Optimization of wave overtopping of slopes

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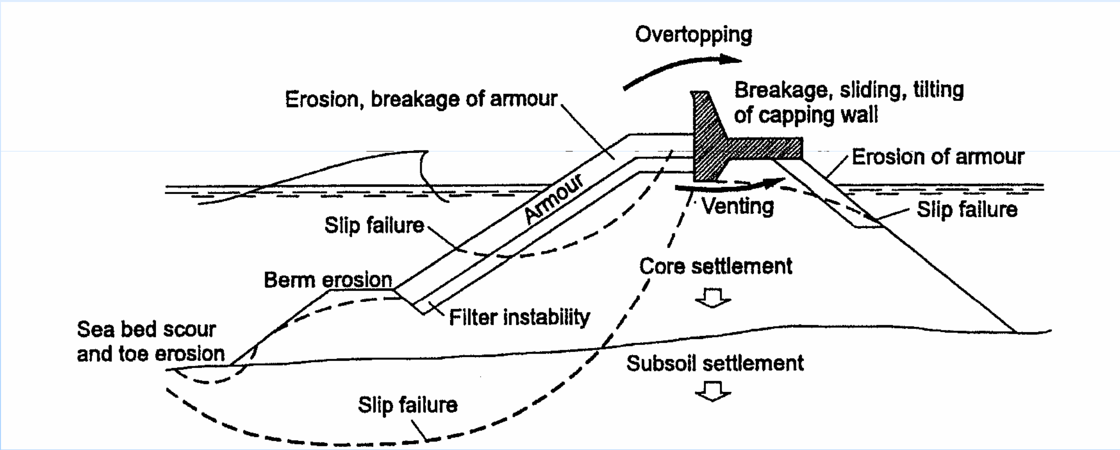
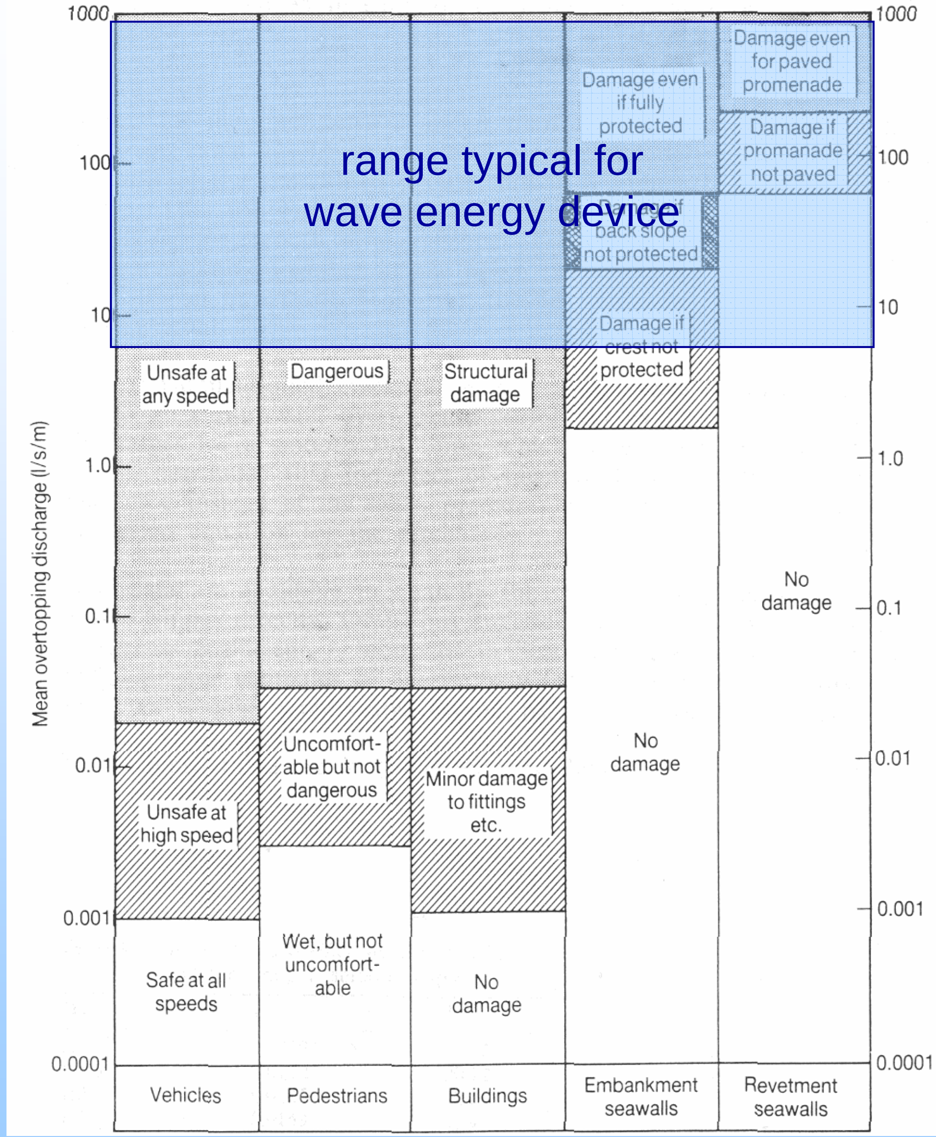
Wave overtopping

- Coastal engineering
  - e.g. Van der Meer and Janssen (1995)

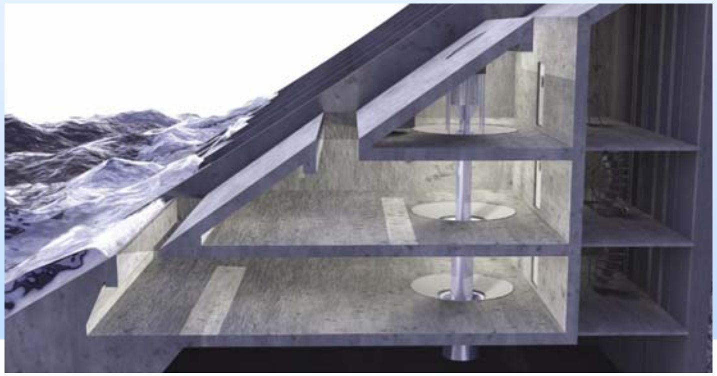


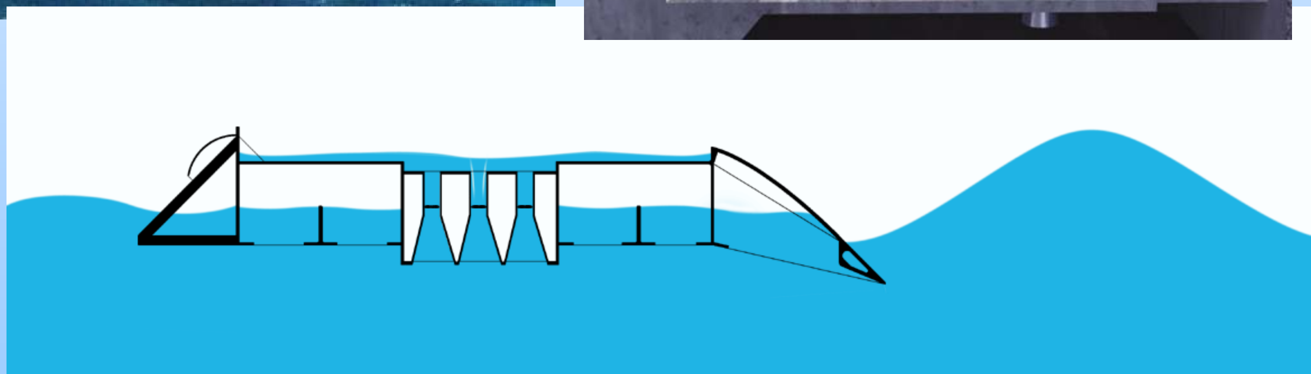
Overtopping discharge levels



Wave overtopping

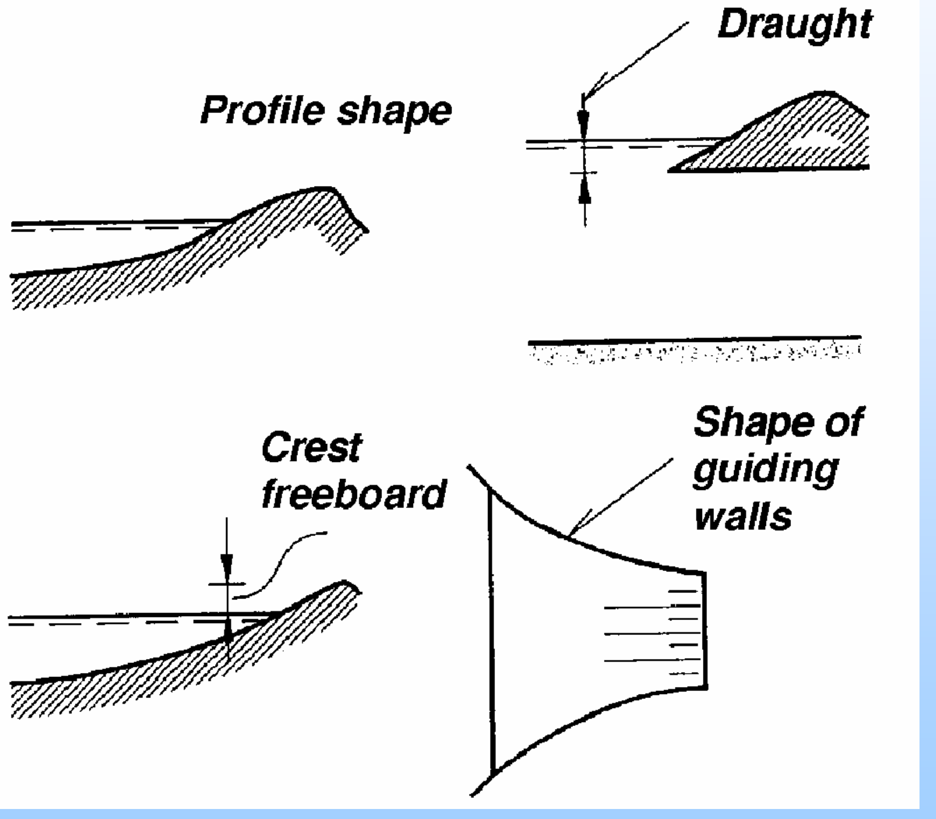
- Utilization of wave energy
  - Ph. D. thesis





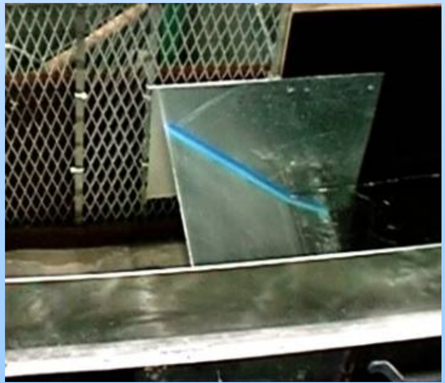
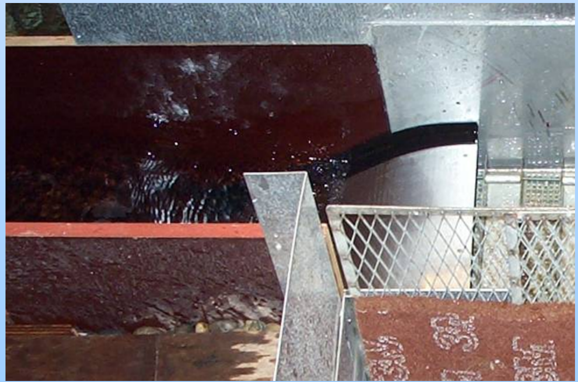
Overtopping of single level reservoirs

- Linear slopes
- Modifications of the slope profile
- Modifications of the side walls of the slope



Tested geometries

- 28 slope geometries tested
  - 13 linear slopes (variables: slope angle α = 20° - 60°, crest freeboard R_c/d = 0.04 - 0.30 and draft d_r/d = 0.20 - 1.00)
  - 10 modifications of slope profile (variables: horizontal plate at the toe of the slope, convex and concave slopes with varying layouts)
  - 5 modifications of slope side-walls (linear and curved converging side walls w_c/w_{dr} = 0.368 - 0.848)

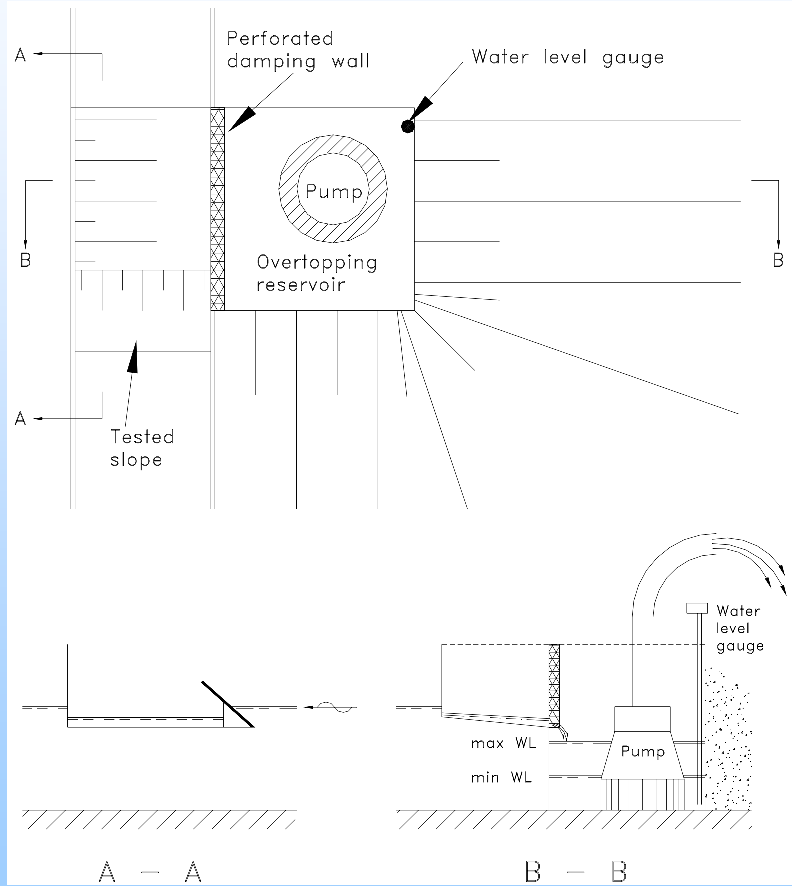

Wave conditions

- *2-D irregular waves*
- *JONSWAP, γ = 3.3*
- H_s varied from 0.50 to 8.00 m
- T_p varied from 4 to 14 s
- Resulting in s_p from 1.1 to 8.9 %
- And ξ_{p0} as given in the table

T_p [s]		H_s [m] 0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
	s_p [%]	**2.0**	**4.0**	**6.0**						
4	ξ_{p0}; $\alpha = 20°$	2.6	1.8	1.3						
	ξ_{p0}; $\alpha = 30°$	4.1	2.9	2.0						
	ξ_{p0}; $\alpha = 40°$	5.9	4.2	3.0						
	ξ_{p0}; $\alpha = 50°$	8.4	6.0	4.2						
	ξ_{p0}; $\alpha = 60°$	12.2	8.7	6.1						
	s_p [%]	**0.9**	**1.8**	**3.6**	**5.4**	**7.2**	**8.9**			
6	ξ_{p0}; $\alpha = 20°$	3.9	2.7	1.9	1.6	1.4	1.2			
	ξ_{p0}; $\alpha = 30°$	6.1	4.3	3.1	2.5	2.2	1.9			
	ξ_{p0}; $\alpha = 40°$	8.9	6.3	4.5	3.6	3.1	2.8			
	ξ_{p0}; $\alpha = 50°$	12.6	8.9	6.3	5.2	4.5	4.0			
	ξ_{p0}; $\alpha = 60°$	18.4	13.0	9.2	7.5	6.5	5.8			
	s_p [%]		**1.1**	**2.1**	**3.2**	**4.3**	**5.4**	**6.4**	**7.5**	**8.6**
8	ξ_{p0}; $\alpha = 20°$		3.6	2.6	2.1	1.8	1.6	1.5	1.4	1.3
	ξ_{p0}; $\alpha = 30°$		5.8	4.1	3.3	2.9	2.6	2.4	2.2	2.0
	ξ_{p0}; $\alpha = 40°$		8.4	5.9	4.8	4.2	3.8	3.4	3.2	3.0
	ξ_{p0}; $\alpha = 50°$		11.9	8.4	6.9	6.0	5.3	4.9	4.5	4.2
	ξ_{p0}; $\alpha = 60°$		17.3	12.2	10.0	8.7	7.7	7.1	6.5	6.1
	s_p [%]			**1.5**	**2.3**	**3.1**	**3.8**	**4.6**	**5.4**	**6.1**
10	ξ_{p0}; $\alpha = 20°$			3.2	2.6	2.3	2.0	1.9	1.7	1.6
	ξ_{p0}; $\alpha = 30°$			5.1	4.2	3.6	3.2	2.9	2.7	2.6
	ξ_{p0}; $\alpha = 40°$			7.4	6.1	5.2	4.7	4.3	4.0	3.7
	ξ_{p0}; $\alpha = 50°$			10.5	8.6	7.4	6.7	6.1	5.6	5.3
	ξ_{p0}; $\alpha = 60°$			15.3	12.5	10.8	9.7	8.8	8.2	7.7
	s_p [%]			**1.2**	**1.8**	**2.4**	**3.0**	**3.6**	**4.2**	**4.8**
12	ξ_{p0}; $\alpha = 20°$			3.9	3.2	2.7	2.4	2.2	2.1	1.9
	ξ_{p0}; $\alpha = 30°$			6.1	5.0	4.3	3.9	3.5	3.3	3.1
	ξ_{p0}; $\alpha = 40°$			8.9	7.3	6.3	5.6	5.1	4.8	4.5
	ξ_{p0}; $\alpha = 50°$			12.6	10.3	8.9	8.0	7.3	6.8	6.3
	ξ_{p0}; $\alpha = 60°$			18.4	15.0	13.0	11.6	10.6	9.8	9.2
	s_p [%]				**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
14	ξ_{p0}; $\alpha = 20°$				3.7	3.2	2.8	2.6	2.4	2.3
	ξ_{p0}; $\alpha = 30°$				5.8	5.1	4.5	4.1	3.8	3.6
	ξ_{p0}; $\alpha = 40°$				8.5	7.3	6.6	6.0	5.6	5.2
	ξ_{p0}; $\alpha = 50°$				12.0	10.4	9.3	8.5	7.9	7.4
	ξ_{p0}; $\alpha = 60°$				17.5	15.2	13.6	12.4	11.5	10.7

Model test setup

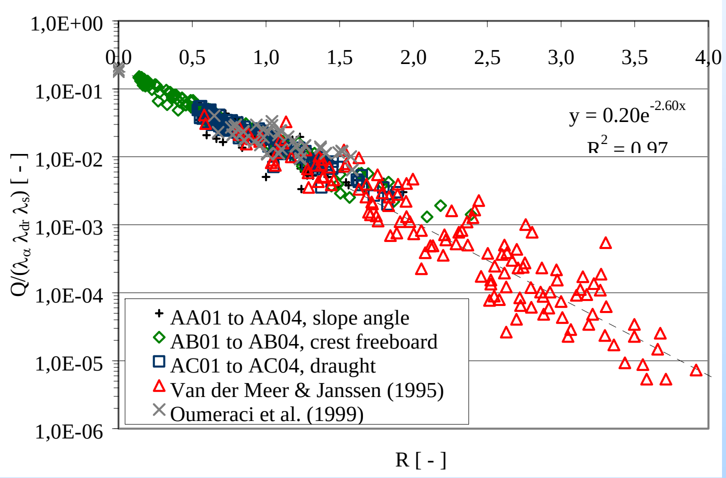
- Physical model tests carried out in wave basin, length scale 1:50

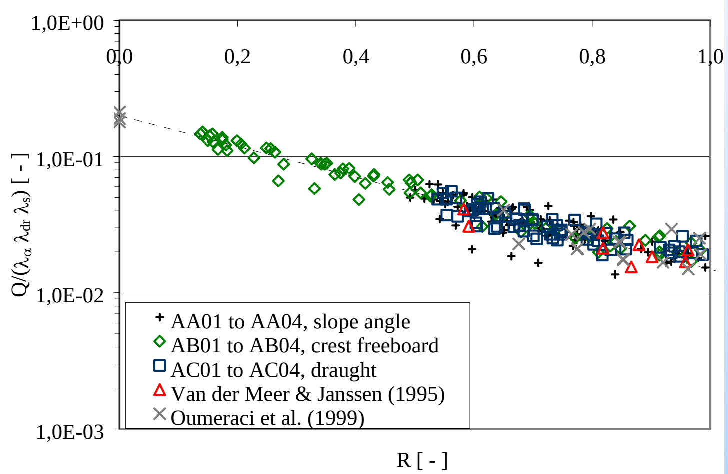


Single level reservoirs

- A study of wave overtopping using geometries and wave conditions not or only partly covered by results from the literature has been performed
  - Low relative crest freeboards
  - Limited draft
  - Various modifications on slope and side wall geometry
- Based on the model test results from this study a new overtopping expression (based on Van der Meer & Janssen [1995]) for non-breaking waves ($\xi_{p0} > 2$) has been proposed

Single level reservoirs





Overtopping expression

Wave overtopping for sloping structures, non-breaking waves ($\xi_{p0} > 2$):

$$\frac{q}{\lambda_\alpha \lambda_{d_r} \lambda_s \lambda_m \sqrt{g H_s}} = 0.2 e^{-2.6 \frac{R}{H_s} \frac{1}{\gamma_r \gamma_b \gamma_h \gamma_\beta}}$$

$$\lambda_\alpha = \cos^3(\alpha - 30°)$$

$$\lambda_s = \begin{cases} 0.4 \sin\left(\frac{2\pi}{3} R\right) + 0.6 & for \quad R < 0.75 \\ 1 & for \quad R \geq 0.75 \end{cases}$$

$$\lambda_{d_r} = 1 - 0.4 \frac{\sinh\left(2k_p d\left(1 - \frac{d_r}{d}\right)\right) + 2k_p d\left(1 - \frac{d_r}{d}\right)}{\sinh(2k_p d) + 2k_p d}$$

λ_m as given in tabel

Optimizing for energy capture

Hydraulic power in overtopping

$$\frac{q}{\sqrt{gH_s}} = Ae^{-B\frac{R_c}{H_s}}$$

$$P = qR_c g\rho_w = \sqrt{gH_s^3}\,Ae^{-B\frac{R_c}{H_s}}R_c g\rho_w$$

Optimal crest freeboard

$$R_{c,opt} = \frac{H_s}{B}$$

$$\Downarrow$$

Optimal hydraulic power

$$P_{opt} = e^{-1}\rho_w \tfrac{A}{B}\sqrt{g^3 H_s^5}$$

Application in typical DK sea conditions

H_s [m]	T_p [s]	P_{occur} [%]	P_{wave} [kW/m]
1.0	5.6	46.8	2.4
2.0	7.0	22.6	11.9
3.0	8.4	10.8	32.2
4.0	9.8	5.1	66.7
5.0	11.2	2.4	119.1

Overall hydraulic efficiency

$$\eta_{overall} = \frac{\sum_{m=1}^{5} P^m P_{occur}^m}{\sum_{m=1}^{5} P_{wave}^m P_{occur}^m}$$

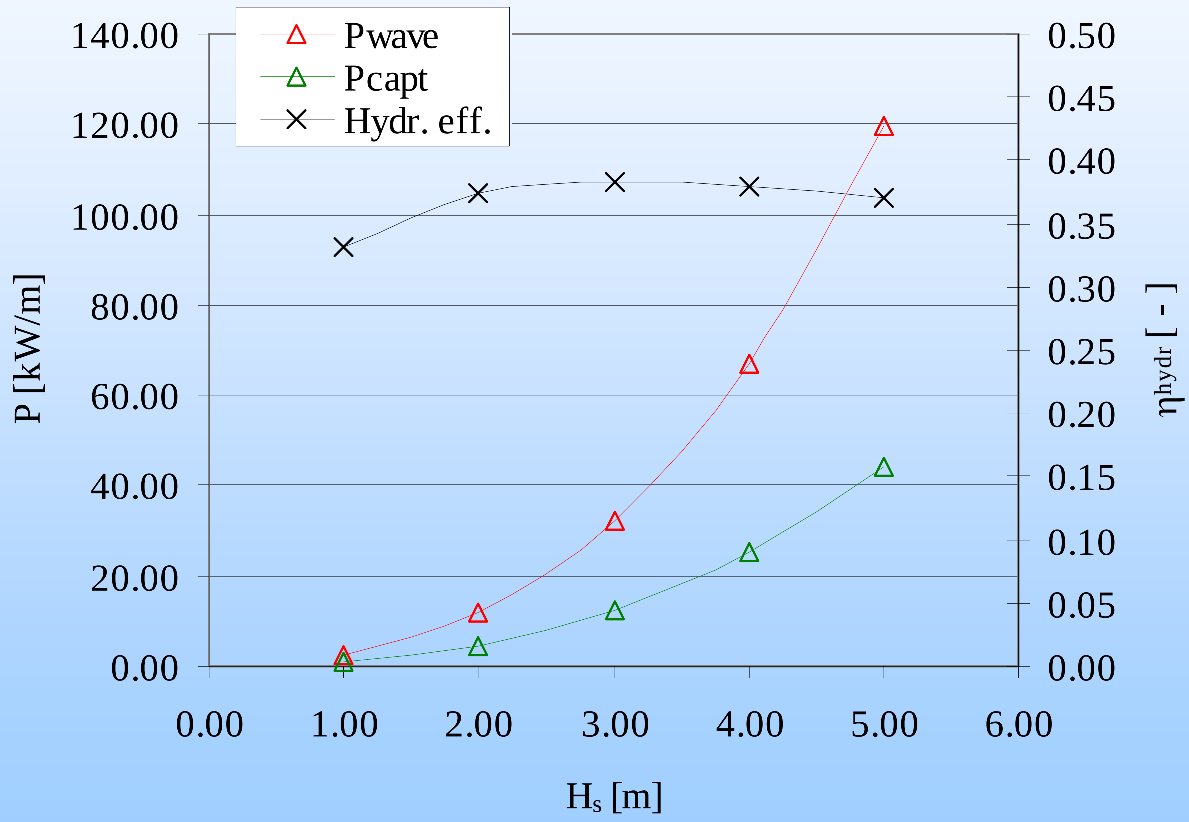
Application in typical DK sea conditions

Crest freeboard adjusted to optimal in all sea conditions

$$\frac{R_{c,opt}}{H_s} = \frac{1}{B} = 0.385$$

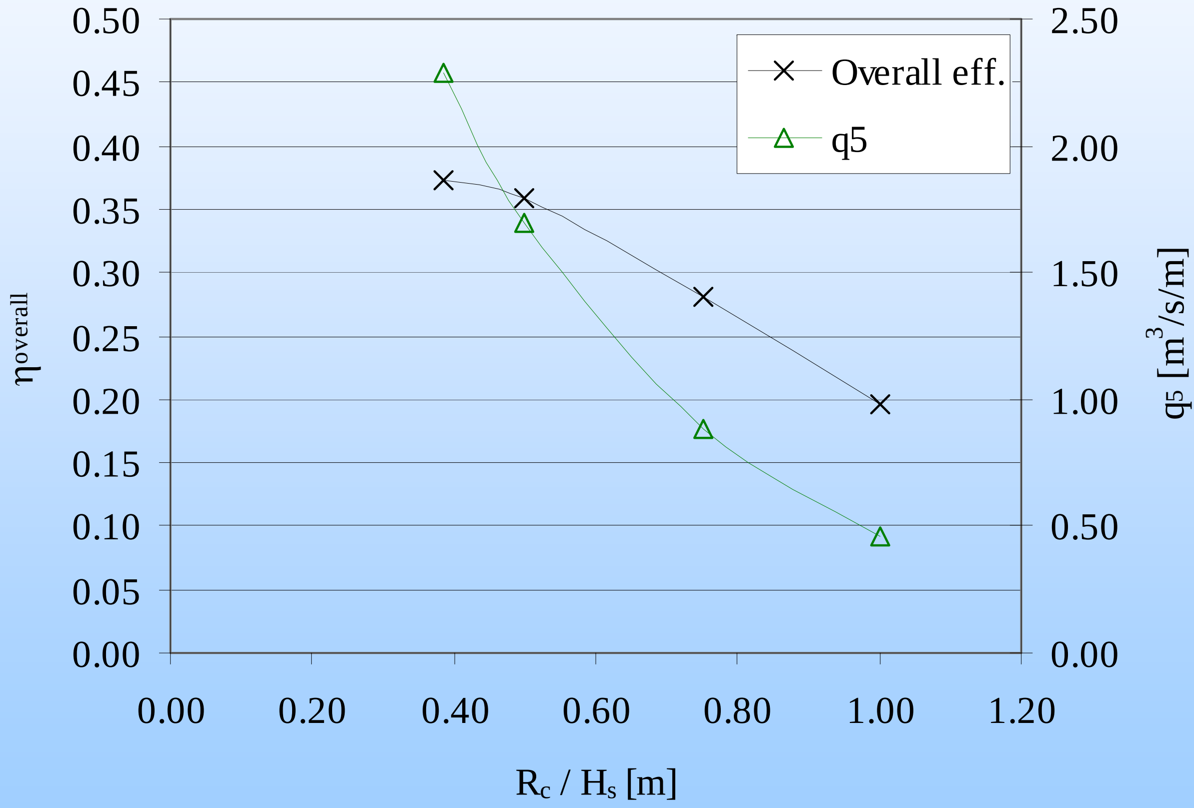
$\eta_{overall} = 37.3\ \%$

$q_5 = 2.29\ m^3/s/m$



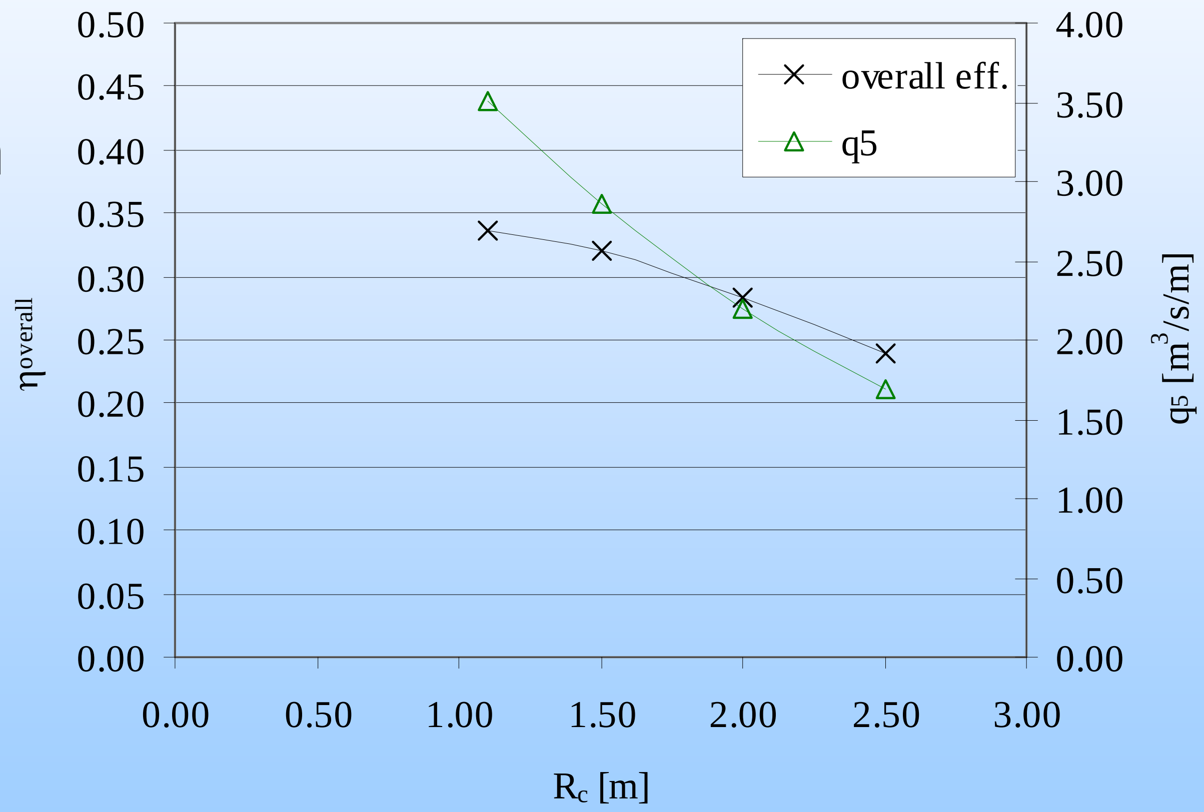
Application in typical DK sea conditions

- R_c adjusted to sea conditions
- Increase in R_c/H_s ratio reduce max. flow rate (turbine demand), but also overall efficiency



Application in typical DK sea conditions

- R_c fixed
- Optimal R_c = 1.1 m
  $\eta_{overall}$ = 33.4 %
  q_5 = 3.51 $m^3/s/m$
- Increase in R_c reduce max. flow rate (turbine demand), but also overall efficiency



Important aspects

- Max. overtopping rates => turbine demand
- Area of reservoir
- Difference between crest freeboard and reservoir water level
- Turbine control strategy
- Turbine characteristics
- Tidal variations (fixed structures)
- …..

Thank you for your attention!