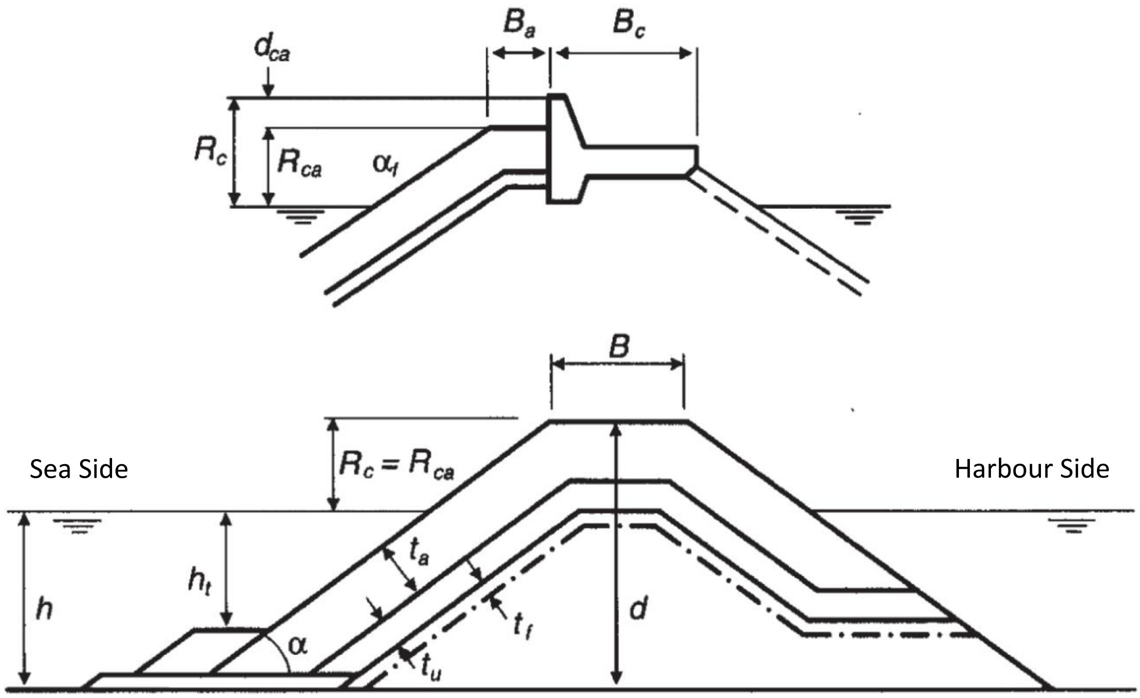
CLASS NOTE 6

Summary for the Design of Rubble Mound Breakwaters and Run-Up Calculations



Governing parameters related to the structure (breakwater) cross-section:

- crest freeboard, relative to still water level (SWL) R_c
- armour crest freeboard relative to SWL R_{ca}
- difference between crown wall and armour crest d_{ca}
- armour crest level/structure height relative to the sea bed d
- structure width B
- width of armour berm at crest B_a
- thickness of armour, underlayer, filter t_a, t_w, t_y,
- angle of structure front slope, α (°)
- depth of the toe below SWL, h_t

Basic approaches to evaluate the stability of rock-armoured slopes: $N_s = H_s/(\Delta D_{n50}) = f\{\cot\alpha, S_d, N, P, \xi\}$

- Hudson formula (1959) - non-breaking waves on the foreshore (deep water)
  - breaking waves on foreshore (depth-limited waves)
- Van der Meer formulae (1988b) - for deep water (non depth-limited waves).

Special conditions – safety / correction factors

- Shallow water and gently sloping foreshores – modified Van der Meer formulae (2004)
- Steep approach slopes – $f_{Dn50} \geq 1.1$, rule of thumb
- Effect of armourstone gradation
- Non-standard armourstone shape
- Armourstone packing and placement

Special conditions – explicit formulae

- Very shallow foreshores – Van Gent *et al* (2004), experimental/no design experience
- Ship-induced waves – Boeters *et al* (1993)

Hudson Formula (1959) - (regular waves)

$$W_{50} = \frac{\gamma_s H^3 \tan\alpha}{(S_r - 1)^3 K_D} \tag{1}$$

W_{50} : median weight of armor unit ($W_{50}=\gamma_s D_{50}^3$ tons)

γ_s : saturated surface dry unit weight of armor unit

(generally γ_s =2.65 t/m^3 for quarry stone, 2.40 t/m^3 for concrete)

S_r : γ_s/γ_w

H : design wave height at the construction depth (d)

K_D : stability coefficient (Table 1)

α : angle of structure slope (α=1/n)

(angle of structure slope steeper than 1 on 1.5 is not recommended)

H: Design Wave Height

Design wave height is determined according to the breaking condition as shown in Figure 1.

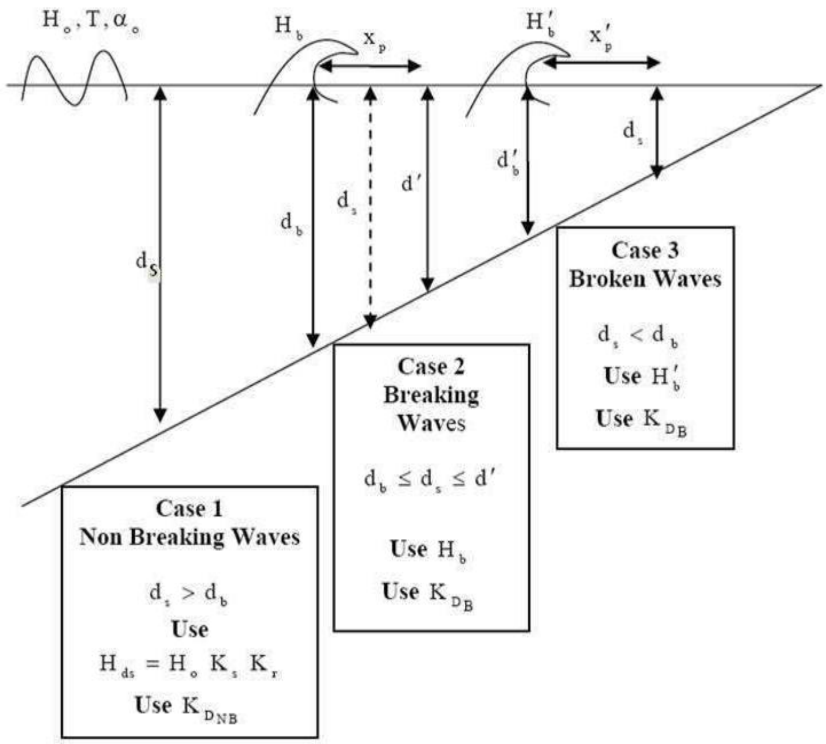


Figure 1: Design wave height and stability parameter according to breaking condition

In Hudson's approach, design wave height at deep water can be selected in two ways. Shore Protection Manual (1977) states that it should be taken as significant wave height $[H_0=(H_s)_0]$, on the other hand, it is recommended to take wave height exceed by 10% of the waves, $H_{1/10}$, $[H_0=(H_{1/10})_0]$ in Shore Protection Manual (1984).

LIMITATIONS for HUDSON FORMULA

- In the Hudson equation stability coefficient, K_D cannot exceed the values given in Table 1 (Coastal Engineering Manual, 2003).
- Suggested K_D values given in Table 1 are for NO DAMAGE CRITERIA and for MINOR OVERTOPPING. No damage criteria allow displacements of (0-5) % of the armor stones from the total number of armor stones.
- The use of regular waves only
- No account of the wave period and the storm duration
- No description of the damage level
- The use of non-overtopped and permeable structures only.

  NOTE: For practical application, the problems that may arise due to these limitations can be overcome by using various specific values of the stability (or damage) coefficient, K_D this particularly applies to permeability of the structure and irregular waves.

Table 1: Kd values for Hudson (1959)

			Structure Trunk		Structure Head		
			K_D[b]		K_D		Slope
Armor units	n	Placement	Breaking Wave	Non-breaking wave	Breaking Wave	Non-breaking wave	cotα
Quarry stone	2,0	Random					
Smooth rounded	>3	Random	1,2	2,4	1,2	1,9	1,5 to 3,0
Smooth rounded	1,0	Random	1,6	3,2	1,4	2,3	(c)
Rough angular	2,0	Random[d]	(d)	2,9	(d)	2,3	(c)
Rough angular	>3	Random	2,0	4,0	1,9 1,6 1,3	3,2 2,8 2,3	1,5 2,0 3,0
Rough angular	2,0	Special [e]	2,2	4,5	2,1	4,2	(c)
Rough angular	2,0	Special [e]	5,8	7,0	5,3	6,4	(c)
Parallelepiped		Random	7,0-20,0	8,5-24	-	-	(c)
Tetrapod Quadripod 2	2,0	Random	7,0	8,0	5,0 4,5 3,5	6,0 5,5 4,0	1,5 2,0 3,0
Tribar	2,0	Random	9,0	10,0	8,3 7,8 6,0	9,0 8,5 6,5	1,5 2,0 3,0
Dolos	2,0	Random	15,0	31,0	8,0 7,0	16,0 14,0	2[b] 3,0
Modified Cube	2,0	Random	6,5	7,5	-	5,0	(c)
Hexapod 2	2,0	Random	8,0	9,5	5,0	7,0	(c)
Toskanes	2,0	Random	11,0	22,0	-	-	(c)
Tribar	1,0	Uniform	12,0	15,0	7,5	9,5	(c)
Quarrystone (KRR) Graded angular	-	Random	2,2	2,5	-	-	-

Table 1 definitions are given below;

(a) n is the number of units comprising the thickness of the armor layer.

(b) Applicable to slopes ranging from 1 on 1.5 to 1 on 5.

(c) Until more information is available on the variation of K_D value with slope, the use of K_D should be limited to slopes ranging from 1 on 1.5 to 1 on 3. Some armor units tested on a structure head indicate a K_D slope dependence.

(d) The use of a single layer of quarry stone armor units subject to breaking waves is not recommended, and only under special conditions for non-breaking waves. When it is used, the stone must be placed carefully.

(e) Special placement with long axis of stone placed perpendicular structure face.

Van der Meer (1988) and Van Gent et al. (2004) Approaches for Rubble Mound Breakwater Design – (irregular waves)

Van der Meer and Van Gent et al. approaches are derived to predict the stability of armor stone on uniform armor stone slopes with crests above the maximum run-up level. These formulas were based, amongst other work, on earlier work by Thompson and Shuttler (1975) and a large amount of model tests. These stability formulas are more complex than the Hudson formula, but – as a great advantage – do include the effects of <u>storm duration</u>, <u>wave period</u>, the structure's <u>permeability</u> and a clearly defined <u>damage level</u>.

These formulas are similar in terms of derivation methodology, data sets used to derive the formulas. Actually, Van Gent et al. formulas are a modified version of Van der Meer formulas (referred as Van der Meer shallow water equations) to extend its applicability to shallow water. Van der Meer formulas are used at deep water and relatively shallow water. On the other hand, Van Gent et al. formulas are used at very shallow water (Figure 2).

Table 5.29 *Overview of fields of application of the Van der Meer stability formulae*

	Water depth characterisation		
Item	**Very shallow water**	**Shallow water**	**Deep water**
Parameter: Relative water depth at the toe: $h/H_{s\text{-}toe}$ Wave height ratio, $R_H = H_{s\text{-}toe}/H_{so}$	≈1.5 – ≈2 < 70%	< 3 70% < R_H < 90%	> 3 > 90%
Stability formulae: Van der Meer – deep water, Equation nos 5.136 and 5.137 Van der Meer – shallow water Equation nos 5.139 and 5.140			

Figure 2: Application Ranges of Van der Meer and Van Gent et al. approaches (Rock Manual, 2007)

Van der Meer (1988) Approach to RMBW Design

By the knowledge of significant wave height at the toe of the structure ($H_{s\text{-}toe}$) and construction depth (d_s), Van der Meer's following approach can be used to design RMBW.

First of all, it is needed to know the breaking type of the waves at construction depth.

ξ_m : surf similarity parameter using the mean wave period,

$$\xi_m = \tan\alpha / \sqrt{(2\pi / g) \times H_{s,toe} / T_m^2} \qquad \xi_{cr} = \left[6.2 P^{0.31} \sqrt{\tan\alpha}\right]^{\frac{1}{P+0.5}}$$

T_m : Mean wave period, $T_m \approx 0.81\, T_s$

For plunging waves: $\xi_m < \xi_{cr}$

$$\frac{H_{s,toe}}{\Delta\ D_{50}} = 6.2P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2}(\xi_m)^{-0.5}$$

For surging waves: $\xi_m \geq \xi_{cr}$

$$\frac{H_{s,toe}}{\Delta\ D_{50}} = 1.0P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2}\sqrt{\cot\alpha}(\xi_m)^{P}$$

where:

N : number of incident waves at the toe (-), which depends on the duration of the wave conditions (usually 6-8 hours of storm duration), Max: 7500 waves

N = duration (h)/T_m (s) × 3600 (s/h)

$H_{s,toe}$: significant wave height, H_s of the incident waves at the toe (water depth: h) of the structure

α : slope angle of the structure (°)

Δ : relative buoyant density, (ρ_s/ρ_w - 1)

P : notional permeability of the structure (-) (Figure 4);

the value of this parameter should be: $0.1 \leq P \leq 0.6$

NOTE: the use of a geotextile reduces the permeability, which may result in the need to apply larger material than without a geotextile.

S : damage level parameter (see Table 2 below)

- start of damage: corresponding to no damage (D = 0-5 %) in the Hudson formula

- intermediate: damage

- failure: corresponding to reshaping of the armor layer such that the filter layer under the armor stone in a double layer is visible.

Table 2: Damage levels for different slopes (Rock Manual, 2007)

Slope (cotα)	Damage level		
	Start of damage	Intermediate damage	Failure
1.5	2	3–5	8
2	2	4–6	8
3	2	6–9	12
4	3	8–12	17
6	3	8–12	17

Damage parameter, S, can be physically described as the number of squares with a side D_{n50} which fit into the erosion area. Erosion area is the area between original profile and eroded profile shown in Figure 3.

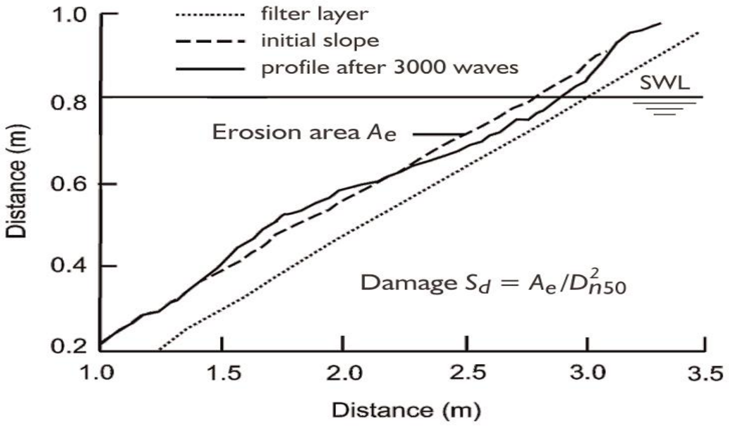


Figure 3: Definition of Damage Parameter

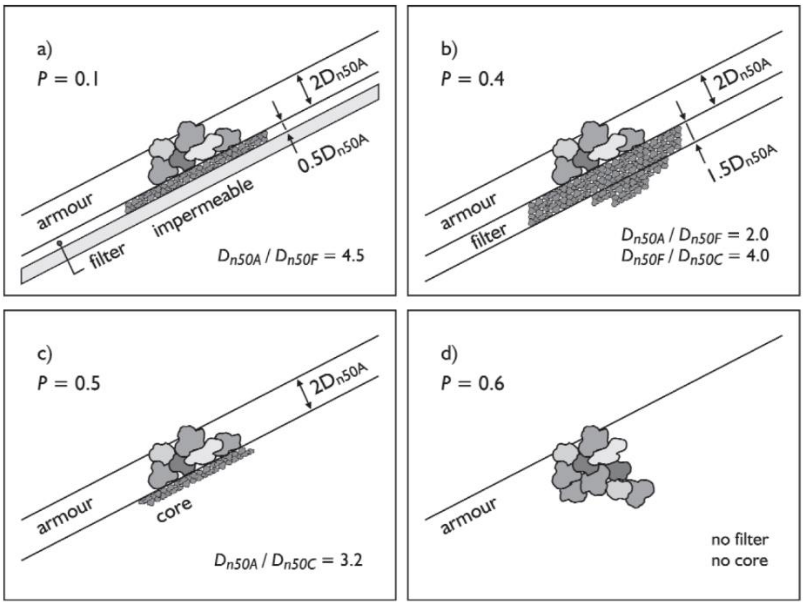


Figure 4: Permeability values for different conditions (Rock Manual, 2007)

Design Methodology:

1) Determine design wave conditions at the toe of the structure ($H_{s,toe}$ and T_m).
2) Define acceptable values of damage level parameter, S.
3) Determine number of waves, N.
4) Determine surf similarity parameter, ξ .
5) Determine whether waves are plunging or surging.
6) Determine required armour stone size, D50.
7) ***Verify your design by physical model experiments!***

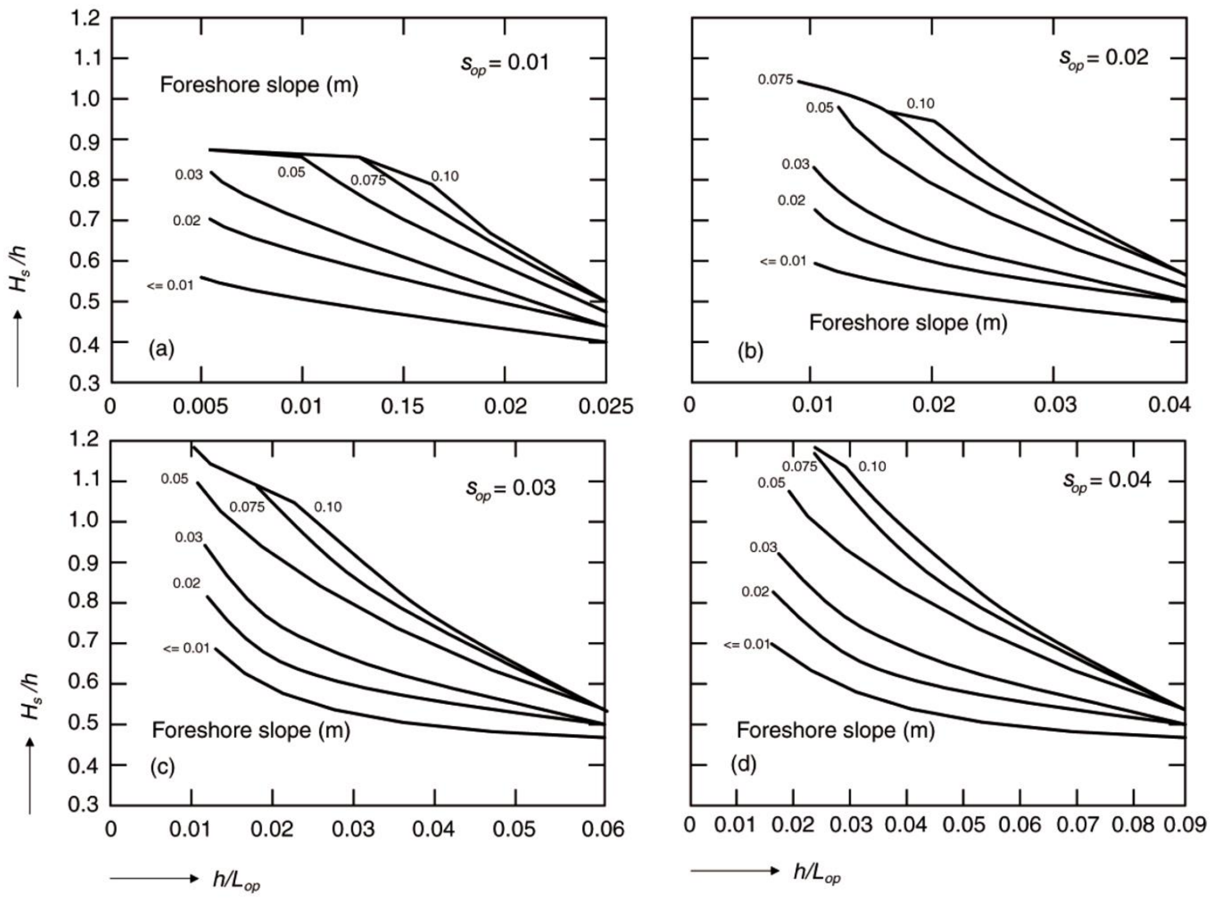
Wave Transformation Methodology to use Van der Meer Equations

To use Van der Meer equations it is needed to find $H_{s\text{-}toe}$ using the charts given by Figure 5. To find $H_{s\text{-}toe}$ the following parameters should be found:

L_{op} : deep water peak wave length **($L_{op}=1.56T_p^2$; $T_p=1.05\ T_s$)**

s_{op} : deep water peak steepness **($s_{op} = H_{s,0}/L_{op}$)**

Note that if the ratio d_s / L_{op} out of the limits of the figure given by Figure 5, use the wave height at the construction depth as $H_{s\text{-}toe}$, i.e. $H_{s\text{-}toe}=H_{d=\text{construction depth}}=H_{s0}*K_s*K_r$.



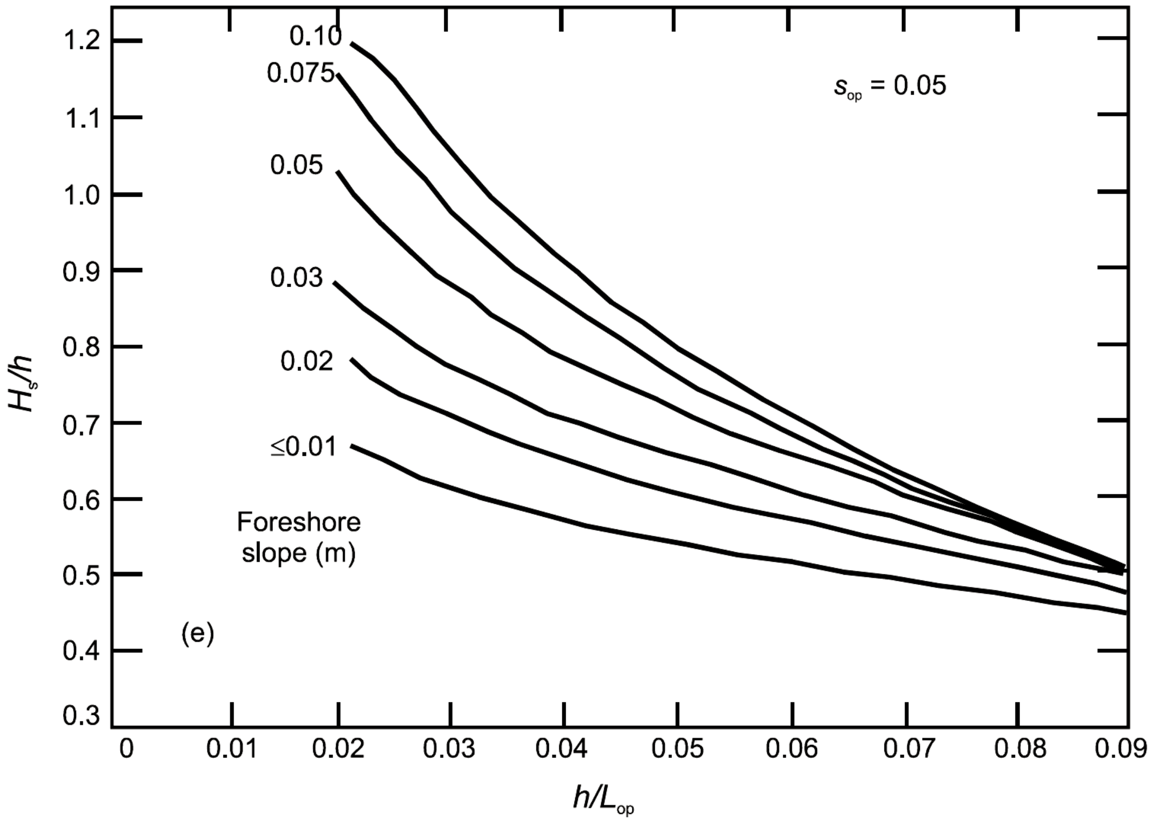


Figure 5: Graphs to determine significant wave height at construction depth (Rock Manual, 2007)

Wave Run-Up Calculations (Eurotop, 2016)

Wave run-up is defined as the extreme level of the water reached on a structure slope by wave action. Run-up defined vertically relative to the still water level (SWL) and will give positive if above SWL as shown in Figure 6.

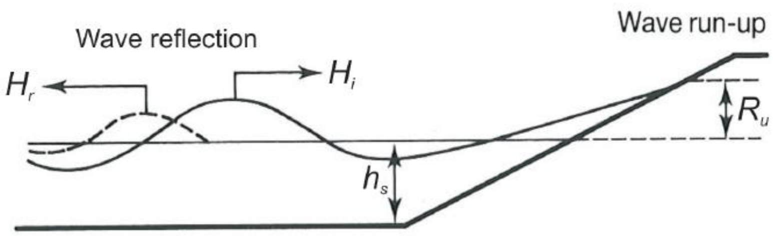


Figure 6: Wave Run-Up (Rock Manual, 2007)

Run-up levels will vary with wave heights and wave lengths in a random sea. Generally, the form of the probability distribution of run-up levels is not well established.

Hydraulic structures can be classified by their slope roughness and their permeability. Most of the field data available on wave run-up apply to impermeable and mainly smooth slopes, although some laboratory measurements have also been made on permeable rock and concrete-armored slopes.

In certain cases prediction methods developed for smooth slopes can be used for rough slopes by applying a roughness correction factor. Correction factors can also be used to take into account complicating conditions such as oblique waves, shallow foreshores and bermed slopes.

Eurotop (2016) presents the following equations for the determination of wave run-up. It should be noted that the validity range of this method is $0.5 < \gamma_b \, \xi_{m-1,0} < 10$:

$$\zeta_{m-1,0} = \tan\alpha / \sqrt{(2\pi / g)\, Hs_{toe} \; / \; T^2_{m-1,0}} \quad \text{where} \quad T_{m-1,0} \approx 0.98 \text{ Ts}$$

$$\frac{R_{u2\%}}{H_{s,toe}} = 1.75 \, \gamma_b \, \gamma_f \, \gamma_\beta \, \xi_{m-1,0} \quad \text{with an upper limit of} \quad \frac{R_{u2\%}}{H_{s,toe}} = 1.07 \gamma_{f,surg} \, \gamma_\beta \, (4.0 - 1.5 / \sqrt{\gamma_b \, \xi_{m-1,0}})$$

where

$T_{m-1,0}$	:	Spectral mean energy wave period
$\zeta_{m-1,0}$	:	Surf similarity parameter using spectral mean energy wave period
$R_{u2\%}$	:	2% exceeded run-up level
α	:	Slope angle of the structure (°)
γ_b	:	Correction factor for bermed structures
γ_f	:	Correction factor for rough slopes
γ_β	:	Correction factor for oblique waves

For straight smooth slopes and perpendicular wave attack (β=0˚) all of the correction factors are 1.0.

Correction Factor for Rough Slopes (γ_f):

A rubble slope will dissipate significantly more wave energy than the equivalent smooth or non-porous slope. Run-up levels will therefore generally be reduced. This reduction is influenced by the permeability of the armor, filter and under layers, and by the wave steepness. In Table 4, correction factors for rough slopes are given.

Table 4: Correction Factors for Rough Slopes (Rock Manual, 2007)

Structure Type	γ_f
Concrete, asphalt and grass	1.0
Pitched stone	0.80-0.95
Armor stone – single layer on impermeable base	0.70
Armor stone – two layer on impermeable base	0.55
Armor stone – permeable base	0.40

Correction Factor for Oblique Waves (γ_β):

For oblique waves, the angle of wave attack, β (˚), is defined as the angle between the direction of propagation of waves and the axis perpendicular to the structure (for normal wave attack: β = 0˚). The correction factor can be calculated as:

$$\gamma_\beta = 1 - 0.0063|\beta| \quad \text{for} \quad 0° \le |\beta| \le 80°$$

For angles of approach, β>80˚, the result of β=80˚ can be applied.

Correction Factor for Bermed Slopes (γ_b):

Bermed slopes are not within the scope of this course; therefore, it can be taken as 1.

Wave Overtopping Calculations (Eurotop, 2016)

The mean overtopping discharge or overtopping rate is often used to judge allowable overtopping. Following formula can be used to find mean overtopping discharge fort he design purposes.

$$\frac{q}{\sqrt{g\,H_{s,toe}^3}} = 0.1035 \exp\left[-\left(1.35\,\frac{R_c}{H_{s,toe}\,\gamma_f\,\gamma_\beta}\right)^{1.3}\right] \quad \text{for steep slopes } 1:2 \text{ to } 1:4/3$$

q	:	Mean overtopping discharge
g	:	Acceleration of Gravity
$H_{s,toe}$	:	Significant wave height at the toe of the structure
R_c	:	Free crest height above the still water level
γ_f	:	Correction factor for rough slopes (given in Table 5 below)
γ_β	:	Correction factor for oblique waves (can be used as given for run-up calculations)

Table 5: Correction Factors for Rough Slopes (Eurotop, 2016)

Structure Type	γ_f
Smooth impermeable surface	1.00
Rocks (1 layer, impermeable core)	0.60
Rocks (1 layer, permeable core)	0.45
Rocks (2 layers, impermeable core)	0.55
Rocks (2 layers, permeable core)	0.40
Cubes (1 layer, flat positioning)	0.49
Cubes (2 layers, random positioning)	0.47
Antifers	0.50
HARO's	0.47
Tetrapods	0.38
Dolosse	0.43

Accropode I	0.46
XBloc, Core-Loc, Accropode II	0.44
Cubipods one layer	0.49
Cubipods two layers	0.47

References

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