TOE STABILITY IN VERY SHALLOW WATER COMBINED WITH STEEP SEA BOTTOM

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It is common to construct a rock toe berm of three to four rocks wide when concrete armor units are placed in the armor layer. This toe berm is a relevant element, especially in very shallow waters combined with steep sea bottoms, where waves directly attack the toe berm and the lowest part of the armor. Several formulas are available to estimate the damage to rock toe berms. In this paper, these formulas are compared for different design conditions within their range of application. Most of these formulas use the damage parameter N_{od}. However, there are often situations in which wider toe berms are required for a safe design, and the damage parameter N_{od} is not recommended. A methodology is thus proposed to design wider toe berms based on the damage to the nominal toe berm of three rocks wide (N_{od}*), considered as the most shoreward part of the toe berm which effectively supports the armor layer.

Keywords: mound breakwaters; rock toe berms; nominal toe berm; sacrificial toe berm; steep sea bottom

INTRODUCTION

When concrete armor units are used, a toe berm of three or four rocks wide (B_t=3-4D_{n50}) is usually placed on the seafloor to provide support to the armor layer. Fig. 1 shows the cross section of a conventional rock toe berm.

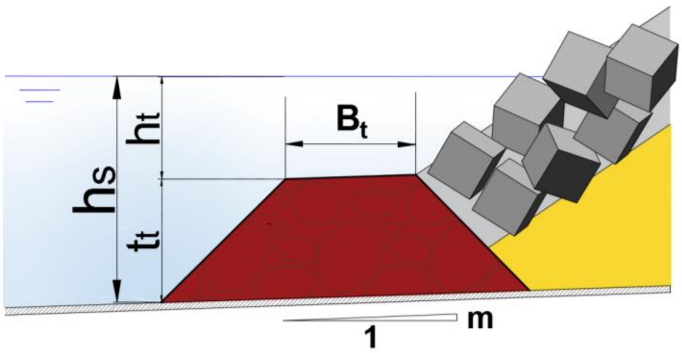

Figure 1. Schematic cross section of conventional rock toe berm.

The design of the toe berm depends mainly on the bottom slope (m), the water depth at the toe (h_s), and the design wave storm (H_s and T_p). USACE (1984) proposed estimating the mass of the toe berm rocks as one order of magnitude lower than the mass of the armor units. However, this design criterion is not valid for depth-limited breaking wave conditions, especially, when breakwaters are placed on rocky coastlines with steep seafloors and shallow waters. In these conditions, mound breakwaters may require emerged toe berms, and the rock size may exceed the armor unit size (see Herrera and Medina, 2015).

This paper focuses attention on the design of rock toe berms, the relevance of the sea bottom slope on the hydraulic stability of toe berms, and the use of wider than conventional rock toe berms to reduce the size of the required rocks. Other design alternatives, not analyzed in this paper, to increase the toe berm hydraulic stability may involve using concrete units in the toe berm (see Burchart and Liu 1995, or Van Gent and Van der Werf 2014), or excavating trenches in the sea bottom to support the rocks in the toe berm (USACE 2006).

DESIGN OF ROCK TOE BERM

Different formulas have been proposed to design rock toe berms. Most of them use the stability number (N_s=H_s/ΔD_{n50}), where H_s is the significant wave height measured at the toe of the structure,

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$\Delta=(\rho_r-\rho_w)/\rho_w$ is the relative submerged mass density, ρ_r and ρ_w are the mass densities of the rocks and the sea water, respectively, and D_{n50} is the nominal diameter of the rocks in the toe berm.

Gerding (1993) proposed Eq. 1 to estimate toe berm damage using the dimensionless damage parameter $N_{od}=N/BD_{n50}$, where N is the number of rocks displaced from the toe, and B is the width of the reference area. Eq. 1 was based on small-scale tests conducted with a bottom slope m=1/20 and water depths at the toe h_s(cm)=30, 40, and 50. Two wave steepnesses ($s_{0p}=2\pi H_{sg}/gT_p^2$=0.02 and 0.04) were tested with increasing significant wave height at the wave generating zone (H_{sg}(cm)=15, 20 and 25). Rock toe berms with D_{n50}(cm)=1.7, 2.5, 3.5 and 4.0 were tested with relative toe berm widths within the range $3D_{n50}\leq B_t\leq 12D_{n50}$, and relative toe berm thicknesses of $2.3D_{n50}\leq t_t\leq 8.8D_{n50}$; however, B_t was not explicitly introduced as an explanatory parameter for toe berm damage.

$$N_{od}=\left(N_s\bigg/\left(0.24\left(\frac{h_t}{D_{n50}}\right)+1.6\right)\right)^{6.67} \quad (1)$$

where h_t is the water depth above the toe berm.

Van der Meer (1998) proposed Eq. 2 to estimate toe berm damage, based on Gerding's tests. This author introduced the ratio h_t/h_s as an explanatory parameter, instead of the relative water depth above the toe, h_t/D_{n50}.

$$N_{od}=\left(N_s\bigg/\left(6.2\left(\frac{h_t}{h_s}\right)+2.0\right)\right)^{6.67} \quad (2)$$

Ebbens (2009) conducted small-scale tests with three bottom slopes m=1/10, 1/20 and 1/50 and water depths at the toe in the range $7\leq h_s(cm)\leq 25$. He measured toe berm damage using the damage parameter N_{od}, and also introduced the damage number $N_{\%}=ND_{n50}/Vtot\ (1-n_v)$, where Vtot is the total volume of the toe berm, and n_v is the void porosity. Tests were conducted with three wave steepnesses ($s_{0p}=2\pi H_{sg}/gT_p^2$=0.02, 0.03 0.04) and four significant wave heights at the wave generating zone (H_{sg}(cm)=6, 8, 10 and 12). Toe berms with D_{n50}(cm)=1.88, 2.15, and 2.68 were considered with a toe berm width of B_t (cm)=10 and toe berm thickness of t_t (cm)=6. According to this author, the bottom slope (m) had a significant influence on toe berm damage (see Fig. 4); thus, it was introduced as an explanatory parameter in the proposed equation (Eq. 3), where $L_{0p}=gT_p^2/2\pi$ is the wave length in deep water conditions and T_p is the peak period. By contrast, h_s, B_t and t_t were not included in Eq. 3.

$$N_{\%}=0.038\left(N_s\sqrt{\frac{m}{\left(H_s/L_{0p}\right)^{1/2}}}\right)^3 \quad (3)$$

Muttray (2013) proposed Eq. 4 to estimate N_{od} based on tests conducted by different authors, including as Gerding (1993) and Ebbens (2009):

$$N_{od}=\left(N_s\left(0.58-0.17\frac{h_t}{H_s}\right)\right)^3 \quad (4)$$

More recently, Van Gent and Van der Werf (2014) proposed Eq. 5 to estimate rock armor damage after conducting small-scale tests with m=1/30 and h_s(cm)=20, 30 and 40. Two wave steepnesses ($s_{0p}=2\pi H_{sg}/gT_p^2$=0.0015 and 0.04) were tested with increasing significant wave height up to H_{sg}(cm)=28. Toe berms with D_{n50}(cm)=1.46 and 2.33 were considered with toe berm widths of $B_t=3D_{n50}$ and $9D_{n50}$, and toe berm thicknesses of $t_t=2D_{n50}$ and $4D_{n50}$. In this case, B_t and t_t were introduced as explanatory parameters for toe berm damage. For wide toe berms ($3D_{n50}<B_t\leq 9D_{n50}$),

these authors proposed multiplying the N_{od} obtained with Eq. 5 by the factor $fb=(n_t/3)^{1/2}$, where n_t is the number of rock rows placed on the upper layer of the toe berm.

$$N_{od}=0.032\left(\frac{t_t}{H_s}\right)\left(\frac{B_t}{H_s}\right)^{0.3}\left(\frac{\hat{u}_\delta}{\sqrt{g\cdot H_s}}\right)\left(N_s\right)^3 \qquad (5)$$

where $\hat{u}_\delta=\dfrac{\pi\cdot H_s}{T_{m-1,0}}\dfrac{1}{\sinh\left(k_{m-1,0}h_t\right)}$, $k_{m-1,0}=\dfrac{2\pi}{L_{m-1,0}}=\dfrac{2\pi}{\dfrac{g}{2\pi}\cdot T_{m-1,0}{}^2}$ and $T_{m-1,0}$ is the spectral wave period.

Herrera and Medina (2015) analyzed the hydraulic stability of emerged and submerged rock toe berms, with m=1/10 and very shallow waters ($-2\le h_s(cm)\le 20$). 2D small-scale tests were conducted in the wave flume of the Laboratory of Ports and Coasts at the *Universitat Politècnica de València* (LPC-UPV). Five peak periods were tested: T_p=1.2, 1.5, 1.8, 2.2 and 2.4s. For each T_p, irregular waves were generated from no damage to waves high enough to break in the wave generating zone ($8\le H_{sg}(cm)<22$). Toe berms with $D_{n50}(cm)$=3.99 and 5.12 were considered with a toe berm width of B_t= $3D_{n50}$, and a toe berm thickness of t_t= $2D_{n50}$. Toe berm damage was measured after each test run using the damage parameter N_{od}, and cumulative damage was considered during each test series defined by h_s (35 to 40 tests per series). Based on test results, Eq. 6 was proposed to estimate N_{od}, where H_{s0} is the significant wave height in deep water conditions.

$$N_{od}=\left(\frac{(H_{s0}\ L_{0p})^{1/2}}{\Delta D_{n50}}-5.5\right)\left[\left(-0.2\frac{h_s}{D_{n50}}+1.4\right)exp\left(0.25\frac{h_s}{D_{n50}}-0.65\right)\right]^{1/0.15} \qquad (6)$$

Herrera et al. (2016) analyzed the influence of toe berm width ($B_t=n_tD_{n50}$) on the hydraulic stability. Small-scale tests were conducted in the LPC-UPV wave flume with m=1/10 and $7.7\le h_s(cm)\le 10.6$. The same wave periods and significant wave heights considered in Herrera and Medina (2015) were tested ($1.2\le T_p(s)\le 2.4$ and $8\le H_{sg}(cm)<22$). Toe berms with $D_{n50}(cm)$=3.04, 3.99 and 5.12 were studied for toe berm widths of $B_t=3D_{n50}$, $5D_{n50}$ and $12D_{n50}$, and fixed toe berm thickness t_t= $2D_{n50}$. To characterize the damage to wide toe berms ($B_t>3D_{n50}$), the authors introduced two new concepts (see Fig. 2):

1. Nominal toe berm: the $3D_{n50}$-wide most shoreward part of the toe berm, necessary to support the armor layer.
2. Sacrificial toe berm: the most seaward part of the toe berm, which protects the nominal toe berm.

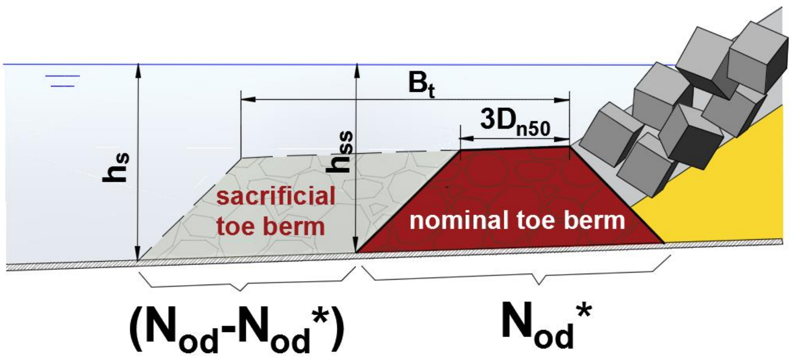

Figure 2. Nominal and sacrificial toe berms (Herrera et al., 2016).

After each test, two damage parameters were measured: (1) N_{od}, corresponding to the total damage to the toe berm, and (2) N_{od}* corresponding only to the damage to the $3D_{n50}$-wide nominal toe berm. Based on the N_{od}* measured in tests, Eq. 6 was modified to take into account the toe berm width ($B_t=n_tD_{n50}$) for toe berm design, where $D_{n50,nt}$ is the nominal diameter required for a n_tD_{n50}-wide toe berm, and h_{ss} is the water depth at the toe of the nominal berm.

$$N_{od}^{*}=\left(\frac{(H_{s0}\,L_{0p})^{1/2}}{\Delta D_{n50,nt}\left(\frac{n_t}{3}\right)^{0.4}}-5.5\right)\left[\left(-0.2\frac{h_{ss}}{D_{n50,nt}\left(\frac{n_t}{3}\right)^{0.4}}+1.4\right)exp\left(0.25\frac{h_{ss}}{D_{n50,nt}\left(\frac{n_t}{3}\right)^{0.4}}-0.65\right)\right]^{1/0.15} \tag{7}$$

Table 1 summarizes the test conditions and the range of parameters used by different authors.

Table 1. Characteristics of tests conducted by authors

		Gerding (1993)	Ebbens (2009)	Van Gent and Van der Werf (2014)	Herrera and Medina (2015)	Herrera et al. (2016)
		Eq. 1	Eq. 3	Eq. 5	Eq. 6	Eq. 7
Waves	-	Irregular	Irregular	Irregular	Irregular	Irregular
Bottom slope [-]	1:m	1:20	1:50, 1:20, 1:10	1:30	1:10	1:10
Water depth at toe [cm]	h_s	30, 40, 50	7.3 –33.9	20, 30, 40	-2 – 20	7.7 –10.6
Relative toe width [-]	B_t/ D_{n50}	3 – 12	3.7– 5.3	3 and 9	3	3, 5 and12
Relative toe thickness [-]	t_t/ D_{n50}	2.3-8.8	2.2-3.2	2 and 4	2	2
Rock toe size [cm]	D_{n50}	1.7 – 4	1.88 –2.68	1.46 – 2.33	3.99 – 5.12	3.04 – 5.12
Relative water depth at toe [-]	h_s / D_{n50}	7.5 – 29.4	2.7– 18	8.6 – 27.4	-0.5 – 5.01	1.5 – 3.5
Wave steepness at toe [-]	$2\pi H_s/gT_p^2$	0.01–0.04	0.008–0.04	0.012–0.042	(0.008–0.08)[a]	(0.008–0.08)[a]
Stability number at toe [-]	$H_s/\Delta D_{n50}$	2.1 - 8.37	1.04 - 4.09	1.2 - 10.5	(0.81 – 3.36)[a]	(0.81 – 4.41)[a]
Total damage level [-]	N_{od}	<9.21	≤4.37	<7.3	< 4.72	<11.1
Damage level for nominal toe berm[-]	N_{od}^*	-	-	-	-	<4.8

[a] Refers to measurements at the wave generating zone.

Eqs. 1 and 2 can be used to estimate rock toe berm damage caused by a single storm of 1000 waves, using H_s measured at the toe of the structure. Eq. 3 considers the cumulative damage of each test series defined by a water depth, and Eq. 5 considers the cumulative damage of each test series defined by a wave steepness. For Eqs. 6 and 7, the model was rebuilt after 35-40 tests with the same water depth, taking into account that breakwaters must withstand several wave storms of less energy than the design storm. Eqs. 3, 5, 6 and 7 also consider the wave period T_p or $T_{m-1,0}$ to characterize the wave storm.

Eqs. 1 to 5 are valid for submerged toe berms (h_t>>0) and relatively gentle sea bottoms, while Eq. 6 is valid for emerged and submerged toe berms placed on steep sea bottoms (m=1/10). Most of the formulas were obtained from laboratory tests with different toe berm geometries; the toe berm width (B_t) and thickness (t_t) were not usually used as explanatory variables for the observed toe berm damage; only Eq. 5 considers B_t and t_t as explanatory variables in the design of submerged toe berms placed on a m=1/30 sea bottom. When considering wider and/or higher toe berms, common damage parameters (N_{od}, $N_{\%}$) are not recommended since larger toe berms require more rocks displaced from the toe (N) to be damaged; rocks situated in the most seaward part of the toe berm do not contribute to support the armor, but only to protect the most shoreward part of the toe berm. Thus, Herrera et al. (2016) proposed a new methodology to design wide toe berms ($3D_{n50}\leq B_t\leq 12D_{n50}$) placed on a m=1/10 sea bottom, based on the damage to the nominal toe berm (N_{od}^*) which actually supports the armor layer. When designing with N_{od}^*, common values for acceptable damage ($N_{od}^*<0.5$-no damage; $N_{od}^*\approx 1$−significant movements; $N_{od}^*\approx 2$−moderate damage; $N_{od}^*>4$−failure) can be directly applied.

ANALYSIS OF RESULTS

Existing formulas for toe berm design are analyzed in this section. Estimations given by existing formulas are compared, considering standard toe berms with $B_t=3D_{n50}$ and $t_t=2D_{n50}$. Additionally, the methods proposed to design sacrificial toe berms ($B_t>3D_{n50}$) are applied for certain wave conditions.

Nominal toe berms

For standard toe berms having $B_t=3D_{n50}$ and $t_t=2D_{n50}$, the influence of wave parameters on toe berm damage (N_{od}) was first analyzed. Fig. 3 shows the N_{od} estimated by Eqs. 1 to 5 as a function of the stability number ($N_s=H_s/\Delta D_{n50}$), fixed wave steepness $s_p=H_s/L_{0p}=0.02$, and relative water depth at toe $h_s/D_{n50}=10$. Eq. 3 is applied with two bottom slopes (m=1/10 and 1/50) and $N_{od}=10N_{\%}$ as considered in Herrera and Medina (2015).

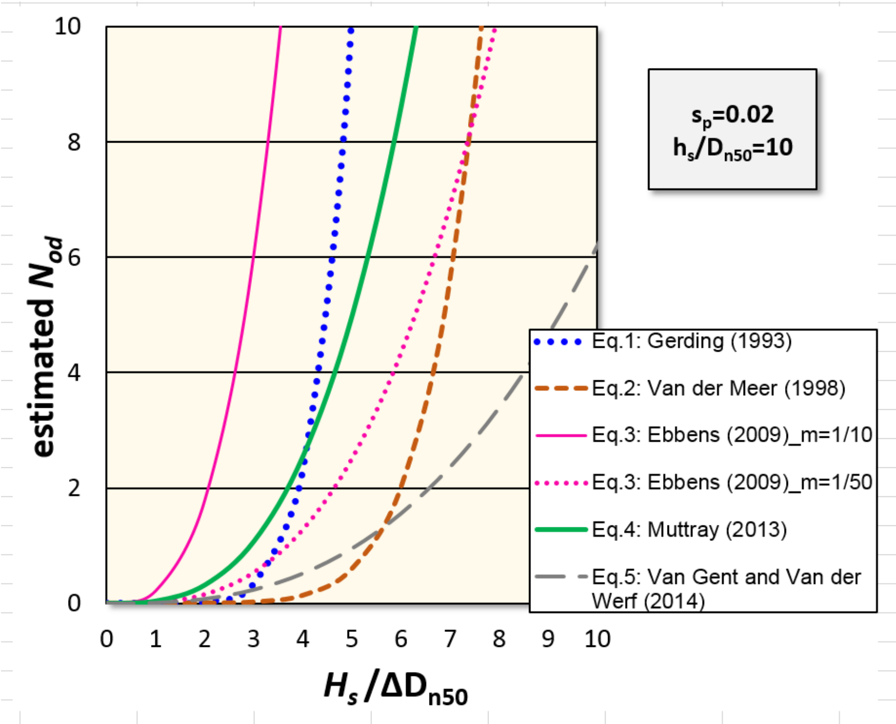

Figure 3. Toe berm damage (N_{od}) estimated by Eqs. 1 to 5 versus the stability number at the toe (N_s).

N_{od} increased when increasing N_s for all equations. Eq. 1 proposed by Gerding (1993) estimated more armor damage than Eq. 2 given by Van der Meer (1998), despite the fact that both were obtained from the same small-scale tests; note that CIRIA/CUR/CETMEF (2007) recommended the design values of $N_{od}=2.0$ for Eq. 1, and $N_{od}=0.5$ for Eq.2. When applying Eq. 3 with m=1/10, a higher N_{od} was estimated than for m=1/50, as noted by Ebbens (2009). Fig. 4 shows the N_{od} measured by Ebbens (2009) as a function of the stability number; steeper slopes led to higher levels of toe berm damage (N_{od} (m=1/10)> N_{od} (m=1/20)> N_{od} (m=1/50)).

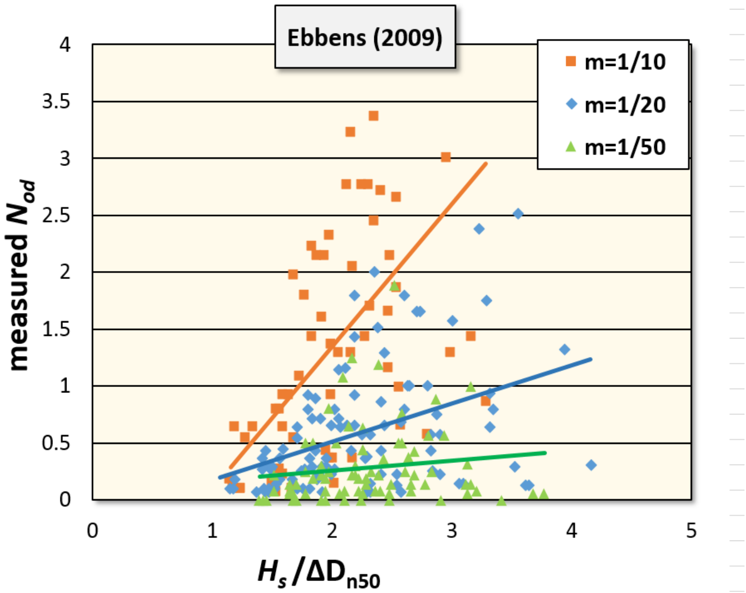

Figure 4. Toe berm damage (N_{od}) measured by Ebbens (2009) versus the stability number.

Fig. 5 shows the estimations of N_{od} reported by Herrera and Medina (2015) compared to the dimensionless variable $(H_{s0}\ L_{0p})^{1/2}/\Delta D_{n50}$, for three relative water depths at the toe. $h_s/D_{n50}=0$ corresponds to an emerged toe berm; $h_s/D_{n50}=4$ corresponds to a submerged toe berm, and $h_s/D_{n50}=2$ corresponds to the still water level (SWL) just at the top of the toe berm. N_{od} increased with $(H_{s0}\ L_{0p})^{1/2}/\Delta D_{n50}$ for the three relative water depths at the toe (h_s/D_{n50}). Note that Eqs. 1 to 5 require knowing H_s at the toe of the structure, while Eq. 6 given by Herrera and Medina (2015) uses the wave parameters in deep water wave conditions (H_{s0}, T_p).

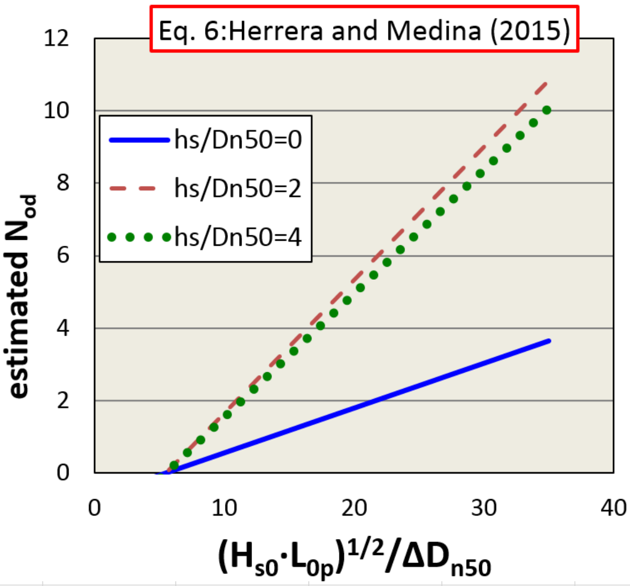

Figure 5. Toe berm damage (N_{od}) estimated by Eq. 6 versus the dimensionless variable $(H_{s0}L_{0p})^{1/2}/\Delta D_{n50}$.

The influence of the relative water depth at the toe (h_s/D_{n50}) on toe berm damage was also analyzed for standard toe berms having $B_t=3D_{n50}$ and $t_t=2D_{n50}$. Fig. 6 shows the N_{od} estimated by Eqs. 1 to 5 as a function of h_s/D_{n50}, for a typical storm in the Alboran Sea (H_s(m)=5, T_p(s)=11) and rocks of 6-tonnes in weight with a mass density of ρ_r(t/m^3)=2.7. Each equation was represented within its range of application: $7.5\leq h_s/D_{n50}\leq 29$ for Eqs. 1 and 2; $2.7\leq h_s/D_{n50}\leq 19$ for Eq. 3; $h_t/H_s<3$

for Eq. 4; and $8.6 \leq h_s/D_{n50} \leq 27.4$ for Eq. 5. For Eqs. 1, 2, 4 and 5, N_{od} decreased when increasing h_s/D_{n50}. For Eq. 3, N_{od} did not vary for m=1/10 and m=1/20 when increasing or reducing h_s/D_{n50}.

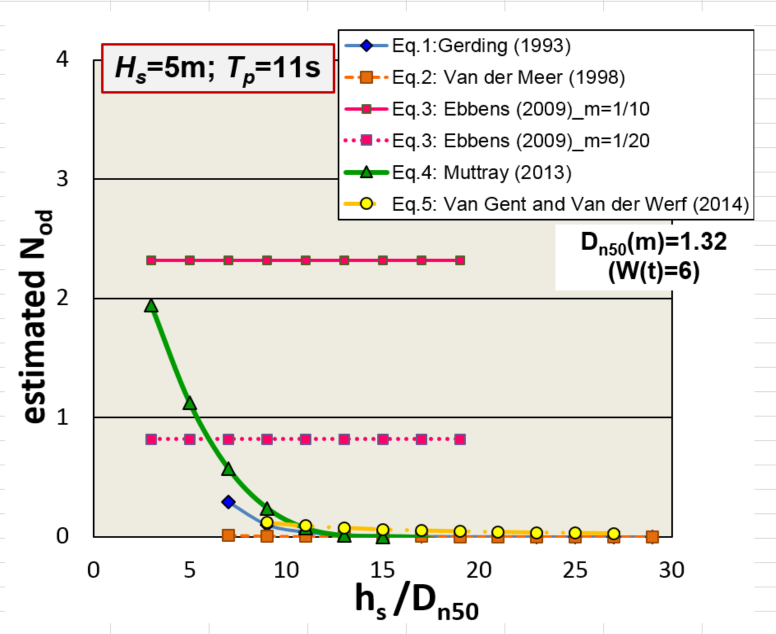

Figure 6. Toe berm damage (N_{od}) estimated by Eqs. 1 to 5 versus the relative water depth at the toe (h_s/D_{n50}).

Fig. 7 shows the estimations of N_{od} reported by Herrera and Medina (2015) compared to h_s/D_{n50}, when considering $H_{s0}(m)=5$, $T_p(s)=11$ in deep water conditions, and rocks of 6-tonnes in weight with a mass density of $\rho_r(t/m^3)=2.7$. N_{od} was highest when the SWL was close to the top of the toe berm ($h_s/D_{n50}=3$). From $h_s/D_{n50}=3$, N_{od} decreased when increasing h_s/D_{n50}. For the rock size and wave storm considered in this example, there was a range of relative water depths for which N_{od} was excessive.

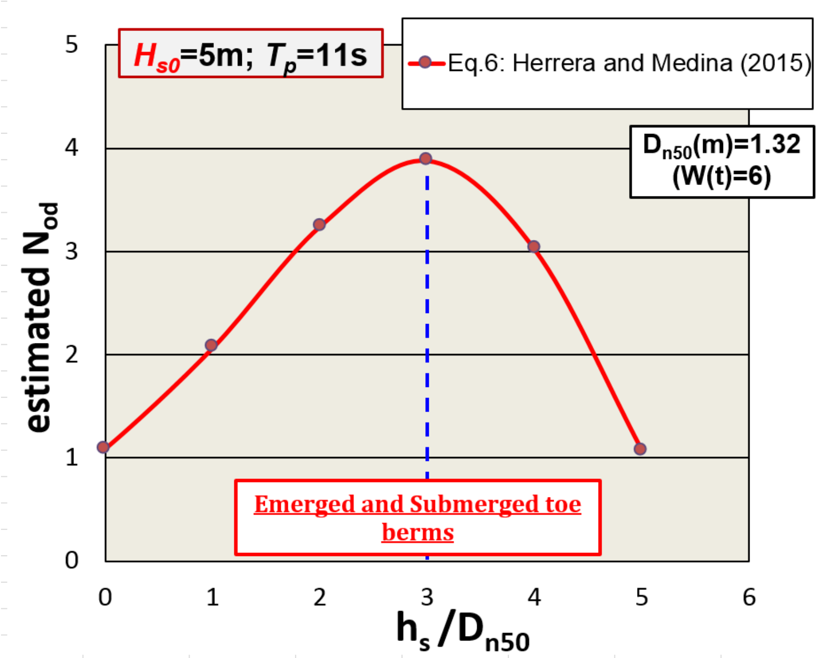

Figure 7. Toe berm damage (N_{od}) estimated by Eq. 6 versus the relative water depth at the toe (h_s/D_{n50}).

In order to reduce toe berm damage, Eq. 6 and Fig. 7 can be used to determine a more stable position if the toe of the structure is moved shoreward or seaward in the range $-0.5 \leq h_s/D_{n50} \leq 5.0$. When it is not feasible to move the toe position of the structure due to environmental, economic or operational constraints, a sacrificial toe berm can be considered following the methodology proposed by Herrera et al. (2016).

Sacrificial toe berms

As mentioned before, when considering wider toe berms, common damage numbers (N_{od} or $N_{\%}$) are not suitable to characterize toe berm stability. When increasing the toe berm width ($B_t=n_tD_{n50}>3D_{n50}$), it is necessary to analyze the behavior of the sacrificial and nominal toe berms. Fig. 8 provides the total toe berm damage (N_{od}) and the nominal toe berm damage (N_{od}*) measured in the laboratory tests conducted by Herrera et al. (2016) with m=1/10, rocks of D_{n50}(cm)=3.99 and n_t=3, 5 and 12, as a function of the variable $(H_{s0}L_{0p})^{1/2}$. The total toe berm damage (N_{od}) increased when the toe berm width (n_t) was increased, while the nominal toe berm damage (N_{od}*) was less when the toe berm width was increased. Thus, given a rock size (D_{n50}), a wider toe berm reduces N_{od}* although the N_{od} increases. As a result, N_{od} is not the best estimator of toe berm damage for wide toe berms (B_t >3D_{n50}); N_{od}* is better and should be considered for design purposes.

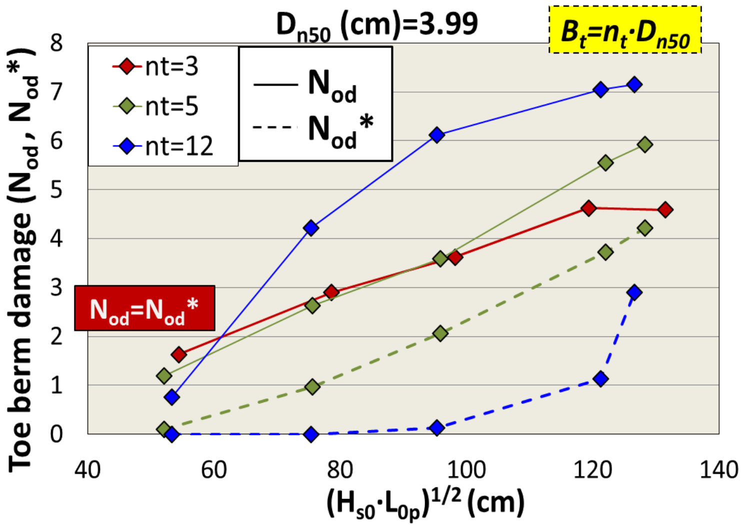

Figure 8. Total toe berm damage (N_{od}) and nominal toe berm damage (N_{od}*) measured in the tests conducted by Herrera et al. (2016) with rock size D_{n50}(cm)=3.99.

Considering the nominal toe berm damage (N_{od}*), Herrera et al. (2006) proposed a methodology to reduce the rock size required for a toe berm placed on a m=1/10 sea bottom, when it is not possible to find this rock size or when the required rock size is not available near the construction site. Given a design wave storm, Eq. 6, proposed by Herrera and Medina (2015), can be first applied to design a standard $3D_{n50}$-wide and $2D_{n50}$-high rock toe berm within the ranges $0.02 \leq s_{0p} \leq 0.07$, $-0.15 \leq h_s/H_{s0} \leq 1.5$, and $-0.5 \leq h_s/D_{n50} \leq 5.0$. Eq. 8 can be used later to reduce the required rock size in the toe berm by increasing the toe berm width ($B_t=n_tD_{n50}$ and $n_t \leq 12$), following a 0.4-power relationship. Fig. 9 shows a sketch of this process.

$$\frac{D_{n50,nt}}{D_{n50,3}} = \left(\frac{3}{n_t}\right)^{0.4} \tag{8}$$

where $D_{n50,3}$ is the nominal diameter required for a nominal toe berm measuring $3D_{n50}$ in width, and $D_{n50,nt}$ is the nominal diameter required for a $n_tD_{n50,nt}$-wide toe berm.

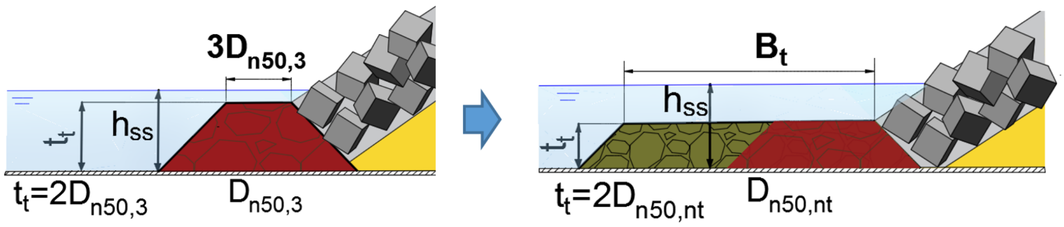

Figure 9. Standard toe berm (left) and equivalent wide toe berm with $B_t=n_tD_{n50}$ (right).

Fig. 10 depicts the reduction in rock mass (M_{50}) given by Eq, 8 when increasing the toe berm width up to n_t=12. For this example, the rock mass required for a standard toe berm (n_t=3) placed on m=1/10 sea bottoms, was calculated first using Eq. 6 with the recommended design value of $N_{od}=N_{od}*=1$. M_{50}(t)=30-tonne rocks (ρ_r(t/m^3)=2.7) is necessary for the toe berm, if the water depth at the nominal toe berm is h_s(m)=h_{ss}(m)=4.5 for the wave storm H_{s0}(m)=5 and T_p(s)=11. When increasing the toe berm width to nt=6, 9 and 12 following Eq. 8, the required rock mass is reduced to M_{50}(t)=13, 8.7 and 5, respectively.

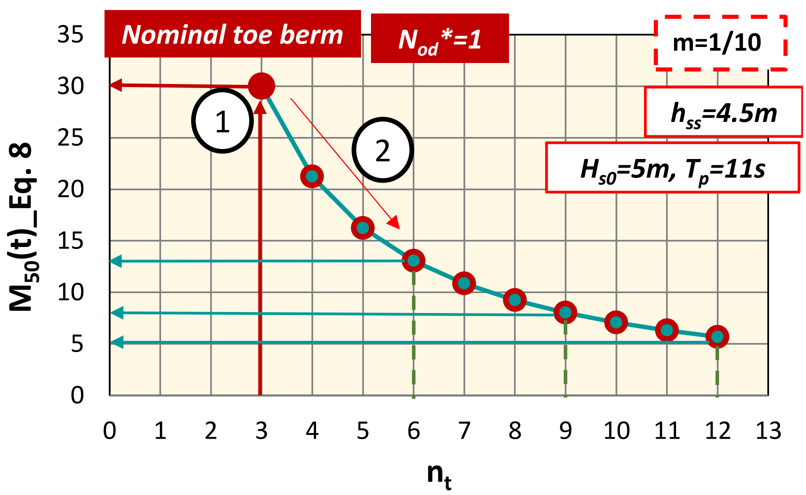

Figure 10. Reduction of rock mass (M_{50}) given by Eq.8 as a function of toe berm width ($B_t=n_tD_{n50}$).

As described in Section 2, other authors, such as Gerding (1993) and Van Gent and Van der Werf (2014), conducted laboratory tests with different toe berm widths. Gerding (1993) did not include B_t as an explanatory parameter for toe berm damage. In contrast, Van Gent and Van der Werf (2014) did include it but only total damage N_{od} was considered; these authors proposed multiplying the design N_{od} by the factor fb=$(n_t/3)^{1/2}$. Following the methodology described by Herrera et al. (2016), Eq. 5 proposed by Van Gent and Van der Werf (2014) was re-written in terms of $D_{n50,nt}$/ $D_{n50,3}$. The ratio $D_{n50,nt}$/ $D_{n50,3}$ also followed the relationship given by Eq. 8 but elevated to the 2/17-power (Eq. 9). Eq. 9 can be applied to rock toe berms placed on m=1/30 sea bottoms with $3D_{n50}\leq B_t\leq 9D_{n50}$ and $2D_{n50}\leq t_t\leq 4D_{n50}$, within the ranges $0.012\leq s_{0p}\leq 0.042$, $1.2\leq h_s/H_s\leq 4.5$, and $8.6\leq h_s/D_{n50}\leq 27.4$.

$$\frac{D_{n50,nt}}{D_{n50,3}}=\left(\frac{3}{n_t}\right)^{2/17} \qquad (9)$$

Fig. 11 portrays the reduction in rock mass (M_{50}) given by Eq. 9, when increasing berm width up to n_t=9. For this example, the rock mass required for a nominal toe berm (n_t=3), placed on m=1/30 sea bottoms, was calculated using Eq. 5 given by Van Gent and Van der Werf (2014) with the design value of $N_{od}=N_{od}*=1$. If the water depth at the nominal toe berm is h_s(m)=h_{ss}(m)=4.5, H_s (m)=5 and T_p(s)=11 at the toe, one-tonne rocks (ρ_r(t/m^3)=2.7) are necessary to build the toe berm.

When increasing the toe berm width to n_t=5, 7 and 9 following Eq. 9, the required rock mass is reduced to $M_{50}(t)$=0.84, 0.74 and 0.68, respectively.

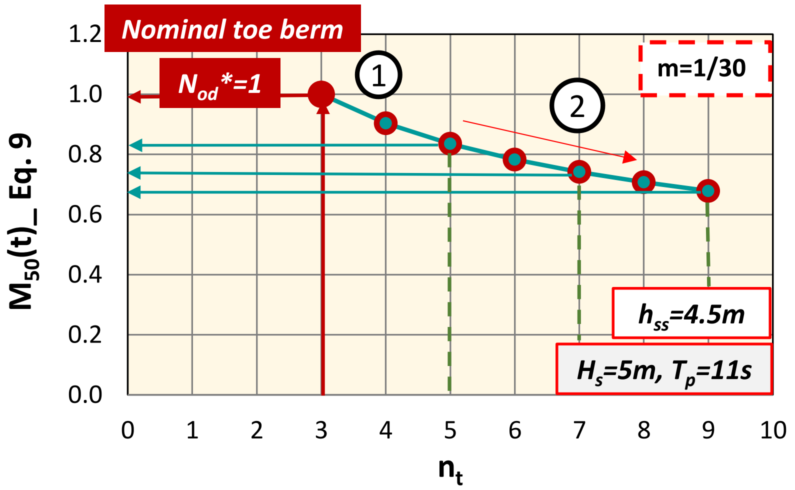

Figure 11. Reduction in rock mass (M_{50}) given by Eq.9 as a function of toe berm width (B_t=$n_t D_{n50}$).

Note that the estimations of the required rock size differ significantly when using Eq. 8 or Eq. 9; toe berms behave differently when dealing with shallow waters and waves breaking on m=1/10 steep sea bottoms (Herrera et al. 2016), than when dealing with less severe wave breaking on m=1/30 gentle sea bottoms (Van Gent and Van der Werf, 2014).

CONCLUSIONS

The hydraulic stability of toe berms depends mainly on (1) design wave storm (H_s and T_p), (2) water depth at the toe (h_s), and (3) bottom slope (m) existing at the construction site.

Most formulas to design rock toe berms are based on laboratory tests with gentle sea bottom slopes and toe berms below the SWL (h_s>>0); in these conditions, toe berm damage usually decreases with increasing h_s. However, on rocky coastlines with steep sea bottoms, sea defenses may require emerged toe berms with heavier rocks. According to Herrera and Medina (2015), the worst situation corresponds to SWL close to the top of the toe berm. The standard rock toe berm has B_t=3D_{n50} and t_t=2D_{n50}; this corresponds to a relative water depth at the toe of h_s/D_{n50}=3. In this situation, for certain design storms, the required rock size may be so large that the construction of toe berms is not feasible with rocks available at quarries. To solve this problem, the toe position may be moved to shallower or deeper waters in order to increase the toe berm stability, or the toe berm width may be enlarged using smaller rocks.

When increasing the toe berm width (B_t>3D_{n50}), common damage parameters (N_{od} or $N_{\%}$) are not recommended, since wider toe berms lead to more damage despite the better performance. Thus, two parts must be distinguished in rock toe berms when B_t>3D_{n50}: (1) nominal toe berm and (2) sacrificial toe berm.

The damage to the nominal toe berm (N_{od}*) should be considered when designing the breakwater. When using N_{od}*, common values for acceptable damage can be used directly (N_{od}*<0.5-no damage; N_{od}*≈1−significant movements; N_{od}*≈2−moderate damage; N_{od}*>4−failure) for wider toe berms (B_t>3D_{n50}).

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