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# Frictional wave dissipation in macro-roughness environments: a comparison of bottom stress and bulk canopy drag models

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## Abstract

Friction dissipation induced by the seabed is a key factor for wave attenuation in nearshore environments presenting large roughness structures, such as rocky or coral shores. Two seminal models are classically used to predict bottom friction dissipation: the bottom stress (BS) and bulk canopy drag (BCD) models. Aiming to compare the performances of both models in controlled laboratory conditions, the present paper reanalyses the wave dissipation data provided by Dealbera et al. (2024). An approach to calculate the frontal transverse area based on real terrain consideration is suggested. The hydraulic parameter and the drag coefficient are optimized from the experimental data using several approaches and model parameterizations. Performance estimators of each model parameterization are compared and reveal a more robust predictive performance of the BCD model. The BS model could be improved by changing the vertical reference of the estimated flow velocity.

*Keywords:* Waves, Macro-roughness, Friction, Canopy, Model

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## 1. Introduction

1 Facing climate change and ever-increasing anthropization, nearshore areas are particu-  
2 larly vulnerable to extreme events that generate coastal floodings and intensified erosion  
3 (Vousdoukas et al., 2020; Kirezci et al., 2020). In order to correctly predict the wave-driven  
4 coastal hazards for coastal engineering and citizen safety needs, the development of accurate  
5 wave models has been a major focus of the last four decades. Modeling the wave propagation  
6 and transformation in nearshore areas requires representing a series of physical processes  
7 driven by the shallowing bathymetry, including shoaling, refraction, diffraction, reflection,  
8 non-linear energy transfers and wave dissipation by breaking or bottom friction (Svendsen,  
9 2005; Sous et al., 2021).  
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11 A growing research effort is engaged to better characterize and predict wave transfor-  
12 mation over rough seabeds, including coral reefs (Lowe et al., 2005a, 2007; Quiroga and  
13 Cheung, 2013; Monismith et al., 2015; Van Dongeren et al., 2013; Rogers et al., 2016; Sous  
14 et al., 2023) or rocky beaches (Farrell et al., 2009; Ogawa et al., 2015; Poate et al., 2018; Gon  
15 et al., 2020; Lavaud et al., 2020; Marques et al., 2024b). The standard approach for bottom  
16 frictional dissipation in spectral wave models relies on the assumption that roughness ele-  
17 ments remain small w.r.t the bottom boundary layer thickness (Madsen, 1995). Such bottom  
18 stress models, hereinafter referred to as BS models, are based on a wave friction factor  $f_w$ ,  
19 which can be predicted from the ratio between the near-bed wave orbital amplitude and a  
20 length-scale characterizing the roughness field, namely the hydraulic roughness (Swart, 1974;  
21 Soulsby et al., 1993; Madsen, 1995; Sous et al., 2023; Dealbera et al., 2024). Using field- and  
22 laboratory-calibrated formulations for  $f_w$ , BS models have been shown to remain usable for  
23 highly rough terrain (Gon et al., 2020; Dealbera et al., 2024), where the initial theoretical  
24 framework is likely no more valid. The general question about the limits of validity of BS  
25 models for macro-roughness conditions, i.e. for which roughness elements widely protrude  
26 above the bottom boundary layer, or mega-roughness conditions, i.e. for which roughness  
27 elements emerge, remains asked.

28 An alternative approach to represent the dissipative effect of rigid obstacles in wave-  
29 driven flow is to consider the drag force applied on the fluid volume (Dalrymple et al., 1984;  
30 Kobayashi et al., 1993). This approach is hereinafter referred to as the bulk canopy drag  
31 (BCD) model. Widely used to represent wave transformation around submerged structures  
32 such as oil platforms or vegetated seabeds (Mendez and Losada, 2004), BCD models are  
33 based on the general assumption of a network of identical rigid structures, usually cylinders.  
34 BCD models are based on the general assumption of a network of identical rigid structures,  
35 usually cylinders. (Mendez and Losada, 2004) mentioned that their formula was applicable  
36 to flexible plants by changing the value of the bulk drag coefficient to cover the ignorance  
37 of the plant motion. Since then, many studies have been devoted to the characterization of  
38 bulk drag coefficient both for rigid and flexible obstacles, including the coefficient dependency  
39 on the obstacle features, such as the geometry, distribution, deformation, and on the local  
40 hydrodynamical regimes described by dimensionless numbers, being generally the Reynolds  
41 number ( $Re$ ) or the Keulegan Carpenter ( $KC$ ) (see e.g. Kobayashi et al. (1993); Mendez and  
42 Losada (2004); Koftis et al. (2013); Anderson and Smith (2014); Ozeren et al. (2014); Losada  
43 et al. (2016); Chastel et al. (2020); Yin et al. (2024)). Note that both BS and BCD models  
44 have been implemented into frequency-integrated, spectral and phase-resolved models.

45 The present paper aims to compare and discuss the ability of BS and BCD models to  
46 represent wave dissipation in macro- to mega-roughness conditions. Yet BS and BCD models  
47 are generally used by distinct communities, to represent wave dissipation over rocky/coral  
48 and vegetated seabeds, respectively. BS models are expected to show degraded performance

49 for growing roughness height Dealbera et al. (2024). By contrast, the BCD model should  
50 be conceptually more capable to account for the roughness effect over the whole water col-  
51 umn. However, standard BCD models are strictly designed for the idealized configuration of  
52 cylinder arrays. While easily applicable to seagrass or mangrove fields where characteristic  
53 vegetation height, diameter and density can be directly identified, BCD models remain ques-  
54 tionable for real rocky or coral reef terrains where the roughness structure presents a fractal  
55 dimension with no defined roughness structure spacing and arrangement (Duvall et al., 2019;  
56 Stewart et al., 2019; Sous et al., 2020, 2024). Therefore, neither filling the condition for  
57 small roughness features compared to the boundary layer thickness required for BS models  
58 nor showing the regular arrangement of elongated obstacles, realistic macro- and mega-rough  
59 terrains fall in an ambiguous and sparsely documented range of seabed topography in terms of  
60 wave dissipation (Monismith et al., 2015; Dodet et al., 2018; Marques et al., 2024b,a). While  
61 widely documented in their specific validity domain, the assessment of the respective perfor-  
62 mances of BS and BCD models remains a challenging issue in macro- and mega-roughness  
63 environments, such as the cyclopean blocks of the Banneg island or the Flysch rocky out-  
64 crops of the Socoa platform (Sous et al., 2024), due to the scarcity of field data on wave  
65 transformation.

66 The series of experiments presented in Dealbera et al. (2024) characterizes a substantial  
67 range of idealized rough seabeds, from small roughness to macro-roughness in a hydrodynam-  
68 ically controlled environment. In this study, we intend to reuse this data (i) to develop an  
69 approach for the BCD model applicable to real rocky or coral reef terrain based on usable bed  
70 metrics, (ii) to compare the performances of various parameterizations of each model and,  
71 (iii), to identify the validity limits of each model. The first section recalls the experimental  
72 setup, the data processing, the theoretical models of the roughness-induced dissipation and  
73 their parameterizations. The second section presents the results, including the comparison of  
74 the performances of both models, while the Discussion section summarizes the observations  
75 and their limitations and provides prospects for future research works.

## 76 2. Methods

### 77 2.1. Experiments

78 The free surface elevation data used here come from the series of experiments carried  
79 out in the CASH wave flume (SeaTech, University of Toulon) and described in details by  
80 Dealbera et al. (2024). The flume is made of glass, 6m long and 0.5m wide, and equipped  
81 with a linearly sloping bed of 1/20. A piston wave-maker, with an absorbing system at  
82 the back, was used to generate waves on the 1m-long horizontal bottom section before the  
83 sloping bed. Five irregular wave conditions were generated from a JONSWAP spectrum with  
84 significant offshore wave heights varying from 0.047 to 0.075 m and peak periods ranging from

85 1 to 1.2 s. Each wave condition was first run over a beach with a 1/20 slope recovered with  
 86 stainless steel plates that mimicked a smooth seabed reference (RF case). Each wave run  
 87 was then repeatedly run over 26 seabed layouts created using LEGO<sup>®</sup> blocks set up on the  
 88 slope. Several patterns were selected to identify the effects of the geometric structure of the  
 89 roughness by varying the block heights, lengths and streamwise dimensions, the spacing and  
 90 shifts between block rows. Appendix A displays an illustrative series of layouts. Free surface  
 91 elevations were recorded using a series of resistive gauges along the cross-shore axis as shown  
 92 in Figure 1. A fast Fourier Transform was then performed to extract  $H_{rms}$  the spectral root  
 93 mean square height of the incident short waves over the  $\frac{f_p}{2} < f < 3f_p$  frequency band, where  
 94  $f_p$  is the frequency peak, using the following formula:  $H_{rms} = \sqrt{8 \int E(f)df}$ , with  $E(f)$  the  
 95 spectral energy density.

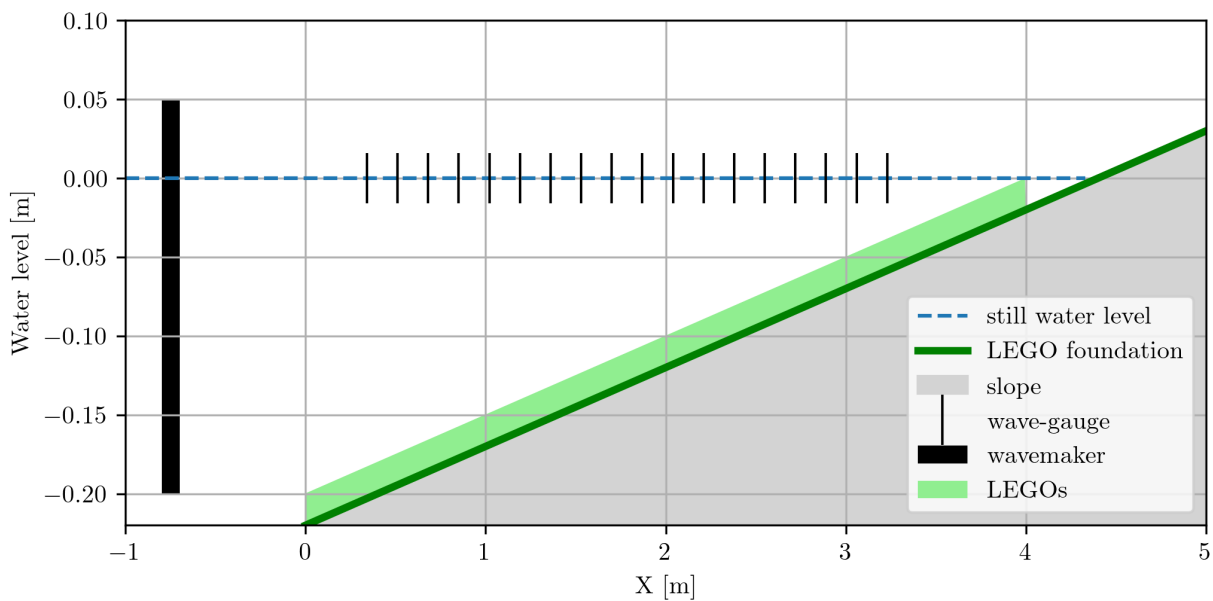


Figure 1: Diagram of the wave flume setup and instrumentation

96 The experimental scaling has been primarily designed to preserve relevant dimensionless  
 97 numbers for wave propagation and breaking in nearshore area. The surf similarity parameter  
 98 ranges from 0.12 to 0.6, while  $kh$  at the breaking point ranges from 0.4 to 0.65 ( $k$  and  $h$   
 99 between local wave number and depth). Due to the scale distortion between horizontal and  
 100 vertical directions, the forced waves are necessarily non-linear,  $ka$  being of the order of 0.15  
 101 at the breaking point ( $a$  being the local wave amplitude), i.e. higher than values typically  
 102 reached on gently sloping beaches. However, previous results on the same experimental

103 setup (Sous et al., 2021; Dealbera et al., 2024) and the present observations demonstrated  
 104 that standard linear wave models remain relevant for the present range of wave case, i.e. the  
 105 effect of the departure from linear wave assumption remains small compared to the monitored  
 106 processes, and consistent with existing laboratory and field observations.

## 107 2.2. Performance estimators

108 Two classical estimators are used hereafter to quantify the accuracy of the agreement be-  
 109 tween observations and model predictions: the normalized root mean square error (NRMSE)  
 110 based on the normalization of the root mean square error (RMSE) and the Willmott index  
 111 (WI) which shows a standardized error measure between 0 and 1:

$$RMSE = \sqrt{\frac{1}{n} \sum_i^n (\hat{\Theta}_i - \Theta_i)^2} \quad (1)$$

$$NRMSE = \frac{RMSE}{\sigma(\Theta)} \quad (2)$$

$$WI = 1 - \frac{\sum_i^n (\hat{\Theta}_i - \Theta_i)^2}{\sum_i^n (|\hat{\Theta}_i - \bar{\Theta}| + |\Theta_i - \bar{\Theta}|)^2} \quad (3)$$

112 Where  $\hat{\Theta}$  is the prediction value,  $\Theta$  the observed value and  $\bar{\Theta}$  the mean of observed values.

## 113 2.3. Theoretical framework

114 In the same perspective as the work of Dealbera et al. (2024), we consider unidirectional  
 115 wave propagation along a reference cross-shore  $x$ -axis, addressed in a frequency-integrated  
 116 approach over the short-wave (SW) band. When averaged over many wave cycles, the wave  
 117 energy flux balance in the absence of mean current can be written as:

$$\frac{\partial EC_g}{\partial x} = \bar{\varepsilon}_t \quad (4)$$

118 where  $E$  is the wave energy,  $C_g$  the wave group velocity and  $\bar{\varepsilon}_t$  is the total wave-averaged  
 119 dissipation.  $E$  and  $C_g$  are estimated by the linear theory formulations for irregular waves:

$$E = \frac{\rho g}{8} H_{rms}^2 \quad (5)$$

120 with  $\rho$  is the density of the water and  $g$  the acceleration of gravity and

$$C_g = \frac{1}{2} \left( 1 + \frac{2kD}{\sinh(kD)} \right) \frac{\omega}{k} \quad (6)$$

121 where  $k$  and  $\omega$  are the wave number and the angular frequency associated with the peak  
 122 period and  $D$  the water depth.

123  $\overline{\varepsilon}_t$  combines the effect of breaking dissipation  $\overline{\varepsilon}_b$  and frictional dissipation  $\overline{\varepsilon}_f$ :

$$\overline{\varepsilon}_t = \overline{\varepsilon}_b + \overline{\varepsilon}_f \quad (7)$$

124 Following previous experiments in the same flume (Sous et al., 2021), frictional dissipa-  
 125 tion is expected to be negligible in the smooth RF reference case. For rough seabed cases,  
 126 the frictional dissipation is overwhelmed by bottom friction and no sidewall dissipation is  
 127 considered.

128 The study of non-linear energy transfers made by Dealbera et al. (2024) showed that,  
 129 for the worst case scenario of the smooth layout, the contribution of non-linear transfers can  
 130 be considered negligible compared to the effect of breaking and friction dissipation (typi-  
 131 cally around 1% of global energy dissipation) and will therefore be neglected for the present  
 132 analysis.

133 The Thornton and Guza (1983) breaking model is used to represent breaking wave dissi-  
 134 pation for all layouts, with adaptation for the specific wave height distribution  $p(H)$  observed  
 135 in our flume (Dealbera et al., 2024) given by the following formula:

$$p(H) = \frac{2H}{H_{rms}^2} \exp \left[ - \left( \frac{H - H_0/4}{H_{rms}} \right)^2 \right] \quad (8)$$

136 Where  $H$  is the crest-to-trough wave height and  $H_0$  is the spectral root mean square of  
 137 incident waves measured at the offshore wave gauge.

138 The rough seabed topography is described for all layouts by a Digital Elevation Model  
 139 (DEM) depicting the 2D seabed elevation  $\aleph(x, y)$ , where  $y$  is the coordinate along the long-  
 140 shore direction, with a 0.008m horizontal resolution. The geometric structure of the rough-  
 141 ness, hereafter referred as to  $\psi_{\aleph}$ , can be characterized by a set of metrics (see reviews of  
 142 Chung et al. (2021); Sous et al. (2024)). In the present study, we focus on the standard  
 143 deviation of seabed elevation  $\sigma_{\aleph}$  and the bulk porosity  $n_{\aleph}$  given by the following formulas:

$$\sigma_{\aleph} = \sqrt{\frac{1}{n} \sum_i^n (\aleph_i - \bar{\aleph})^2} \quad (9)$$

$$n_{\aleph} = 1 - \frac{\sum (\sum \max(\aleph(x, y), 4\sigma_{\aleph}) \Delta y) \Delta x}{L_x L_y 4\sigma_{\aleph}} \quad (10)$$

$$(11)$$

144 Their values are given in Appendix B.

145 *2.4. Wave energy dissipation models*

146 Two wave dissipation models are assessed and compared: the BS model and the BCD  
147 model.

148 *2.4.1. The bottom stress model*

149 The SW-integrated BS model follows the previous analysis of Dealbera et al. (2024) on  
150 the same experimental database, based on the seminal work of TG83, followed by Lowe et al.  
151 (2005a); Péquignot et al. (2011) and others, which defines the frictional dissipation term as:

$$\overline{\varepsilon}_f = \frac{1}{2} \rho f_w |u_{ref}|^3 \quad (12)$$

152 where  $u_{ref}$  is the reference velocity, taken as the standard near-bed velocity for BS models,  
153 i.e. at reference depth  $D_{ref} = D$ . For irregular waves,  $u_{ref}$  is generally inferred from the  
154 linear wave theory, leading to:

$$\overline{\varepsilon}_f = \frac{\rho f_w}{4\sqrt{\pi}} \left( \frac{\pi H_{rms}}{T_{m01} \sinh k D_{ref}} \right)^3 \quad (13)$$

155 where  $T_{m01}$  is the average wave period and  $k$  the wave number associated with  $T_{m01}$ .

156 Following Swart (1974); Madsen et al. (1988); Nielsen (1992), the wave friction factor  
157  $f_w$  is related to the ratio of the wave orbital excursion at the bottom to a typical vertical  
158 roughness scale, the so-called hydraulic roughness  $k_r$  (or equivalent Nikuradse roughness  
159 height), through the following expression:

$$f_w = \exp \left( a_1 \left( \frac{A_{ref}}{k_r} \right)^{a_2} + a_3 \right) \quad (14)$$

160 where  $a_1$ ,  $a_2$  and  $a_3$  are dimensionless empirical constants taken as 5.0, -0.15 and -5.9 (Sous  
161 et al., 2023; Dealbera et al., 2024) and  $A_{ref} = u_{o,ref}/\omega$  the bottom orbital excursion with  
162  $u_{o,ref}$  the bottom orbital velocity given by the linear theory:

$$u_{o,ref} = \frac{\pi H_{rms}}{T_{m01} \sinh k D_{ref}} \quad (15)$$

163 *2.4.2. The bulk canopy drag model*

164 **The base model**

165 The SW-integrated BCD model is based on the work of Mendez and Losada (2004)  
166 (ML04), which follows Dalrymple et al. (1984) on an array of immersed cylinders. Energy



167 loss is estimated using the drag forces induced by the cylinders on the fluid in Morison's  
 168 equation, neglecting skin friction and inertia:

$$\overline{\varepsilon_f} = \frac{2}{3\pi} \rho C_d A_v \left( \frac{k_p g}{2\omega} \right)^3 \frac{\sinh(k_p \alpha_v D)^3 + 3 \sinh(k_p \alpha_v D)}{3k_p \cosh(k_p D)^3} \int_0^\infty H^3 p(H) dH \quad (16)$$

169 where  $k$  is the wave number associated with the peak period  $T_p$ ,  $C_d$  is the bulk drag coefficient,  
 170  $A_v$  is the transverse frontal area, i.e. the frontal area exposed to the flow divided by the  
 171 vegetation mean height, and  $\alpha_v$  is the relative height of the vegetation given by  $\alpha_v D = \overline{h_v}$ ,  
 172 where  $\overline{h_v}$  is the mean height of roughness blocks. Here the probability distribution of wave  
 173 heights  $p(H)$  is the modified Rayleigh distribution given by Eq. 8.

#### 174 $C_d$ dependency to local hydrodynamics and roughness structure

175 The drag coefficient  $C_d$  has been shown to depend both on obstacle structure and on  
 176 local hydrodynamic conditions (Wang et al., 2021). For the former dependency, in order to  
 177 overcome the standard case of vertical vegetation-mimicking cylinders and to assess the wider  
 178 applicability of the BCD model, we will simply state that  $C_d$  is affected by the roughness  
 179 geometrical structure  $\psi_{\mathcal{N}}$ . The hydrodynamics control on  $C_d$  is generally predicted using di-  
 180 mensionless parameters characterizing the local flow: the Reynolds number  $Re = u_c l_v / \nu$  that  
 181 compares inertial and viscous forces or the Keulegan-Carpenter number  $KC = u_c T_p / l_v$  that  
 182 indicates the relative importance of drag forces over inertia forces, where  $\nu$  is the kinematic  
 183 viscosity,  $l_v$  the characteristic length of vegetation and  $u_c$  is the characteristic velocity acting  
 184 on the plant and defined as the maximum horizontal velocity at the reference vegetation  
 185 depth  $D_v = D - \alpha_v D$ . The early work of Mendez and Losada (2004) proposed a hydro-  
 186 dynamic exponential formulation of  $C_d$  versus  $KC$ , considering the  $\alpha_v$  ratio. Since then,  
 187 power-law formulation for  $C_d$  have been largely used (Wang et al., 2021):

$$\begin{aligned} C_d &= a_{Re} (1 + (b_{Re}/Re)^{c_{Re}}) \\ C_d &= a_{KC} (1 + (b_{KC}/KC)^{c_{KC}}) \end{aligned} \quad (17)$$

188 where  $a_{Re}$ ,  $b_{Re}$ ,  $c_{Re}$ , respectively  $a_{KC}$ ,  $b_{KC}$ ,  $c_{KC}$  are empirical parameters for  $Re$ -based and  
 189  $KC$ -based models, respectively. Wide ranges of values have been proposed for these param-  
 190 eters (Wang et al., 2021), with dependency on wave forcing, vegetation characteristics and  
 191 methodology (in particular the definition of  $u_c$  and  $l_c$ ).

192 Aiming to provide a more unified view of the canopy drag approach possibly extended  
 193 to rocky or coral seabeds, we propose to discriminate the contributions of canopy geometry  
 194 and hydrodynamics in the power-law  $C_d$  formulations by introduction  $f_d$ , a drag factor solely  
 195 controlled by roughness structure:

$$\begin{aligned}
C_d &= f_{d,Re}(\psi_N) a_{Re} (1 + (b_{Re}/Re)^{c_{Re}}) \\
C_d &= f_{d,KC}(\psi_N) a_{KC} (1 + (b_{KC}/KC)^{c_{KC}})
\end{aligned}
\tag{18}$$

196 Here the  $a$ ,  $b$  and  $c$  parameters are been assumed to be universal for a selected dimen-  
197 sionless parameter, i.e., the geometry dependency can be fully represented by  $f_d$  while the  
198 hydrodynamical control is fully accounted for by the power-law. The coefficient values used  
199 hereafter have been retrieved from three selected studies of the standard vegetation ap-  
200 proaches Koftis et al. (2013); Anderson and Smith (2014); Chastel et al. (2020), hereinafter  
201 named K13, A14 and C20 respectively, that cover a large range of  $Re$  and  $KC$  values for  
202 irregular waves. In addition, representative average values, hereafter named D24, have been  
203 extracted by fitting a compiled dataset from published experiments and numerical models  
204 (Mendez et al., 1999; Mendez and Losada, 2004; Wu and Shu, 2011; Koftis et al., 2013;  
205 Anderson and Smith, 2014; Chastel et al., 2020; van Veelen et al., 2020). The parameter  
206 values for K13, A14, C20 and D24 together with their ranges of hydrodynamical regimes are  
207 presented in Table 1.

Refer- ence	$a_{Re}, b_{Re}, c_{Re}$	$a_{KC}, b_{KC}, c_{KC}$	Hydrodynamical regimes
<i>K13</i>	0, 2400, 0.77	-	$1000 < Re < 3500$
<i>A14</i>	0.76, 744.2, 1.27	1.10, 27.4, 3.08	$533 < Re < 2296$ $26 < KC < 112$
<i>C20</i>	1.56, 1644, 1.26	2.23, 30.1, 1.37	$500 < Re < 3500$ $15 < KC < 170$
<i>D24</i>	0.25, 2500, 1	0.7, 192, 0.8	$213 < Re < 1600$ $1 < KC < 166$

Table 1: Summary of empirical formulations proposed for the BCD model coefficients.

## 208 Geometric vs topographic approaches

209 Studies of wave damping by vegetation have mainly based their calculations of charac-  
210 teristic dimensions on idealized geometries, such as cylinder and cube networks. However, in  
211 the context of natural topography observed over coral reefs and rocky platforms, geometrical  
212 parameters are hardly identified since neither repeated patterns are present (not even a domi-  
213 nant roughness wavelength (Stewart et al., 2019; Duvall et al., 2019; Sous et al., 2020, 2024))  
214 nor identifiable isolated elements of roughness. We develop in this study two approaches  
215 based on different conceptions of roughness.

- 216 • *the geometric approach* based on the classical strategy developed for vegetation studies

217 on regular arrays of idealized obstacles. The canopy structure parameters are here  
 218 directly inferred from the obstacle dimensions.

- 219 • *the topographic approach* which aims to be applicable to natural rough sites. The terrain  
 220 is here described in terms of statistical or bulk properties, without any assumption on  
 221 the presence of regularly spaced and easily measurable obstacles.

222 The geometric approach reuses the classical parameters given in the review of Wang et al.  
 223 (2021):  $l_c$  is taken as  $b_v$ , the stem diameter of the roughness blocks, which gives an estimation  
 224 of  $A_v = b_v N_v$ , where  $N_v$  is the density of the blocks. The  $\overline{h_v}$  height is calculated as the mean  
 225 of all roughness block heights.

226 For the topographic approach, the difficulty is to establish an equivalent for  $A_v$  in equation  
 227 16 usable in natural terrain. The method used here is based on the solid volume calculation.  
 228 For idealized geometries, the solid volume is expressed as follows:

$$V_{solid} = b_v^2 h_v N_v S \quad (19)$$

229 where  $h_v$  is the block height and  $S$  is the plane reference surface. For a natural topography,  
 230 the solid volume can be expressed as follows:

$$V_{solid} = \int_x \int_y \max(4\sigma_{\aleph}, \aleph(x, y)) dx dy \quad (20)$$

231 Considering the equivalence between both expressions of solid volume given by Eq. 19 and  
 232 20, a proxy for  $b_v N_v$  can be estimated for natural terrain:

$$b_v N_v = \frac{\int_x \int_y \max(4\sigma_{\aleph}, \aleph(x, y)) dx dy}{b_v h_v S} = \frac{1 - n_{\aleph}}{b_v} \quad (21)$$

233 We then assume that a natural terrain (i) has a characteristic maximum height equal to 4  
 234 times the standard deviation of the bottom elevation  $\sigma_{\aleph}$  and (ii) has a horizontal roughness  
 235 scale equivalent to its vertical scale (isotropy), i.e.  $4\sigma_{\aleph}$ . Note that the latter hypothesis is  
 236 rather weak, considering the absence of a dominant horizontal length scale in most natural  
 237 rough seabeds (Sous et al., 2024). However, the necessary introduction of roughness isotropy  
 238 at this stage should be, at least partly, compensated by the later inclusion of bottom elevation  
 239 statistics in  $C_d$  and  $f_d$  parameters, allowing the introduction of distortion between horizontal  
 240 and vertical scaling of the roughness. The calculation of  $A_v$  is therefore simplified as follows:

$$A_v = \frac{1 - n_{\aleph}}{4\sigma_{\aleph}} \quad (22)$$

241 Table 2 summarizes the definitions of the different calculated parameters for both BCD  
 242 approaches.

Approach	$A_v$	$l_c$	$h_v$
Geometric	$b_v N_v$	$b_v$	$\overline{h_v}$
Topographic	$(1 - n_{\text{R}})/4\sigma_{\text{R}}$	$4\sigma_{\text{R}}$	$4\sigma_{\text{R}}$

Table 2: BCD approach parameters.

243 *2.5. Procedure summary*

244 For each wave run and rough seabed layout, after estimating total incident dissipation  
 245 from Eq. 4 and subtracting breaking dissipation modeled by the TG83 model, both dissipa-  
 246 tion models, i.e. the BS model and the BCD model, are optimized. Performances of each  
 247 model are calculated by comparing the profiles of reconstructed  $H_{rms}$  from Eq. 7 to the  
 248 measured  $H_{rms}$  profiles, aiming to maximize WI and to minimize NRMSE. The optimization  
 249 uses the frictional parameters as free parameters. For the BS model, the wave friction  $f_w$  is  
 250 the free parameter. For the BCD model, three optimizations are performed:

- 251 • an optimization directly on  $C_d$ , assuming  $C_d$  to be spatially uniform for a given wave/seabed  
 252 case, i.e. without any dependency on hydrodynamics;
- 253 • an optimization on  $f_{d,Re}$ , assuming that  $C_d$  varies along the beach profile due to the  
 254 evolution of local hydrodynamics and that the dependency to hydrodynamics can be  
 255 represented by *Re*-based power-law formulation (Eq. 18);
- 256 • similarly, an optimization on  $f_{d,KC}$ , assuming that  $C_d$  varies along the beach profile due  
 257 to the evolution of local hydrodynamics and that the dependency to hydrodynamics  
 258 can be represented by *KC*-based power-law formulation (Eq. 18).

259 The three optimizations are performed for both geometric and topographic approaches.  
 260 Optimizations of *Re*- and *KC*-dependent models are performed using K13, A14, C20 and  
 261 D24A and A14, C20 and D24 parameterizations, respectively. A summary of the optimization  
 262 strategy for the BCD model is depicted in Figure 2.

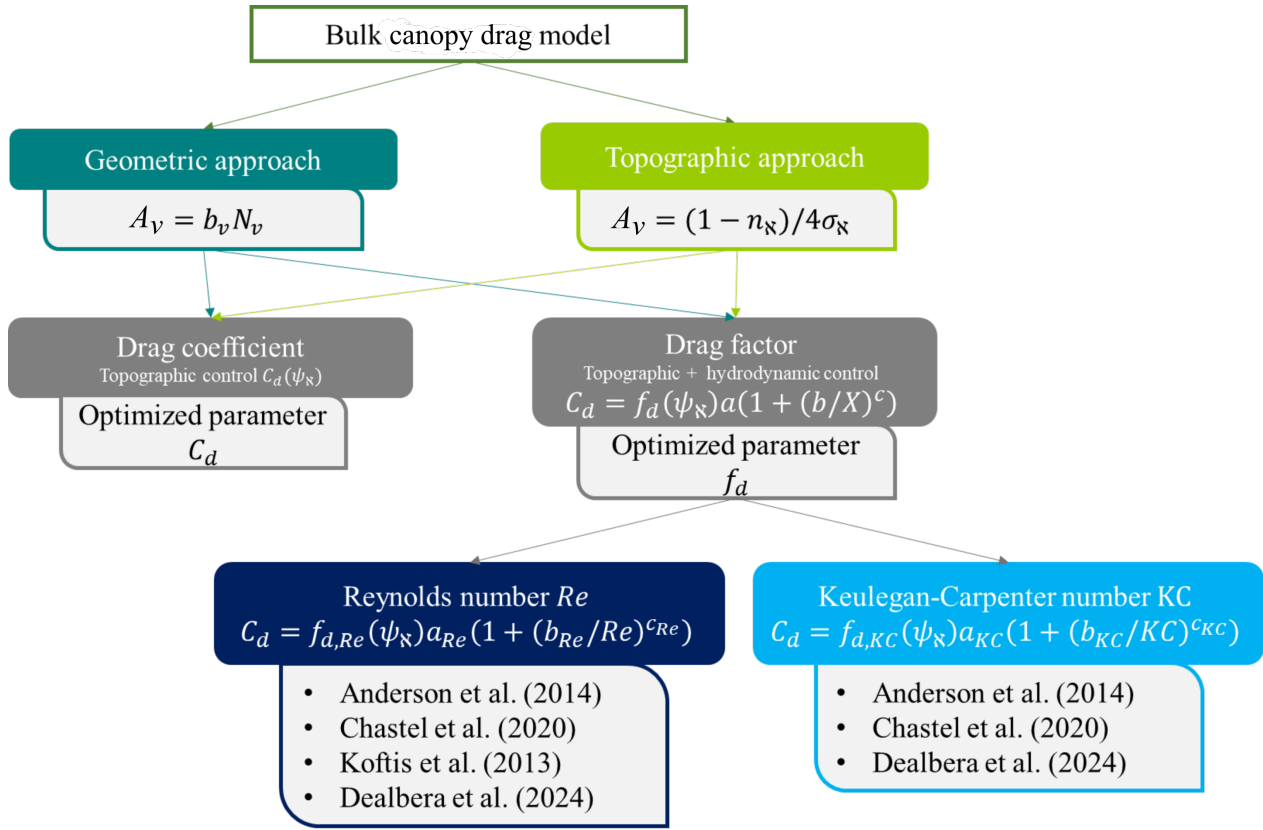


Figure 2: Summary of BCD tests: transverse frontal area  $A_v$  approaches in green, optimized parameters in grey and hydrodynamics parameterizations in blue.

### 263 3. Results

264 In this section, we compare the performances of optimizations in order to establish relevant  
 265 valid parameterizations for the comparison between the two models. We focus first on the  
 266 BCD model, comparing geometric and topographic approaches, and then assessing  $Re$  and  
 267  $KC$ -based parameterizations for the BCD topographic model. Then, the BS and BCD model  
 268 performances are compared w.r.t. the hydrodynamical context. Lastly, a comparison between  
 269 different parameterizations is performed to identify which coefficients fit our data the best.

#### 270 3.1. BCD model: geometric vs topographic approaches

271 The first step of the analysis is to assess the robustness of our topographic approach vs  
 272 the standard geometric approach. The assessment is carried out on three models: uniform  
 273  $C_d$ ,  $f_{d,Re}$  and  $f_{d,KC}$  with D24 parameterization. Figure 3 displays compared boxplots for  
 274 NMRSE (left) and WI (right).

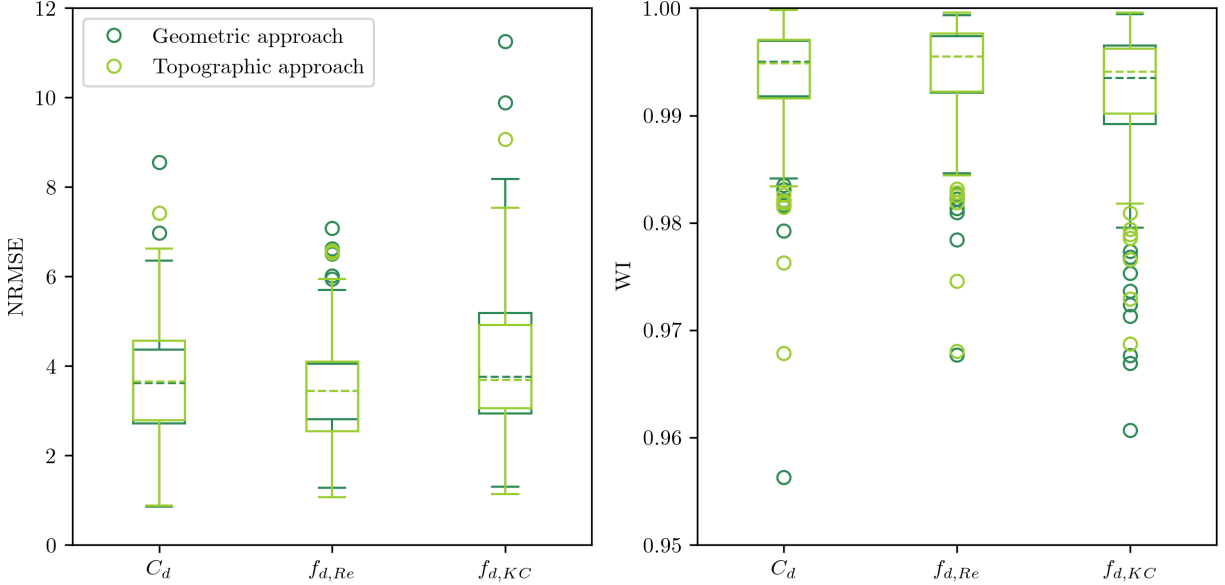


Figure 3: Boxplots of NRMSE (left side) and WI (right side) for the BCD geometric (dark green) and topographic (light green) approaches versus the  $C_d$ ,  $f_{d,Re}$  and  $f_{d,KC}$  optimizations. The central dotted line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extend to 1.5 of the interquartile range while the outliers are plotted individually as circles.

275 A first overview shows that the best results (low NRMSE, high WI) for both approaches  
 276 are obtained for the  $f_{d,Re}$  optimization, with median NRMSE and WI of about 3.5% and  
 277 0.996. A slight degradation of performances is observed for the  $C_d$  and  $F_{d,KC}$  respective  
 278 optimizations but the accuracy remains correct with median NRMSE and WI of about 3.7%  
 279 and 0.995, 3.8% and 0.994 respectively. The comparison between the geometric (dark green)  
 280 and topographic (light green) approaches does not outline straightforward differences for each  
 281 optimization strategy. The performances are slightly enhanced for the geometric approach  
 282 in  $C_d$  optimization, while the topographic approach gives better adjustment for the  $f_{d,Re}$   
 283 optimization and reduced spread for the  $f_{d,KC}$  optimization. Overall, the performance being  
 284 very similar between topographic and geometric approaches, we will focus on the former one  
 285 owing to its potential to apply on real terrain.

### 286 3.2. BCD model: sensitivity to parameterization

287 A second series of tests is performed on the topographic approach by comparing perfor-  
 288 mance estimators for different parameterizations. The analysis depicted in Figure 4 focuses  
 289 on  $f_{d,Re}$  and  $f_{d,KC}$  optimizations using D24, A14 and C20 parameterizations.

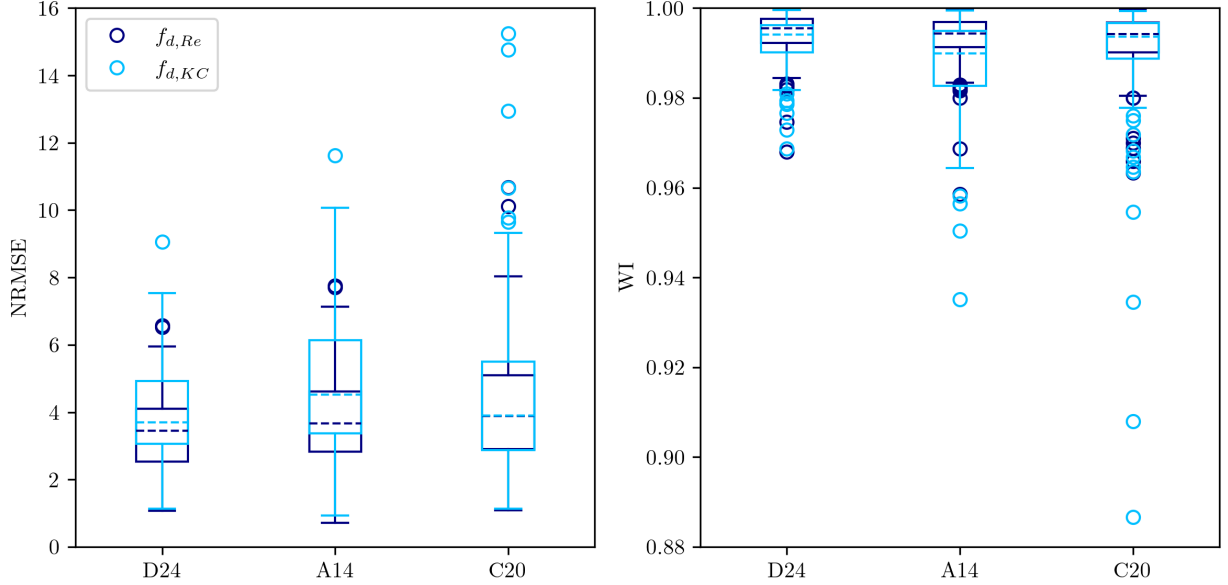


Figure 4: Boxplots of NRMSE (left side) and WI (right side) for the BCD  $f_{d,Re}$  (dark blue) and the BCD  $f_{d,KC}$  (light blue) versus the D24, A14 and C20 parameterizations. The central dotted line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extend to 1.5 of the interquartile range while the outliers are plotted individually as circles. Note the changes in the y-axis.

290 At first glance, we note better performances for  $f_{d,Re}$  parameterizations (dark blue) than  
 291 for  $f_{d,KC}$  ones (light blue). While medians of NRMSE and WI for the D24 and A14 are  
 292 better for the  $f_{d,Re}$  parameterizations, the C20 parameterization displays the same median  
 293 (3.9% for NRMSE and 0.994 for WI) but a greater spread for the outliers. NRMSE and WI  
 294 respectively stay below 8% and over 0.98 respectively for the  $f_{d,Re}$  parameterizations, but  
 295 reach over 10% and below 0.98 for the  $f_{d,KC}$  ones. Considering that the  $f_{d,KC}$  formula gives  
 296 poorer performance for each selected parameterization, the following analysis will be focused  
 297 on the  $f_{d,Re}$  approach.

### 298 3.3. Friction dissipation model comparison

299 The previous analysis demonstrated (i) the relevancy of the topographic approach for  
 300 the BCD model and (ii) the prevailing performance of  $Re$ -based parameterization. The next  
 301 step is to compare performance estimators for the BS, the  $C_d$ - and the  $f_{d,Re}$ -optimized BCD  
 302 models, depicted in Figure 5 in brown, light green and dark blue, respectively. We first test  
 303 the agreement between experiments and model against the  $A_o/\sigma_N$  ratio, in order to explore  
 304 the potential degradation of the predictive capacities for large relative roughness height.  
 305 For all models, the best results are obtained for the  $A_o/\sigma_N > 2.5$ , with similar values of the

306 estimators as the NRMSE remains lower than 3.2 % and WI higher than 0.996. A degradation  
 307 of the performance is observed as  $A_o/\sigma_N$  decreases but the accuracy remains correct, with  
 308 NRMSE and WI below 10% and over 0.96, respectively, in the 0.0-1.0 interval. For each  
 309  $A_o/\sigma_N$  interval, the BS model displays the lower performance as the medians in NRMSE and  
 310 WI are around 4.4% and 0.996 for the 1.2-2.5 interval and around 5.4% and 0.990 for the  
 311 0.0-1.0 interval. The  $C_d$ -optimized BCD model shows better performance for small values of  
 312  $A_o/\sigma_N$  and yet taking into account local hydrodynamics with the  $f_{d,Re}$ -optimized BCD model  
 313 improves performances as the medians in NRMSE and WI are around 3.4% and 0.996 for  
 314 the 1.2-2.5 interval and around 3.9% and 0.995 for the 0.0-1.0 interval.

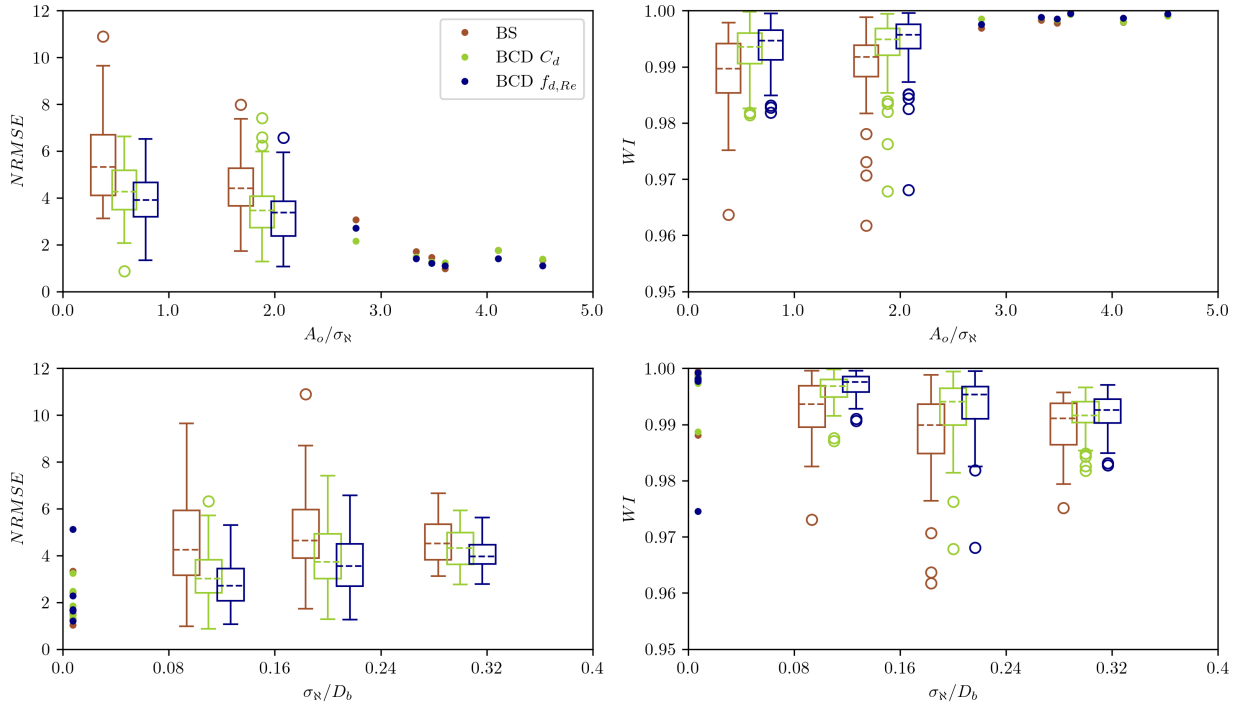


Figure 5: Plot and binned boxplots of NRMSE and WI versus  $A_o/\sigma_N$  for the following intervals : [0,1,1.6,2.6] and  $\sigma_N/D_b$  for the following intervals : [0.07,0.15,0.25,0.35]. The central dotted line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extend to 1.5 of the interquartile range while the outliers are plotted individually as circles. Single points are individual datapoints. The BS model is represented in brown, the BCD topographic  $C_d$  model in light green and the BCD topographic  $f_d(Re)$  model in dark blue. Note that the abscissa values for boxplots have been slightly shifted to improve visibility but presented data has been obtained with similar  $A_o/\sigma_N$  and  $\sigma_N/D_b$

315 A second series of tests is performed on the relative roughness submergence ratio, i.e.  
 316 the ratio between roughness height and local depth, which becomes an important parameter



317 for frictional dissipation in rough shallow areas (Davis et al., 2021). The submergence ratio  
 318 being variable across the profile in our sloping beach configuration, the breaking point value  
 319  $\sigma_N/D_b$  is used, where  $D_b$  is the breaking depth obtained at  $H_{rms}/D_b \approx 0.7$  (Symonds et al.,  
 320 1995). The best results are obtained for the smallest  $\sigma_N/D_b$  for each model. The BS model  
 321 shows degrading performances for higher  $\sigma_N/D_b$  with NRMSE and WI medians around 4.2%  
 322 and 0.993 in the 0.08-0.16 interval. However, the performance remains rather stable and does  
 323 not strongly drop for high submergence ratios. Overall, the  $C_d$ -optimized BCD model gives  
 324 better results than the BS model, but  $f_{d,Re}$ -optimized model is once again more efficient. We  
 325 note a slight degradation of performance with higher  $\sigma_N/D_b$  as NRMSE and WI median move  
 326 from 2.8% and 0.998 in the 0.08-0.16 interval to 4.0% and 0.993 in the 0.24-0.40 interval,  
 327 drawing closer to the BS and  $C_d$ -optimized BCD models.

### 328 3.4. BCD hydrodynamic parameterization comparison

329 The previous results demonstrate the overall superiority of  $f_{d,Re}$ -optimized BCD model  
 330 over other approaches. The question arises then on the performance of the formulation pro-  
 331 posed here from a compilation of published studies (D24 in Table 1) w.r.t selected references  
 332 (K13, A14 and C20 in Table 1). Compared NRMSE and WI are depicted in Figure 6.

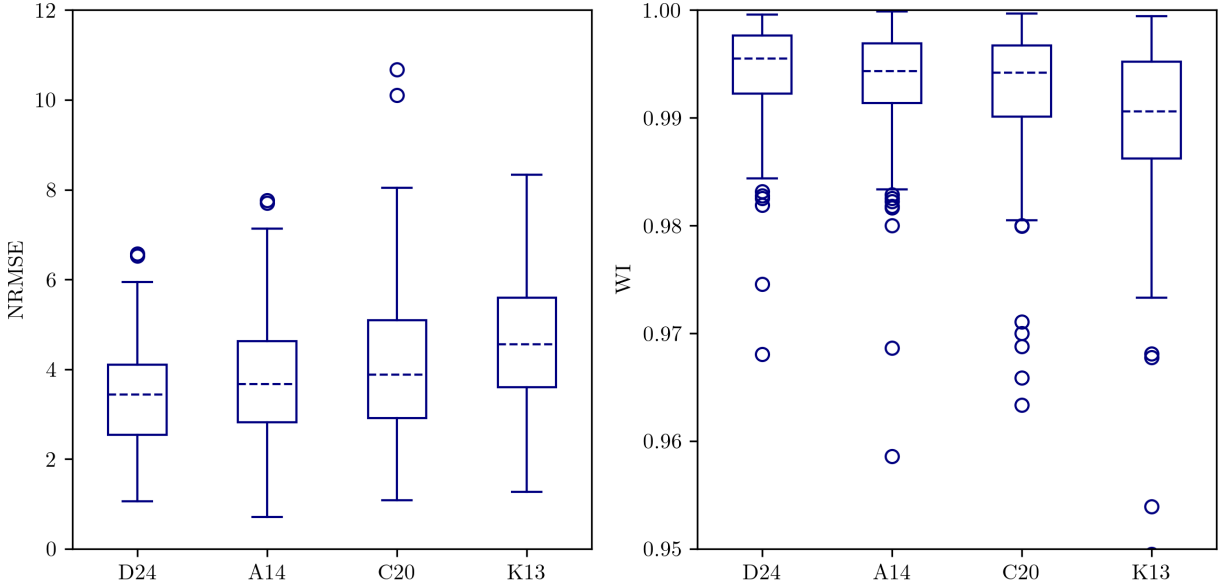


Figure 6: Boxplots of NRMSE (left side) and WI (right side) for the BCD  $f_{d,Re}$  (dark blue) versus the D24, A14, C20 and K13 parameterizations. The central dotted line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extend to 1.5 of the interquartile range while the outliers are plotted individually as circles.

333 A clear performance increase is brought by D24 compared to other study-specific parame-  
334 terizations. A strong improvement is observed when comparing D24 to K13 parameterization,  
335 leading to a median NRMSE decrease from 4.60% to 3.43% and a median WI increase from  
336 0.991 to 0.996. Slightly weaker improvements are observed when comparing D24 to A14 and  
337 C20, but the overall trend remains satisfactory for D24.

## 338 4. Discussion

### 339 4.1. *Synthesis of the findings*

340 Based on laboratory experiments, the present study aimed to identify the most robust  
341 approach to describe wave dissipation over macro- and mega-rough terrain in phase-averaged  
342 wave models. The main finding is that, once each model has been carefully optimized, the  
343 bulk drag canopy model consistently shows better predicting capacities than the bottom stress  
344 model, which is in agreement with their respective theoretical frameworks. The inclusion of  
345 local hydrodynamics in the drag coefficient improves the model performance, in particular  
346 considering the compiled *Re*-based formulation proposed here.

### 347 4.2. *BCD model: the role of roughness architecture*

348 In order to gain further insight into the role played by roughness architecture, a local  
349 analysis of the topographic approach has been performed. Local values of  $C_d$  are inferred  
350 along the beach profile, combining Equations 7 and 16 for each wave run and roughness layout  
351 case. The retrieved  $C_d$  data has been bin-averaged logarithmically-spaced *Re* and *KC* bins  
352 depending on the tested formulation. Figure 7 displays the bin-averaged  $C_d$  vs *Re* (left plot)  
353 and *KC* (right plot), while the color/symbol code depicts the different seabed layouts. The  
354 experimental bin-averaged drag coefficient ranges from 0.12 to 8.84.

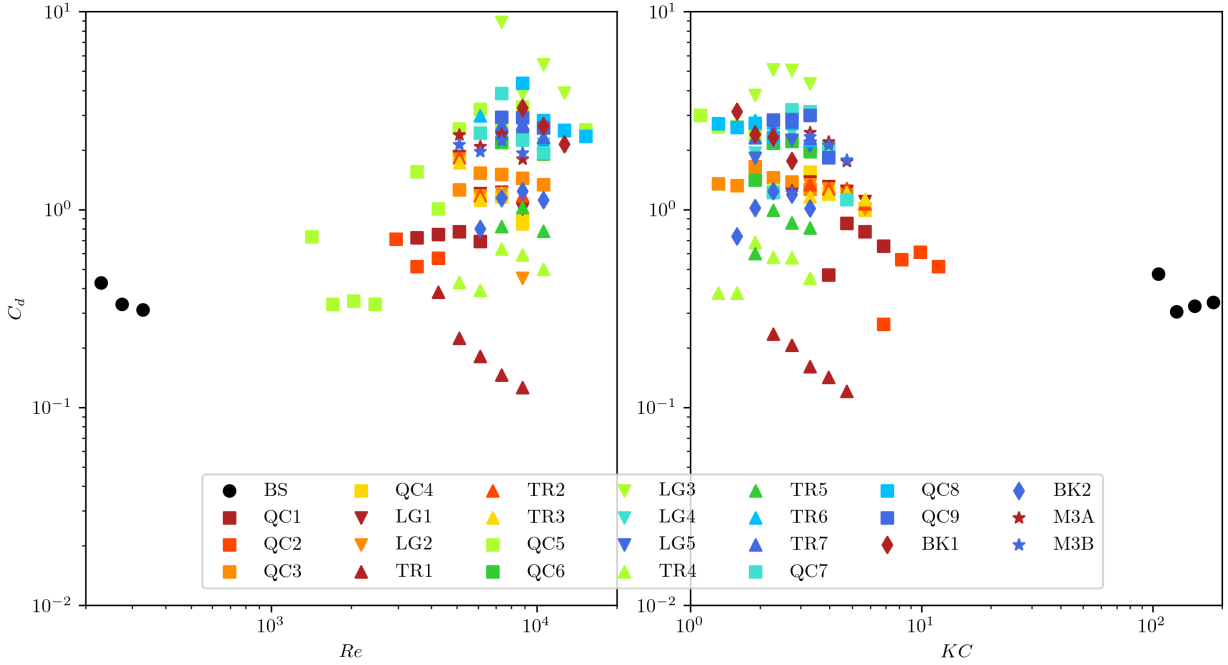


Figure 7: Bin-averaged values of measured  $C_d$  plotted as a function of  $Re$  (left side) and  $KC$  (right side) colored by seabed layouts.

355 We observe for each layout an overall decrease in  $C_d$  in response to an increase in  $Re$   
 356 or  $KC$  which is consistent with the existing power law formulation. However, a striking  
 357 variability is observed between the different layouts for given  $Re$  or  $KC$ . This emphasizes  
 358 the need for establishing a roughness-dependent drag factor  $f_d$ . The qualitative analysis  
 359 from a closer look at Figure 7 underlines the effect of the plane solidity by comparing the  
 360 BK1, QC6 and BK2 layouts which have decreasing skewness. The smaller the skewness is,  
 361 the higher the  $C_d$  is. The directionality effect is assessed by comparing the LG3, QC6 and  
 362 TR5, which shows that longitudinal/transverse alignments produce an increase/decrease of  
 363 drag for the same statistical moments. This observation may appear contradictory with the  
 364 findings of Dealbera et al. (2024) on the wave friction factor, which demonstrates higher  
 365 frictional dissipation for transverse anisotropic roughness systems when compared to longi-  
 366 tudinally oriented ones. This apparent contradiction must be interpreted keeping in mind  
 367 that roughness metrics are already involved in the definition of  $A_v$ , which indicates that a  
 368 higher  $C_d$  does not systematically indicate a higher drag force. More generally, though the  
 369 effects of those metrics can be visually identified for contrasted architecture, no simple rela-  
 370 tionship between  $f_d$  and the dimensionless metrics of the roughness  $\psi_{\mathbb{N}}$  has been identified  
 371 based on the present BCD dataset. The BCD topographic approach proposed here is based

372 on a unique length scale,  $\sigma_{\mathbb{N}}$ , implicitly assuming that it encompasses the scaling of vertical,  
 373 longitudinal and transverse dimensions of the roughness geometry. Such assumption likely  
 374 does not hold for real rough terrains, which are characterized by a fractal structure, i.e. no  
 375 dominant horizontal length-scales (Duvall et al., 2019; Sous et al., 2020, 2024). If relevant  
 376 in the present context, this  $\sigma$ -scaling assumption would allow to define the drag factor  $f_d$  as  
 377 a dimensionless parameter, expected to depend on topographical metrics  $\psi_{\mathbb{N}}$  only. However,  
 378 the retrieved  $f_d$  remains predominantly explained by  $\sigma$ , with 53 % of  $f_d$  variability being  
 379 explained. This likely indicates a shortcoming in the dimensional scaling, which can not be  
 380 simply unravelled with the present dataset. The secondary explanatory variable is the Direc-  
 381 tionality index proposed by Dealbera et al. (2024) (20 % explained variability). For practical  
 382 application, a simple parametric formulation can be proposed to replace the product  $A_v f_d$   
 383 for the topographic approach by:

$$K(1 - 0.6\Delta)(1 - n_{\mathbb{N}}) \quad (23)$$

384 with  $K$  being an empirical dimensional constant optimized here at  $60m^{-1}$  and  $\Delta$  the Direc-  
 385 tionality index of Dealbera et al. (2024).

386 Further observations on more realistic terrains, both in the laboratory and on the field,  
 387 are required to determine if a robust relationship can be established by  $f_d$  and non-idealized  
 388 roughness architecture metrics (Chung et al., 2021; Sous et al., 2024).

#### 389 *4.3. BS model: introducing the canopy top velocity*

390 The BS model, which remains widely used in nearshore spectral wave modeling, shows  
 391 lower performance than the BCD model. It is worthwhile to mention that the reduction in  
 392 predicting accuracy remains moderate, of the order of a few percents even for large roughness  
 393 conditions, even beyond the base theoretical framework. In particular, the use of a reference  
 394 near-bed flow velocity can be irrelevant in the macro-roughness case, where we can expect  
 395 that the orbital motion does not fully penetrate the roughness (Tang et al., 2019). Keeping  
 396 the simplicity of the standard BS model, an alternative definition of the reference flow velocity  
 397 is tested here, using the velocity estimated at the top of the roughness blocks, as performed  
 398 in the BCD ML04 model. Equations 13 and 14 are estimated taking now at the reference  
 399 depth at the canopy top elevation  $D_{ref} = D_v = D - \alpha_v D$ . The modified model is referred to  
 400 as the BS-RT approach. Figure 8 displays the comparison between the standard BS and the  
 401 BS-RT models, similar to the analysis performed in Figure 5.

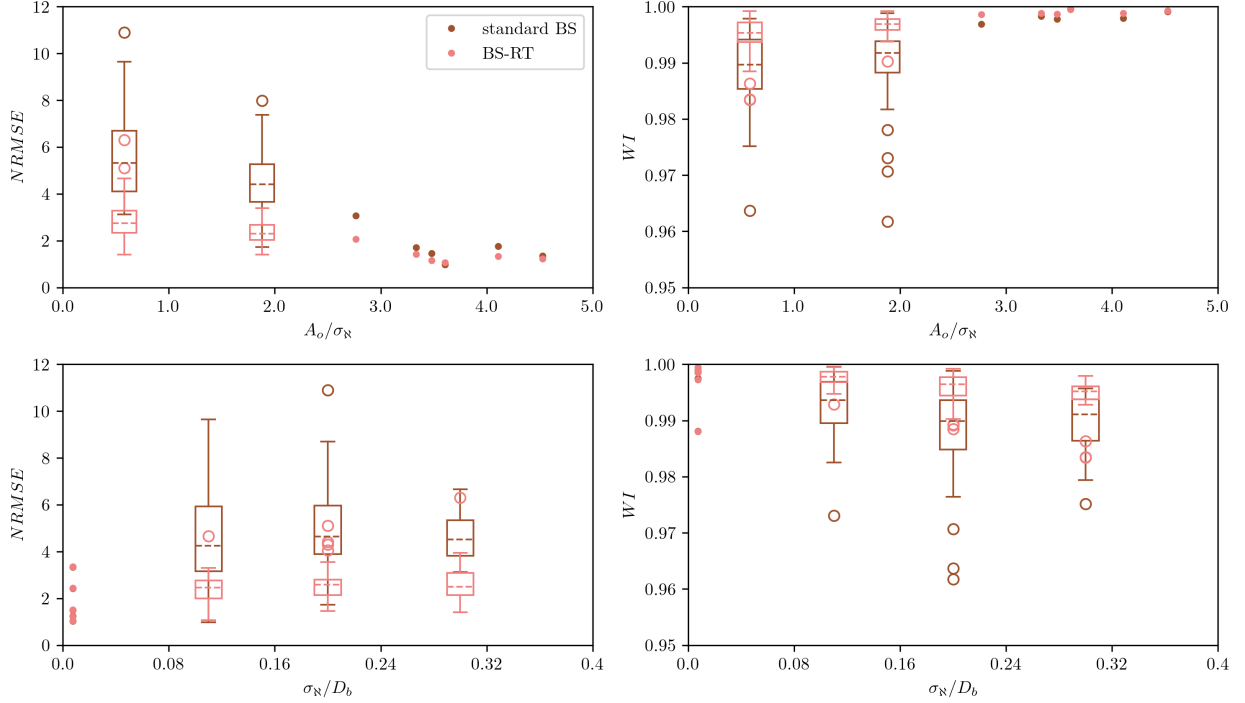


Figure 8: Plot and binned boxplots of NRMSE and WI versus  $A_o/\sigma_N$  for the following intervals :  $[0.30,0.80,1.30,2.00]$  and  $\sigma_N/D_b$  for the following intervals :  $[0.00,0.30,0.70]$ . The central dotted line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extend to 1.5 of the interquartile range while the outliers are plotted individually as circles. Single points are individual datapoints. The standard BS model is represented in brown and the BS-RT model in red.

402 A clear improvement is noted for the BS-RT approach against the standard BS approach,  
 403 with the reduction of the spread of estimators below 6% instead of 10% for the NRMSE and  
 404 above 0.98 instead of 0.96 for the WI. While already useful for practical applications, further  
 405 systematic tests on the BS-RT model should be carried out to evaluate the effect of reference  
 406 depth for the calculation. In particular, the inflexion of the vertical current profile inside  
 407 and outside the canopy and its dependency on the roughness architecture and/or the local  
 408 hydrodynamical conditions might affect the parameterization of the reference depth (Lowe  
 409 et al., 2005b). Note that the BS-RT approach has the potential advantages of being easily  
 410 tested from simple modified of standard BS formulations, which are already implemented  
 411 in most spectral models, and being only dependent on external parameters of the system,  
 412 without requiring knowledge of the internal flow inside and above the canopy Lowe et al.  
 413 (2007).

#### 414 4.4. Prospects

415 The present study is based on a macroscopic description of the roughness canopy, i.e. that  
416 the influence of the obstacles on the wave field is spatially integrated. The individual effect of  
417 each element is not described by the present modelling approach, which aims to be applicable  
418 to typical scales of operational nearshore models. However, the question necessarily arises on  
419 the validity of such bulk approaches for large roughness elements scaling as the depth or the  
420 wave height, able to induce local reflection and strongly affects the breaking (Sambe et al.,  
421 2011). The present results confirm, at the laboratory scale, the robustness of the macroscopic  
422 approach throughout the range of tested conditions but the exact limitations remain to be  
423 established by high-resolution numerical simulations or experiments.

424 Following the base works of Dalrymple et al. (1984) and Mendez and Losada (2004), the  
425 assumption has been made that the obstacle-induced drag force can be represented by a single  
426 quadratic formulation, i.e. implicitly assuming that the turbulent drag largely dominates  
427 over laminar and inertial components. Using classical regime diagram (Gu and Wang, 1991;  
428 Van Gent, 1993), the turbulence dominance assumption is expected to be validated for most  
429 of the tested roughness elements but for the largest ones, a comparable effect of turbulent and  
430 inertial drag components is expected, while laminar contribution remains small in each case.  
431 The missing inertial drag may likely explain part of the decrease of predictive performance  
432 of the BCD model observed for the large roughness cases, corresponding to small  $A_o/\sigma_N$  or  
433 large  $\sigma_N/D_b$  ratios. The implementation of the inertial component of drag is one of the main  
434 prospects of the present research works.

## 435 5. Conclusion

436 In very rough environments, bottom-induced wave dissipation is expected to be compa-  
437 rable or even dominant over depth-induced breaking dissipation. The present study aimed  
438 to compare several modeling strategies against the laboratory dataset presented by Dealbera  
439 et al. (2024). Two standard models, conventionally named here BS (bottom stress model)  
440 and BCD (bulk canopy drag model), are traditionally used to predict the energy dissipation  
441 generated by the stress exerted on the flow by irregular seabeds. The first model consid-  
442 ers the dissipation inside the bottom boundary layer for small roughness while the second  
443 one estimates the drag over the water column portion affected by the canopy. As the BCD  
444 model has been mainly implemented for idealized geometry, a new approach called the topo-  
445 graphic approach has been developed in this study to extend the model application to real  
446 rough (rocky or coral reef) terrain. In addition, the BCD model is assessed by testing either  
447 a uniform drag coefficient or a variable drag coefficient controlled by local hydrodynamics  
448 parameters,  $Re$  and  $KC$  through a power-law formulation. Several power-law parameteriza-  
449 tions have been tested. The comparisons of the performance estimators between the classical

450 geometric approach and the topographic approach show similar agreements between the ob-  
451 servations and the predictions, while the comparison between the  $Re$ - and  $KC$ -controlled  
452 parameterizations shows a lower performance for the  $KC$ -controlled parameterizations. The  
453 comparison between the BS and the BCD models underlines the better agreement found for  
454 the BCD model for all hydrodynamics conditions explored, though the gap between the two  
455 tends to narrow for high submergence ratios. The  $Re$ -based formulation obtained from a  
456 compilation of published datasets provides the best results. An interesting prospect for the  
457 BS model relies on the calculation of the reference velocity at the top of the roughness while  
458 the BCD model optimizations call for a deepening of the calculation of the transverse area.

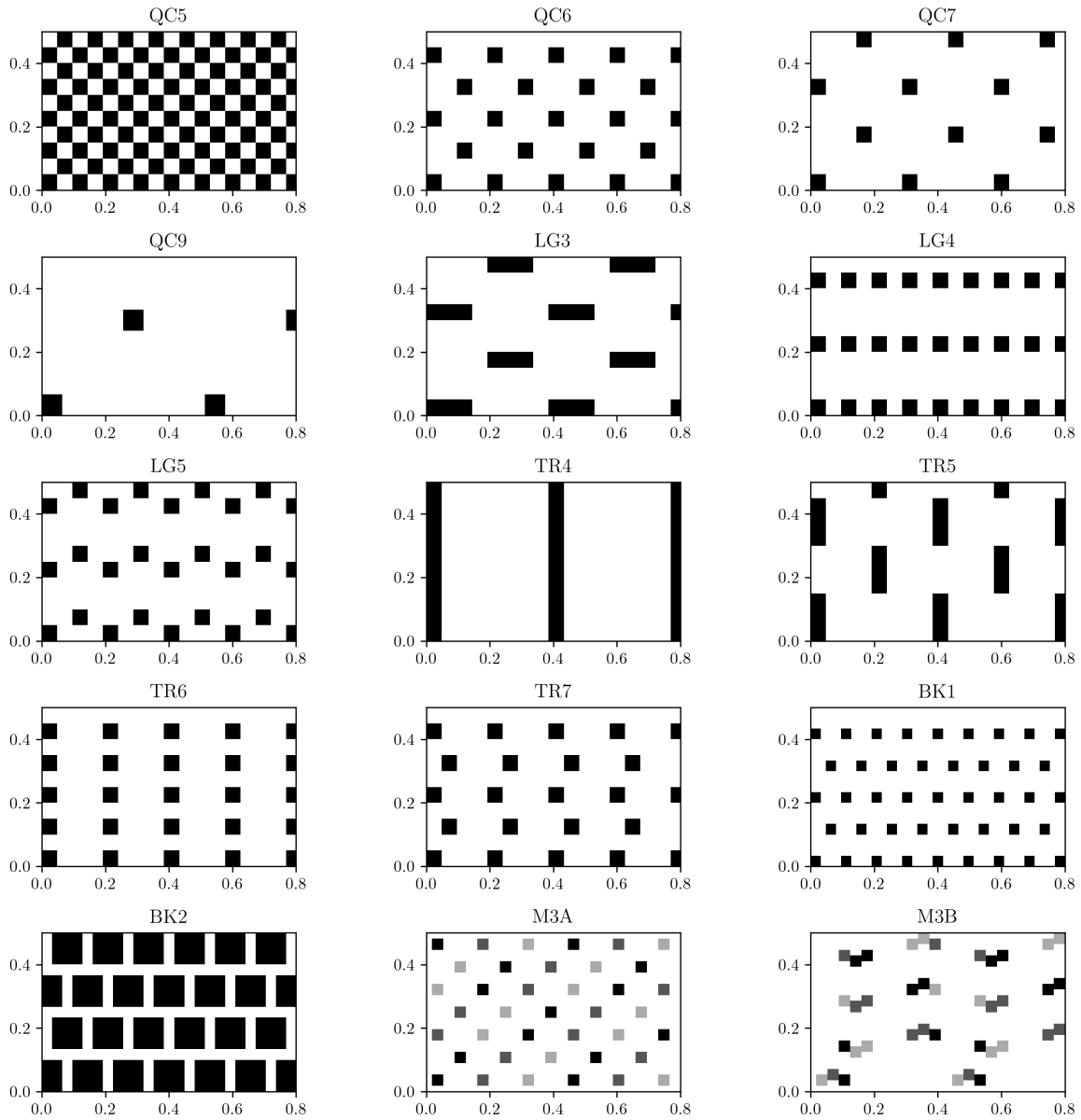


Figure .9: Plane view examples of seabed layouts. x- and y-axes correspond to cross- and along-shore directions. Waves come from the left side. Grey color levels for M3A and M3B indicated the different bloc heights.



460 **Appendix B: Table of seabed layout parameters**

Seabed layout name	Block height	$\sigma_N$	$n_N$
<i>RF</i>	0.000	0.000	1.000
<i>BS</i>	0.001	0.000	0.881
<i>QC1</i>	0.016	0.008	0.906
<i>QC2</i>	0.016	0.005	0.750
<i>QC3</i>	0.032	0.016	0.906
<i>QC4</i>	0.032	0.011	0.750
<i>QC5</i>	0.048	0.024	0.906
<i>QC6</i>	0.048	0.016	0.750
<i>QC7</i>	0.048	0.013	0.927
<i>QC8</i>	0.064	0.022	0.900
<i>QC9</i>	0.064	0.015	0.944
<i>LG1</i>	0.032	0.011	0.906
<i>LG2</i>	0.032	0.011	0.906
<i>LG3</i>	0.048	0.017	0.899
<i>LG4</i>	0.048	0.016	0.906
<i>LG5</i>	0.048	0.016	0.906
<i>TR1</i>	0.032	0.012	0.888
<i>TR2</i>	0.032	0.011	0.906
<i>TR3</i>	0.032	0.011	0.906
<i>TR4</i>	0.048	0.016	0.906
<i>TR5</i>	0.048	0.016	0.906
<i>TR6</i>	0.048	0.016	0.906
<i>TR7</i>	0.048	0.016	0.906
<i>BK1</i>	0.064	0.020	0.912
<i>BK2</i>	0.032	0.016	0.728
<i>M3A</i>	0.016 & 0.032 & 0.048	0.012	0.915
<i>M3B</i>	0.016 & 0.032 & 0.048	0.012	0.917

Table .3: Seabed layout metrics.

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