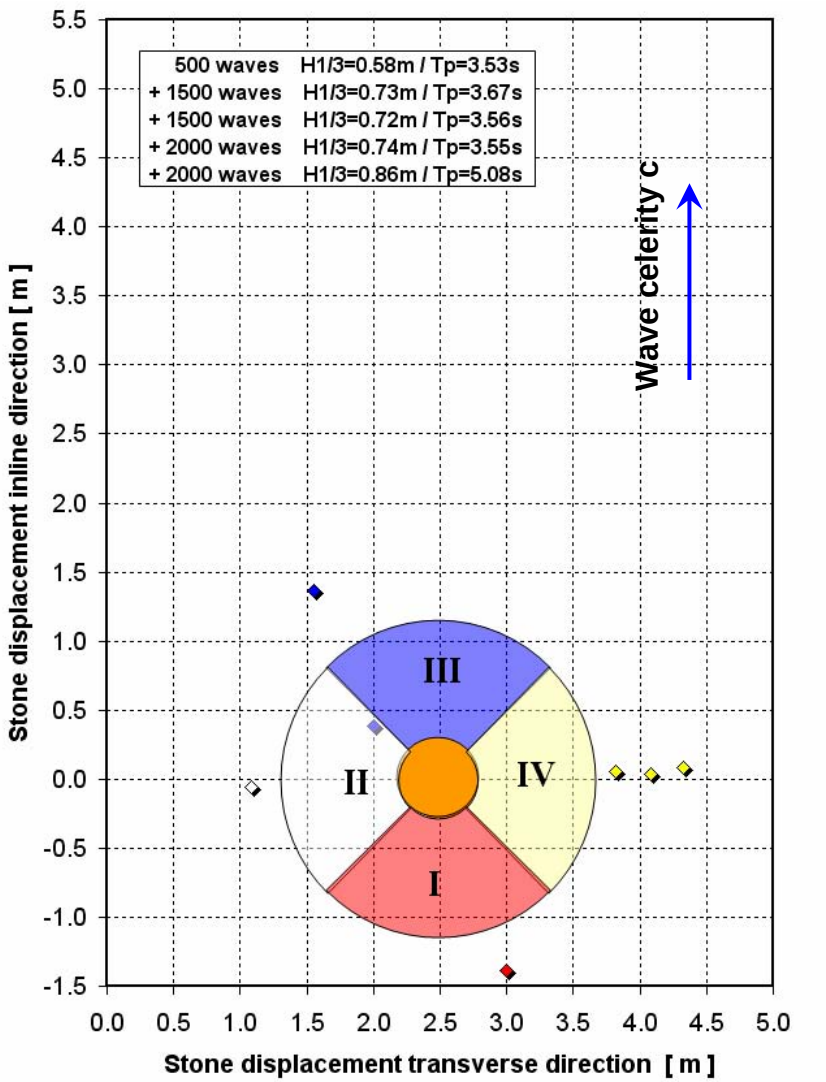
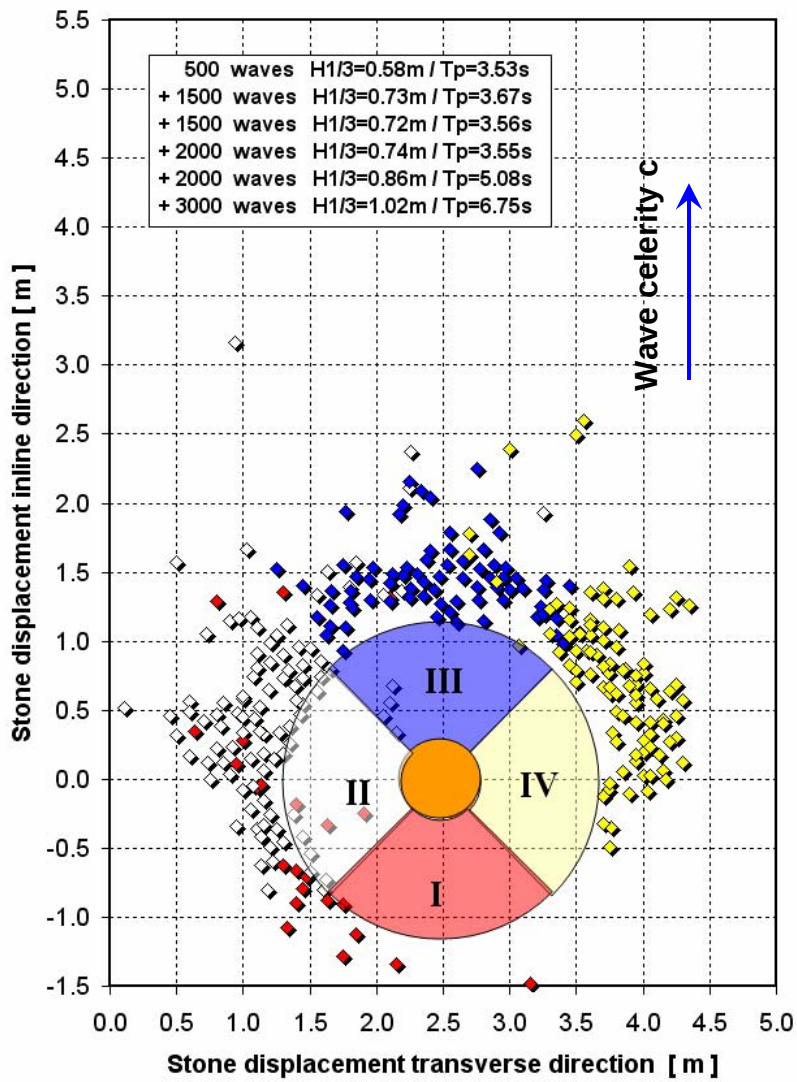
(1) Displacement of **6** stones

after **7500** waves (H1/3 = 0.86 m, Tp = 5.08 s)



(2) Displacement of **283** stones

after **10500** waves (H1/3 = 1.02 m, Tp = 6.76 s)



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(1) Displacement of
6 stones
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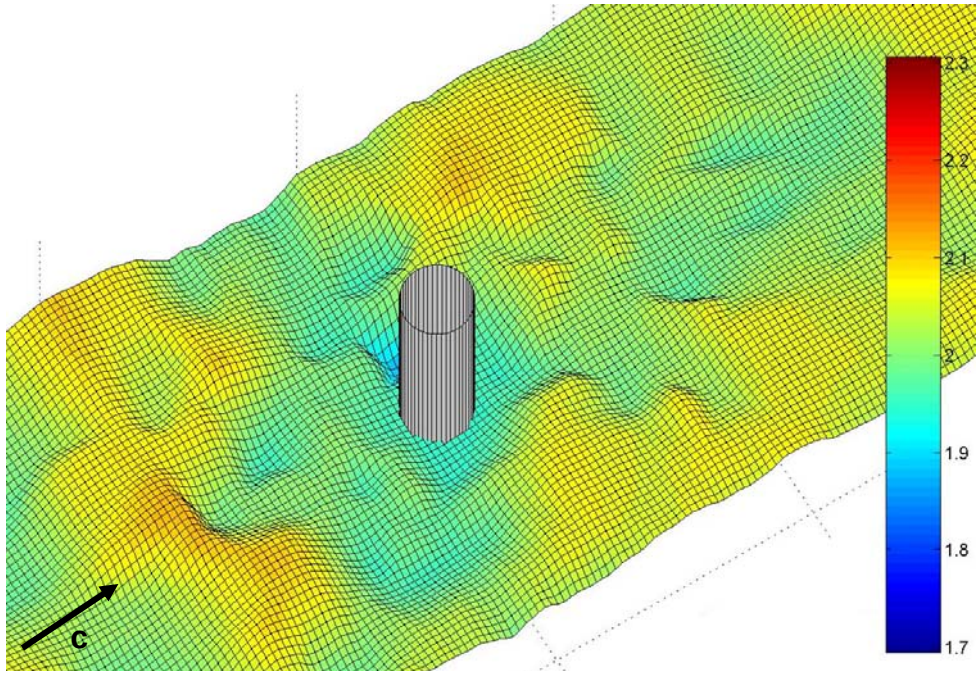


Testseries for scour evolution

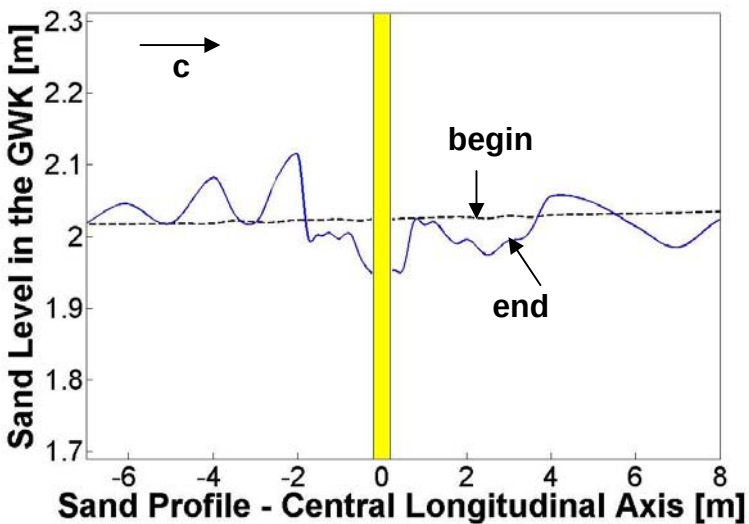
Generated wave spectra

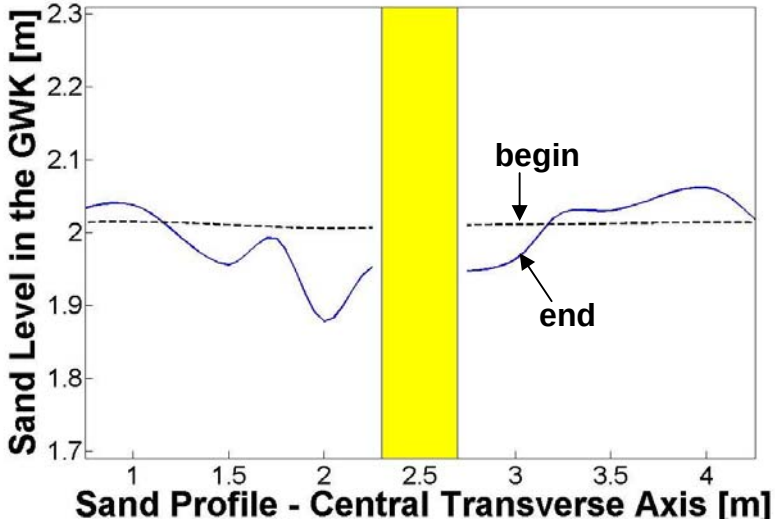
H 1/3 = 0.75 m

T p = 5.04 s

N = 9000 waves

No typical scour occurrence





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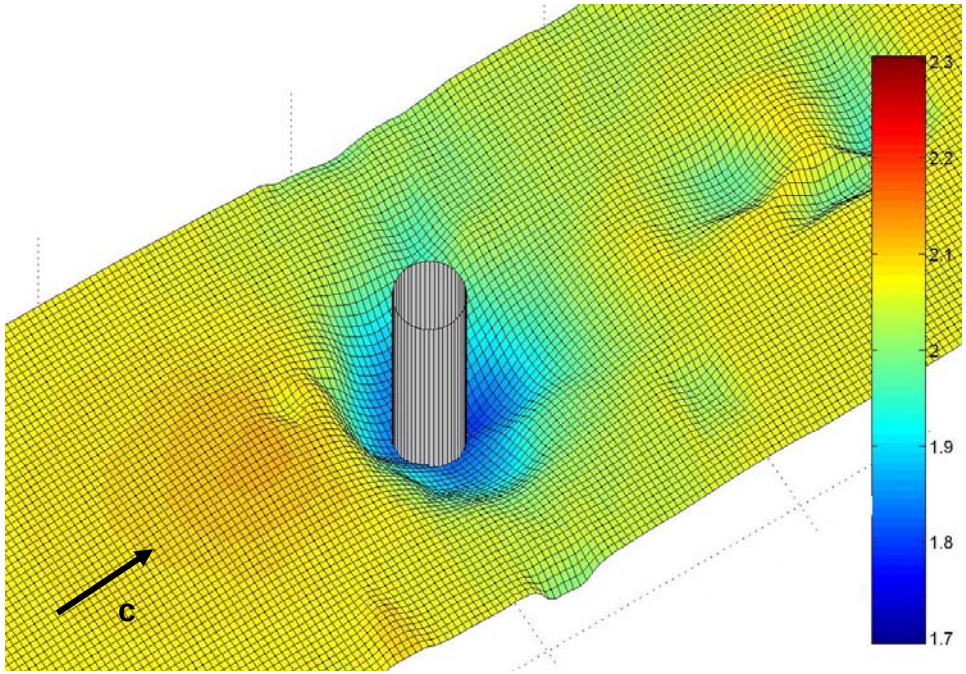


Testseries for scour evolution

Generated wave spectra

H 1/3 = 0.80 m

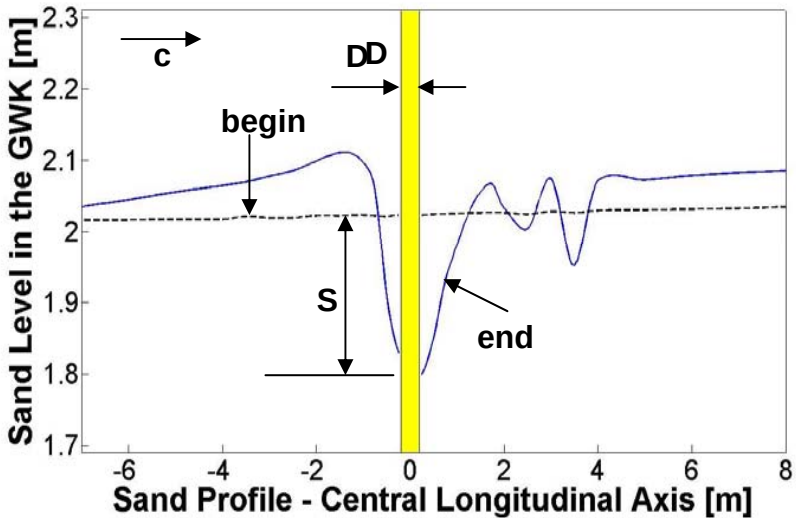
T p = 6.66 s

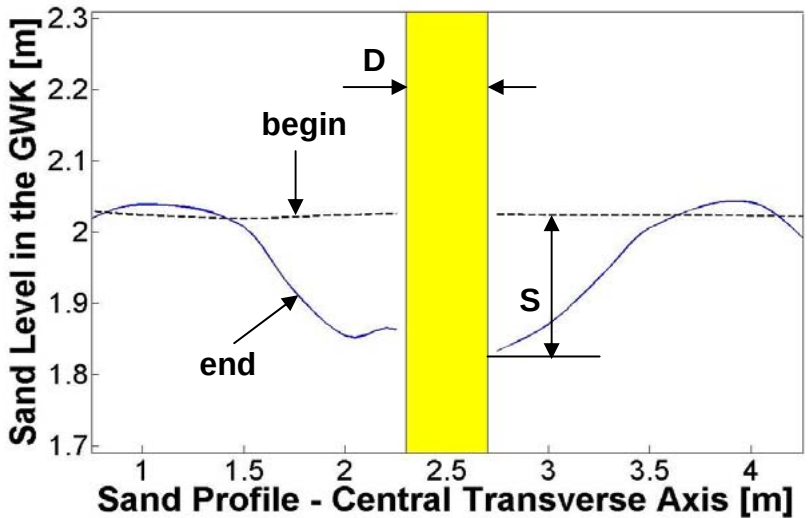
N = 6000 waves

First result:

Ratio max. scour depth

to pile diameter: S/D = 0.42





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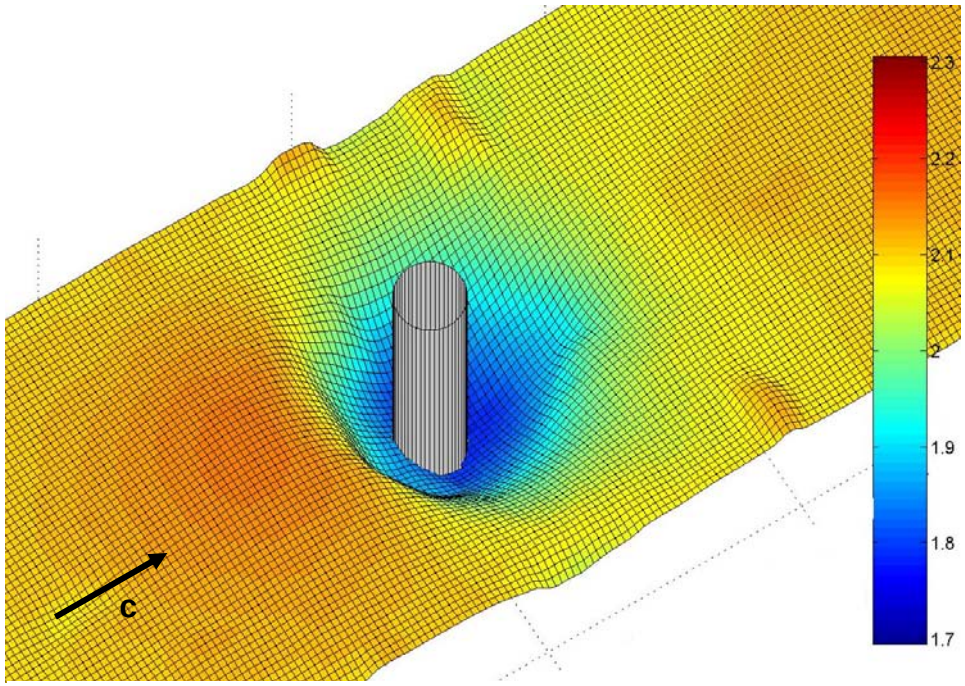


Testseries for scour evolution

Generated wave spectra

$H_{1/3}$ = 0.90 m

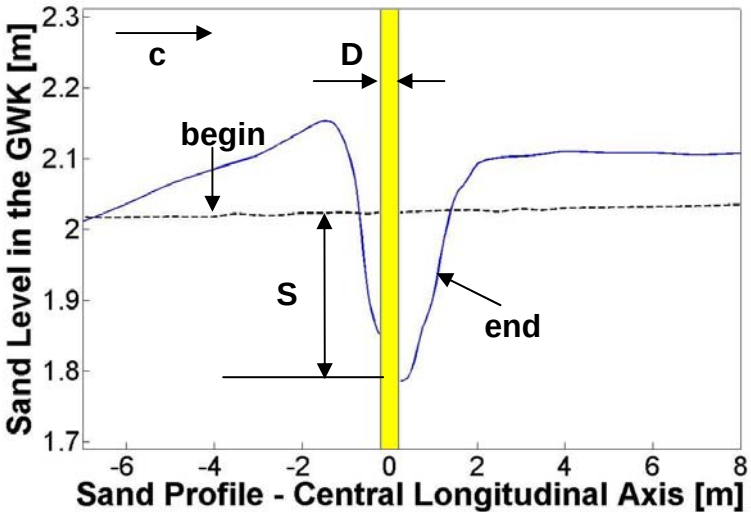
T_p = 7.60 s

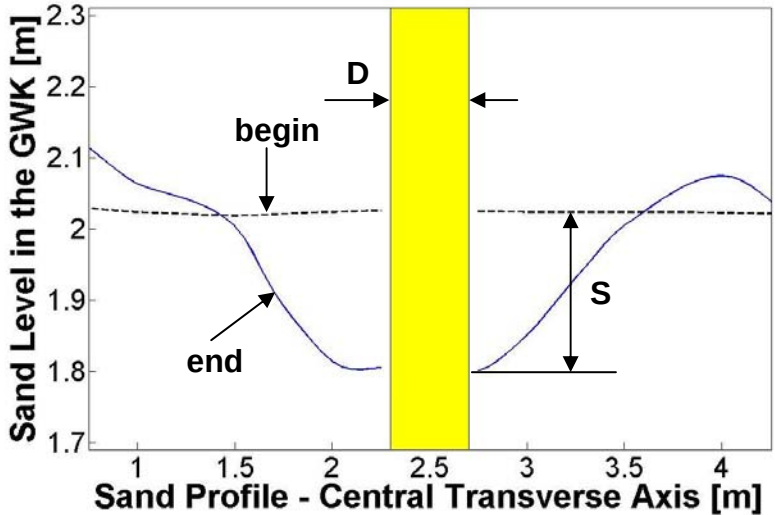
N = 6000 waves

First result:

Ratio max. scour depth

to pile diameter: S/D = 0.45





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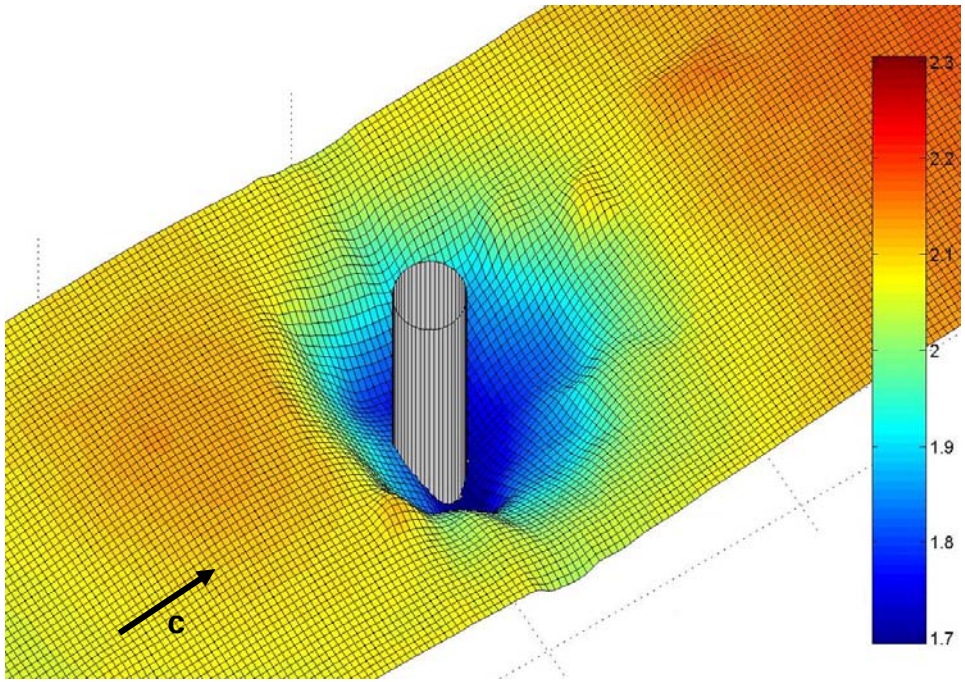


Testseries for scour evolution

Generated wave spectra

H 1/3 = 1.00 m

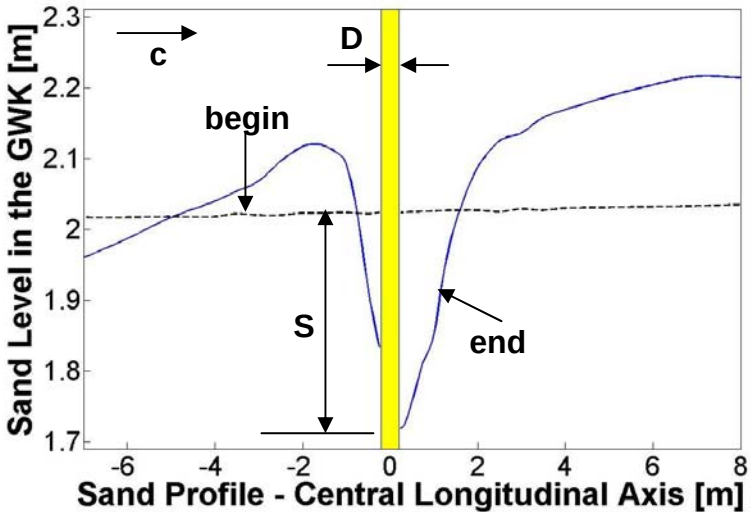
T p = 8.60 s

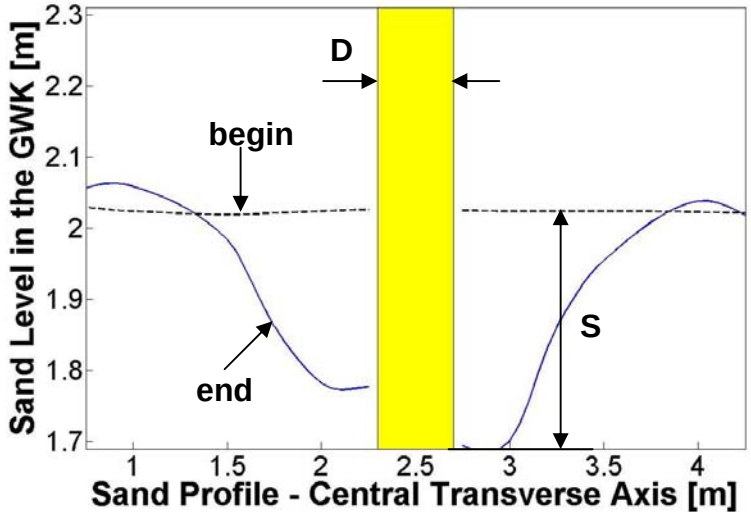
N = 6500 waves

First result:

Ratio max. scour depth

to pile diameter: S/D = 0.64





Concluding remarks and outlook

Scour protection with geotextile sand containers:

> The stability is not only a function of the weight but also of the filling percentage and the direction of the wave attack.

> For regularly placed sand containers the process of displacing continues faster in comparison to irregularly placed sand containers.

> For irregularly placed sand containers a self correcting placing occurs at the beginning of the wave attack.

> For the Butendiek windpark geotextile sand containers of about 3.0 to 3.5 tons (1900 kg/m^3) with nearly 85 % filling should be a safe solution.

> The final definitions of the failure criteria are still in preparation.

Scour protection with rock material:

> With reference to the Butendiek windpark a cover layer of mixed stones from 0.4 to 1.4 tons (2900 kg/m^3) should be a safe solution.

> The final definitions of the failure criteria are still in preparation.

Scour evolution at the monopile:

> Under model sea states of $H_{1/3}$ = 1.0 m and T_p = 8.6 s and a water depth of 2.1 m the scour depth ratio S/D = 0.64 is measured.

> The transfer of the scour measurements to prototype conditions and the dependency of the Keulegan-Carpenter-Number are currently under final analysis.