Chapter 15: Failure modes and optimisation

Sri Lanka, Kudawella
Tsunami damage of breakwater
2004

ct5308 Breakwaters and Closure Dams

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March 28, 2012

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What is the most important element of a breakwater or closure dam ??

- the element which is the most expensive one
- the section which is the most costly one
- the element which is the most unreliable one
- the element which is the most sensitive to variations in the boundary conditions

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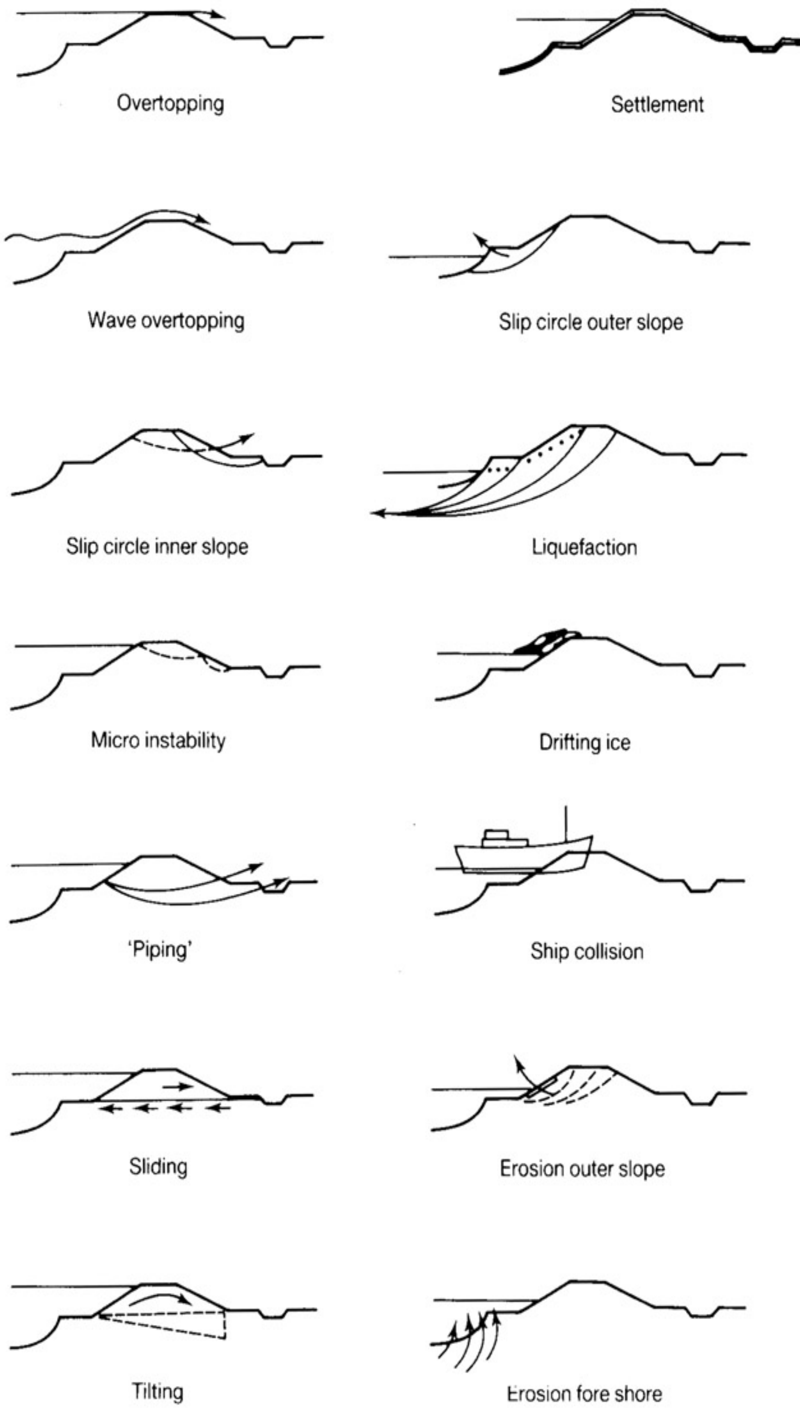

failure modes for dike-type structures

Failure of breakwater by earthquake

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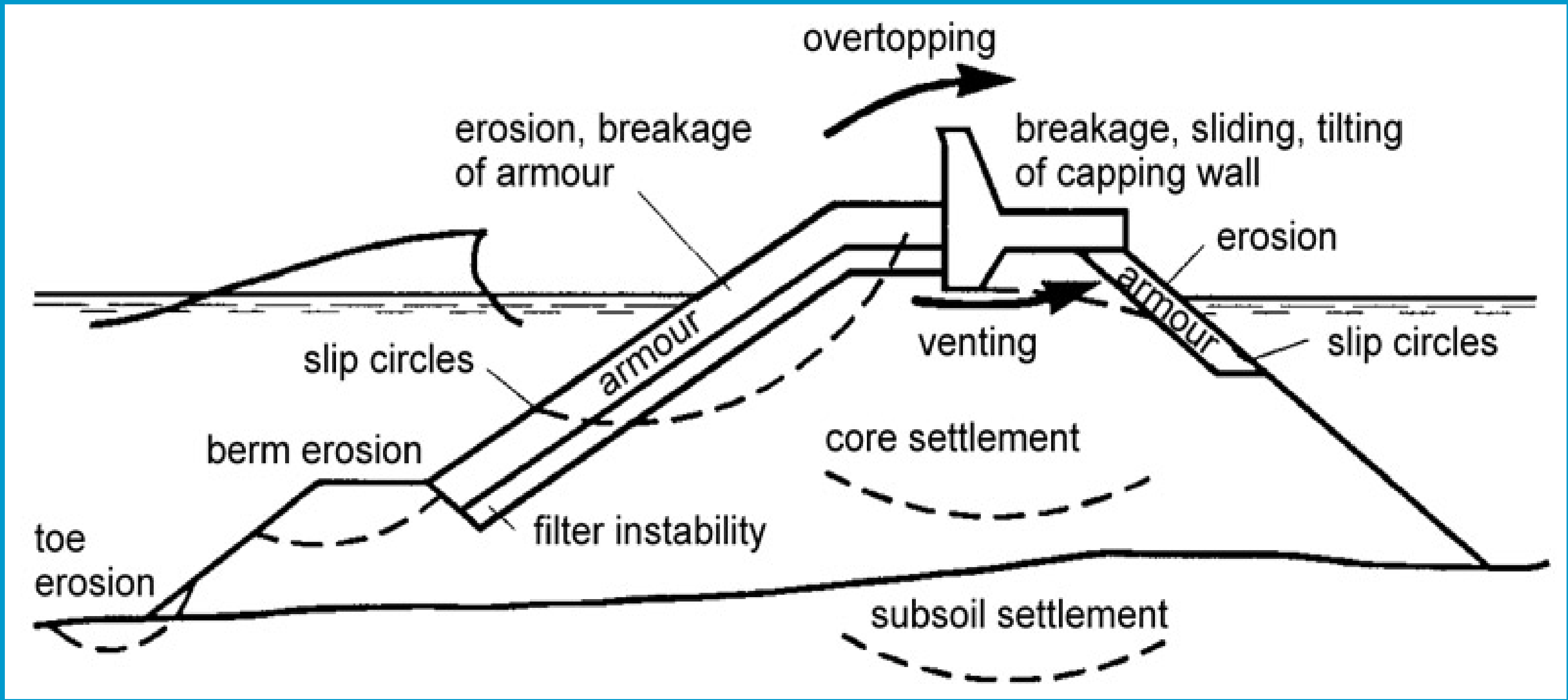
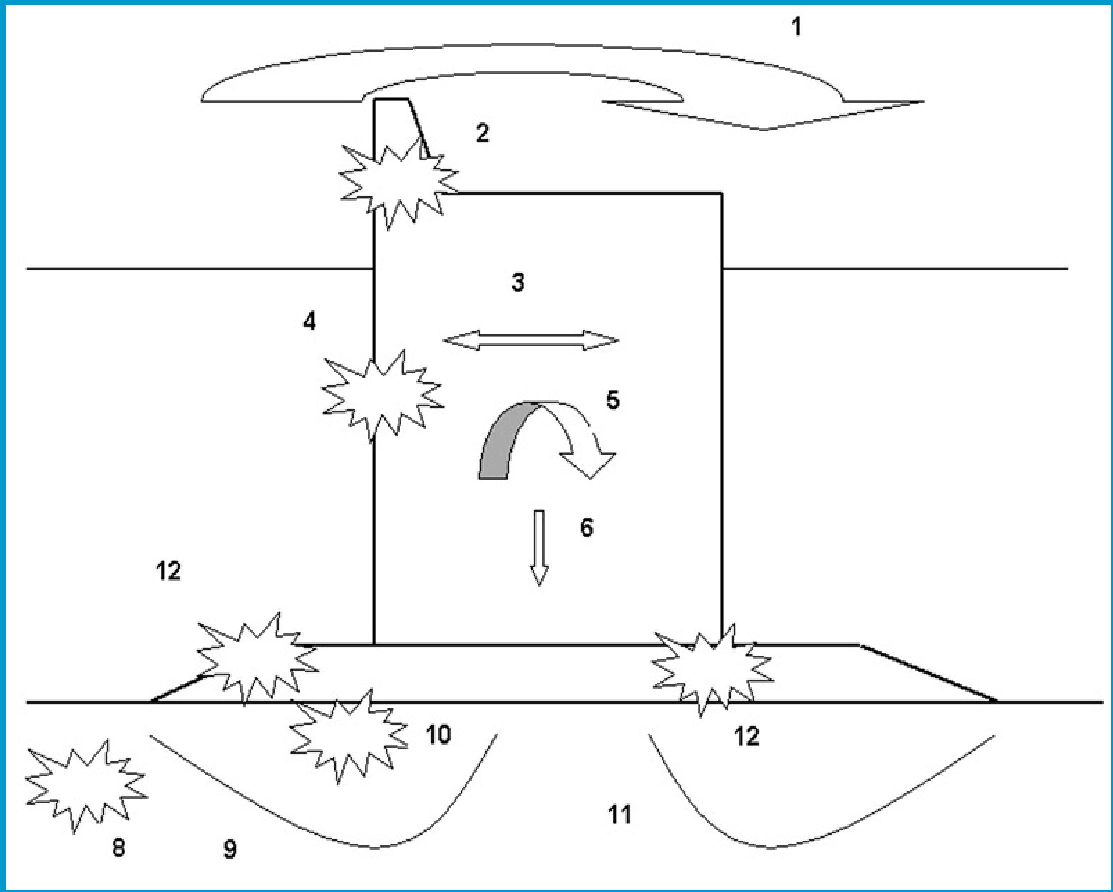
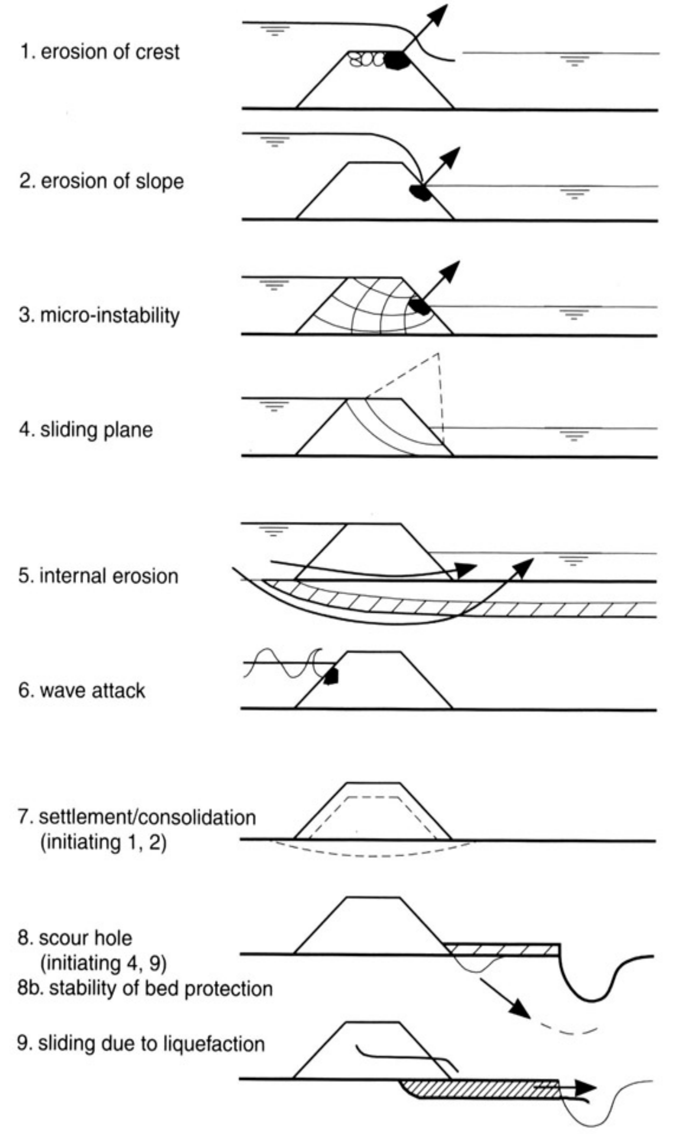
failure modes for a rubble mound (Burcharth, 1992)



Failure modes for a monolithic breakwater





rock fill overflow dam failure modes

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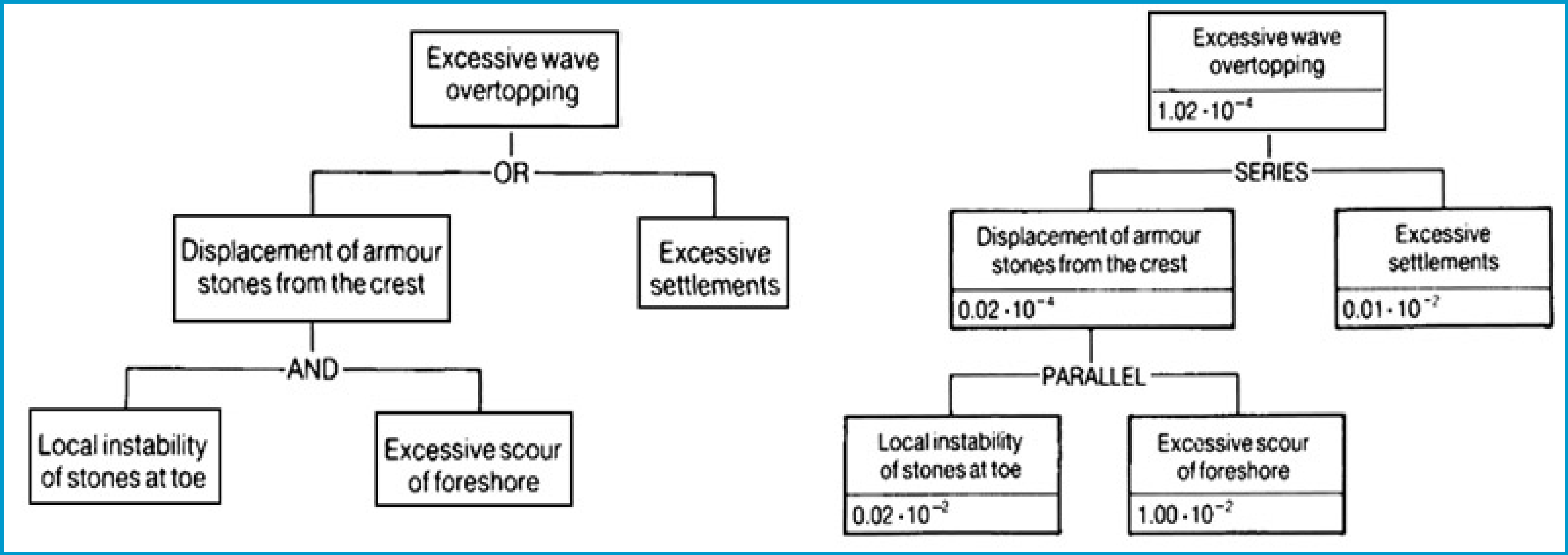
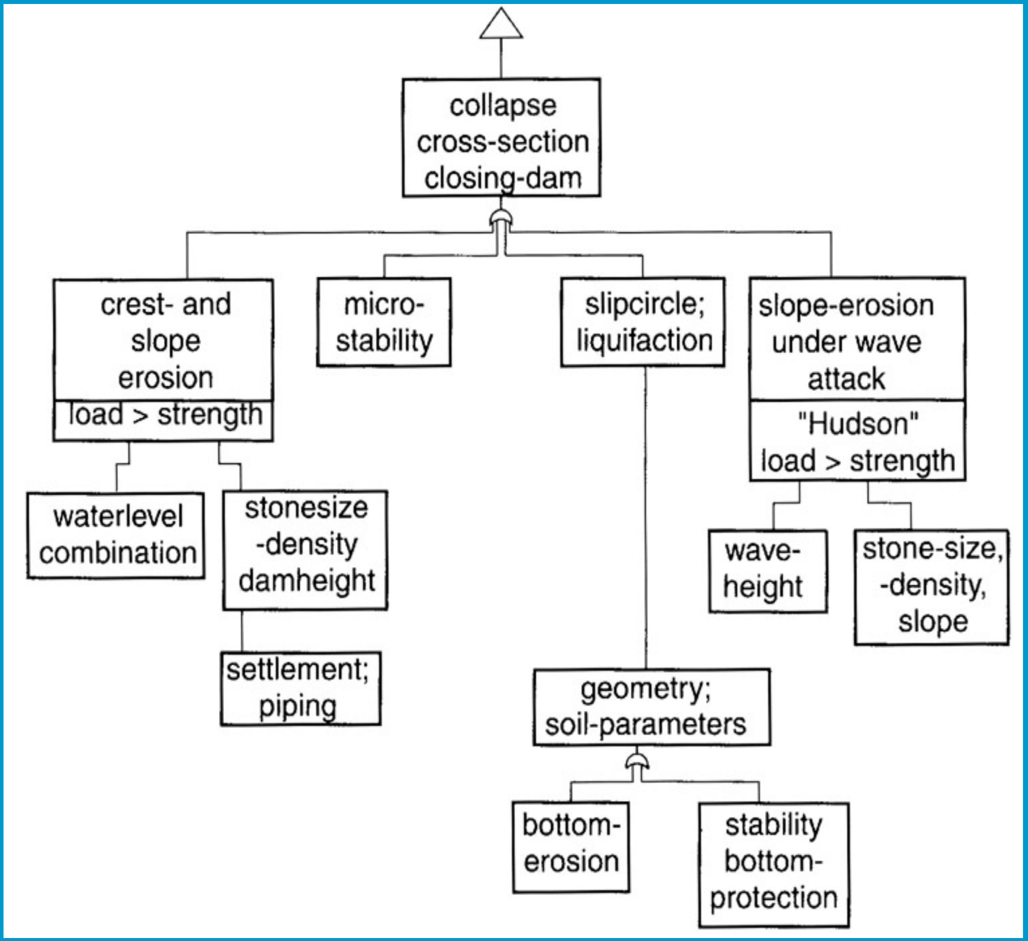
fault tree

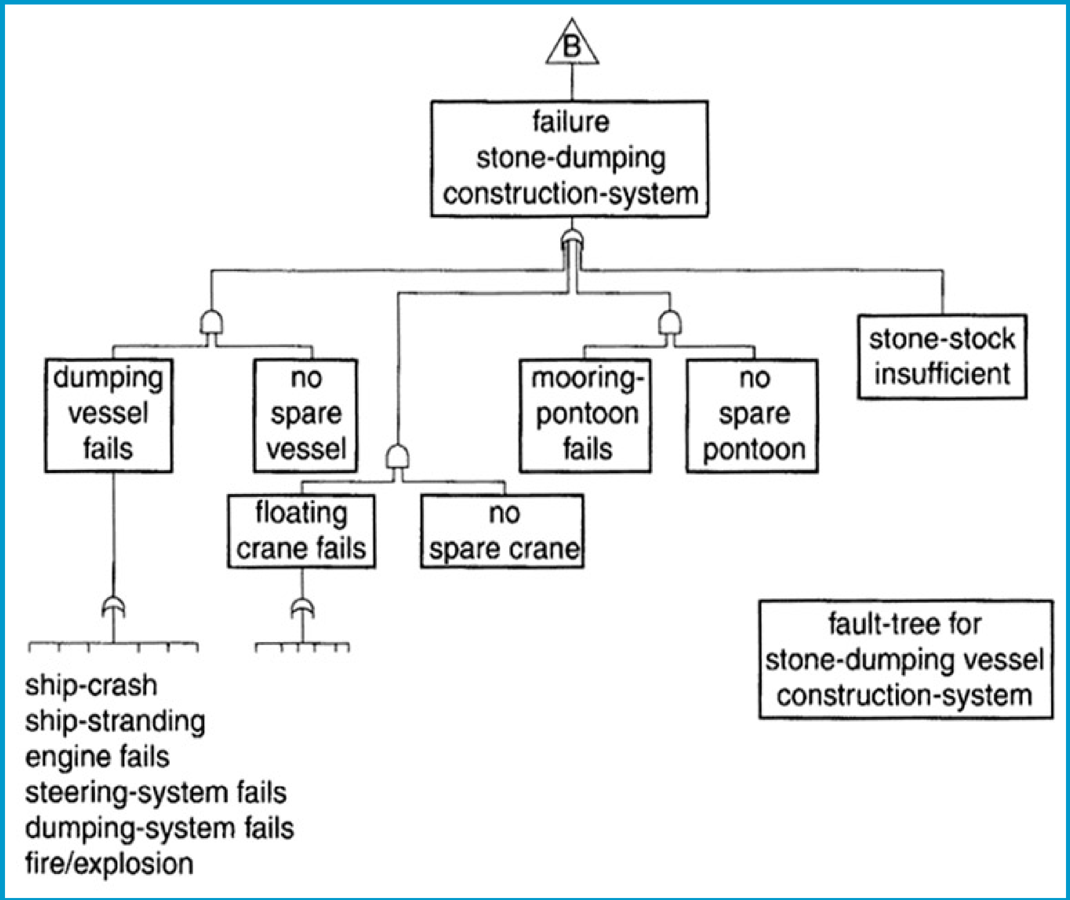


Excessive wave overtopping
OR
Displacement of armour stones from the crest
Excessive settlements
AND
Local instability of stones at toe
Excessive scour of foreshore
Excessive wave overtopping
1.02 · 10⁻⁴
SERIES
Displacement of armour stones from the crest
0.02 · 10⁻⁴
Excessive settlements
0.01 · 10⁻²
PARALLEL
Local instability of stones at toe
0.02 · 10⁻²
Excessive scour of foreshore
1.00 · 10⁻²

fault tree for closure dam (cross section)



fault tree for closure dam (equipment)



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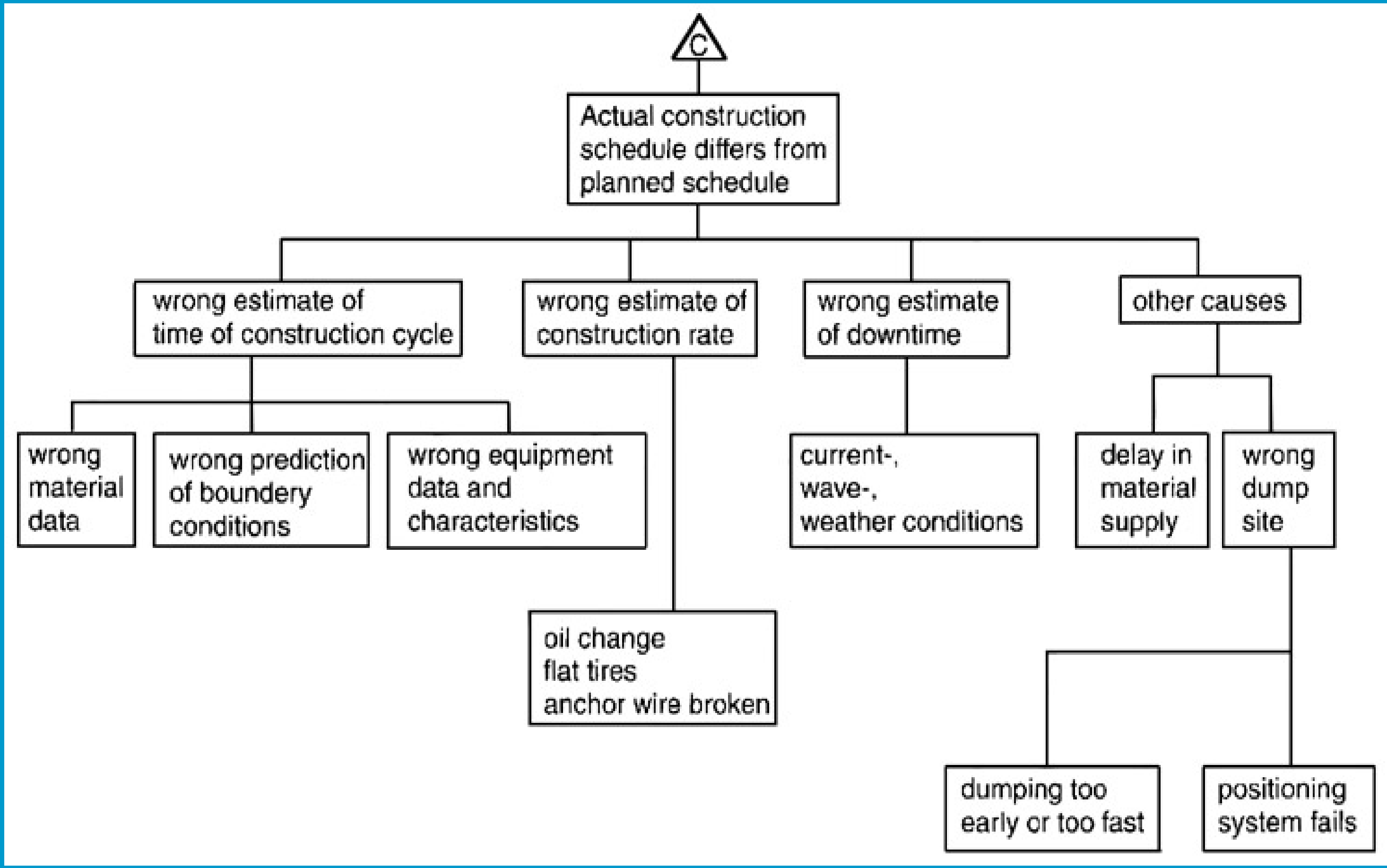
fault tree for construction planning



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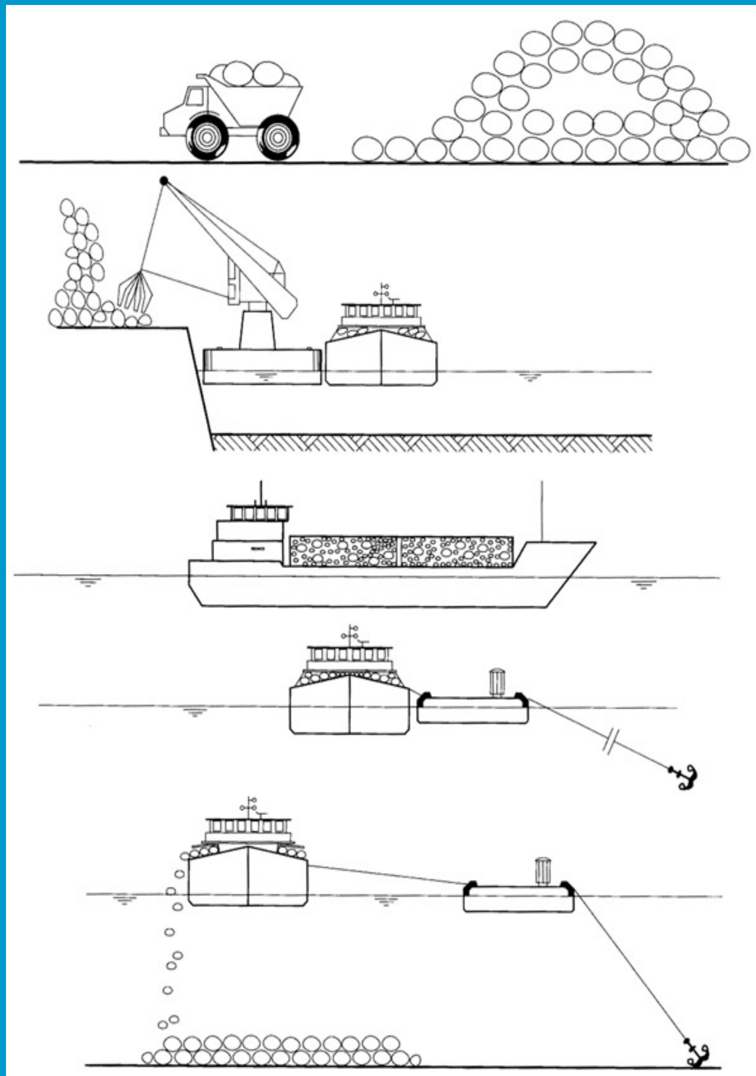

equipment utilisation in relation to fault tree

The Dilemma

- A strong and heavy breakwater does not require maintenance

  ... but is very expensive to construct
- A light breakwater is much cheaper to construct

  ... but requires a lot of maintenance

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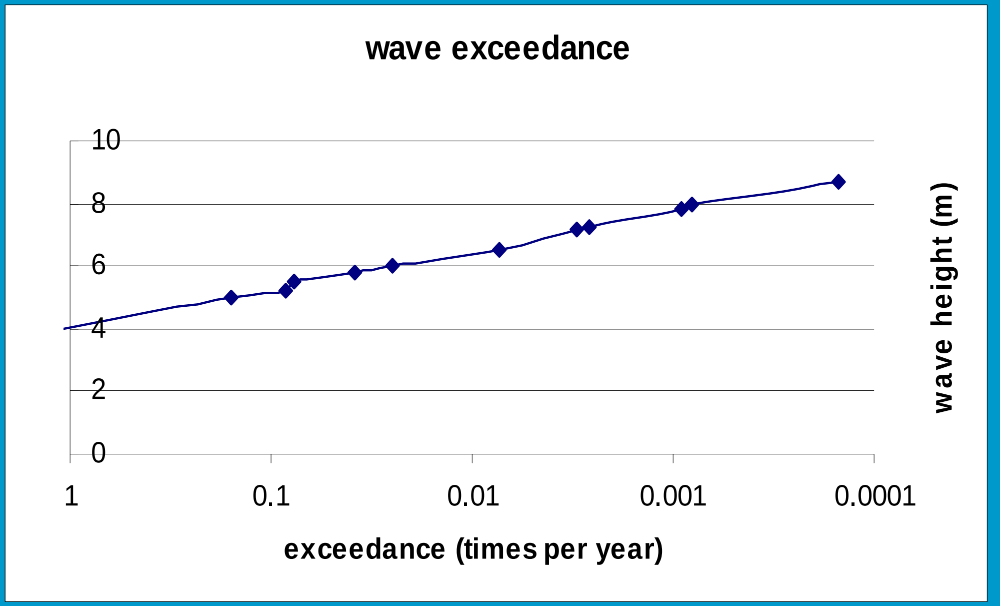
Wave climate

Wave Height *H* (m)	Probability of Exceedance (times per annum)
4	1.11
5	$1.58*10^{-1}$
5.2	$8.4*10^{-2}$
5.5	$7.62*10^{-2}$
5.8	$3.8*10^{-2}$
6	$2.47*10^{-2}$
6.5	$7.35*10^{-3}$
7.15	$3.0*10^{-3}$
7.25	$2.63*10^{-3}$
7.8	$9.0*10^{-4}$
7.98	$8.0*10^{-4}$
8.7	$1.5*10^{-4}$



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development of damage

Actual Wave Height H	Damage in % of armour layer
$H < H_{nd}$	0
$H_{nd} < H < 1.3H_{nd}$	4
$1.3H_{nd} < H < 1.45\ H_{nd}$	8
$H > 1,45\ H_{nd}$	Collapse

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Cost of construction

Initial cost for armour units: € 1320 * H_d
for core: € 8620

Design wave height H_{nd}	Initial cost breakwater "C"	Initial cost Amour Layer "A"
(m)	(€) per running meter	(€) per running meter
4	13900	5280
5	15220	6600
5.5	15900	7280
6	16540	7920

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annual risk

H_{nd}	$1 < H < 1.3\ H_{nd}$ n = 4% damage			$1.3\ H_{nd} < H < 1.45\ H_{nd}$ n = 8% damage			$H > 1.45\ H_{nd}$ Collapse		
	Δp	Δw	$\Delta p.\Delta w$	Δp	Δw	$\Delta p.\Delta w$	Δp	Δw	$\Delta p.\Delta w$
(m)	(1/year)	(€)	(€/year)	(1/year)	(€)	(€/year)	(1/year)	(€)	(€/year)
4	1.02	420	430	$4.6\ 10^{-2}$	860	40	$3.8\ 10^{-2}$	13900	530
5	$1.5\ 10^{-1}$	530	80	$4.7\ 10^{-3}$	1060	5	$2.6\ 10^{-3}$	15220	40
5.5	$7.4\ 10^{-2}$	580	40	$2.2\ 10^{-3}$	1160	-	$8\ 10^{-4}$	15900	10
6	$2.4\ 10^{-2}$	630	15	$7.5\ 10^{-4}$	1260	-	$1.5\ 10^{-4}$	16540	3

Δp probability of occurrence of the wave height

Δw cost of repair of the armour layer (2nA) respectively cost of replacement (C)

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average annual risk

H_{nd}	$s = \Sigma(\Delta p.\Delta w)$		
	Full repair of partial damage	Only repair of serious damage(>8%)	No repair of partial damage
(m)	(€ per year)	(€ per year)	(€ per year)
4	1000	570	530
5	125	45	40
5.5	50	10	10
6	18	3	3

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capitalised maintenance cost

H_{nd}	Capitalised risk *S*		
	Full repair of partial damage	Only repair of serious damage(>8%)	No repair of partial damage
(m)	(€)	(€)	(€)
4	30000	17100	15900
5	3750	1350	1200
5.5	1500	300	300
6	540	90	90

lifetime of 100 years; rate of interest 3.33%

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total cost

H_{nd}	Total cost $I + S$		
	Full repair of partial damage	Only repair of serious damage(>8%)	No repair of partial damage
(m)	(€)	(€)	(€)
4	43900	31000	29800
5	18970	16570	16420
5.5	17400	**16200**	**16200**
6	**17080**	16630	16630
6.5	17300		

Adding up initial cost plus capitalised maintenance cost

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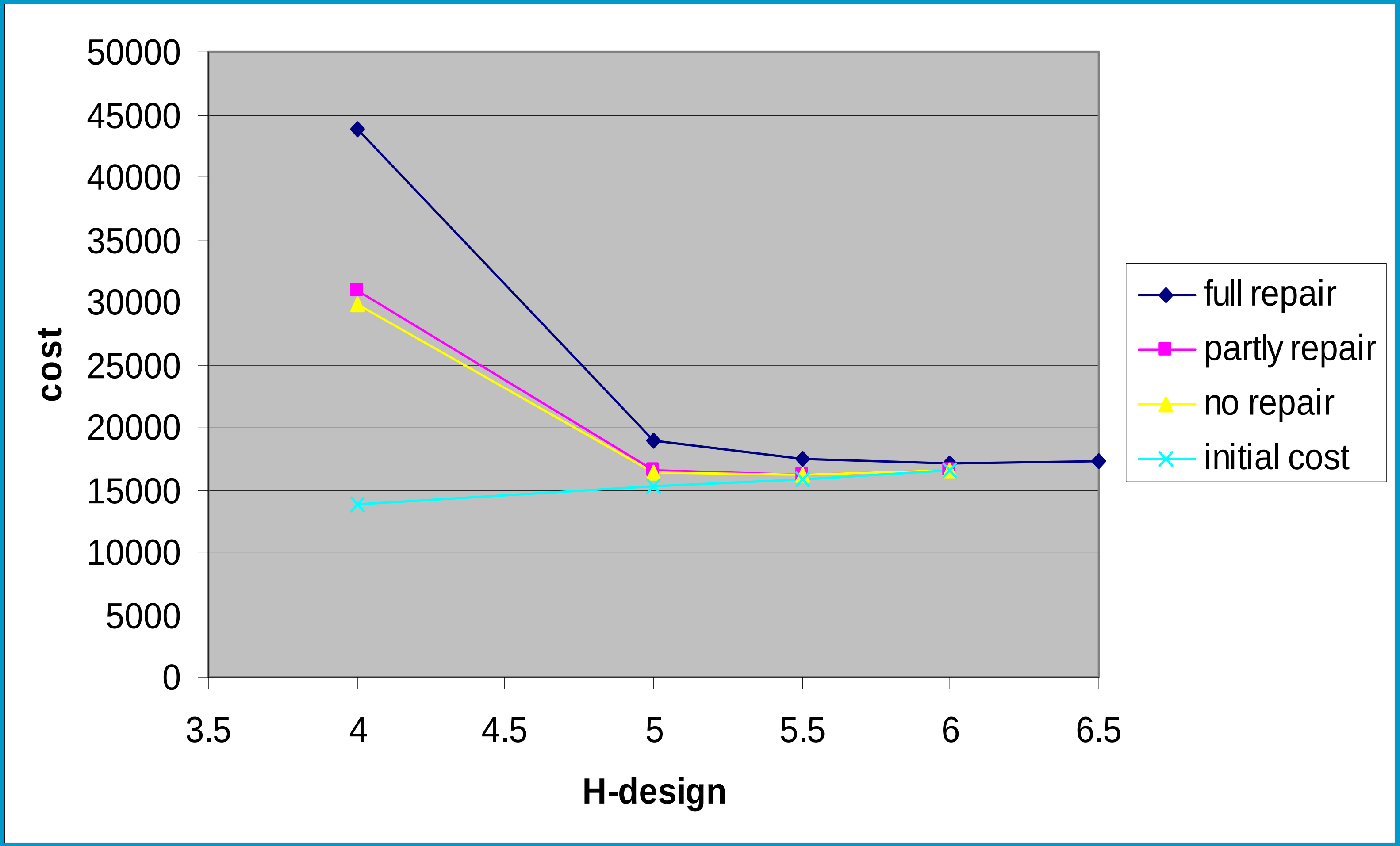
total cost for various strategies



Conclusions for Rubble Mound Breakwaters

- There is an optimum design wave height
- Accepting regular maintenance is the best option
- This implies that the design also should allow a “repairable” breakwater

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differences in breakwater type

- In case of overload a Rubble mound breakwater will suffer from some damage, which can be repaired.
- In general for Rubble mounds:

  the amount of repair costs increase linear with the amount of overload:

  $$cost = B * (H_{storm} - H_{design})$$

- In general for Vertical wall breakwaters:

  you have always a given fixed amount of damage, not depending on the amount of overload:

  $$cost = A + B (H_{storm} - H_{design})$$

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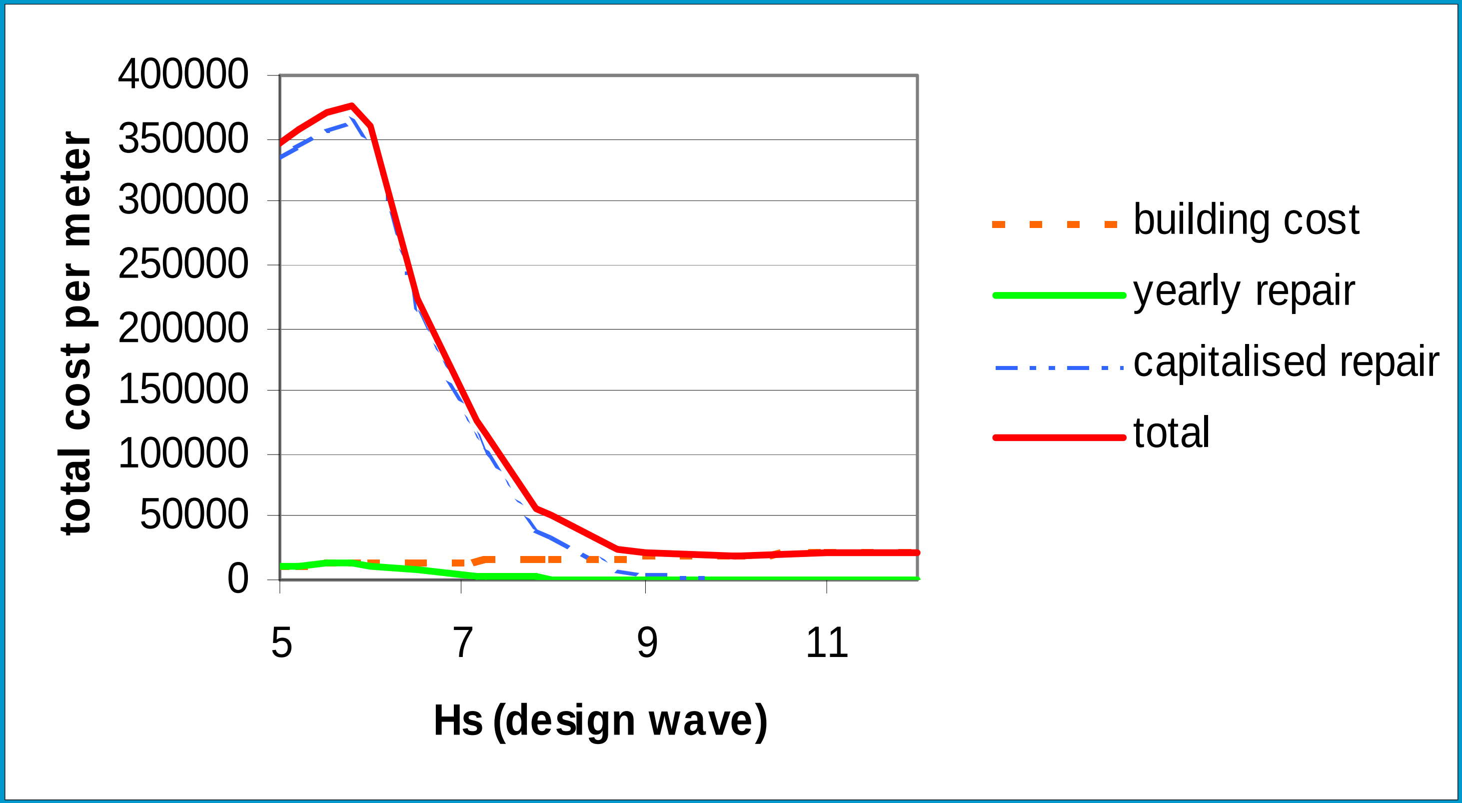
Vertical wall breakwater



damage cost = 4000 + 1500*H_s

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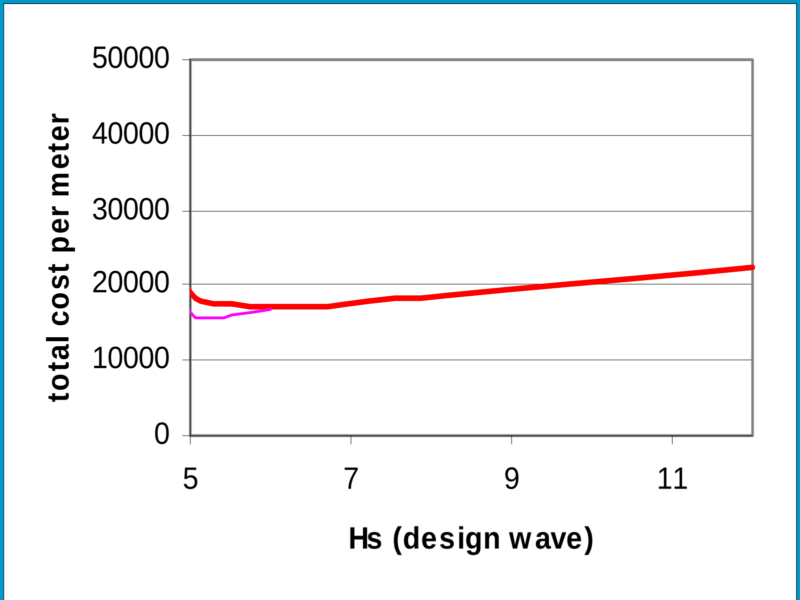
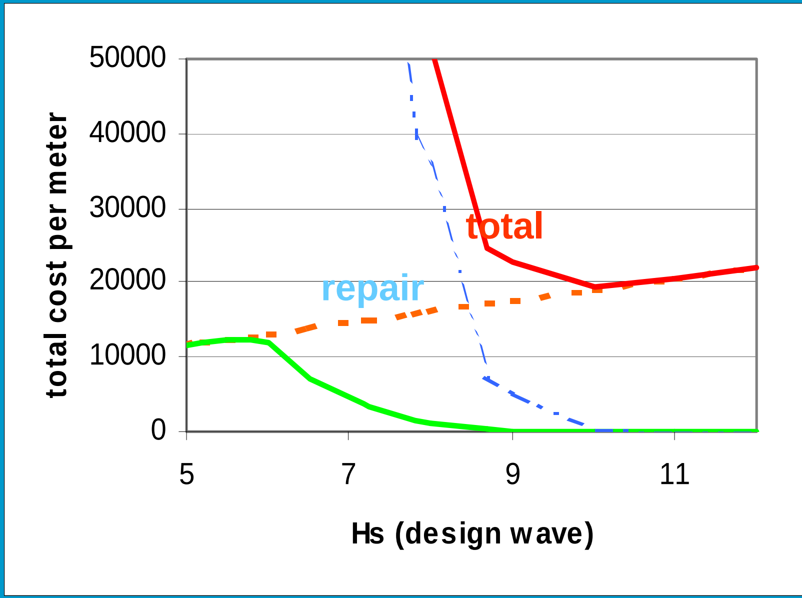
Conclusions





Rubble mound breakwater **Vertical wall breakwater**

Conclusions (2)

- Rubble mound breakwaters are less sensitive to uncertainties in wave data
- If there is no overload, a Vertical wall breakwater requires less maintenance
- If there is overload, Vertical wall breakwaters cause much more problems

Including "secondary damage"

- When a breakwater is damaged, the port cannot function well
- The cost because of loss of production should be included in the calculation
- In general secondary damage will not change the tendency of the conclusion before, but make them more even more stronger:
  - The optimum for a rubble mound breakwater is allowing quite some damage, and doing a lot of repair

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