

Summary of existing formulas for the design of the armor units of rubble-mound breakwaters

Reference	Structure	Armor unit	Wave condition	Formula	
Hudson (1974)	Two-layer armored, non-overtopped	Various	Regular waves, deep and shallow waters, breaking and non-breaking waves	$W_{50} = \frac{\rho_a g H^3}{K_D \Delta^3 \cot \alpha} \rightarrow \frac{H_s}{\Delta D_{n50}} = \frac{(K_D \cot \alpha)^{1/3}}{1.27}$ <p>with CV = 18%</p>	(1)
Powell and Allsop (1985)	Two-layer armored, overtopped but not submerged, low-crested	Rock	Irregular waves	$\frac{N_{od}}{N_a} = a \exp[bs_p^{-1/3} H_s / (\Delta D_{n50})] \rightarrow \frac{H_s}{\Delta D_{n50}} = \frac{s_p^{1/3}}{b} \ln\left(\frac{1}{a} \frac{N_{od}}{N_{tot}}\right)$	(2)
van der Meer (1988a)	Two-layer armored, non-overtopped	Rock	Irregular waves, deep waters, shallow waters	$\frac{H_s}{\Delta D_{n50}} = \begin{cases} c_{Pl} \cdot S_{BA}^{0.2} P^{0.18} N^{-0.1} \xi_m^{-0.5} & (\text{plunging waves } \xi_m < \xi_{cr}) \\ c_S \cdot S_{BA}^{0.2} P^{-0.13} N^{-0.1} (\cot \alpha)^{0.5} \xi_m^P & (\text{surging waves } \xi_m > \xi_{cr}, \cot \alpha < 4) \end{cases}$ <p>for $0.005 < s_m < 0.06$</p> $c_{Pl} = \begin{cases} 6.2 (CV = 6.5\%) & \text{for deep waters} \\ 8.7 (CV = 6.5\%) & \text{for shallow waters} \end{cases}$ $c_S = \begin{cases} 1.0 (CV = 8\%) & \text{for deep waters} \\ 1.4 (CV = 8\%) & \text{for shallow waters} \end{cases}$ <p>$N \leq 7500$ (for higher values, $N = 7500$) and $0.1 \leq P \leq 0.6$</p>	(3)
van der Meer (1991)	Two-layer armored, overtopped but not submerged, low-crested	Rock	Irregular waves, deep and shallow waters	$\frac{H_s}{\Delta f_i D_{n50}} = \begin{cases} c_{Pl} \cdot S_{BA}^{0.2} P^{0.18} N^{-0.1} \xi_m^{-0.5} & (\text{plunging waves } \xi_m < \xi_{cr}) \\ c_S \cdot S_{BA}^{0.2} P^{-0.13} N^{-0.1} (\cot \alpha)^{0.5} \xi_m^P & (\text{surging waves } \xi_m > \xi_{cr}) \end{cases}$ <p>for $0.005 < s_m < 0.06$</p> $c_{Pl} = \begin{cases} 6.2 (CV = 6.5\%) & \text{for deep waters} \\ 8.7 (CV = 6.5\%) & \text{for shallow waters} \end{cases}$ $c_S = \begin{cases} 1.0 (CV = 8\%) & \text{for deep waters} \\ 1.4 (CV = 8\%) & \text{for shallow waters} \end{cases}$ <p>$N \leq 7500$ (for higher values, $N = 7500$) and $0.1 \leq P \leq 0.6$</p> $f_i = \left(1.25 - 4.8 \frac{R_c}{H_s} \sqrt{\frac{s_p}{2\pi}}\right)^{-1} \text{ for } 0 < \frac{R_c}{H_s} \sqrt{\frac{s_p}{2\pi}} < 0.052$	(4)
van der Meer (1991)	Two-layer armored, submerged	Rock	Irregular waves	$\frac{h'_c}{h} = (c_{sub} + 0.1S) \exp(-0.14N_s \cdot s_p^{-1/3})$ <p>where $c_{sub} = 2.1$ (CV = 17%)</p>	(5)
Melby and Kobayashi (1998)	Two-layer armored, 1:2 slope, marginally overtopped	Rock	Irregular waves, breaking condition	$[\bar{S}(t)]^{1/b_{MK}} = [\bar{S}(t_n)]^{1/b_{MK}} + (a_S N_S^5)^{1/b_{MK}} \frac{t - t_n}{T_m}; \quad t_n \leq t \leq t_{n+1}$	(6)
van Gent et al. (2003)	Two-layer armored, non-overtopped	Rock	Irregular waves, shallow waters	$\frac{H_s}{\Delta D_{n50}} = \begin{cases} c_{Pl} \cdot S_{BA}^{0.2} P^{0.18} N^{-0.1} \frac{H_s}{H_{2\%}} \xi_{m-1,0}^{-0.5} & (\text{plunging waves } \xi_{m-1,0} < \xi_{cr}) \\ c_S \cdot S_{BA}^{0.2} P^{-0.13} N^{-0.1} \frac{H_s}{H_{2\%}} (\cot \alpha)^{0.5} \xi_{m-1,0}^P & (\text{surging waves } \xi_{m-1,0} \geq \xi_{cr}) \end{cases}$ <p>$c_{Pl} = 8.4$ (CV = 8%) and $c_S = 1.3$ (CV = 12%)</p> <p>$N \leq 7500$ (for higher values, $N = 7500$) and $0.1 \leq P \leq 0.6$</p>	(7)
van Gent et al. (2004)	Two-layer, slope 1:2 and 1:4, non-overtopped	Rock	Irregular waves, deep and shallow waters, breaking and non-breaking conditions	$\frac{S_{BA}}{\sqrt{N}} = \left(0.57 \frac{H_s}{\Delta D_{n50}} \sqrt{\tan \alpha} \frac{1}{1 + D_{n50core}/D_{n50}}\right)^5$ <p>for $0.6 < \frac{H_s}{\Delta D_{n50}} < 4.3$, $1 < \xi_m < 5$, $0.18 < \frac{H_{s0}}{h} < 2.7$, $0 < \frac{D_{n50core}}{D_{n50}} < 2.7$</p> <p>with CV = 11%</p>	(8)

Melby and Hughes (2004); Melby and Kobayashi (2011)	Two-layer armored, 1:1.5 and 1:2 slope, marginally overtopped	Rock	Irregular waves, deep waters using vdM database	$N_m = \begin{cases} 5 P^{0.18} \sqrt{\cot \alpha} \left(\frac{S}{\sqrt{N}}\right)^{0.2} & s_m \geq s_{mc} \\ 5 P^{0.18} \cot \alpha^{0.5-P} \left(\frac{S}{\sqrt{N}}\right)^{0.2} \frac{P}{s_m^{\frac{P}{3}}} & s_m < s_{mc} \end{cases}$ $N_m = \left(\frac{M_{fmax}}{\rho_w g h^2 \Delta}\right)^{\frac{1}{2}} h D_{n50}^{-1}$ $s_{mc} = -0.0035 \cot \alpha + 0.028$	(9)
Eldrup and Andersen (2019)	Two-layer armored, 1:1.5 and 1:2 slope, non-overtopped	Rock	Irregular waves, shallow waters	$\frac{H_s}{\Delta D_{n50}} = \begin{cases} 4.5 \left(\frac{S_{BA}}{\sqrt{N}}\right)^{0.2} 1.6^P \xi_{m-1,0}^{(0.4P-0.67)} & (\text{plunging waves } \xi_{m-1,0} < \xi_{cr}) \\ 3.1 \left(\frac{S_{BA}}{\sqrt{N}}\right)^{0.2} P^{0.17} \min[\cot \alpha, 2]^{0.23} & (\text{surging waves } \xi_{m-1,0} \geq \xi_{cr}) \end{cases}$	(10)
Etemad-Shahidi et al. (2020)	Two-layer armored, 1:2 slope, non-overtopped	Rock	Irregular waves, deep and shallow waters, breaking and no-breaking conditions	$\frac{H_s}{\Delta D_{n50}} = \begin{cases} 4.5 \cdot C_p N^{-1/10} S_{BA}^{1/6} \xi_{m-1,0}^{-7/12} (1-3m) & (\text{plunging waves } \xi_{m-1,0} < 1.8) \\ 3.9 \cdot C_p N^{-1/10} S_{BA}^{1/6} \xi_{m-1,0}^{-1/3} (1-3m) & (\text{surging waves } \xi_{m-1,0} \geq 1.8) \end{cases}$ <p>with CV = 11%</p> <p>where $C_p = [1 + (D_{n50core}/D_{n50})^{3/10}]^{3/5}$</p>	(11)
Scaravaglione et al. (2025)	Two-layer armored, non-overtopped	Rock	Irregular waves, shallow waters from intermediate to extremely shallow water conditions	$\frac{H_{m0}}{\Delta D_{n50}} = 3.3 \sqrt{\cot \alpha} (1 + D_{n50core}/D_{n50}) s_{m-1,0}^{0.1} \left(\frac{S}{\sqrt{N}}\right)^{0.2}$ <p>for $1.47 < \frac{H_{m0}}{\Delta D_{n50}} < 3.44$, $0.42 < \frac{H_{m0,0}}{h} < 4.94$, $0.21 < \frac{D_{n50core}}{D_{n50}} < 0.71$</p> <p>with $\sigma = 0.36$</p>	(12)
van der Meer (1988b)	Two-layer armored, 1:1.5 slope, non-overtopped	Cube	Irregular waves, deep waters	$\frac{H_s}{\Delta D_n} = \left(6.7 \frac{N_{od}^{0.4}}{N^{0.3}} + 1\right) s_m^{-0.1} \quad \text{for } 3 < \xi_m < 6 \text{ and } P = 0.4$ <p>with CV = 10%</p>	(13)
van Gent et al. (1999, 2002)	One-layer, slope 1:1.5	Cube	Irregular waves, deep waters	$\frac{H_s}{\Delta D_n} = \begin{cases} 2.0 \div 3.0 \text{ start of damage } (N_{od} = 0) \\ 3.0 \div 3.5 \text{ failure } (N_{od} = 0.2) \end{cases}$	(14)
van der Meer (1988b)	Two-layer armored, 1:1.5 slope, non-overtopped	Tetrapod	Irregular waves, deep waters, surging waves	$\frac{H_s}{\Delta D_n} = \left(3.75 \frac{N_{od}^{0.5}}{N^{0.25}} + 0.85\right) s_m^{-0.2} \quad \text{for } 3.5 < \xi_m < 6 \text{ and } P = 0.4$ <p>with CV = 10%</p>	(15)
d'Angremond et al. (1994)	Two-layer armored, 1:1.5 slope, non-overtopped	Tetrapod	Irregular waves, shallow waters	$\frac{H_{2\%}}{\Delta D_n} = 1.4 \left(3.75 \frac{N_{od}^{0.5}}{N^{0.25}} + 0.85\right) s_m^{-0.2} \quad \text{for } 3.5 < \xi_m < 6 \text{ and } P = 0.4$ <p>with CV = 10%</p>	(16)
De Jong (1996)	Two-layer armored, 1:1.5 slope, non-overtopped	Tetrapod	Irregular waves, deep waters, plunging waves	$\frac{H_s}{\Delta D_n} = \left(8.6 \left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 3.94\right) s_m^{0.2}$ <p>with CV = 50%</p>	(17)
De Jong (1996)	Two-layer armored, 1:1.5 slope, low-crested	Tetrapod	Irregular waves, deep waters, plunging waves	$\frac{H_s}{\Delta D_n} = \left(8.6 \left(\frac{N_{od}}{N^{0.5}}\right)^{0.5} + 2.64k_t + 1.25\right) s_m^{0.2} \left[1 + 0.17 \exp\left(-0.61 \frac{R_c}{D_n}\right)\right]$ <p>with CV = 50%</p>	(18)
van der Meer (1988b)	One-layer, slope 1:1.33	Accropode 7	Irregular waves, deep waters, non-breaking waves	$\frac{H_s}{\Delta D_n} = \begin{cases} 3.7 (CV = 20\%) \text{ no damage } (N_{od} = 0) \\ 4.1 (CV = 20\%) \text{ failure } (N_{od} > 0.5) \end{cases}$ <p>It is recommended to use a safety coefficient for design of about 1.5.</p>	(19)

Burcharth et al. (1998)	One-layer, slope 1:1.33, non-overtopped or marginally overtopped	Accropode 7	Irregular waves, breaking and non-breaking conditions	$\frac{H_s}{\Delta D_n} = A(N_d^{0.2} + 7.70) \quad \text{for } 3.5 < \xi_m < 4.5$ $A = 0.46 (CV = 0.02 + 0.05(1 - N_d)^6)$	(20)
Burcharth and Liu (1992)	Two-layer armored, 1:1.5 slope, non-overtopped	Dolos	Irregular waves, breaking and non-breaking conditions	$\frac{H_s}{\Delta D_n} = (47 - 72r)\varphi D^{1/3} N^{-0.1} = (17 - 26r)\varphi^{2/3} N_{od}^{1/3} N^{-0.1}$ $0.32 < r < 0.42 \quad 0.61 < \varphi < 1 \quad 1\% < D < 15\% \quad 2.49 < \xi_0 < 11.7$ <p style="text-align: center;">with $CV = 22\%$</p>	(21)
Holtzhausen (1996)	Two-layer armored, 1:1.5 slope, non-overtopped	Dolos	Irregular waves, breaking and non-breaking conditions	$N_{od} = 6.95 \cdot 10^{-5} \left(\frac{H_s}{\Delta^{0.74} D_n} \right)^7 \varphi^{1.51}$	(22)
Brown (1983)	Uniformly placed armor units	Seebes	Irregular waves	$\frac{H_s}{\Delta D_n} = (1 - n_v) C_B \cot \alpha^{\frac{1}{3}}$	(23)

Summary of existing formulas for the estimation of mean wave overtopping discharge of rubble-mound breakwaters

Reference	Armor units	Formula	
Smolka et al. (2009)	Cube, Cubipod	$\frac{q}{\sqrt{gH_s^3}} = 0.2 \cdot \exp\left(0.53\xi_p - 3.27\frac{A_c}{R_c} - 2.16\frac{R_c}{H_s} \cdot \frac{1}{\gamma_f}\right) \quad \text{for } 2.7 < \xi_p < 7, \quad \cot \alpha = 1.5, \quad 1.30 < \frac{R_c}{H_s} < 2.80$ $\gamma_f = \begin{cases} 0.50 & \text{for Cubes - 2 layers } (0.70 < A_c/R_c < 1.00) \\ 0.46 & \text{for Cubipods - 1 layer } (0.40 < A_c/R_c < 0.65) \\ 0.44 & \text{for Cubipods - 2 layers } (0.58 < A_c/R_c < 0.80) \end{cases}$	(24)
Jafari and Etemad-Shahidi (2012) and Etemad-Shahidi and Jafari (2014)	Various - CLASH database	$\frac{q}{\sqrt{gH_s^3}} = \begin{cases} \exp\left(-0.6396\frac{R_c}{\gamma_f\gamma_\beta H_s \tan \alpha} - 0.7085 \tan \alpha - 11.4897\right) & \text{if } \frac{R_c}{H_s} > 2.08 \text{ and } \frac{G_c}{H_s} > 1.51 \\ \exp\left(-6.18\frac{R_c}{\gamma_f\gamma_\beta H_s \tan \alpha} - 3.21\right) & \text{if } \frac{R_c}{\gamma_f\gamma_\beta H_s \tan \alpha} \leq 0.86 \\ \exp\left(-3.1\frac{R_c}{\gamma_f\gamma_\beta H_s \tan \alpha} - 6.05 \tan \alpha - 2.63\right) & \text{if } \frac{R_c}{\gamma_f\gamma_\beta H_s \tan \alpha} > 0.86 \end{cases}$ $\text{for } 1.31 < \xi_p < 9.27, \quad 0.50 < \frac{R_c}{H_s} < 2.59, \quad 0.00 < \frac{G_c}{H_s} < 3.88$ $\gamma_\beta = \begin{cases} 1 - 0.0063 \beta & \text{for } 0^\circ \leq \beta \leq 80^\circ \\ 1 - 0.063 \cdot 80 & \text{for } \beta \geq 80^\circ \end{cases}$	(25)
Molines and Medina (2016)	Various - CLASH database (conventional breakwaters)	$\frac{q}{\sqrt{gH_s^3}} = \exp\left(\lambda_2\lambda_3\lambda_4\lambda_5\lambda_6 \left[a_1 + b_1 \cdot \frac{R_c}{H_s} \cdot \frac{1}{\gamma_f\gamma_\beta}\right]\right)$ $\text{for } 1.65 < \xi_{m-1,0} < 7.21, \quad 0.52 < \frac{R_c}{H_s} < 3.75, \quad 0.00 < \frac{G_c}{H_s} < 3.50, \quad 0.09 < \frac{R_c}{h} < 1.34, \quad 0.38 < \frac{A_c}{H_s} < 1.38,$ $0.00 < \frac{B}{H_s} < 15.9, \quad 1.45 < \frac{h_t}{H_s} < 17.50$ $\lambda_2 = a_2 + b_2 \cdot (\xi_{m-1,0}\sqrt{R_c/H_s}) \quad \lambda_3 = a_3 + b_3 \cdot \exp(c_3 R_c/H_s) \quad \lambda_4 = \max[c_4; a_4 + b_4 \cdot G_c/H_s]$ $\lambda_5 = a_5 + b_5 \cdot A_c/R_c \quad \lambda_6 = \begin{cases} \max[c_6; a_6 + b_6 \cdot R_c/h] \\ d_6 & \text{if } B_t = 0 \end{cases}$ $\gamma_\beta = \begin{cases} 1 - 0.0077 \beta \\ 1 - 0.0058 \beta \end{cases}$	(26)
EurOtop (2018)	Various - extended CLASH database	$\frac{q}{\sqrt{gH_s^3}} = a_E \cdot \exp\left[-\left(b_E \frac{R_c}{H_s\gamma_f\gamma_\beta}\right)^{1.3}\right] \quad \text{for } 2 < \cot \alpha < 4/3, \quad 0.00 < \frac{R_c}{H_s} < 3.50, \quad \xi_p \geq 2$ $a_E = 0.09 \quad (\sigma = 0.0135) \quad \text{and} \quad b_E = 1.5 \quad (\sigma = 0.15)$ $\gamma_\beta = \begin{cases} 1 - 0.0063 \beta & \text{for } 0^\circ \leq \beta \leq 80^\circ \\ 1 - 0.063 \cdot 80 & \text{for } \beta \geq 80^\circ \end{cases}$	(27)
Vieira et al. (2021)	Cube (single layer)	$\frac{q}{\sqrt{gH_s^3}} = 0.20 \cdot \exp\left(-6.45\frac{R_c}{H_s\gamma_f^3} \frac{1}{\sqrt{2\pi/gT_{m-1,0}^2 G_c}}\right)$ $\text{for } \cot \alpha = 1.5, \quad 1.4 < \frac{R_c}{H_s} < 3.7, \quad 2.8 \leq \xi_{m-1,0} \leq 4.4, \quad s_p = 0.02 \text{ and } 0.05, \quad 3.1 \leq \frac{h}{H_s} \leq 6.6$ $\gamma_f = 0.52$	(28)
Etemad-Shahidi et al. (2022)	Various - data from Thompson and Shuttler (1975), van der Meer (1988a, c), van Gent et al. (2003), Vidal et al. (2006)	$\frac{q}{\sqrt{gH_s^3}} = a_{ES} \cdot \exp\left[b_{ES}\left(\frac{R_{2\%} - R_c}{H_s}\right) - c_{ES}\frac{G_c}{H_s}\right]$ $\text{for } 0.25 < \tan \alpha < 0.80, \quad 0.43 < \frac{R_c}{H_s} < 2.70, \quad 1.27 < \xi_{m-1,0} \leq 11.74$ $a_{ES} = 1.22 \cdot 10^{-4} \quad (\sigma = 1.30 \cdot 10^{-5}), \quad b_{ES} = 3.50 \quad (\sigma = 0.13), \quad c_{ES} = 0.64 \quad (\sigma = 0.07)$	(29)

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