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# The role of roughness geometry in frictional wave dissipation

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## Abstract

Bottom friction dissipation is a key factor for wave attenuation in nearshore environments presenting complex geomorphological structures, such as rocky or coral shores. The present paper reports on a series of laboratory experiments performed in a wave flume with controlled wave conditions and seabed structures. Using the frequency-integrated short-wave analysis and classical models for bottom friction and breaking dissipation, the wave friction factor and the hydraulic roughness parameter were estimated from the experimental data. The former varies from 0.17 to 98 while the latter varies from 0 to 0.291 m. The observations reveal the combined influence of several topographical metrics, including the standard deviation, the skewness, the directionality and the effective slope of the seabed elevation. A metric-based multi-varied model for the hydraulic roughness parameter is proposed and confronted with other field data recovered on coral and rocky shores.

*Keywords:* Waves, Roughness, Friction, Surf zone, Physical model

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## 1. Introduction

Nearshore areas worldwide combine a growing interest from human societies, leading to continually expanding anthropization, and strong vulnerability to extreme events and climate change effects. Understanding nearshore hydrodynamics remains a major challenge for developing accurate modeling systems able to prevent coastal hazards, such as coastal flooding during extreme events and coastline erosion (Fringer et al., 2019). A strong focal point in nearshore studies is the wave-driven hydrodynamics, playing a key role in circulation, sediment transport and shoreline exposure.

Nearshore area is characterized by shallowing bathymetry that strongly affects wave propagation inducing a series of hydrodynamic processes including shoaling, reflection, refraction,

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11 depth-induced breaking (Dean and Dalrymple, 1991), non-linear transfers between frequency  
12 bands (Hasselmann et al., 1973) and bottom-induced friction dissipation (Madsen, 1995). The  
13 contributions of those processes to nearshore wave transformation were mostly investigated  
14 for sandy beaches with gently sloping and relatively smooth bottom. However, sandy beaches  
15 represent less than 30% of the world’s coastlines (Bird, 2000). The remaining nearshore ar-  
16 eas are characterized by more complex morphological structures including rough seabeds on  
17 rocky or coral shores, steep slopes and/or uneven bathymetry or seagrass canopies. Model-  
18 ing wave transformation in such environments remains a challenge, due to a more complex  
19 physics and often to a lack of detailed in-situ documentation due to access difficulty.

20 In the presence of large roughness elements, such as rocks and coral pinnacles, bottom  
21 friction can be expected to play an important role in wave transformation, potentially dom-  
22 inant over depth-induced breaking in wave attenuation for very rough terrain. In the past  
23 few years, field experiments over coral reefs (Lowe et al. (2005a, 2007); Quiroga and Cheung  
24 (2013); Monismith et al. (2015); Van Dongeren et al. (2013); Rogers et al. (2016); Sous et al.  
25 (2023)) and rocky platforms (Farrell et al. (2009); Ogawa et al. (2015); Poate et al. (2018);  
26 Gon et al. (2020); Lavaud et al. (2020)) have provided detailed analysis of frictional wave  
27 dissipation over rough seabeds, leading in particular to a series of field estimates of the wave  
28 friction factor  $f_w$ , identified as a key quantity for bottom friction dissipation. The overall  
29 trend is that an increase in roughness results in an increase in  $f_w$ . Consequently, classical  
30 bottom friction models (Swart, 1974; Soulsby et al., 1993; Madsen, 1995) connect  $f_w$  with  
31 the ratio of the near-bed wave orbital amplitude  $A_o$  to a single length-scale characterizing  
32 the roughness, the so-called hydraulic roughness parameter  $k_r$ . However, while the existing  
33 parameterizations have shown robust performance for high values  $A_o/k_r$ , the application of  
34 classical bottom friction models in very rough environments remains uncertain. In particu-  
35 lar, data are very sparse for  $A_o/k_r < 1$  (Nielsen, 1992; Gon et al., 2020)(Simons et al., 2000;  
36 Dixen et al., 2008; Sumer and Fuhrman, 2020). In addition, one might expect that in the  
37 presence of very large roughness, the relative submergence (ratio between  $k_r$  and the local  
38 depth  $D$ ) can become a critical parameter in shallow areas such as surf-zones Davis et al.  
39 (2021).

40 A second unresolved issue is the definition of a clear quantitative connection between  
41 frictional processes and geometrical roughness structure. A few studies have simultaneously  
42 documented hydrodynamic processes and topographical structure. The recurring trend is  
43 that  $k_r$  should primarily scale with the standard deviation of fine-scale seabed elevation, both  
44 for unidirectional (Aberle et al., 2010; Flack and Schultz, 2014) or wave-driven oscillatory  
45 (Lowe et al., 2005a; Sous et al., 2023) flows. However, discrepancies between studies for  
46 identical ratios of  $A_o/k_r$  (Gon et al., 2020) tend to indicate that other roughness features  
47 may be involved in the definition of  $k_r$ . Most of the existing insights into the relation  
48 between fine bed features and shear stress have been provided by analysis of the rough

49 turbulent canonical boundary layer (see the recent review of Chung et al. (2021)). A series  
50 of roughness metrics have been highlighted to assess the effect of roughness structure height  
51 (based on average roughness height or standard deviation of roughness elevation), frontal  
52 solidity related to pressure drag exposure, plane solidity (ratio of plan area of roughness  
53 elements to total plan area) or spatial arrangements of roughness structures such as clustering,  
54 directionality or spatial heterogeneity. Laboratory experiments have provided a few empirical  
55 formulas accounting for statistical metrics of bed topography (Chung et al., 2021). However,  
56 relevant experimental observations in comparable ranges of metrics remain sparse, mainly  
57 due to the cost of performing such parametric studies. Furthermore, note that bed metrics  
58 developed for idealized geometries, such as networks of vertical cylinders or cubic elements  
59 (Lowe et al., 2005b; Chung et al., 2021), may be barely applicable on real seabeds where the  
60 roughness structure presents a fractal dimension with no clear roughness structure spacing  
61 and arrangement (Duvall et al. (2019); Stewart et al. (2019); Sous et al. (2020)).

62 The present laboratory study aims to improve our understanding of frictional wave dissipa-  
63 tion in the surf zone for rough seabeds by i) assessing the performance of standard friction  
64 parameterizations over a wide range of roughness conditions and ii) proposing quantitative  
65 relationships between  $k_r$ , the classical frictional length-scale, and a selection of relevant met-  
66 rics describing the geometrical structure of seabed roughness. In this context, a series of  
67 laboratory experiments were carried out considering several roughness layouts to obtain a  
68 wave friction database exploring a wide range of  $A_o/k_r$  and  $D/k_r$  ratios. The first section  
69 describes the experimental setup, the data processing, the theoretical models used to extract  
70 wave friction parameters and the seabed topographical metrics. The second section presents  
71 the results, including the mono- and multi varied statistical models of the hydraulic roughness  
72 while the Discussion section summarizes the observations and their limitations and provides  
73 prospects for future research works.

## 74 2. Methods

### 75 2.1. Experimental facility

76 The experiments were carried out in the CASH (Canal Aéro-Sédimento-Hydrodynamique)  
77 wave flume at Seatech engineering school, University of Toulon. The flume is made of glass,  
78 6m long and 0.5m wide, and equipped with a linearly sloping bed of 1/20. A piston wave-  
79 maker, with an absorbing system at the back, was used to generate waves on the 1m-long  
80 horizontal bottom section before the sloping bed (Figure 1).

#### 81 2.1.1. Instrumentation

82 A series of resistive wave gauges were used to measure the free surface elevation over the  
83 sloping bed. The wave gauges were deployed along three alignments: a central alignment in

84 the axis of the channel where 20 wave gauges are distributed every 17 cm, and two secondary  
 85 alignments as control points, parallel to the central one and placed at 12.5 cm on either side  
 86 of it, with one wave gauge out of 4 (Figure 1). The acquisition frequency was 100Hz.

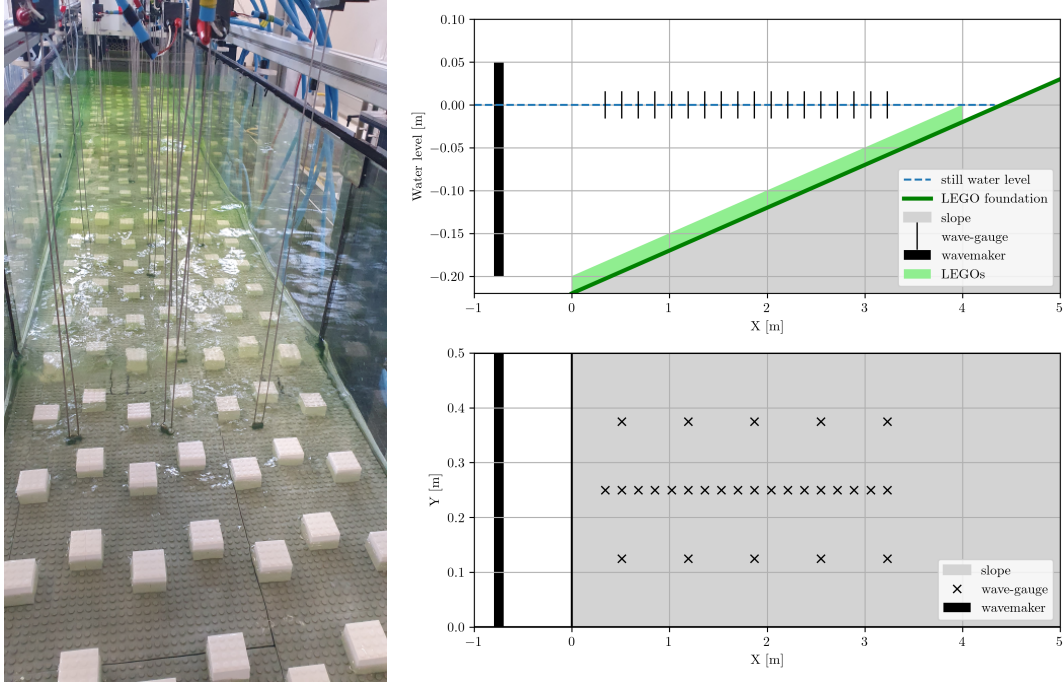


Figure 1: Picture of the TR3 layout and diagram of the wave flume setup and instrumentation.

87 *2.1.2. Wave runs*

88 Each experiment consisted of a 5-min run of irregular waves generated from a JONSWAP  
 89 spectrum (peak enhancement factor at 7). Wave parameters are summarized in Table 1. The  
 90 still water depth was kept constant at 0.22m.

Wave run	Peak period [s]	Mean period [s]	Significant wave height [m]	Iribarren number
W1	1.0	0.8	0.065	0.089
W2	1.0	0.8	0.075	0.083
W3	1.2	1.0	0.047	0.086
W4	1.2	1.0	0.061	0.075
W5	1.2	1.0	0.071	0.070

Table 1: Wave run parameters.

91 The Iribarren number is given by the following relationship  $\xi = \beta / \sqrt{2\pi H_{s,o} T_{p,o}^2}$ , where  $\beta$   
 92 is the slope of the seabed,  $H_{s,o}$  and  $T_{p,o}$  are the measured offshore significant wave height and  
 93 peak period, corrected for the effect of the shoaling. The Iribarren values range between 0.064  
 94 and 0.079 and indicate a spilling breaker (Galvin Jr., 1968), validated by visual observations  
 95 in the flume.

### 96 2.1.3. Wave gauge processing

97 The spectral density of variance at each gauge was first computed from the free surface  
 98 elevation time series using a fast Fourier transform. Incident and reflected spectral wave  
 99 components are then separated using the three-gauge method (Drevard et al., 2009). The  
 100 incident spectra are then integrated over the short wave (SW) frequency band  $\frac{f_p}{2} < f < 3f_p$ ,  
 101 where  $f_p$  is the peak frequency, to provide  $H_{rms}$  the spectral root mean square height of the  
 102 incident short waves given by the following formula:  $H_{rms} = \sqrt{8 \int E(f) df}$ , with  $E(f)$  the  
 103 spectral energy density.

### 104 2.1.4. Seabed layouts

105 A series of 27 seabed layouts was tested on the beach slope while the horizontal section  
 106 of the flume remained untouched. The reference smooth seabed layout, referred to as RF,  
 107 was made using stainless steel plates. The first rough layout, referred to as BS, was made  
 108 of LEGO<sup>®</sup> plastic base plates showing an isotropic distribution of short cylinders of 1mm  
 109 diameter, 8mm spacing and 1mm height. Twenty-five additional types of beds were created  
 110 using selected layouts of plastic blocks fixed on the BS seabed. Three main patterns studied  
 111 were the isotropic quincunx (referenced as QC), the anisotropic brick (referenced as BK)  
 112 and the trimodal height block (referenced as M3). For each pattern, several configurations  
 113 (referred to as the *layouts*) of height, width, and spacing were tested. The quincunx layouts  
 114 were defined by the cubic block height (H) and spacing (SP) while the brick layouts were  
 115 defined by the cobbled block height (H), length (L - transverse dimension) and spacing (SP),  
 116 as shown in Figure 2 and described in Table 2. Variations in alignments of the quincunx  
 117 pattern created new layouts with cross-shore (TR) and along-shore (LG) bars, by changing  
 118 either the transversal shift (LX) or longitudinal shift (LY), their height (H), length (L) and  
 119 streamwise dimension (P). As for the trimodal pattern, two layouts were arranged, one with  
 120 a quincunx pattern with varying heights and one with random groups of different height  
 121 blocks. Figure 3 displays an illustrative series of layouts. Statistical topographical features  
 122 for each layout are described in Section 2.5 and listed in Appendix A.

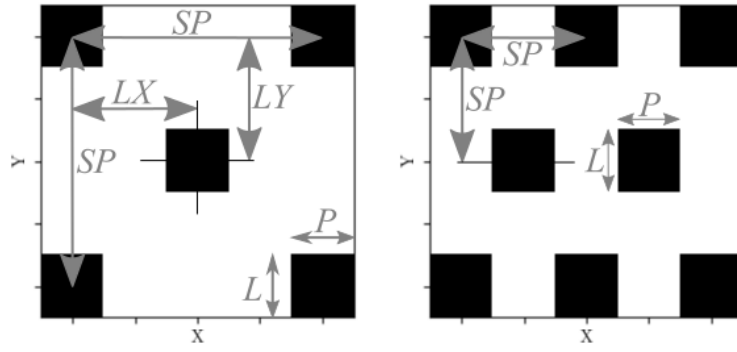


Figure 2: Main seabed patterns: quincunx on the left and brick on the right. Parameters definition are based on waves coming from the left side.

<b>Layout</b>	<b>H</b>	<b>L</b>	<b>P</b>	<b>SP</b>	<b>LX</b>	<b>LY</b>
<i>Layout name</i>	<i>Height [m]</i>	<i>Length [m]</i>	<i>Streamwise dimension [m]</i>	<i>Spacing between block lines [m]</i>	<i>Transversal shift between block lines [m]</i>	<i>Longitudinal shift between block lines [m]</i>
RF	0	0	0	-	-	-
BS	0.001	0.001	0.001	-	0.008	0.008
QC1	0.016	0.016	0.016	0.032	0.016	0.016
QC2	0.016	0.016	0.016	0.064	0.032	0.032
QC3	0.032	0.032	0.032	0.064	0.032	0.032
QC4	0.032	0.032	0.032	0.128	0.064	0.064
QC5	0.048	0.048	0.048	0.096	0.048	0.048
QC6	0.048	0.048	0.048	0.192	0.096	0.096
QC7	0.048	0.048	0.048	0.288	0.144	0.144
QC8	0.064	0.064	0.064	0.256	0.128	0.128
QC9	0.064	0.064	0.064	0.512	0.256	0.256
LG1	0.032	0.032	0.032	0.128	0.064	0.000
LG2	0.032	0.032	0.032	0.128	0.064	0.032
LG3	0.048	0.048	0.144	0.288	0.192	0.144
LG4	0.048	0.048	0.048	0.192	0.096	0.000
LG5	0.048	0.048	0.048	0.192	0.096	0.048
TR1	0.032	0.480	0.032	0.256	-	-
TR2	0.032	0.032	0.032	0.128	0.000	0.064
TR3	0.032	0.032	0.032	0.128	0.032	0.064
TR4	0.048	0.480	0.048	0.384	-	-
TR5	0.048	0.144	0.048	0.384	0.192	0.192
TR6	0.048	0.048	0.048	0.192	0.000	0.096
TR7	0.048	0.048	0.048	0.192	0.048	0.096
BK1	0.064	0.032	0.032	0.096	-	-
BK2	0.032	0.096	0.096	0.128	-	-
M3A	0.016 - 0.032 - 0.048	0.032	0.032	0.128	0.064	0.064
M3B	0.016 - 0.032 - 0.048	0.032	~ 0.096	-	-	-

Table 2: Seabed layout parameters



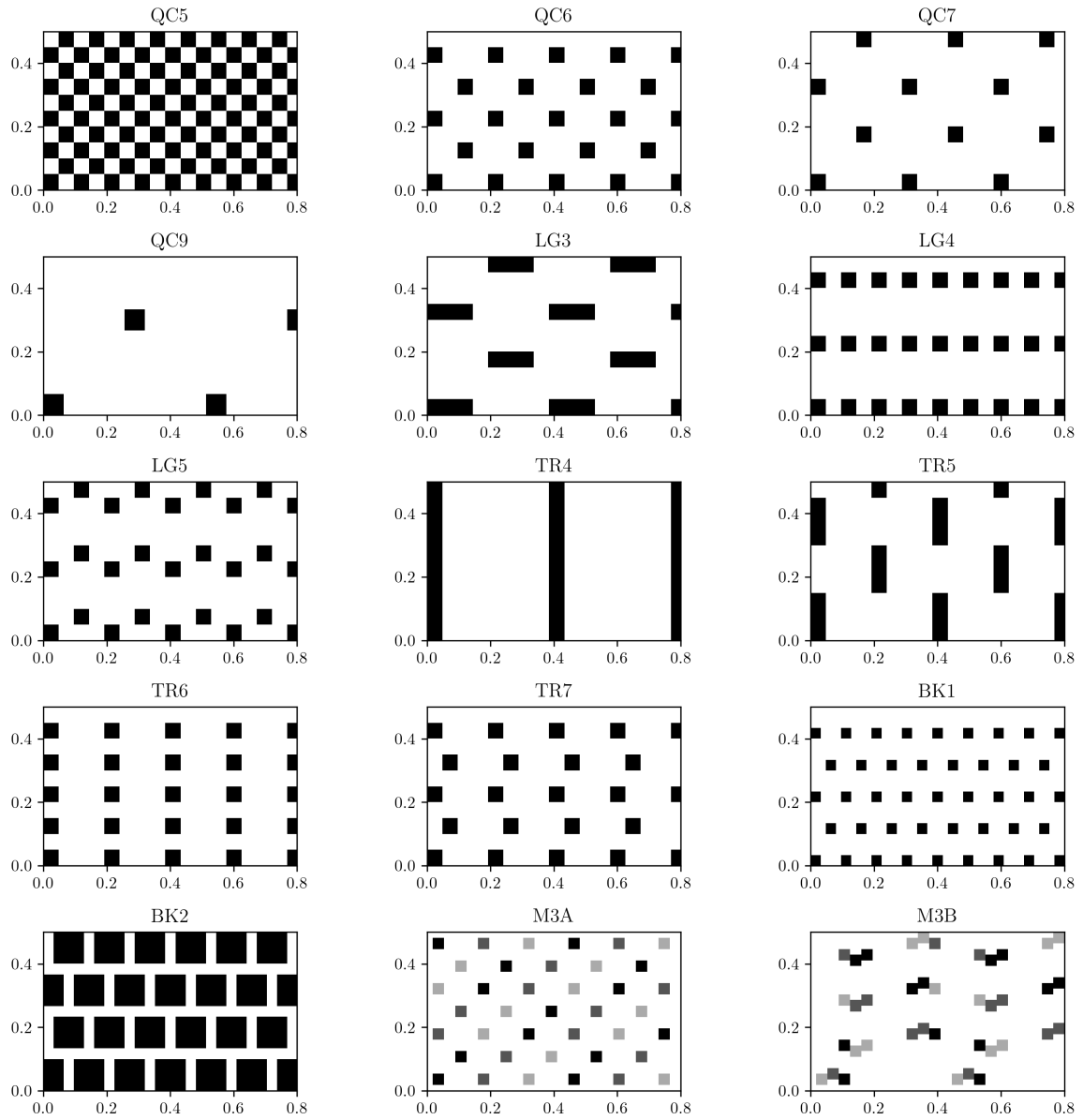


Figure 3: Plane view examples of seabed layouts. x- and y-axes correspond to cross- and along-shore directions. Waves come from the left side. Grey color levels for M3A and M3B indicated the different bloc heights.

123 *2.2. Performance estimators*

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

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

$$NRMSE = \frac{RMSE}{\sqrt{\frac{1}{n} \sum_i^n \Theta_i^2}} \times 100 \quad (2)$$

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

124 where  $n$  is the number of values,  $\hat{\Theta}$  is the prediction value,  $\Theta$  the observed value and  $\bar{\Theta}$  the  
 125 mean of observed values.

126 *2.3. Determination of wave dissipation contributions*

127 The present section describes the implementation of a simple wave energy model used to  
 128 process the experimental observations. The aim is to compare the combined contributions of  
 129 wave breaking and bottom friction with the total measured dissipation, allowing to extract  
 130 wave frictional parameters from the measurements, namely the wave friction factor and the  
 131 hydraulic roughness.

132 *2.3.1. Energy flux balance*

We consider unidirectional wave propagation along a reference cross-shore  $x$ -axis, addressed in a frequency-integrated approach over the SW band. When averaged over many wave cycles, the wave energy flux balance in the absence of mean current can be written as:

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

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

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

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

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

133 where  $k$  and  $\omega$  are the wave number and the angular frequency associated with the peak  
 134 period and  $D$  the water depth, using the dispersion relationship  $\omega^2 = gk \tanh(kD)$ .

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

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

135  $\overline{\varepsilon}_t$  is calculated at each wave gauge using a centered scheme with the two neighbouring gauges,  
 136 for each wave case and each seabed layout.

137 Following previous experiments in the same CASH wave flume (Sous et al., 2021), fric-  
 138 tional dissipation over smooth surfaces is negligible, i.e. we neglect sidewall friction for rough  
 139 cases and sidewall and bottom friction for smooth RF case. A bi-spectral analysis has been  
 140 performed on a smooth representative case, using RF layout and W2 wave conditions, to  
 141 estimate the non-linear energy between SW and IG bands. The process has been detailed in  
 142 Appendix C. It has showed a weak effect of non-linear energy transfer on the estimation of  
 143 friction factor and we expect them to play an even weaker role in shallow rough environments.

#### 144 2.3.2. Breaking-induced dissipation

The standard wave model of Thornton and Guza (1983) (Eq. 24, hereinafter named TG83) is used to estimate breaking-induced dissipation  $\overline{\varepsilon}_b$ :

$$\overline{\varepsilon}_b = \frac{B^3}{4} \rho g \frac{f_p}{D} \int_0^\infty H^3 p(H) \left( \frac{H_{rms}}{\gamma D} \right)^n \left[ 1 - \exp \left( - \left( \frac{H}{\gamma D} \right)^2 \right) \right] dH \quad (8)$$

145 where  $B$  is a breaking coefficient,  $p(H)$  the probability density function of the crest-to-trough  
 146 wave height  $H$ ,  $\gamma$  a breaking parameter and  $n$  a constant coefficient taking at 2, following  
 147 TG83. The model parameters  $\gamma$  and  $B$  and the wave height distribution  $p(H)$  are optimized  
 148 against the smooth RF reference seabed layout for each wave run.  $\gamma$  is first estimated from the  
 149 linear fit of the  $H_{rms}/D$  ratio relationship obtained from the inner surf zone measurements.  
 150 The second adjustable parameter  $B$  is optimised by minimising the NRMSE and maximising  
 151 the WI by comparing the measured and modelled dissipation. The  $\gamma$  and  $B$  parameter pair  
 152 is estimated for each wave case on the smooth RF seabed and assumed to be constant for  
 153 all other seabed layouts. The final  $\gamma$  values are 0.36, 0.45, 0.30, 0.40 and 0.45 for W1 to W5  
 154 cases, respectively, while the  $B$  values are 0.57, 0.66, 0.63, 0.70 and 0.73 for W1 to W5 cases,  
 155 respectively.

To model  $p(H)$ , we use a modified Rayleigh distribution to take into account the statistics observed in our flume, with a stronger weight of high waves in the surf zone:

$$p(H) = \frac{2H}{H_{rms}^2} \exp \left[ - \left( \frac{H - H_0/4}{H_{rms}} \right)^2 \right] \quad (9)$$

156 where  $H_0$  is the spectral root mean square of incident waves measured at the offshore wave  
 157 gauge. Figure 4 displays comparisons of cross-shore profiles of wave height and energy flux  
 158 dissipation between measurements, standard TG83 model, with same values of  $\gamma$  and the  
 159 following optimized values of B for each wave run: 0.80, 0.83, 0.86, 0.97 and 1.03, and  
 160 distribution-adjusted TG83 model. The improvements provided by the adjusted distribution  
 161 in the TG83 model are straightforward for both wave height and energy flux dissipation.

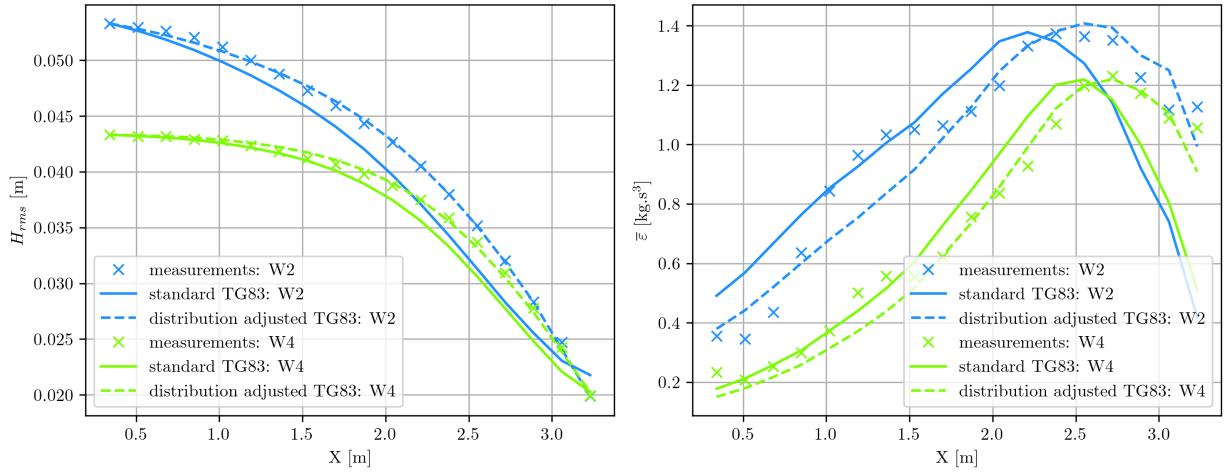


Figure 4: Cross-shore profiles of  $H_{rms}$  (left panel) and  $\bar{\epsilon}_t$  (right panel). Laboratory measurements are depicted by cross symbols while standard and distribution adjusted TG83 model are presented in solid and dashed lines, respectively. Green and blue colors correspond to W2 and W4 cases.

### 162 2.3.3. Frictional dissipation

The SW-integrated bottom friction dissipation model is again based on the seminal work of TG83:

$$\bar{\epsilon}_f = \frac{\rho f_w}{4\sqrt{\pi}} \left( \frac{\pi H_{rms}}{T_{m01} \sinh kD} \right)^3 \quad (10)$$

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

Following Swart (1974); Madsen et al. (1988); Nielsen (1992), the wave friction factor  $f_w$  is related to the ratio of the wave orbital excursion at the bottom to a typical vertical

roughness scale, the so-called hydraulic roughness parameter  $k_r$  (or equivalent Nikuradse roughness height), through the following expression:

$$f_w = \exp \left( a_1 \left( \frac{A_o}{k_r} \right)^{a_2} + a_3 \right) \quad (11)$$

where  $a_1$ ,  $a_2$  and  $a_3$  are dimensionless empirical constants taken as 5.0, -0.15 and -5.9 (Sous et al., 2023) and  $A_o = u_o/\omega$  the bottom orbital excursion with  $u_o$  the bottom orbital velocity given by the linear theory:

$$u_o = \frac{\pi H_{rms}}{T_{m01} \sinh kD} \quad (12)$$

#### 164 2.4. Extraction of wave frictional parameters

165 For each wave run and rough seabed layout, the measured total dissipation can be com-  
 166 pared to the combined contributions of breaking and frictional dissipation to infer two govern-  
 167 ing frictional parameters from the measurements: the wave friction factor and the hydraulic  
 168 roughness.

##### 169 2.4.1. Wave friction factor

The wave friction factor  $f_w$  is directly estimated from experimental data combining Equa-  
 tions 7 and 10:

$$f_w = 4\sqrt{\pi} \left( \frac{\bar{\varepsilon}_t - \bar{\varepsilon}_b}{\rho} \right) \left( \frac{T_{m01} \sinh kD}{\pi H_{rms}} \right)^3 \quad (13)$$

170 where  $\bar{\varepsilon}_t$  is deduced from the experimental estimations of energy flux gradient using Equation  
 171 4 and  $\bar{\varepsilon}_b$  from the calibrated breaking model.

##### 172 2.4.2. Dissipation-optimized hydraulic roughness

173 The wave energy flux model from Equation 4, combining the breaking dissipation from  
 174 Equation 8 and the frictional dissipation from Equation 10, is used to predict the cross-shore  
 175 evolution of  $H_{rms}$ . The sole free parameter is  $k_r$ , the hydraulic roughness, which is used  
 176 as a fitting parameter to obtain the best agreement with the measured  $H_{rms}$  profile. The  
 177 optimization is performed by minimising the NRMSE and maximising the WI, limiting the  
 178 analysis to  $H_{rms} > 0.01 m$  data. Therefore, for each wave run and rough seabed layout, a  
 179 single optimized value of the hydraulic roughness parameter  $k_{r,o}$  is obtained.

#### 180 2.5. Topographical metrics

The rough seabed topography is described for all layouts by a Digital Elevation Model  
 (DEM) depicting the 2D seabed elevation  $\aleph(x, y)$ , where  $y$  is the coordinate along the long-  
 shore direction, with a 0.008m definition (see e.g. Figure 3). For all rough seabed layouts,

statistical properties were calculated, focusing on statistical metrics remaining workable on non-idealized topography:  $\sigma_{\aleph}$  the standard deviation of seabed elevation,  $Sk_{\aleph}$  the skewness,  $\Delta_{\aleph}$  the directionality and  $ES_{\aleph,x}$  the cross-shore effective slope. The former two statistical moments are computed on the full 2D DEM matrix, classically defined as:

$$\sigma_{\aleph} = \sqrt{\frac{1}{n} \sum_i^n (\aleph_i - \bar{\aleph})^2} \quad (14)$$

$$Sk_{\aleph} = \frac{\frac{1}{n} \sum_i^n (\aleph_i - \bar{\aleph})^3}{\left[ \frac{1}{n} \sum_i^n (\aleph_i - \bar{\aleph})^2 \right]^{3/2}} \quad (15)$$

where  $\bar{\aleph}$  is the seabed elevation mean defined as  $\bar{\aleph} = \frac{1}{n} \sum_i^n \aleph_i$ . The directionality estimator  $\Delta_{\aleph}$  is based on the computation of directional standard deviations  $\sigma_{\aleph,x}$  and  $\sigma_{\aleph,y}$ , in cross-shore and along-shore directions, respectively:

$$\Delta_{\aleph} = \frac{\overline{\sigma_{\aleph,x}} - \overline{\sigma_{\aleph,y}}}{\overline{\sigma_{\aleph,x}} + \overline{\sigma_{\aleph,y}}} \quad (16)$$

181  $\Delta_{\aleph}$  is equal to zero for a fully isotropic roughness structure and tends to -1/1 for increas-  
 182 ingly anisotropic layouts with along-shore/cross-shore uniform roughness structure, respec-  
 183 tively.

The alongshore-averaged cross-shore effective slope (Napoli et al., 2008; Chung et al., 2021), which is a measure of the frontal solidity, is estimated as:

$$ES_{\aleph,x} = \frac{1}{L_x} \sum \left| \frac{\partial \aleph(x)}{\partial x} \right| \quad (17)$$

184 with  $L_x$  is the cross-shore length and  $\aleph(x)$  is the seabed elevation in the cross-shore direction.

## 185 2.6. Procedure summary

186 The overall data analysis procedure is summarized in Figure 5. In addition to the steps  
 187 described above, a multi-variate regression (MVR) is used to build a predictive model for  
 188 hydraulic roughness, see Section 3.5.

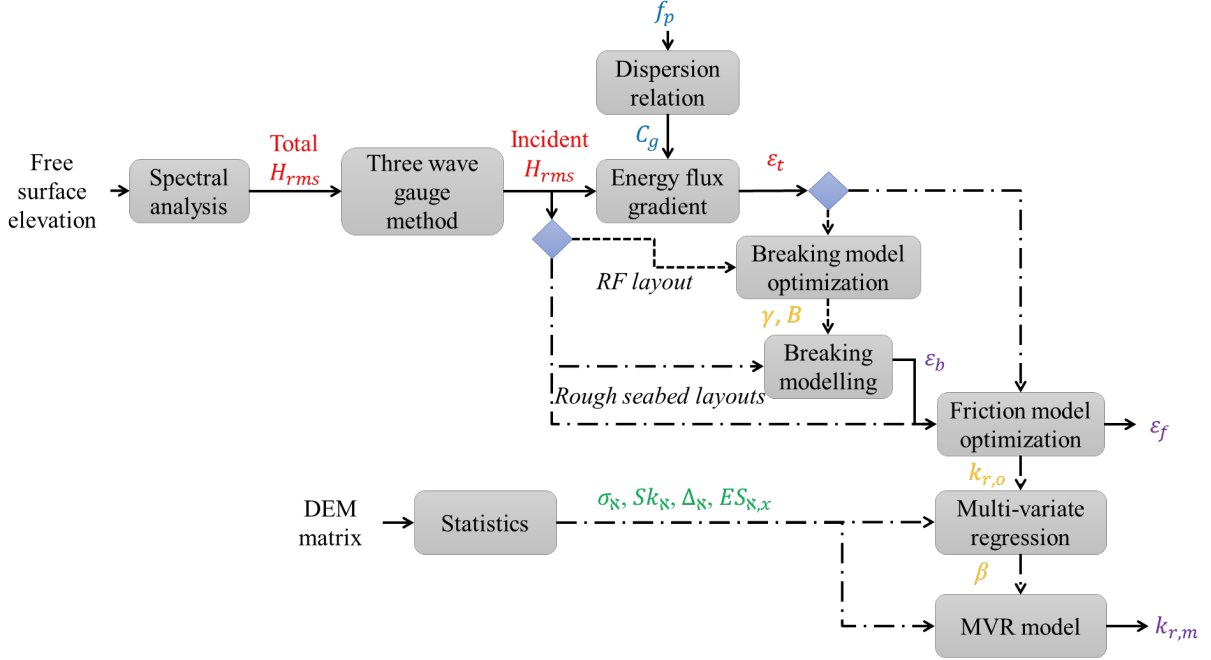


Figure 5: Method summary: wave parameters are shown in blue, seabed geometry statistics in green, measured values in red, optimized values in orange and modelled values in purple.

### 189 3. Results

#### 190 3.1. Illustrative cases

191 Figure 6 depicts, for wave case W3 (see Table 1), the cross-shore  $H_{rms}$  profiles for four  
 192 different seabed layouts: RF, QC4, TR1 and QC6. The smooth RF profile (black line)  
 193 shows a first nearly constant section in the wave propagation and then a decrease due to  
 194 the overwhelming effect of wave breaking starting around  $X = 2m$ . For rough seabeds, the  
 195 first main trend is an enhancement of wave dissipation with  $\sigma_N$ . Comparing for instance  
 196 RF, QC4 and QC6 with  $\sigma_N = 0, 0.011$  and  $0.016$  m, respectively, we observe both stronger  
 197 dissipation rate and earlier inception of dissipation across the profile, even far offshore from  
 198 the breaking point for the rougher case. However,  $\sigma_N$  is not the only controlling factor of  
 199 frictional dissipation. This is demonstrated by TR1, which has a smaller  $\sigma_N$  (0.012) than  
 200 QC6 but a stronger wave attenuation, with different  $\Delta_N$  values (respectively 1 and 0).

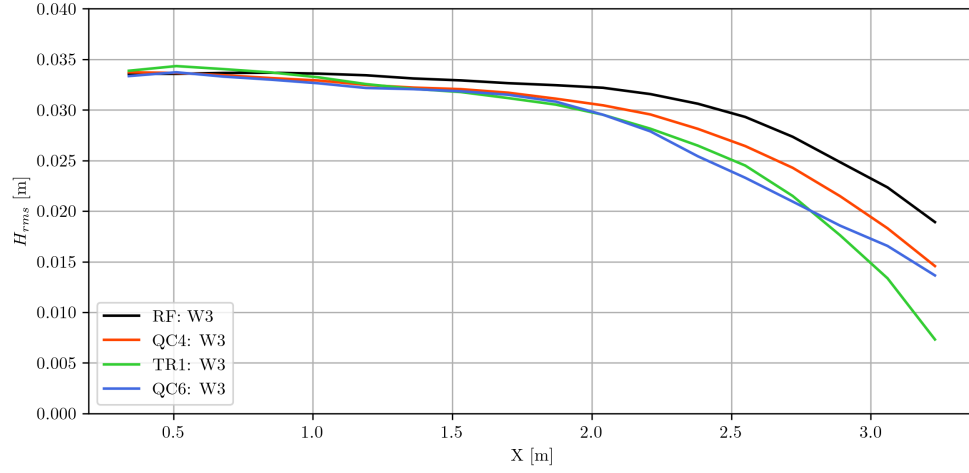


Figure 6: Cross-shore profile for  $H_{rms}$  for three seabed layouts : RF (black), QC4 (red), TR1 (green) and QC6 (blue). QC4 and TR1 have the same  $\sigma_N = 0.011$  and QC4 and QC6 have the same  $\Delta_N = 0$ . Profiles are shown for the W3 wave run.

201 *3.2. Wave friction factor vs monoscale hydraulic roughness*

202 Figure 7 depicts the relationship between the experimental wave friction factor  $f_w$  (Eq.  
 203 13) and  $A_o/k_r$  ratio. It is first assumed here that  $k_r = k_r^{\sigma_N}$ , a monoscale function only  
 204 depending on  $\sigma_N$ :  $k_r^{\sigma_N} = 6\sigma_N$ . The experimental  $f_w$  are bin-averaged over logarithmically-  
 205 spaced  $A_o/k_r$  bins, while the color levels depict the different seabed layouts. An additional  
 206 comparison is made with the prediction of the theoretical formulation from Equation 11.



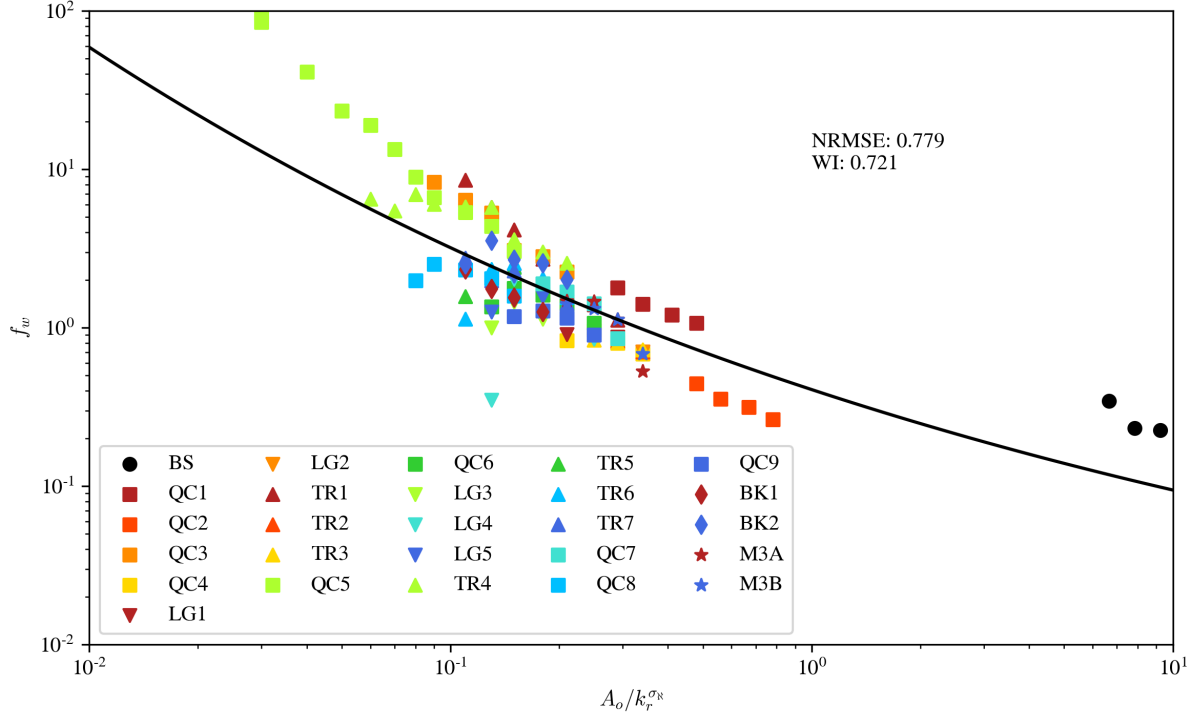


Figure 7: Bin-averaged values of measured  $f_w$  plotted as a function of  $A_o/k_r^{\sigma_N}$  colored by seabed layouts, where  $k_r^{\sigma_N}$  is the hydraulic roughness modelled using a monoscale relation as  $k_r^{\sigma_N} = 6\sigma_N$ . The solid black line represents Madsen’s prediction Madsen (1995) (Equation 11) using Sous et al’s parameterization Sous et al. (2023).

207 The experimental bin-averaged friction factor ranges from 0.17 to 98. The overall trend  
 208 of the  $f_w$  data shows the expected behavior, i.e. a decrease of friction for increasing  $A_o/k_r$   
 209 ratio. For the purpose of comparison with other datasets, the range of  $A_o/k_r$  covered by the  
 210 present experiments corresponds to  $0.15 < A_o/\sigma_N < 30.90$ , i.e. in the typical range of rough  
 211 bed friction studies documented in the field Lowe et al. (2005a); Gon et al. (2020); Poate  
 212 et al. (2018); Sous et al. (2023). The experimental  $f_w$  shows a reasonable overall agreement  
 213 with the friction model prediction (NRMSE=0.779, WI=0.721). However, a visible spread is  
 214 observed between the different seabed layouts with a factor more than 5 for  $f_w$  obtained at  
 215 similar  $A_o/k_r$ . Following the previous observations on  $H_{rms}$  profiles in Figure 6, it is expected  
 216 that at least part of the observed discrepancies are due to the variation in roughness structure,  
 217 suggesting that the standard deviation may not be the sole scaling of hydraulic roughness.  
 218 The first qualitative analysis can be inferred from a closer look at Figure 7. The plane solidity  
 219 effect can be assessed by comparing cases QC6 and BK2, the latter showing a much lower

220 skewness than the former (2.26 vs -0.4). Low-skewness BK2 shows overall higher  $f_w$  than  
 221 QC6, which tends to indicate that higher plane solidity is associated with higher friction,  
 222 at least in the documented range. Roughness directionality shows a significant effect on  
 223 wave friction factor. Comparing for instance QC6 with LG4, LG5, TR4 and TR5, one notes  
 224 that longitudinal/transverse alignments produce a decrease/increase of friction for the same  
 225 statistical moments. The only effect of effective slope, related to frontal solidity, is poorly  
 226 identified with direct observations in Figure 7.

### 227 3.3. Dissipation-optimized $k_{r,o}$

228 The calculation of dissipation-optimized roughness height described in Section 2.4.2 pro-  
 229 vides  $k_{r,o}$  values ranging from 0 m to 0.291 m. As expected the lowest values are observed for  
 230 the smoothest layouts (BS and QC2) while the largest values  $k_{r,o} > 0.2 m$  are obtained for  
 231 the highest  $\sigma_N$  layout (QC5), including the extreme 0.291m value associated with the most  
 232 energetic wave run W2.

233 In order to gain further insight into the potential multi-varied nature of hydraulic rough-  
 234 ness, Figure 8 depicts scatterplots of the dissipation-optimized  $k_{r,o}$  versus  $\sigma_N$ , indicating the  
 235 different wave cases as color levels. The previous conclusion is confirmed: a strong depen-  
 236 dence between  $k_{r,o}$  and  $\sigma_N$ , indicating that  $\sigma_N$  is a key parameter in the formulation of the  
 237 background friction parameterization. However, for identical values of  $\sigma_N$ , a noticeable vari-  
 238 ability of  $k_{r,o}$  is shown, meaning other metrics should be involved in the bottom friction  
 239 parameterization.

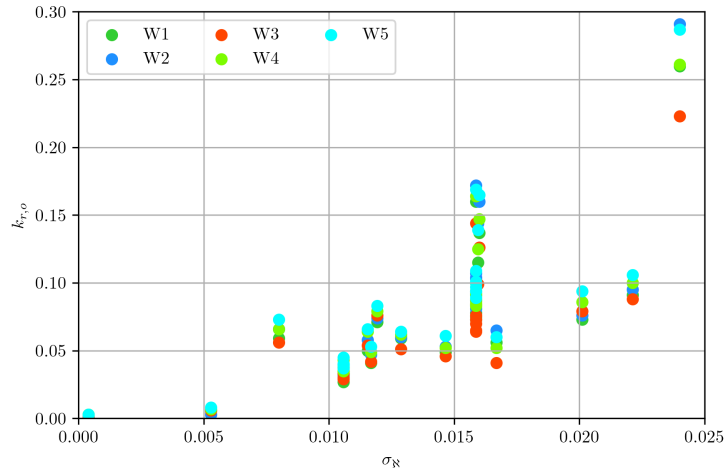


Figure 8: Scatterplots of  $k_{r,o}$  versus  $\sigma_N$  colored wave cases.

240 *3.4. Performance of the standard friction parameterization in high roughness environment*

241 Further tests are carried out on the dissipation-optimized hydraulic roughness to assess  
242 the limitations of the standard friction parameterization given by Equation 11. Once the  
243 optimized hydraulic roughness  $k_{r,o}$  has been obtained for each seabed and each wave run,  
244 a series of tests is performed comparing the agreement between the measured  $H_{rms}$  profile  
245 and the modeled  $H_{rms}$  computed from the energy flux balance (Eq. 4) including breaking  
246 dissipation given by Equation 8 and frictional dissipation from Equation 10 based on  $k_{r,o}$ .  
247 We first test the agreement between experiments and model against the  $A_o/\sigma_N$  ratio, in order  
248 to explore the potential degradation of the predictive capacities for large relative roughness  
249 height. The best results are obtained for  $A_o/\sigma_N > 2.5$ , with NRMSE lower than 4 % and  
250 WI higher than 0.995. A degradation of the performance is observed for smaller values of  
251  $A_o/\sigma_N$  but the accuracy remains correct, with median NRMSE and WI of about 5 % and  
252 0.99, respectively. The model prediction capacity does not further degrade for the lowest  
253 values of  $A_o/\sigma_N$ .

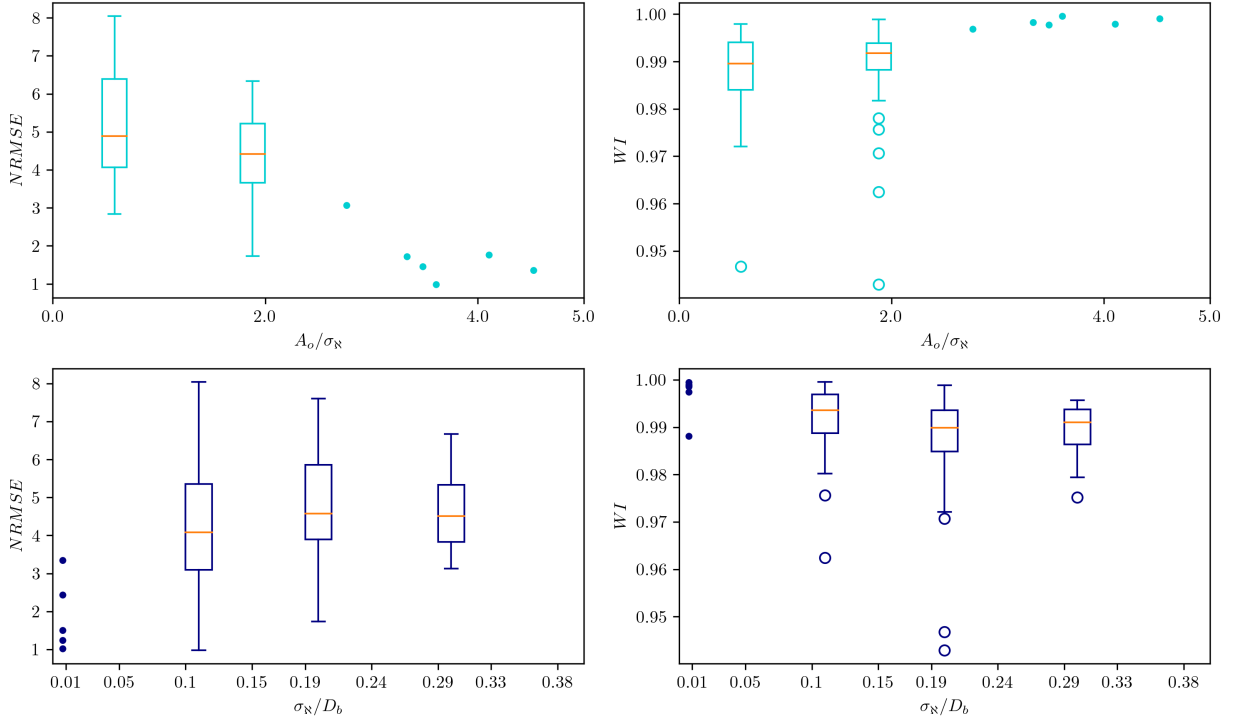


Figure 9: Plot and binned boxplots of NRMSE and WI versus  $A_o/\sigma_N$  for the following intervals :  $[0.30,0.80,1.30,2.00]$  (in cyan) and  $\sigma_N/D_b$  for the following intervals :  $[0.00,0.30,0.70]$  (in blue). The central red line is the median, the edges of the box are the 25 and 75-th percentiles, the whiskers extends to 1.5 of the interquartile range while the outliers are plotted individually as circles. Single points are individual datapoints.

254 A second series of tests is performed on the relative roughness submergence ratio. This  
255 being variable across the profile, the breaking point value  $\sigma_N/D_b$  is used, where  $D_b$  is the  
256 breaking depth obtained at  $H_{rms}/D_b \approx 0.7$  (Symonds et al., 1995). The first observation is  
257 that, similarly to the previous results, best wave model prediction performances are observed  
258 at low submergence ratio ( $\sigma_N/D_b < 0.1$ ) with NRMSE and WI remaining mostly lower than  
259 4 % and higher than 0.990, respectively. A degradation of the accuracy is observed for  
260  $\sigma_N/D_b > 0.1$  but the performance remains rather stable and does not strongly drop for high  
261 submergence ratio. Most of the poor-accuracy outliers are again related to the W3 wave run,  
262 without any straightforward explanation.

### 263 3.5. Multi-varied hydraulic roughness model

Based on the previous observations, a multi-varied analysis is carried out to connect the optimized hydraulic roughness  $k_{r,o}$  to the topography metrics and then provide a pre-

dictive model for hydraulic roughness. The most important controlling factor for frictional dissipation is the seabed elevation standard deviation, as expected from several decades of observations (e.g. Swart (1974); Nielsen (1992); Madsen (1995); Lowe et al. (2005a); Sous et al. (2023)), among others. A linear dependency is first assumed here, following Lowe et al. (2005a); Sous et al. (2023). The effect of skewness, identified for instance by comparing cases QC6 and BK2 in Figure 7, is observed to be non-linear, maybe related to regime changes of the boundary layer (Flack et al., 2020). Over the studied range of skewness, the best fit has been obtained using a tanh-based relationship. Power-law formulations, such as those used in steady boundary layer studies Flack and Schultz (2010); Flack et al. (2020), do not provide clear improvement. The effects of directionality and effective slope are both taken into account using a simple linear relationship. Finally, we propose the following hydraulic roughness model:

$$k_{r,m} = 4\sigma_{\mathbb{N}}(1 + \beta_s + \beta_d + \beta_e) \quad (18)$$

where respectively  $\beta_s$ ,  $\beta_d$  and  $\beta_e$  are the adjusted parameterizations for respectively  $Sk_{\mathbb{N}}$ ,  $\Delta_{\mathbb{N}}$  and  $ES_{\mathbb{N},x}$  given by:

$$\beta_s = -0.3(\tanh(Sk_{\mathbb{N}} - 0.8) - 1) \quad (19)$$

$$\beta_d = \Delta_{\mathbb{N}} \quad (20)$$

$$\beta_e = 1.1ES_{\mathbb{N},x} \quad (21)$$

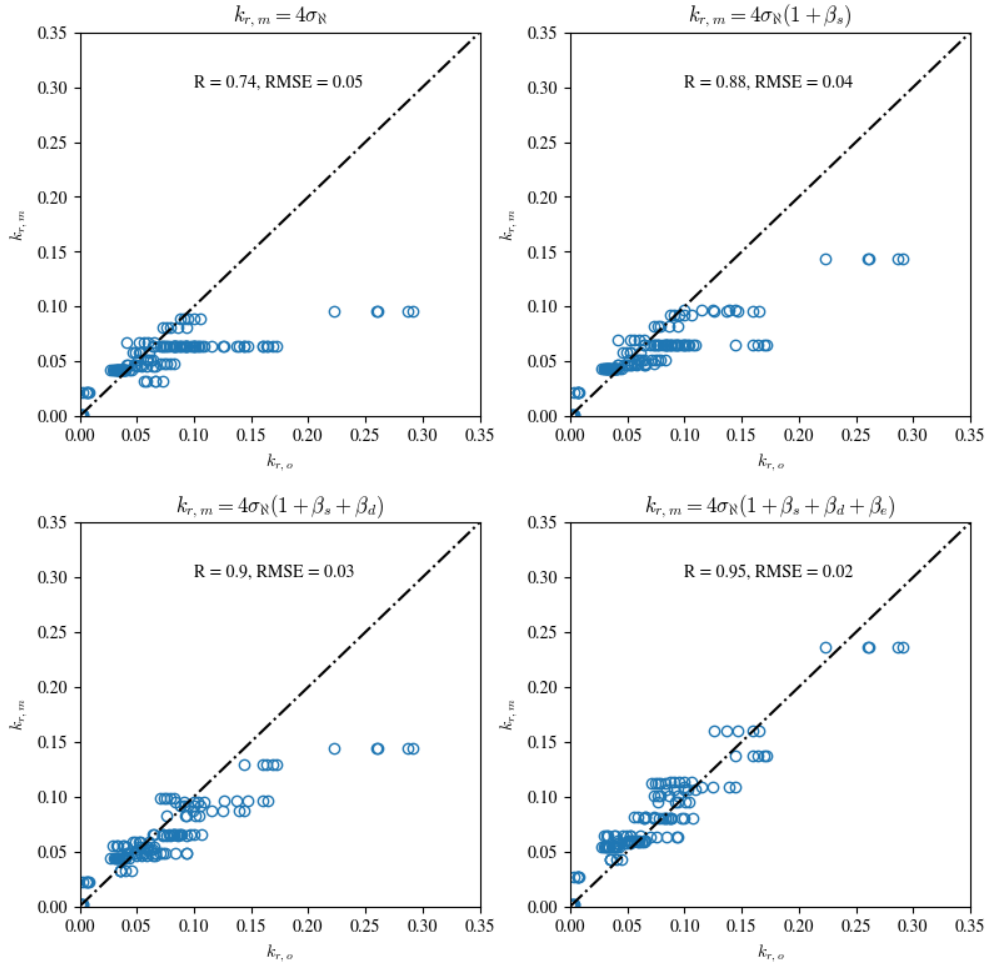


Figure 10: Plots of multi-variate modelled  $k_{r,m}$ . Values for  $k_{r,m}$  and  $k_{r,o}$  are given in Appendix B.

264 The experimental wave friction factor  $f_w$  is plotted against the  $A_o/k_{r,m}$  to assess the  
 265 improvement brought by the consideration of additional topography statistical metrics in the  
 266 definition of the hydraulic roughness. The results displayed in Figure 11 show an overall  
 267 better collapse of the data than for the mono-varied model from Figure 7. The agreement  
 268 with the friction model is also clearly improved, with significantly decreased NRMSE and  
 269 increased WI values.

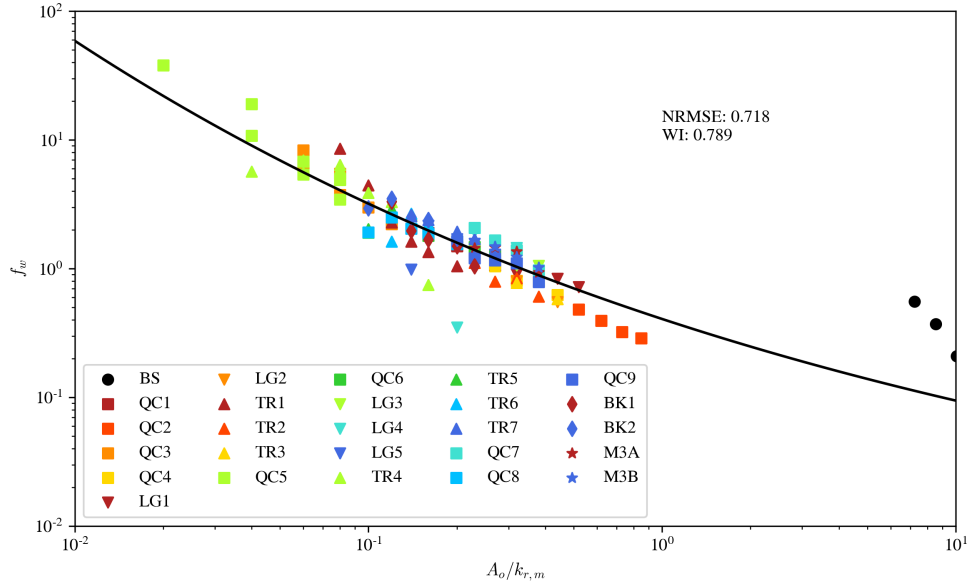


Figure 11: Bin-averaged values of measured  $f_w$  plotted as a function of  $A_o/k_{r,m}$  colored by seabed layouts. The solid black line represents Madsen’s prediction Madsen (1995) (Equation 11) using Sous et al’s parameterization Sous et al. (2023).

#### 270 4. Discussion

271 The present study aimed to compare novel laboratory data on wave attenuation by fric-  
 272 tional dissipation over rough seabeds with standard wave friction models. The first observa-  
 273 tion is that the linear wave model, including classical breaking and friction parameterization,  
 274 shows satisfactory predictive capability even for the larger roughness layout studied here,  
 275 related to small orbital amplitude to roughness ratio and large relative submergence ratio. A  
 276 slight degradation is observed when increasing roughness height, but the performance remains  
 277 overall stable. These observations tend to support the use of traditional wave boundary layer  
 278 theory for parameterizing friction, even when the actual roughness height exceeds the initial  
 279 framework assumptions Madsen (1995). This indicates furthermore that the prediction errors  
 280 associated with standard wave models would not be able to fully explain the difference in  
 281 wave friction factors observed between sites (Gon et al., 2020; Sous et al., 2023).

282 The observed variability of  $f_w$  is certainly largely controlled by the dynamics of the inter-  
 283 actions between coherent structures and topography. One may for instance expect that the  
 284 larger space between roughness elements will allow the development of larger coherent struc-  
 285 tures, which can explain the observed relationship between topography skewness and friction  
 286 factor. However, the 3D structure of most layouts combined with the oscillating forcing and

287 the breaking-induced turbulence should strongly complicate the coherent vortex patterns.  
288 Current instrumentation does not allow us to detail these interactions, and developing new  
289 measurement methods coupled with 3D Navier-Stokes modelling will be a required step to  
290 enhance the understanding of the internal flow dynamics.

291 Based on an optimisation of the modeled cross-shore wave height evolution against experi-  
292 mental data, the hydraulic roughness is estimated for each type of roughness and connected to  
293 a series of topographical metrics to provide a multi-varied model for hydraulic roughness. For  
294 the sake of interpretability, the statistical model proposed here assumes simple relationships  
295 between topography metrics and hydraulic roughness. While this approach provides useful  
296 new insights into the hydraulic roughness for wave studies, more complex dependencies may  
297 likely be involved. A variety of correlation formulations have been proposed in the case of  
298 canonical boundary layer cases (Flack and Schultz, 2010; Barros et al., 2018; Forooghi et al.,  
299 2017; Flack et al., 2020) but their direct application to the present wave friction study have  
300 not provided improved performance. The further improvement of the  $k_r$  model will require a  
301 much denser experimental plan, combining laboratory data on more realistic terrain together  
302 with real-scale field data at the required resolution, with regard to both hydrodynamic and  
303 topographical aspects. Here, experimental constraints fixed the seabed slope value at 1/20,  
304 which is considered as very steep in regard to most studied sites where it does not go be-  
305 low 1/30 (Poate et al., 2018), except for the Banneg island rocky cliff sites documented by  
306 Dodet et al. (2018). It is difficult to estimate *a priori* the effect of such a slope on friction  
307 processes without having access to fine documentation of turbulent processes close to the  
308 seabed. Further experiments will have to be carried out on flat seabed and gentle slopes to  
309 identify and discard any potential slope effect. Furthermore, the peak enhancement factor  
310 was kept constant at 7 for wave-maker control constraints. The role of spectrum shape on  
311 dissipative processes will merit further exploration, although there is generally good consis-  
312 tency between full spectral approaches (Madsen, 1995; Sous et al., 2023; Lowe et al., 2005a)  
313 and frequency-integrated approaches (Gon et al., 2020) in terms of friction factor.

314 The roughness metrics assessed in the present paper have been selected for their simplic-  
315 ity, making them generalizable for other laboratory and in-situ configurations. However, it  
316 is worthwhile mentioning that a number of other metrics have been proposed (Chung et al.,  
317 2021), with potential complex interdependencies. The role of roughness directionality has  
318 been accounted for using a simple metric and a linear parameterization in the  $k_r$  model, pro-  
319 viding a clear improvement when compared to the model which ignores directionality. How-  
320 ever, two cases with partial streamwise alignments (LG4 and LG5) are still poorly described  
321 by the model, with a lower friction factor than predicted. Further improvements are needed,  
322 both in metric definition and parameterization in the  $k_r$  model to improve the description  
323 of directionality in such configurations. The effects of higher-order statistical moments, such  
324 as kurtosis, could not have been explored independently by the present experiments due to



325 a strong correlation with the skewness. The spatial heterogeneity of roughness appeared to  
 326 play a role by reducing the friction factor for increasing heterogeneity. This can be observed  
 327 by comparing cases QC4 and M3A in Figure 7, the former/latter showing regular/irregular  
 328 roughness height distribution, respectively, for the same  $\sigma_N$ . The regular distribution (QC4)  
 329 shows generally higher friction factors than the irregular one (M3A). However, no unequivocal  
 330 metric of spatial heterogeneity has been found when applied to the present seabed layout, but  
 331 its effect is likely accounted for, at least partly, by the metrics selected for the multi-varied  
 332 hydraulic roughness model. It has also been hypothesized that different spatial clustering  
 333 scales may have led to stronger impacts on frictional dissipation (Sarakinos and Busse, 2019;  
 334 Chung et al., 2021). The effect of roughness clustering appeared to be weak for the tested  
 335 configurations. This is highlighted by the comparison of M3A and M3B layouts in Figure  
 336 7, which show very close values of  $f_w$  despite a widely different spatial arrangement, M3B  
 337 being much more clustered than M3A for similar other properties.

338 The comparison of the proposed  $k_r$  model with field estimates is not straightforward,  
 339 mainly due to the lack of documentation of the fine topographical statistics of the studied field  
 340 sites. A first view is given in Figure 12 which depicts the wave friction factor against  $A_o/k_r$   
 341 for the present data (averaged over wave cases) and a selected set of field observations from  
 342 Lowe et al. (2005a); Lentz et al. (2016); Poate et al. (2018); Gon et al. (2020). For the latter  
 343 field data points, the seabed standard elevations have been provided by the authors while  
 344 we attribute arbitrary, but a priori realistic, values for skewness, directionality and effective  
 345 slope taken at 0.5, 0 and 0.15, respectively. These taken values are based on a comparative  
 346 study of 9 rocky and coral sites (Sous et al., 2024). The overall agreement is satisfactory  
 347 both in terms of the trend in  $A_o/k_r$  dependency and order of magnitude, indicating that both  
 348 the laboratory data and the statistical  $k_r$  model proposed here can be used as guidelines for  
 349 predictions of wave frictional dissipation. Discrepancies between the observations and the  
 350 model remain, which calls for further adjustments of the model and emphasizes the need  
 351 for further laboratory experiments to explore more realistic seabed structures, together with  
 352 site-comparative in-situ surveys allowing to identify the differentiating metrics between field  
 353 sites. The values obtained here remain sensitive to the choice of topographical parameters.  
 354 The comprehensive testing of the present parameterization requires, for each test site, a  
 355 combined survey of hydrodynamics and fine topography, which remains very rare in the  
 356 existing published data but should be planned in further studies, where possible. Studies  
 357 carried out by Simons et al. (2000); Dixen et al. (2008); Sumer and Fuhrman (2020) propose  
 358 that the friction factor can be modelled proportionally to  $\left(\frac{A_o}{k_r}\right)^{-1}$  for small values of  $\frac{A_o}{k_r}$ .  
 359 Attempt to fit this model to our data points is pictured Figure 12 with an optimized value  
 360 of 0.3.

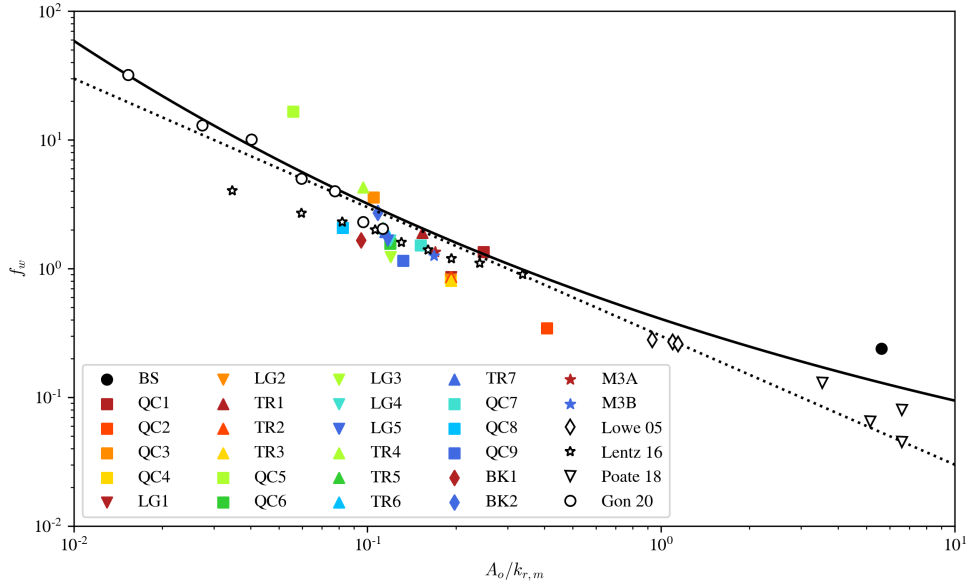


Figure 12: Seabed layout averaged values of measured  $f_w$  plotted as a function of  $A_o/k_{r,m}$  colored by seabed layouts. Empty-filled black symbols represent field data from previous studies (Lowe et al. (2005a); Lentz et al. (2016); Poate et al. (2018); Gon et al. (2020)) plotted against  $A_o/k_{r,m}$  using typical values for  $Sk_N = 0.5, \Delta = 0$  and  $ES_{N,x} = 0.15$ . The solid black line represents Madsen’s prediction Madsen (1995) (Equation 11) using Sous et al.’s parameterization Sous et al. (2023). The dotted black line represents the  $0.3(A_o/k_{r,m})^{-1}$  prediction of (Dixen et al., 2008).

361 Note finally that the definition of the bathymetry remains an important and challenging  
362 issue when attempting to build unified parameterization from observations at various sites.  
363 The bathymetry is generally reconstructed from topographical surveys using low-pass filters  
364 or rolling averaging techniques. Using different approaches will lead to different definitions of  
365 depth, which remains a key parameter of the wave action balance. The present study, based  
366 on the reference smooth layout, should provide comparable depth referential to the moving-  
367 window 10-th percentile approach used by Sous et al. (2023) but may lead to differences for  
368  $f_w$  estimates inferred with other frameworks.

## 369 5. Conclusion

370 Bottom friction caused by the boundary layer is known to be a dominant factor in coastal  
371 areas with complex bathymetry. Conventional integrated approach models for small rough-  
372 ness have been developed to estimate the friction coefficient and remain in use within their  
373 range of validity. The aim of this study was to produce a database of wave friction in a  
374 controlled environment to study the impact of roughness structure on frictional dissipation.

375 The presence of roughness elements impeding the flow induces a general offshore shift of  
376 the inflexion point in the cross-shore profile of root mean square wave height. Optimization  
377 of the friction model using hydraulic roughness shows that despite the wide range of wave-  
378 induced conditions in the surf zone, the model predictions remain robust, although degraded  
379 for weakly submerged flows. Wave attenuation was shown to be not only strongly controlled  
380 by the standard deviation of the bottom elevation but also by other bottom characteristics,  
381 which were identified as the frontal porosity via the effective slope and skewness, and as the  
382 arrangement of roughness structures via the directionality. As the effective slope increases,  
383 the coefficient of friction increases. The more the arrangements form bars in the direction  
384 of wave propagation (longitudinal), the more the coefficient decreases and conversely for the  
385 case of perpendicular bars (transverse). With a multi-variate regression, a simple relationship  
386 connecting these metrics to hydraulic roughness was established and significantly improves  
387 the results of the friction model. The comparison of the hydraulic roughness model with the  
388 results of previous studies suggests that further analysis is needed to explore the effects of  
389 the roughness structure metrics on frictional dissipation and to improve this model before  
390 confrontation with relevant field measurements and implementation in spectral models.

### 391 **Acknowledgements**

392 The authors acknowledge the assistance of V. Rey in providing a scientific contribution  
393 to reflection component processing.

394 Appendix A: Table of seabed layout parameters

Seabed layout name	Block height	$\sigma_N$	$Sk_N$	$\Delta_N$	$ES_{N,x}$
<i>RF</i>	0.000	0.000	0.000	0.000	0.000
<i>BS</i>	0.001	0.000	1.626	0.000	123.647
<i>QC1</i>	0.016	0.008	0.000	0.000	119.792
<i>QC2</i>	0.016	0.005	2.268	0.000	29.948
<i>QC3</i>	0.032	0.016	0.000	0.000	114.583
<i>QC4</i>	0.032	0.011	2.268	0.000	28.646
<i>QC5</i>	0.048	0.024	0.000	0.000	109.375
<i>QC6</i>	0.048	0.016	2.268	0.000	27.344
<i>QC7</i>	0.048	0.013	3.144	0.000	15.625
<i>QC8</i>	0.064	0.022	2.088	0.000	27.778
<i>QC9</i>	0.064	0.015	3.881	0.000	10.417
<i>LG1</i>	0.032	0.011	2.268	-0.268	28.646
<i>LG2</i>	0.032	0.011	2.268	0.000	28.646
<i>LG3</i>	0.048	0.017	2.068	-0.224	7.813
<i>LG4</i>	0.048	0.016	2.268	-0.268	27.344
<i>LG5</i>	0.048	0.016	2.268	0.000	27.344
<i>TR1</i>	0.032	0.012	1.789	1.000	31.250
<i>TR2</i>	0.032	0.011	2.268	0.268	26.042
<i>TR3</i>	0.032	0.011	2.268	0.000	28.646
<i>TR4</i>	0.048	0.016	2.268	1.000	15.625
<i>TR5</i>	0.048	0.016	2.268	0.464	21.484
<i>TR6</i>	0.048	0.016	2.268	0.268	23.438
<i>TR7</i>	0.048	0.016	2.268	0.000	27.344
<i>BK1</i>	0.064	0.020	2.475	-0.225	52.083
<i>BK2</i>	0.032	0.016	-0.167	-0.153	39.062
<i>M3A</i>	0.016 & 0.032 & 0.048	0.012	2.910	0.000	16.927
<i>M3B</i>	0.016 & 0.032 & 0.048	0.012	2.955	0.023	11.393

Table .3: Seabed layout metrics.

<b>Wave run</b>	<b>W1</b>	<b>W2</b>	<b>W3</b>	<b>W4</b>	<b>W5</b>	
<i>Seabed layout</i>						
<i>name</i>			$k_{r,o}$ [m]			$k_{r,m}$ [m]
<i>BS</i>	0.002	0.001	0.000	0.003	0.003	0.002
<i>QC1</i>	0.059	0.066	0.056	0.066	0.073	0.082
<i>QC2</i>	0.006	0.003	0.006	0.007	0.008	0.027
<i>QC3</i>	0.137	0.160	0.126	0.147	0.165	0.160
<i>QC4</i>	0.034	0.039	0.037	0.043	0.040	0.054
<i>QC5</i>	0.260	0.291	0.223	0.261	0.287	0.236
<i>QC6</i>	0.073	0.083	0.064	0.083	0.089	0.081
<i>QC7</i>	0.059	0.060	0.051	0.062	0.064	0.059
<i>QC8</i>	0.091	0.095	0.088	0.100	0.106	0.114
<i>QC9</i>	0.049	0.053	0.046	0.052	0.061	0.064
<i>LG1</i>	0.035	0.040	0.035	0.035	0.045	0.043
<i>LG2</i>	0.033	0.032	0.033	0.038	0.037	0.054
<i>LG3</i>	0.056	0.065	0.041	0.052	0.060	0.064
<i>LG4</i>	0.075	0.093	0.070	0.084	0.094	0.059
<i>LG5</i>	0.078	0.081	0.065	0.085	0.097	0.081
<i>TR1</i>	0.071	0.074	0.076	0.079	0.083	0.112
<i>TR2</i>	0.033	0.032	0.029	0.038	0.039	0.065
<i>TR3</i>	0.027	0.031	0.030	0.038	0.040	0.054
<i>TR4</i>	0.160	0.172	0.144	0.164	0.169	0.138
<i>TR5</i>	0.091	0.103	0.084	0.100	0.109	0.107
<i>TR6</i>	0.094	0.104	0.076	0.092	0.101	0.096
<i>TR7</i>	0.087	0.107	0.073	0.088	0.100	0.081
<i>BK1</i>	0.073	0.076	0.079	0.086	0.094	0.101
<i>BK2</i>	0.115	0.144	0.099	0.125	0.139	0.109
<i>M3A</i>	0.050	0.058	0.054	0.064	0.066	0.060
<i>M3B</i>	0.041	0.047	0.042	0.049	0.053	0.058

Table .4: Optimized  $k_{r,o}$  and MVR modelled  $k_{r,m}$  values.

396 **Appendix C: Non-linear energy transfers**

397 The assumption is made that non-linear energy transfers can be neglected in our SW-  
 398 frequency-integrated energy flux balance. An estimation of the so-called  $S_{nl}$  term has been  
 399 performed on a smooth representative case, using RF layout and W2 wave conditions. As  
 400 the relative contribution of non-linear transfers to the energy balance is expected to decrease  
 401 with increasing rough due to a growing importance of frictional dissipation, the smooth bed  
 402 is considered as the worst case scenario in terms on non-linear transfers.

403 The method used here is to compare the measured SW-integrated flux gradient with  $S_{nl}$ .  
 404 The former is estimated between successive sensor pairs along the beach profile using Equa-  
 405 tions 4, 5 and 6. The latter is the spatially-averaged and SW-frequency-averaged triad source  
 406 term  $\langle S_{nl} \rangle$ . First, at each sensor, the spectral nonlinear transfers of energy between triads  
 407 of frequencies  $S_{nl,j}$  ( $j$  denotes the frequency component) are modelled with the Boussinesq  
 408 theory of Herbers et al. (2000) over the full wave spectrum, assuming that the wave field is  
 409 weakly nonlinear, weakly dispersive, and that these effects are of similar order (Herbers and  
 410 Burton, 1997; Martins et al., 2021):

$$411 \quad S_{nl,j} = \rho g \frac{3\pi f}{D} \sum_{m=-\infty}^{m=\infty} \Im \{ B_{m,j-m}^* \} \quad (.1)$$

412 where  $B$  is the bispectrum of the free surface elevation computed after Kim and Powers  
 413 (1979),  $\Im\{\cdot\}$  refers to the imaginary part and  $*$  denotes the complex conjugate.  $S_{nl,j}$  is then  
 414 frequency-integrated over the SW band. Finally,  $\langle S_{nl} \rangle$  approximated as the spatial average  
 415 of its values at the adjacent sensors using the method of Sous et al. (2023).

416 Figure .13 depicts the results of the  $S_{nl}$  analysis for the REF/W2 experiment. Excepted an  
 417 adjustment phase close to the wave maker, the estimated flux gradient remains negative with  
 418 a maximum magnitude reached within the surf zone, in agreement with the observations  
 419 performed on the SW profile.  $\langle S_{nl} \rangle$  remains very weak portion of the wave energy flux  
 420 gradient, with a local peak contribution lower than 11% of the wave energy balance but  
 421 generally lower than 1 %. This observation confirms the validity of a negligible influence of  
 422 non-linear energy transfers in the present experimental configuration.

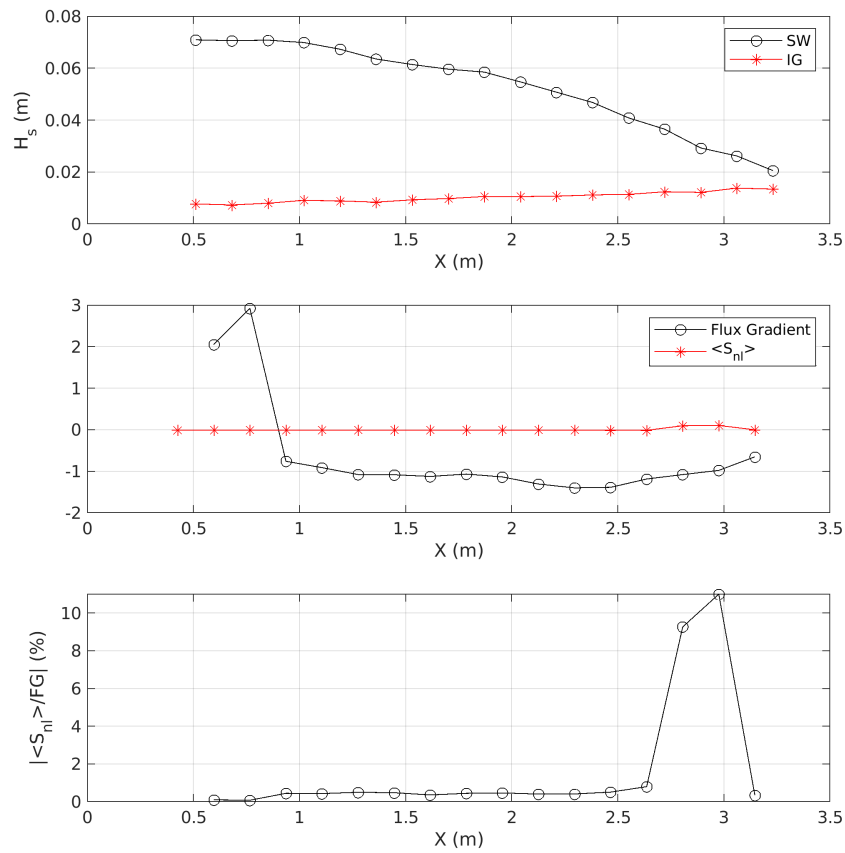


Figure .13: Non-linear transfers for the REF/W2 experiment. Top: compared wave height profiles in the SW (black circles) and IF (red stars) bands. Middle: compared cross-shore profiles of measured wave energy flux gradient and spatially-averaged and SW-frequency-averaged triad source term  $\langle S_{nl} \rangle$ . Bottom: ratio between  $\langle S_{nl} \rangle$  and the wave energy flux gradient.

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