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Abstract: The performance of three spectral wave models based on different types of governing equations, REF/DIF S, MIKE 21 BW module, and SWAN, was compared by using four laboratory or field experimental data sets. The comparison was focused on accurate prediction of measured wave heights. Characteristics of the three wave models were discussed and their overall predictability of the measured data was evaluated by calculating mean absolute relative errors of wave height. All the numerical models simulated fairly well shoaling and breaking of waves propagating on a plane sloping beach, but the model accuracy was somewhat degenerated in simulating waves propagating over a barred beach. Among the three models, MIKE 21 BW was the most insensitive to the bathymetric change. Combined refraction-diffraction over a shoal without breaking was quite well simulated by the models, especially by REF/DIF S and MIKE 21 BW. When waves break over the shoal, however, all the models failed to reproduce the wave field behind the shoal. The agreement with data in simulating wave diffraction around breakwater was remarkably good for MIKE 21 BW, but poor for other two models. Except the last simulation, the mean absolute relative errors of wave height from the three models ranged between 3 and 27%.

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**Performance Comparison of Spectral Wave Models Based on  
Different Governing Equations Including Wave Breaking**

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## ABSTRACT

The performance of three spectral wave models based on different types of governing equations, REF/DIF S, MIKE 21 BW module, and SWAN, was compared by using four laboratory or field experimental data sets. The comparison was focused on accurate prediction of measured wave heights. Characteristics of the three wave models were discussed and their overall predictability of the measured data was evaluated by calculating mean absolute relative errors of wave height. All the numerical models simulated fairly well shoaling and breaking of waves propagating on a plane sloping beach, but the model accuracy was somewhat degenerated in simulating waves propagating over a barred beach. Among the three models, MIKE 21 BW was the most insensitive to the bathymetric change. Combined refraction-diffraction over a shoal without breaking was quite well simulated by the models, especially by REF/DIF S and MIKE 21 BW. When waves break over the shoal, however, all the models failed to reproduce the wave field behind the shoal. The agreement with data in simulating wave diffraction around breakwater was remarkably good for MIKE 21 BW, but poor for other two models. Except the last simulation, the mean absolute relative errors of wave height from the three models ranged between 3 and 27%.

**Keywords:** spectral wave model, model comparison, irregular waves, wave breaking, refraction-diffraction

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6 **1. Introduction**  
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11 Accurate modeling of random wave propagation over an uneven bathymetry is  
12 an essential prerequisite for design of coastal structures and prediction of  
13 nearshore currents and sediment transport. During the last few decades, a number  
14 of spectral wave models have been developed to improve the modeling accuracy  
15 and a great progress has been made until recently. Most spectral wave  
16 transformation models are classified into three categories depending on the  
17 governing equations that are employed: the mild slope equation, Boussinesq  
18 equation, and the wave action balance equation. Although the theoretical  
19 background and target range of application of these governing equations are much  
20 different, many wave models based on these equations have been widely applied  
21 to resolving practical problems of wave propagation in the coastal zone.  
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36 Several researches have been carried out to compare the performance of  
37 different wave models. For numerical models of the mild slope equation using  
38 finite difference scheme, a comparative study has been carried out by Maa et al.  
39 (2000). In their study, the effects of shoaling, refraction, and diffraction of six  
40 regular wave transformation models were analyzed, while energy dissipation due  
41 to wave breaking was not considered. Lin and Demirbilek (2005) compared the  
42 overall performance of two spectral wave models solving the wave action balance  
43 equation with an idealized inlet data. However, to the knowledge of the authors,  
44 there is no study comparing simulation results of the spectral wave models based  
45 on different governing equations including the effects of wave breaking, which is  
46 the main interest of the present study.  
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Three numerical wave models, REF/DIF S (Kirby and Özkan, 1994), MIKE 21 BW module (DHI Software, 2004), and SWAN (The SWAN team, 2007), were selected for the comparison, which are the most widely used wave models in the coastal engineering community. The performance of these models was examined by comparing their calculation with four well-documented data sets obtained from laboratory experiments or field measurements (Vincent and Briggs, 1989; Mase and Kirby, 1992; Briggs et al., 1995; Birkemeier et al. 1997). Since most of the data sets provide only wave height data, the major focus of the comparison was placed on this physical quantity.

**2. Brief Description of the Spectral Wave Models**

2.1 REF/DIF S

REF/DIF S is a weakly nonlinear combined refraction and diffraction model developed by Kirby and Özkan (1994). By solving the parabolic form of the mild slope equation developed by Kirby (1986), this model can simulate the effects of shoaling, refraction, diffraction, and energy dissipation, while wave reflection and wave-wave interaction are neglected. In REF/DIF S, individual wave components of a given frequency and direction are simultaneously propagated through the computing domain and the statistical wave parameters are calculated after each forward spatial step. Accurate results are restricted to waves propagating on a mild bottom slope within 45° from the mean wave direction.

2.2 MIKE 21 BW

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6 MIKE 21 BW is composed of two wave modules (1DH and 2DH) based on  
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8 the enhanced Boussinesq equations (Madsen et al., 1991; Madsen and Sørensen,  
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10 1992), which can simulate the propagation of directional waves within the depth  
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12 to deepwater-wavelength ratio of  $h/L_0 \leq 0.5$ . MIKE 21 BW can simulate the  
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14 combined effects of almost all wave phenomena occurring in nearshore regions,  
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16 including wave grouping, surf-beats, and triad wave interactions (DHI Software,  
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18 2004). The wave model generates time series of wave trains by the internal wave  
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20 generation technique and uses the sponge layers to absorb wave energy at the  
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22 model boundaries where required. In this study, the 2DH (two horizontal  
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24 dimensions) module was used.  
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### 31 2.3 SWAN 32 33 34 35

36 SWAN is a phase-averaged wave model that computes random, short-crested  
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38 wind-generated waves in coastal regions and inland waters (The SWAN team,  
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40 2007). The model is based on the wave action balance equation with various  
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42 sources and sinks that accounts for generation, dissipation, and wave-wave  
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44 interactions of waves in deep and shallow waters (Booij et al., 1999). In SWAN,  
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46 wave diffraction, which is not explained by the original wave action balance  
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48 equation, is modeled by a phase-decoupled refraction-diffraction approximation  
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51 (Holthuijsen et al., 2003). This enables its application to the simulation of wave  
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53 transformation in coastal areas where wave reflection and diffraction are  
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55 significant, such as wave field around coastal structures. In this study SWAN  
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6 version 40.51 was used.  
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8 In Table 1, the main features of the above three spectral wave models are  
9 summarized.  
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### 14 **3. Comparison of the Numerical Simulation Results**

#### 15 16 17 18 19 20 3.1 Shoaling and breaking over constant slope 21

##### 22 23 24 3.1.1 Experimental Data 25

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Mase and Kirby (1992) conducted experiments in a wave flume of 47 cm water depth. Unidirectional wave trains of Pierson-Moskowitz spectrum were mechanically generated and propagated over a 1:20 slope beach. Figure 1 shows the schematic view of the experimental setup. Water surface elevations of two different types of waves were measured at 12 locations along the flume at water depths of 47 to 2.5 cm. In the present study, the numerical simulation was made for the Case 1 of Mase and Kirby (1992). In this test condition, the peak frequency of the wave spectrum was 0.6 Hz and plunging-type wave breaking occurred on the sloping beach.

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6 unidirectional waves (for example,  $\sigma_m = 3$  in REF/DIF S model). For other two  
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8 models, the values of corresponding parameters that control the directional  
9 spreading were adjusted to represent almost equal directional spreading among the  
10 models. In the following simulations, default values were used for all the physical  
11 parameters of each wave model unless their specific values were mentioned.  
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18 The computational domain for wave propagation was  $0 \leq x \leq 11.35$  m,  
19  $0 \leq y \leq 0.4$  m, and the grid spacing was 0.05 m in both  $x$  and  $y$  directions. In  
20 MIKE 21 BW model, a sponge layer of 50 grids was placed both in front of the  
21 wave generation line and behind the shoreline to absorb the wave energy. The  
22 wave spectrum was discretized with 25 frequency bins within the cutoff frequency  
23 of 2.5 Hz and 60 directional bins for REF/DIF S and SWAN models. The numbers  
24 of frequency and directional bins in MIKE 21 BW were designated by the model.  
25 The time step in MIKE 21 BW was 0.01 s, which satisfies the Courant stability  
26 condition. The model was run for the duration of 250 peak wave periods and the  
27 final result was produced using the last 50 waves.  
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### 43 3.1.3 Results

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45 Figure 2 compares the significant wave heights predicted by the three wave  
46 models with the experimental data. On the whole, all the models showed good  
47 agreement with the experimental data. In some detail, REF/DIF S and SWAN  
48 somewhat overpredicted wave heights in the shoaling region, while MIKE 21 BW  
49 predicted slightly smaller wave heights in this region. Within the surf zone,  
50 meanwhile, REF/DIF S and SWAN showed better agreement with the  
51 measurement than MIKE 21 BW. Note that the wave height of MIKE 21 BW is  
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6 non-zero at the shoreline because the model considers the effect of wave setup by  
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8 the moving shoreline scheme implemented in the model. Also, the wave height of  
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10 SWAN at the depth smaller than 5 cm could not be calculated due to the depth  
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12 limitation of the model.  
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## 15 16 17 3.2 Wave diffraction around breakwater 18 19

### 20 21 22 3.2.1 Experimental Data 23

24 Briggs et al. (1995) conducted laboratory experiments of wave diffraction  
25 around a semi-infinite breakwater installed in a wave basin of 35 m wide and 29  
26 m long. As shown in Figure 3, the breakwater was located 8.38 m in front of and  
27 parallel to the wave generator. The breakwater was 10 cm thick, and 18.22 m long,  
28 extending from centerline of the wave generator to the side wall of the wave basin.  
29 Water depth was 46 cm and the breakwater crest was 15 cm high from the still  
30 water level. To minimize reflections between the breakwater and the wave  
31 generator, wave absorber material was piled on the seaward side of the breakwater.  
32 The edge of the wave absorber extended diagonally between the breakwater tip  
33 and the end of the wave generator to minimize interference with the desired  
34 energy. Waves were measured at three radial transects covering 60° sector of the  
35 shadow zone in the lee of the breakwater, at intervals of about 76 cm extending  
36 out from the breakwater tip to the point of three times of wavelength. The wave  
37 measurement locations are shown as solid dots in Figure 3. Among a total of six  
38 different wave conditions, the N2 case ( $H_s = 0.0775$  m,  $T_s = 1.3$  s,  $\gamma = 20$ ,  
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6  $\sigma_m = 10$ ) were selected for the present numerical simulation.  
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### 10 11 3.2.2 Model Setup 12

13 The computational domain was  $0 \leq x \leq 25$  m and  $0 \leq y \leq 27.4$  m with 0.1 m  
14 grid spacing in both coordinates. In MIKE 21 BW model, a sponge layer of 50  
15 grids was placed in front of the wave generation line ( $x = 0$  m), behind the end of  
16 the computational domain ( $x = 25$  m), and at both sides ( $y = 0$  m and  $y = 27.4$  m).  
17 In addition, another sponge layer was placed in the triangular region on the  
18 seaward side of the breakwater shown in Figure 3. In REF/DIF S and SWAN  
19 models, the wave absorber on the seaward side of the breakwater could not be  
20 reproduced. The input spectrum was discretized with 25 frequency components  
21 within the cutoff frequency of 2.5 Hz and 60 directional components. The time  
22 step in MIKE 21 BW was 0.02 s satisfying the Courant stability condition. The  
23 model was run for 400 peak wave periods and the final wave field was obtained  
24 by analyzing the surface elevation during the second half of the run.  
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### 43 3.2.3 Results 44

45 Figure 4 shows the measured and calculated values of the diffraction  
46 coefficient, the ratio of local wave height to the incident wave height, along the  
47 three radial transects. The abscissa of the figure is the radial distance from the  
48 breakwater tip normalized by the incident wavelength. As shown in the figure,  
49 MIKE 21 BW remarkably well predicted the wave diffraction at the three radial  
50 transects. REF/DIF S presented a similar trend to the measurement, but it  
51 underestimated the diffraction coefficient for all the transects. This implies that  
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6 the model allowed less transfer of wave energy behind the breakwater than the  
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8 measurement. The performance of SWAN was good at the 90° transect, but  
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10 showed some disagreement with the measurement for other two transects.

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12 In SWAN, the wave field is smoothed to suppress slight wiggles in geographic  
13 space that may arise during computation of wave diffraction. Numerically, the  
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15 diffraction effect is mainly controlled by adjusting values of the smoothing  
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17 parameter and the number of smoothing steps. During every smoothing step, all  
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19 grid points exchange wave energy with their neighbors at a rate assigned by the  
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21 smoothing parameter. In the present simulation, the number of smoothing steps  
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23 was assigned to be 30, approximately equal to  $1/(3\Delta x^2)$ , following the  
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25 recommendation of the model. For the smoothing parameter, we tested six  
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27 different values between 0 and 0.25 at an interval of 0.05 and found that 0.2  
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29 yielded the best agreement with the measurement. The result of SWAN simulation  
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31 shown in Figure 4 was obtained by assigning the smoothing parameter of 0.2. The  
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33 value of greater than 0.25 was not tried because it may result in too excessive  
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35 smoothing of the wave field.  
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### 45 3.3 Combined refraction and diffraction over a shoal

#### 46 47 48 49 3.3.1 Experimental Data

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51 Vincent and Briggs (1989) made comprehensive measurements of wave  
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53 deformation over an elliptical shoal installed in a wave tank of 35 m wide and 29  
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55 m long. As shown in Figure 5, waves were generated by the spectral wave  
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57 generator and propagated over the shoal. The center of the shoal, whose radius  
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6 was 3.05 m in  $x$  direction and 3.96 m in  $y$  direction, was located at  $x= 6.10$  m and  
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8  $y= 13.7$  m. The water depth was 45.72 cm at the bottom of the tank and 15.24 cm  
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10 at the center of the shoal. Wave elevation data were collected at 9 locations along  
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12 the transect at  $x = 12.2$  m behind the shoal (See Figure 5). Among a total of 17  
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14 experimental conditions, two cases (N4 and B5) shown in Table 2 were selected  
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16 for the present numerical simulation.  
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### 22 3.3.2 Model Setup

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24 The computational domain for wave propagation was  $0 \leq x \leq 25$  m and  
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26  $0 \leq y \leq 27.4$  m with 0.1 m grid spacing in both coordinates. In MIKE 21 BW  
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28 model, a sponge layer of 30 grids was placed in front of the wave generation line  
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30 ( $x = 0$  m), behind the end of the computational domain ( $x = 25$  m), and at both  
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32 sides ( $y = 0$  m and  $y = 27.4$  m) to absorb the wave energy. The input spectrum was  
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34 discretized with 25 frequency components within the cutoff frequency of 2.5 Hz  
35  
36 and 60 directional components in REF/DIF S and SWAN models. The time step in  
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38 MIKE 21 BW was 0.02 s satisfying the Courant stability condition. The model  
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40 was run for 400 peak wave periods and the final wave field was obtained by  
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42 analyzing the surface elevation during the second half of the run.  
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### 50 3.3.3 Results

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52 Figure 6 shows a comparison of the calculated and measured wave heights  
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54 along the transect at  $x = 12.2$  m for Case N4. The ordinate in the figure is the local  
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56 wave height at the transect normalized by the incident wave height. The wave  
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58 heights calculated by REF/DIF S and MIKE 21 BW agreed fairly well with the  
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6 measured heights. In contrast, the result of SWAN showed some difference with  
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8 the experimental data. In Figure 6, the SWAN result without wave diffraction  
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10 (Diff off) was also provided to show the effect of wave diffraction in the model. It  
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12 is clearly seen that wave height increased for all the grid points at the transect  
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14 when wave diffraction was taken into account in the model. The SWAN result  
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16 with wave diffraction shown in Figure 6 was obtained by the smoothing parameter  
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18 value of 0.2, same as in the wave simulation shown in section 3.2. In the present  
19  
20 computation, the value of the smoothing parameter was also changed from 0 to  
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22 0.25 at an interval of 0.05 as in section 3.2, and the value of 0.2 again produced  
23  
24 the best agreement with the experimental data.  
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29 Figure 7 shows a similar comparison made for Case B5. In this experimental  
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31 setup, the incident wave height was much greater than Case N4, so that wave  
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33 breaking occurred over the shoal. As shown in Figure 7, the measured wave  
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35 height was distributed as a concave pattern along the transect, higher waves at  
36  
37 both sides than the center of the transect. However, this trend was poorly  
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39 simulated by all the wave models, which predicted almost the same wave heights  
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41 along the transect. Among the three wave models, the wave heights of REF/DIF S  
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43 were slightly greater than other two models. In SWAN, the effect of wave  
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45 diffraction was not so prominent as in the simulation of Case N4.  
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## 51 3.4 Propagation of obliquely incident waves over a barred beach

### 52 3.4.1 Experimental Data

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56 Comprehensive data of nearshore currents, waves, wind, tide, and bathymetry  
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6 was collected in the barred beach at Duck, North Carolina during the DELILAH  
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8 field measurement from October 1 to 19, 1990. The bottom topography of the  
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10 beach is characterized as the planar mild slope with a bar at approximately 50 m  
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12 seaward from the shoreline. During the field measurement, the bottom bathymetry  
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14 was surveyed every day over the so-called minigrid area that covers about 550 m  
15  
16 in the alongshore direction and 400 m in the cross-shore direction from the  
17  
18 shoreline. Meanwhile, waves were measured at the offshore station of 8 m water  
19  
20 depth, approximately 800 m seaward from the shoreline, and at nine nearshore  
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22 locations along the cross-shore line within the range of 250 m from the shoreline.  
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24 Full details of the field experiment are explained in the report of Birkemeier et al.  
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26 (1997).  
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### 33 3.4.2 Model Setup

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35 Among the extensive field data available, we selected two conditions for the  
36  
37 present simulation as listed in Table 3. The selected test conditions are designated  
38  
39 as Case D1 and D2, respectively. The water depth and wave parameters shown in  
40  
41 Table 3 are the values measured at the offshore station. In the numerical  
42  
43 simulation, the computational domain was constructed to the extent of the  
44  
45 offshore wave station, further offshore of the daily surveyed minigrid area. The  
46  
47 bottom bathymetry outside the minigrid area was created based on the assumption  
48  
49 of a constant bottom slope to the depth of the offshore station. This is justified  
50  
51 because the bathymetric change was insignificant outside the minigrid area as  
52  
53 reported by Birkemeier et al. (1997). As shown in Table 3, the incident wave angle  
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55 at the offshore boundary,  $\theta_0$ , is not perpendicular to the shoreline. Hence, the  
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6 computational domain was further extended in the alongshore direction by  
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8 prolonging the south cross-shore boundary ( $y = 724$  m) to the extent at  $y = 174$  m.  
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10 Figure 8 illustrates bottom contours of thus created computational domain for  
11  
12 Case D1. The coordinates in the figure follow the FRF (Field Research Facility)  
13  
14 system. The nine dotted symbols in the figure indicate the locations of nearshore  
15  
16 wave measurement.  
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20 The computational domain covers  $50 \leq x \leq 914$  m and  $174 \leq y \leq 1274$  m with  
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22 the grid spacing of 4 m in the longshore direction and 2 m in the crossshore  
23  
24 direction. For MIKE 21 BW setup, a sponge layer of 50 grids was placed  
25  
26 beforehand the offshore wave generation line ( $x = 914$  m). The input spectrum  
27  
28 was discretized with 40 frequency components within the cutoff frequency of 0.5  
29  
30 Hz and 60 directional components in REF/DIF S and SWAN models. The time  
31  
32 step in MIKE 21 BW was 0.2 s satisfying the Courant stability condition. The  
33  
34 model was run for 100 peak wave periods and the final wave field was obtained  
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36 by analyzing the surface elevation during the second half of the simulation time.  
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### 42 3.4.3 Results

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45 In Figure 9, the calculated significant wave heights are compared with the  
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47 measurement for Case D1. Also shown in the figure is the beach profile along the  
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49 cross-shore transect at  $y = 984$  m, in the range of covering nine nearshore wave  
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51 measurement locations. Outside the surf zone, the computed wave heights by the  
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53 three models agreed well with the measurement overall. The wave breaking point,  
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55 which is located at the seaward slope of the bar, was also predicted relatively well  
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57 by the three models. SWAN showed the best agreement with the experimental  
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6 data, while other two models predicted more shoreward breaking point than the  
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8 measurement. Meanwhile, apparent differences were found between the  
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10 calculated results and the measurement inside the surf zone. The energy  
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12 dissipation rate over the bar was much lower in the numerical models than the  
13  
14 measurement. Hence, the predicted wave heights at the bar trough ( $x \approx 160$  m)  
15  
16 were about 30~40% higher than the measured wave height. The underprediction  
17  
18 of surf zone wave height in Case D1 was also reported by Chen et al. (2003) who  
19  
20 used the same field data for simulating nearshore waves and longshore current  
21  
22 with a different type of Boussinesq model. Meanwhile, the step-like variation of  
23  
24 wave height due to the barred bathymetry was not clearly captured in MIKE 21  
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26 BW model. Besides, the wave height at the shoreline was non-zero because the  
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28 effect of wave setup was taken into account in the model.  
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34 Comparison of the measured and computed wave heights for Case D2 is  
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36 shown in Figure 10. In this test condition, the incoming wave height at the  
37  
38 offshore boundary is approximately half of Case D1. In addition, the bar trough is  
39  
40 less noticeable than the previous test case. As shown in Figure 10, wave shoaling  
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42 was somewhat overestimated by REF/DIF S and SWAN models. The incipient  
43  
44 wave breaking was anticipated to occur at further shoreward location than the  
45  
46 measurement. Among the three models, SWAN predicted the most seaward  
47  
48 location whereas MIKE 21 BW was opposite to this, which is the same tendency  
49  
50 as in Case D1. Inside the surf zone, the measured wave height decreased  
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52 monotonously without the step-like variation of wave height along the cross-shore  
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54 line. In contrast, the simulation results of REF/DIF S and SWAN showed the step-  
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56 like change of wave height inside the surf zone. In MIKE 21 BW, the predicted  
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6 wave height decreased without the step-like pattern, but the value was much  
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8 higher than the measured height.  
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## 10 11 12 **4. Discussion**

### 13 14 15 16 17 4.1 Qualitative comparison of the model characteristics

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22 As shown in Figures 2, 9 and 10, wave shoaling was well simulated in general  
23  
24 by all the wave models tested in this study. However, the shoaling wave heights  
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26 shown in Figure 10 were slightly higher than the observation, especially for  
27  
28 REF/DIF S and SWAN. In this test condition, it seems that the simulated wave  
29  
30 heights outside the surf zone were also somewhat higher than the observation,  
31  
32 which might result in the disagreement of wave height due to wave shoaling.  
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34 Judging from the simulation results shown in this study, MIKE 21 BW predicts  
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36 the smallest increase of wave height due to shoaling. Other two models give  
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38 similar results for wave shoaling.  
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43 The location of depth-limited wave breaking was also predicted reasonably  
44  
45 well by the three models. Compared to REF/DIF S, SWAN and MIKE 21 BW  
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47 respectively predicted slightly seaward and shoreward point of incipient breaking.  
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49 The three models performed relatively well in predicting the decrease of wave  
50  
51 height due to wave breaking on the constant sloping bottom as shown in Figure 2.  
52  
53 However, the wave energy dissipation rate over the barred beach was much  
54  
55 smaller than the field observational results as shown in Figures 9 and 10. Among  
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57 the three models, surf zone wave height decreased most rapidly in REF/DIF S. In  
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6 contrast, MIKE 21 BW predicted the slowest decrease of wave height inside the  
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8 surf zone. Considering that this model predicted the slowest increase of wave  
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10 height in the shoaling region, MIKE 21 BW seems to be the least sensitive model  
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12 to the bathymetric change among the wave models tested in this study.  
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15 Wave diffraction was remarkably well simulated by MIKE 21 BW model,  
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17 which is the most outstanding advantage of the model against the other two  
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19 models. As shown in Figure 4, the model results almost completely agreed with  
20  
21 the experimental data. The diffraction coefficient of REF/DIF S showed almost  
22  
23 the same transitional pattern as the measurement for all the transects. However,  
24  
25 the model underestimated the magnitude of wave diffraction, especially at the  
26  
27 radial transect that made smaller angle with respect to the breakwater. Based on  
28  
29 this result, it seems that less wave energy is diffracted into the shadow zone  
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31 behind the breakwater than the measurement. This may be due to the parabolic  
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33 approximation used in REF/DIF S, which makes the solution inaccurate as the  
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35 wave direction deviates from the principal direction. SWAN was similar to  
36  
37 REF/DIF S in that its performance becomes worse as the angle between the radial  
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39 transect and the breakwater becomes small. Judging from the result shown in  
40  
41 Figure 4, the ability of SWAN in predicting wave diffraction around the  
42  
43 breakwater is comparable to REF/DIF S. Considering that wave diffraction in  
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45 SWAN is somewhat incompletely implemented by the approximation suggested  
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47 by Holthuijsen et al.(2003), this result is quite satisfactory.  
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54 As shown in Figure 6, the combined refraction and diffraction over the shoal  
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56 under non-breaking condition was fairly well simulated by both REF/DIF S and  
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58 MIKE 21 BW models. In contrast, the simulation result of SWAN without wave  
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6 diffraction showed apparent disagreement with the measured data in the central  
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8 region of the transect. This discrepancy occurs mainly because the location of  
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10 wave focusing would be nearer than the measurement when wave diffraction was  
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12 not taken into account. When wave diffraction was activated, the wave height  
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14 increased over the whole transect, which resulted in disagreement of wave heights  
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16 at both sides as well as the center of the transect. On the whole, SWAN produced  
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18 more smoothed distribution of wave height behind the shoal than the  
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20 measurement.  
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24         Meanwhile, when wave breaking occurs over the shoal, the measured wave  
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26 height behind the shoal was distributed as the concave pattern shown in Figure 7.  
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28 This was not satisfactorily simulated by any of the three models because they do  
29  
30 not consider the strong breaking-generated current that defocuses the wave field  
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32 behind the shoal. Recent researches (Yoon et al., 2004; Choi et al., 2007) have  
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34 shown that the accuracy in simulating waves breaking over the shoal can be  
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36 improved by including the effect of breaking-induced currents in REF/DIF S or  
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38 SWAN models.  
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#### 45 4.2 Quantitative evaluation of the model performance 46 47 48 49

50         In order to quantitatively compare overall performance of the three spectral  
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52 wave models, the mean of absolute relative errors of wave height was calculated  
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54 for all the numerical simulations. The quantity is defined as the percent change of  
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56 the predicted wave height to the measured wave height as in Lin and Demirbilek  
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58 (2005).  
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$$\varepsilon = \frac{1}{N} \sum \frac{|H_s^p - H_s^m|}{H_s^m} \quad (1)$$

where  $\varepsilon$  is the mean of absolute relative errors,  $N$  is the number of experimental data, and  $H_s^p$  and  $H_s^m$  is the predicted and measured wave heights, respectively. The calculated values of  $\varepsilon$  by the three wave models for all the wave simulations in this study are shown in Table 4.

In comparison with the experiment of Mase and Kirby (1992), the mean of absolute relative errors by the three models ranged from 3.2 to 6.7%. Hence, it can be stated that all the models predict fairly well wave shoaling and breaking over a constant slope.

The simulation of wave diffraction around a breakwater showed significantly different results depending on the wave model. The performance of MIKE 21 BW was good as the values of  $\varepsilon$  varied only 3.6 to 12.3% for all the transects. In contrast, other two models showed poor agreement of wave height with measurement, particularly for the transect of smaller angle with the breakwater. The errors of REF/DIF S varied from 11.7% to 53.3% while those of SWAN from 6.7% to 38.2%. Note that the errors in SWAN were smaller than REF/DIF S for all the transects.

Combined refraction and diffraction over the shoal without wave breaking was quite well simulated by the wave models. As shown in Table 4, the mean of absolute relative error was only 3.2% for REF/DIF S and 3.6% for MIKE 21 BW. The corresponding value for SWAN was 7.3%, slightly higher than the other two

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6 models. Meanwhile, when the diffraction effect was not considered in SWAN, the  
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8 error was reduced to 4.8% as indicated in the parenthesis. This was caused by the  
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10 overall increase of wave height behind the shoal by activating wave diffraction as  
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12 shown in Figure 6, which resulted in greater absolute relative errors. On the other  
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14 hand, the errors by the three models slightly increased to the range between 9.2  
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16 and 12.3% when wave breaking occurred over the shoal. The greater errors in this  
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18 test condition are ascribed to the inability of simulating strong breaking-induced  
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20 current that prevent wave diffraction behind the shoal. Meanwhile, the error in  
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22 SWAN was reduced by only 0.2% when wave diffraction was deactivated in the  
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24 model.  
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29 The errors in simulating wave propagation over a barred beach by the three  
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31 models varied in the range of 17.8 to 23.7% for D1 case, whereas 20.1 to 26.7%  
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33 for D2 case. For the two test cases, the values of  $\varepsilon$  were not so different among the  
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35 three models as in the simulation over a constant slope. However, the errors were  
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37 much greater because the predicted wave heights in the range of the barred  
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39 bathymetry deviated much from the measurement as seen in Figures 9 and 10.  
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## 45 **5. Conclusion**

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50 On the whole, the three spectral wave models tested in this study showed good  
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52 performance in predicting the height of waves propagating over a varying  
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54 bathymetry although they are based on intrinsically different types of governing  
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56 equations. The mean absolute relative errors of wave height from the three models  
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58 ranged between 3 and 27% for all the test conditions except for the case of wave  
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6 diffraction around breakwater, for which the most obvious difference was found  
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8 among the numerical models. MIKE 21 BW was overwhelmingly good in  
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10 predicting wave heights at the entire radial transects in the shadow zone behind  
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12 the breakwater. In contrast, the simulation results of REF/DIF S and SWAN were  
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14 reasonably good at the transect perpendicular to the breakwater, but were  
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16 deteriorated at other transects whose angle from the breakwater was smaller.  
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20 The variation of wave height behind a submerged shoal due to combined  
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22 refraction-diffraction over the shoal was fairly well simulated by both REF/DIF S  
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24 and MIKE 21 BW models unless waves break on the shoal. Meanwhile, SWAN  
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26 predicted less focused distribution of wave height along the transect behind the  
27  
28 shoal. Judging from the simulation results of the two different test conditions  
29  
30 including wave diffraction, it can be stated that wave diffraction might be  
31  
32 successfully simulated by REF/DIF S as long as the bottom varies smoothly so as  
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34 not to invoke strong wave reflection. In addition, SWAN seems to produce the  
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36 most smoothed distribution of wave height along the direction perpendicular to  
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38 wave propagation. When waves break on the shoal, on the other hand, the three  
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40 wave models were not able to simulate the concave distribution of wave height  
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42 behind the shoal because none of the models considers the effect of breaking-  
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44 generated current that defocuses the wave field behind the shoal.  
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50 All the numerical models showed relatively good performance in predicting  
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52 wave shoaling and subsequent breaking on a plane sloping beach. However, the  
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54 model accuracy decreased in the simulation of obliquely incident waves over a  
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56 barred beach since the energy dissipation rate inside the surf zone was  
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58 underpredicted by the numerical models. It might be necessary to further  
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6 investigate this feature by using another well-documented field data. Meanwhile,  
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8 among the wave models tested in this study, MIKE 21 BW showed the most  
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10 gradual variation of wave height in the direction of wave propagation, which  
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12 implies the least sensitiveness of the model to the bathymetric change.  
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### 17 **Acknowledgements**

18  
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20  
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### 26 **References**

- 27  
28  
29  
30 Birkemeier, W.A., Donohue, C., Long, C.E., Hathaway, K.K., and BARON, C.F.  
31 (1997). *The 1990 DELILAH Nearshore Experiment: Summary Report. Technical*  
32 *Report CHL-97-24*, U.S. Army Corps of Engineers, Waterways Experiment  
33 Station, Vicksburg, Ms.  
34  
35 Booij, N., Ris, R.C., Holthuijsen, L.H. (1999). "A third-generation wave model  
36 for coastal regions. Part I. model description and validation." *J. Geophys. Res.*,  
37 Vol. 104 No. C4, pp. 7649–7666.  
38  
39 Briggs, M.J., Thomson, E.F., and Vincent, C.L. (1995). "Wave diffraction around  
40 breakwater." *J. Wtrwy., Port, Coast., and Ocean Engrg., ASCE*, Vol. 121, No. 1,  
41 pp. 23-35.  
42  
43 Chen, Q., Kirby, J.T., Dalrymple, R.A., Shi, F., and Thornton, E.B. (2003).  
44 "Boussinesq modeling of longshore currents." *J. Geophys. Res.*, Vol. 108, No. C11,  
45 3362, doi:10.1029/2002JC001308.  
46  
47 Choi, J., Lim, C.-H., Jeon, Y.-J., and Yoon, S. B. (2007). "Numerical simulation of  
48 irregular wave transformation due to wave-induced current." *J. Hydro-environ.*  
49 *Res.*, Vol. 1, pp. 133-142, doi:10.1016/j.jher.2007.08.001  
50  
51 DHI Software. (2004). *MIKE 21 Boussinesq Wave Modules, User Guide*, DHI  
52 Water & Environment, Hørsholm, Denmark.  
53  
54 Holthuijsen, L.H., Herman, A., and Booij, N. (2003). "Phase-decoupled refraction  
55 –diffraction for spectral wave models." *Coast. Engrg.*, Vol. 49, pp. 291–305.  
56  
57 Kirby, J.T. (1986). "Higher-order approximations in the parabolic equation  
58 method for water waves." *J. Geophys. Res.*, Vol. 91, No. C1, pp. 933-952.  
59  
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2  
3  
4  
5  
6 Kirby, J.T. and Özkan, H.T. (1994). *Documentation and user's manual, Combined Refraction/Diffraction Model for Spectral Wave Conditions, REF/DIF S, Version 1.1. CACR Report. No. 94-04*, University of Delaware, Department of Civil Engineering, Center for Applied Coastal Research, Newark, Delaware.
- 7  
8  
9  
10  
11 Lin, L. and Demirbilek, Z. (2005). "Evaluation of two numerical wave models with inlet physical model." *J. Wtrwy., Port, Coast., and Ocean Engrg., ASCE*, Vol. 131, No. 4, pp. 149-161.
- 12  
13  
14  
15 Maa, J.P.-Y., Hsu, T.-W., Tsai, C.-H., and Juang, W.J. (2000). "Comparison of wave refraction and diffraction models." *J. Coast. Res.*, Vol. 16, No. 4, pp. 1073-1082.
- 16  
17  
18  
19 Madsen, P.A. and Sørensen, O.R. (1992). "A new form of the Boussinesq equations with improved linear dispersion characteristics. Part 2. A slowly-varying bathymetry." *Coast. Engrg.*, Vol. 18, pp. 183-204.
- 20  
21  
22  
23 Madsen, P.A., Murray, R., and Sørensen, O.R. (1991). "A new form of the Boussinesq equations with improved linear dispersion characteristics." *Coast. Engrg.*, Vol. 15, pp. 371-388.
- 24  
25  
26  
27 Mase, H. and Kirby, J.T. (1992). "Hybrid frequency-domain KdV equation for random wave transformation." *Proc. 23th Int. Conf. Coast. Engrg. ASCE*, Venice, Italy, pp.474-487.
- 28  
29  
30  
31 The SWAN team. (2007). *SWAN User Manual, SWAN Cycle III Version 40.51AB*. Faculty of Civil Engineering and Geosciences, Delft University of Technology, GA Delft, The Netherlands.
- 32  
33  
34  
35 Vincent, C.L. and Briggs, M.J. (1989). "Refraction-diffraction of irregular waves over a mound." *J. Wtrwy., Port, Coast., and Ocean Engrg., ASCE*, Vol. 115, No. 2, pp. 269-284.
- 36  
37  
38  
39 Yoon, S.B., Cho, Y.-S., and Lee, C. (2004). "Effects of breaking-induced currents on refraction-diffraction of irregular waves over submerged shoal." *Ocean Engrg.*, Vol. 31, pp. 633-652.
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Table 1. Summary of the three spectral wave model capabilities.

	REF/DIF S	MIKE 21 BW	SWAN
Governing equation	Parabolic mild slope equation	Boussinesq type equation	Wave action balance equation
Solution method	Phase resolving	Phase resolving	Phase averaging
Refraction	Yes	Yes	Yes
Shoaling	Yes	Yes	Yes
Diffraction	Yes	Yes	Yes (Approximation)
Wave-current interaction	Yes	Yes	Yes
Wave-wave interaction	No	Yes (Nonlinear)	Yes (Triad + Quadruplet)
Whitecapping	No	No	Yes
Wave breaking	Yes	Yes	Yes
Reflection	No	Yes	Yes (Specular)
Transmission	No	Yes	Yes
Dissipation by bottom friction	Yes	Yes	Yes
Generation by wind input	No	No	Yes

Table 2. Input wave parameters of the selected test cases (Vincent and Briggs, 1989).

Case	$H_s$ (m)	$T_s$ (s)	$\gamma$	$\sigma_m$
N4	0.0254	1.3	20	10
B5	0.1900	1.3	2	30

Table 3. Test conditions of the selected cases of DELILAH experiment.

Case ID	Time & Date	Tide (m)	Depth (m)	$H_s$ (m)	$T_s$ (s)	$\theta_0$ ( $^\circ$ )	$\sigma_m$	$\gamma$
D1	04:00, Oct. 10	-0.29	7.37	1.13	10.7	-34	16	4
D2	04:00, Oct. 06	-0.41	7.80	0.53	12.0	-22	13	6

Table 4. Mean of absolute relative errors (%) of wave height by the three wave models.

Test condition	REF/DIF S	MIKE 21 BW	SWAN
<i>Shoaling/Breaking over a plane slope</i>			
	6.7	5.2	3.2
<i>Diffraction around breakwater</i>			
30° transect	53.3	12.3	38.2
60° transect	30.0	3.6	23.0
90° transect	11.7	6.2	6.7
<i>Refraction-Diffraction over a shoal</i>			
N4 case	3.2	3.6	7.3 (4.8)
B5 case	9.2	12.3	11.8 (11.6)
<i>Inclined propagation over a barred beach</i>			
D1 case	20.4	23.7	17.8
D2 case	20.1	26.7	23.7

### Captions of Figures

1. Sketch of the experimental setup (Mase and Kirby, 1992).
2. Significant wave heights measured from the experiment (Mase and Kirby, 1992) and computed by the three models.
3. Sketch of the experimental setup (Briggs et al., 1995).
4. Diffraction coefficient along the three transects from the experimental data (Briggs et al., 1995) and from the computational results of the three models.
5. Sketch of the experimental setup (Vincent and Briggs, 1989).
6. Normalized wave heights along the transect measured from the experiment (Vincent and Briggs, 1989) and computed by the three models (Case N4).
7. Normalized wave heights along the transect measured from the experiment (Vincent and Briggs, 1989) and computed by the three models (Case B5).
8. Bottom contours of the barred beach for the numerical computation (4:00 AM, on 10 October 1990).
9. Significant wave heights of the DELILAH field measurement and computational results by the three models (Case D1).
10. Significant wave heights of the DELILAH field measurement and computational results by the three models (Case D2).

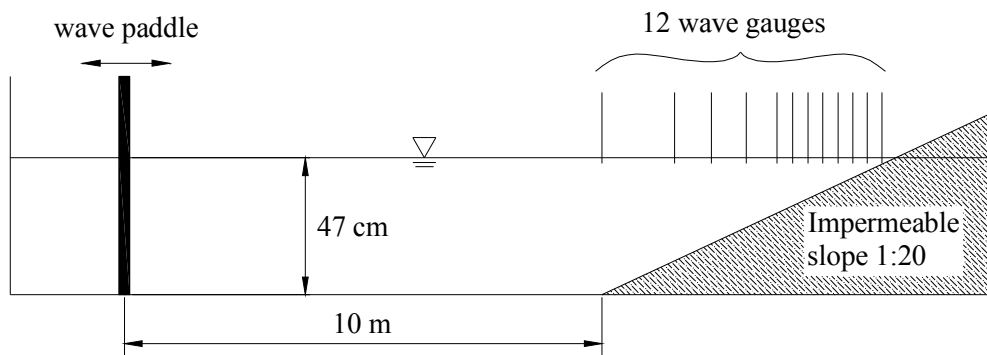


Figure 1. Sketch of the experimental setup (Mase and Kirby, 1992).

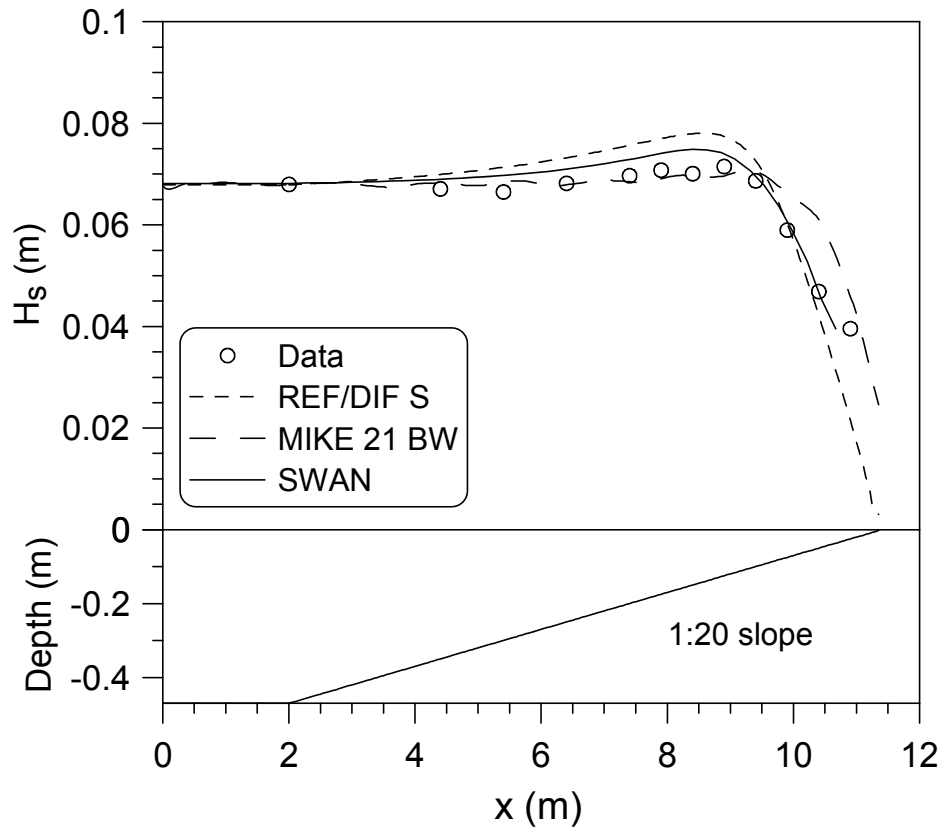


Figure 2. Significant wave heights from the experimental data (Mase and Kirby, 1992) and computed by the three spectral wave models.



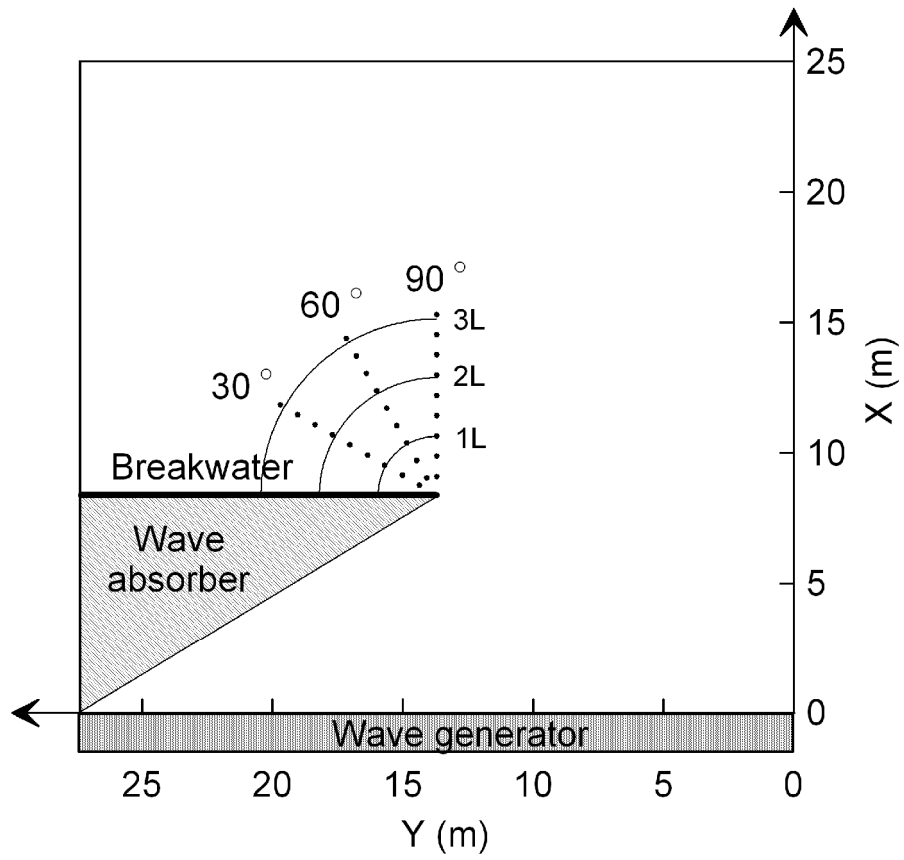


Figure 3. Sketch of the experimental setup (Briggs et al., 1995).

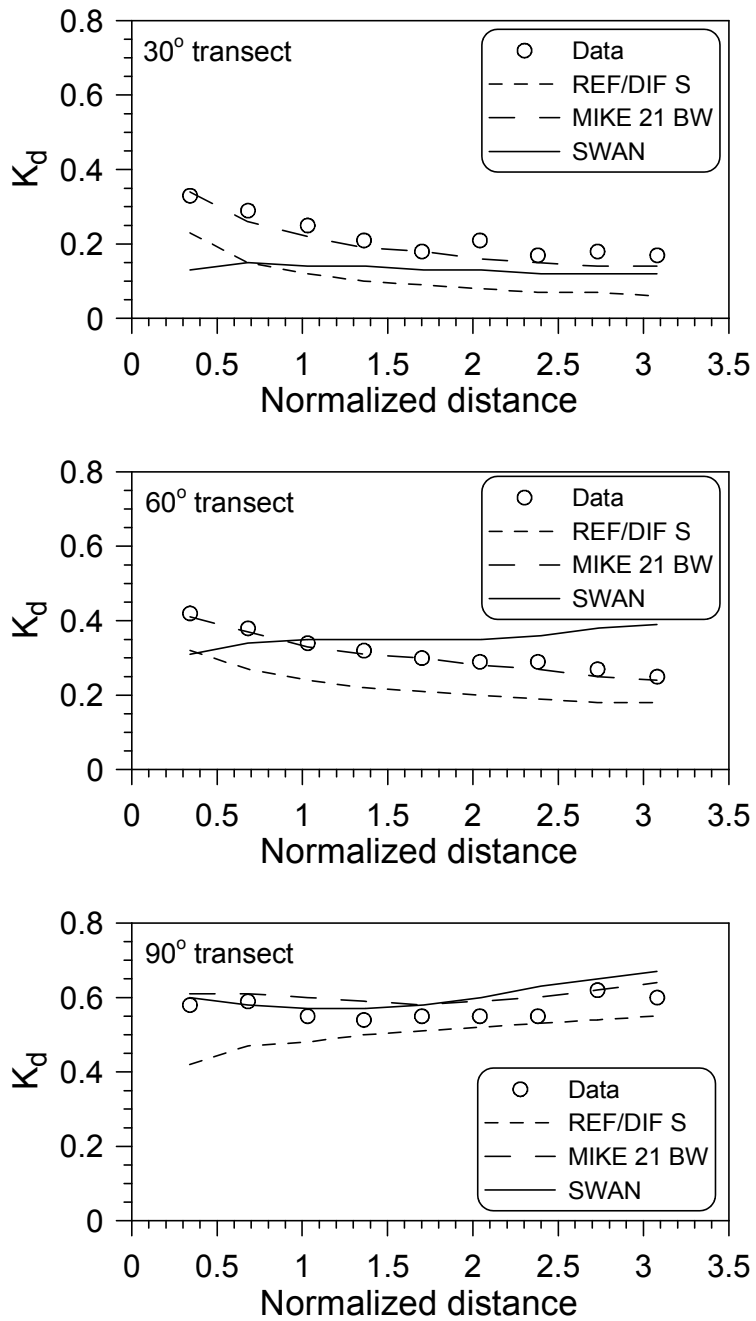


Figure 4. Diffraction coefficient along the three transects from the experimental data (Briggs et al., 1995) and from the computational results of the three models.

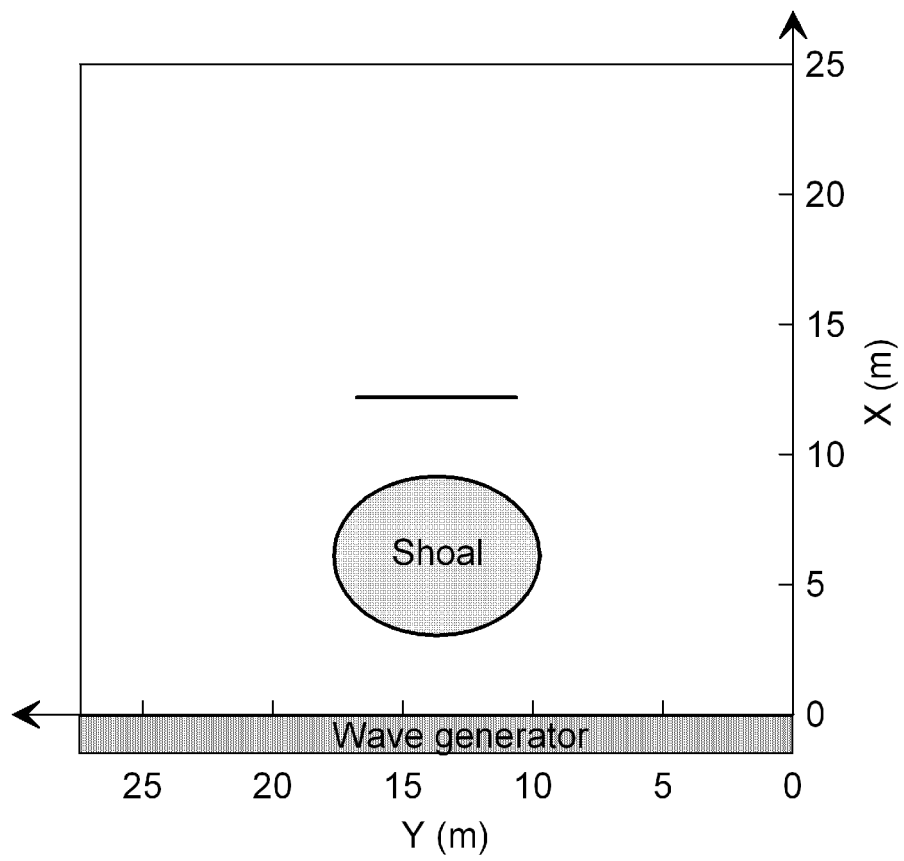


Figure 5. Sketch of the experimental setup (Vincent and Briggs, 1989).

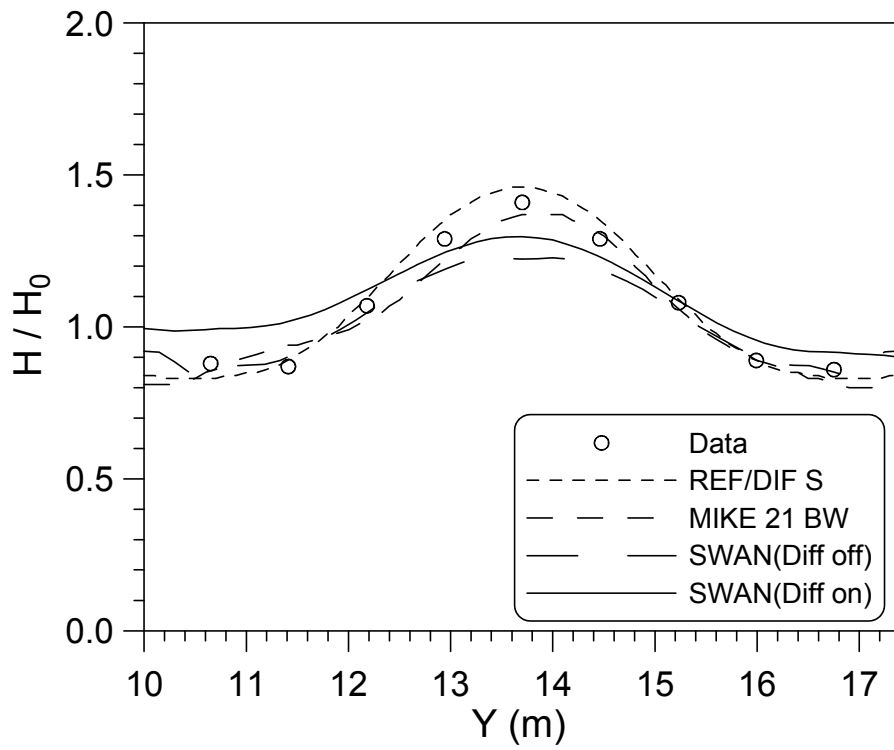


Figure 6. Values of normalized wave height along the transect measured from the experiment (Vincent and Briggs, 1989) and computed by the three models (Case N4).

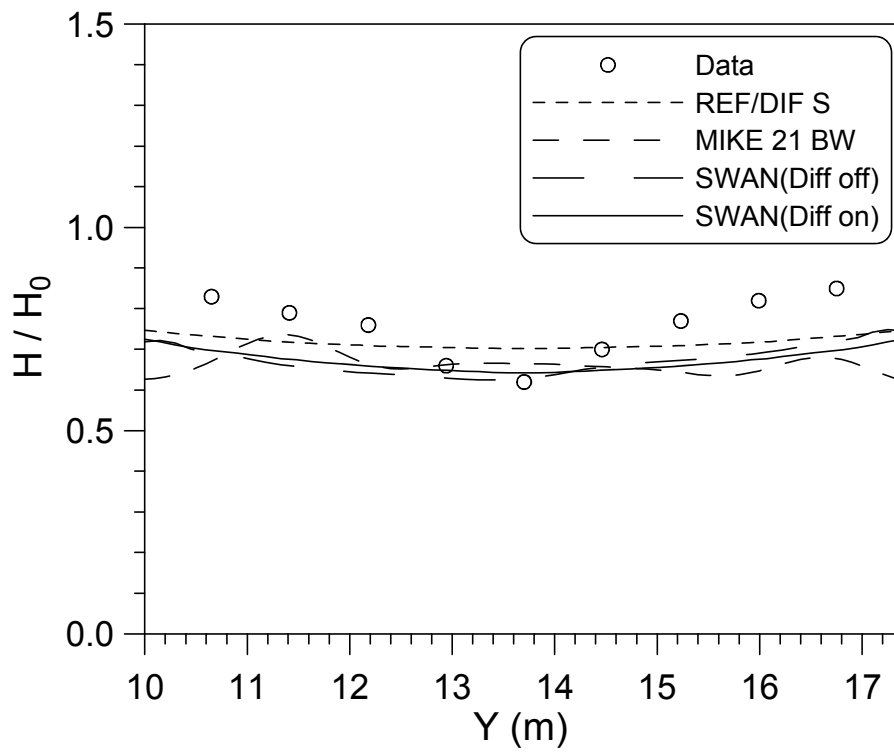


Figure 7. Values of normalized wave height along the transect measured from the experiment (Vincent and Briggs, 1989) and computed by the three models (Case B5).

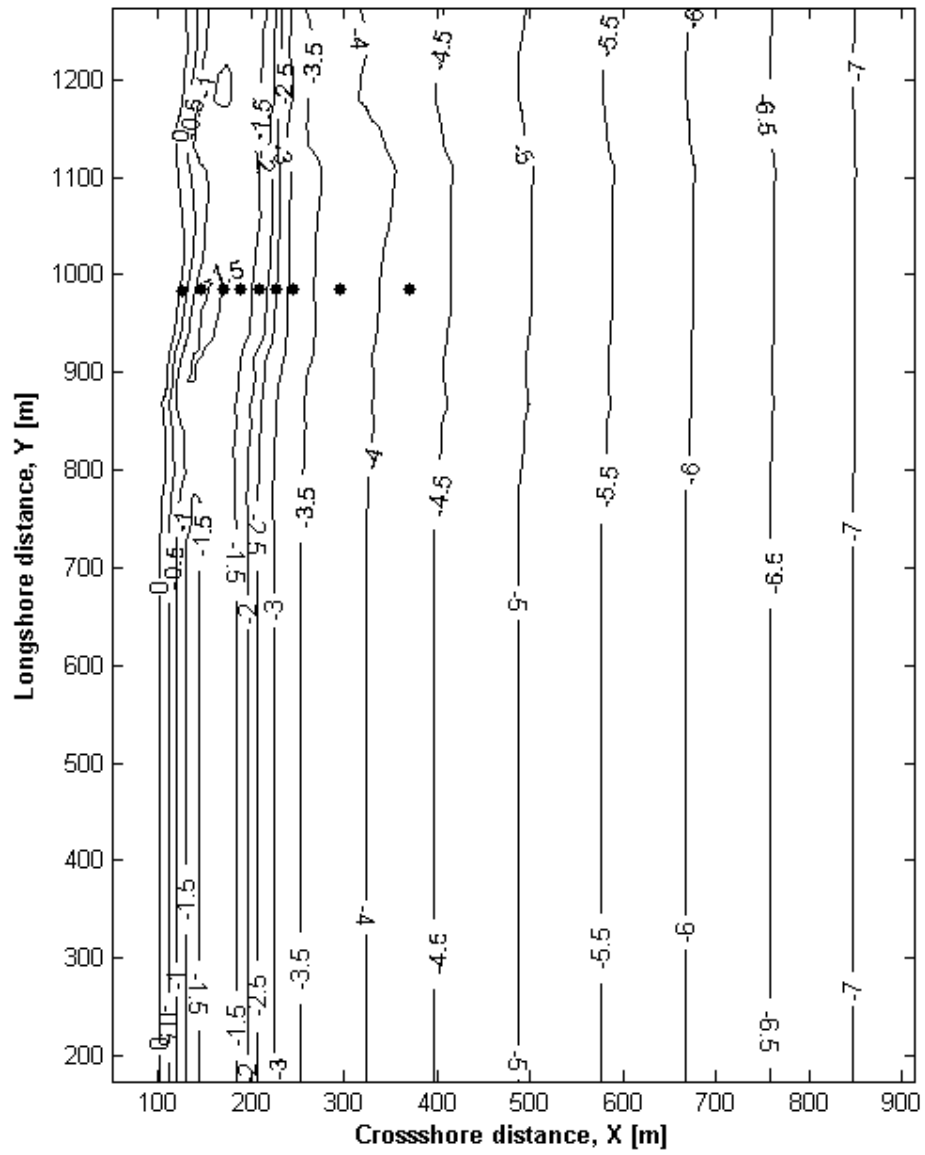


Figure 8. Bottom contours of the barred beach for the numerical computation (4:00 AM, on 10 October 1990).

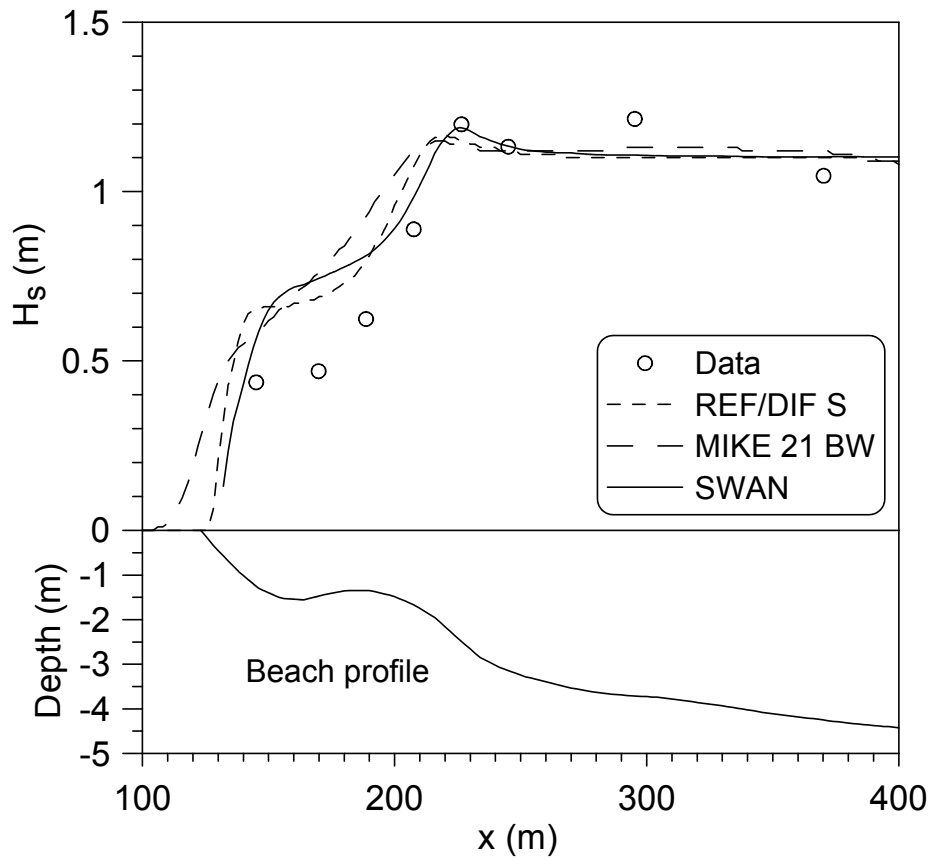


Figure 9. Significant wave heights of the field measurement (Birkemeier et al., 1997) and computational results by the three models (Case D1).

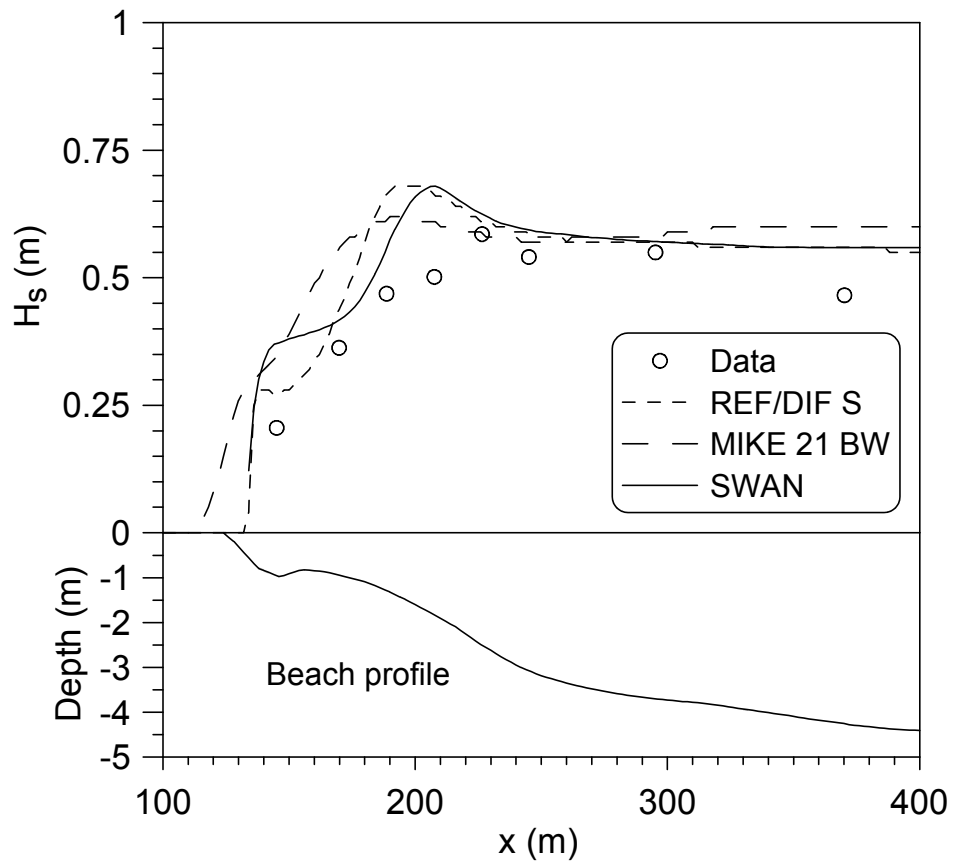


Figure 10. Significant wave heights of the field measurement (Birkemeier et al., 1997) and computational results by the three models (Case D2).