Wave climate investigation for an array of wave power devices

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Abstract

This paper presents the results of a study carried out to determine the change in wave climate around an array of hypothetical wave devices. The main objective of this work is to investigate the change in wave height in the upstream and downstream of the devices for different levels of wave absorption. This is achieved by modeling the wave devices as porous structures with different porosity levels, with the inclusion of partial reflection and partial transmission. The MIKE 21 suite wave models, (i) Spectral wave and (ii) Boussinesq wave are used for this purpose. The former wave model is employed for the estimation of various phase averaged wave parameters for the Orkney Islands. These wave parameters are then used as input to the Boussinesq model to study wave-device array interactions. The results are presented in the form of wave disturbance coefficients defined as a ratio of the significant wave height at a particular location relative to the incoming or input significant wave height. This study illustrates how the variations in wave absorption by the devices affect the degree of wave reflection and transmission around the devices.

Keywords: Boussinesq wave model, Device spacing, Wave device array, Wave disturbance coefficients.

Introduction

The need for pollution-free power generation is recognised worldwide and has resulted in a renewed interest in renewable energy. One such form of renewable energy derives from ocean waves and there are now numerous device concepts proposed for the extraction of wave energy, designed for locations from the shore to deep water. To be cost effective these devices will be deployed in arrays as a 'wave farm'. When a number of devices are installed in arrays, then the power production of each individual device will depend on the geometric configuration and will include parameters such as device spacing and orientation to the predominant wave direction.

The first objective in evaluating a site is to estimate the wave parameters required to quantify the amount of wave power available and the second is to estimate the effect upon the wave climate of wave energy extraction from an array of devices. This paper examines these issues using numerical wave models. The intention of the paper is to apply the wave modeling to a case where diffraction and refraction are the predominant effects. For this reason an array consisted of a series of bottom mounted devices are considered rather than floating devices where radiation effects might dominate. The wave interaction with an array of floating devices is described in a paper (to this conference) by Child & Venugopal [1].

The objective of this paper is to show how the wave climate around an array of bottom mounted devices is modified. This is a preliminary study where only one row of devices is used to illustrate the array effect on wave climate. It is shown in this paper that a single row of devices can substantially reduce the downstream wave height and thus this model can be used to extract individual wave properties before and after the installation of a wave farm, from which the wave climate modification by the array can easily be evaluated. Further the presence of the array may affect the downstream sediment transport patterns and this may result in beach erosion/deposition which depends on the nature of waves, its directional characteristics, tidal current flow and bathymetry etc. Calculation of wave particle velocities in the vicinity, downstream of the devices and close to shore would give an indication of how and to what extend the sediment flow patterns and shoreline topography would be changed. Another application of this study would be in assisting the prediction of wave scenario near wave farm sites where leisure time activities such as surfing and water sports are taking place. The results from this study can also be applied in the planning of various coastal structures and for other environmental issues.

This study has been carried out using MIKE 21 wave suite [2]. Two wave models from this software have been used for this study. The first model, 'Spectral wave model' was used to obtain phase averaged wave parameters for the Orkney Islands, particularly around the area where European Marine Energy Centre (EMEC) is established as a wave energy converter prototype testing site. The second model, the nonlinear 'Boussinesq wave model' was used to study the interaction between waves and an array of bottom

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mounted hypothetical wave energy devices. The Boussinesq wave model was formulated to include wave propagation or interaction with a structure of solid or permeable nature and this model has been successfully applied to many port and harbour engineering problems. It is to be noted that this model can only be applied to fixed structures and does not have the capability of handling dynamics of a moving structure. As this model accounts for several wave phenomena including diffraction and wave transmission through a structure, the authors have made an attempt to apply this model to a wave energy device assuming that the device is bottom fixed. Similar approaches have been used in other studies by Miller et al.[3] and Beels et al.[4] to model wave devices.

The interaction of waves with an array of structures which find applications in many marine and offshore engineering practices have already been carried out in numerous research works. Kagemoto & Yue [5] developed an interaction theory for a finite number of bodies of arbitrary geometry in water of finite depth, which allows the incident wave on each body from the scattered wave due to all the other bodies. This interaction theory was extended to infinite depth by Peter and Meylan [6]. In the context of wave energy devices, the hydrodynamic interaction between devices was studied theoretically by Budal [7], Falnes and Budal [8] and Evans [9]. Mavrakos and McIver [10] used three different methods in modelling wave devices namely the multiple scattering method, the plane-wave method and the point-absorber approximation to compute the wave excitation forces, hydrodynamic coefficients and q factors (used to estimate the power absorption characteristic of a device array) for a row of vertical circular cylinders. They concluded that the plane-wave approximation can accurately calculate the hydrodynamic forces. Falcao [11] derived special analytical expressions for wave absorption by a periodic linear array of rectangular and circular planform oscillating water columns devices. Falcao concluded that the maximum capture-width of a phase-controlled non-scattering circular oscillating water column is independent of chamber radius and the hydrodynamic interaction can substantially change the maximum energy absorption, depending on the array and geometry of the circular chamber and angle of incidence. Most of the above work concentrates on the performance of the devices as an array, whereas in the present work the effect of wave array to the neighbouring wave climate is illustrated. The hydrodynamics of wave power absorption by oscillating bodies involves the combination of wave diffraction problem and wave radiation problem. However, in the present work, the diffraction effect from the device array has only been modelled as the devices are considered to be fixed and further the software used here does not have the capability of modelling the radiation effect.

Miller et al.[3] modelled a wave farm off the North Cornwall coast by a 4km length partially transmitting obstacle using the SWAN wave model and studied the variation in the wave height in the downstream by varying the transmission by the obstacle at 0%, 40%, 70% and 90%. Beels et al.[4] used a mild-slope wave model (MildWAVE) by implementing sponge layers for power absorption. Sponge layers with (i) constant coefficients and (ii) varying coefficients were used in modelling the power absorbed by the device and the resulting effects on incident, reflected and transmitted wave heights were discussed. They found that varying the sponge coefficients had minimal effect on the reflected waves but a much greater influence on the transmitted waves. They have simulated a WEC in a constant water depth of 30m with 25% absorption and noticed a large shadow zone downstream of the device. Thiruvenkatasamy and Neelamani [12] conducted experiments to investigate the efficiency of the power absorption by multi-resonant caisson type oscillating wave devices in an array. They reported that the average reflected energy by the array is 30%. Other interesting research on wave-arrays interaction can be found in McIver [13]. The following sections include a brief description of wave models, methodology used to model device arrays and discussion on the significance of the results from the two wave models.

Numerical models

Spectral wind wave model

In this section a short description of this wave model is given. The spectral wind-wave model simulates the growth, decay and transformation of wind-generated sea and swells. This model includes two methods of wave simulation namely, (i) directional decoupled parametric formulation and (ii) a fully spectral formulation. This model accounts the physical phenomena of wave growth by the action of wind, non-linear wave-wave interaction, dissipation of energy by white capping, bottom friction and depth induced wave breaking, refraction and shoaling, wave-current interaction and the effect of time varying water depth, flooding and drying. A cell-centered finite volume method is used in the discretization of the governing equations and a multi-sequence explicit method is used for the wave propagation with the time integration carried out using a fractional step approach. This model produces phase averaged wave parameters as output for the computational area. Further details can be found in [2].

Boussinesq wave model

The Boussinesq wave model is widely used for various studies in ports, harbours and coastal areas. This model is capable of reproducing the combined effect of all important wave phenomena such as diffraction, refraction, shoaling, wave breaking, non-linear wave-wave interaction, bottom dissipation etc. It can handle partial reflection from the structure, wave transmission through the structure, directional wave spreading and internal wave generation. The Boussinesq model produces phase resolved output.

This wave model is based on the numerical solution of the time domain formulations of Boussinesq type equations, using a flux-formulation with improved frequency dispersion characteristics. The Boussinesq equations include nonlinearity as well as frequency dispersion. The formulations include two types; (i) enhanced Boussinesq type equations [14,15] which are used for describing the propagation of directional wave trains from deep to shallow water, where the maximum water depth to deep-water wave length is $h/L_o \approx 0.5$ and (ii) classical Boussinesq equations [14,15] suitable for $h/L_o \approx 0.22$. This model is further classified into 1DH (one horizontal space co-ordinates) and 2DH (two horizontal space co-ordinates) Boussinesq wave models. The numerical implementation is different for these two models. In the case of the 1DH model the simulation of waves in time is in one-dimension, thus excluding the directional spreading of the waves and the enhanced Boussinesq equations are solved by a standard Galerkin finite element method with mixed interpolation. In the 2DH model wave spreading is included and can generate instantaneous wave surface elevations as a wave time series. Here, the enhanced Boussinesq equations are solved by an implicit finite difference technique.

Wave simulation for Orkney Islands

The wave simulation for the Orkney Islands has been performed with the spectral wave model. The main purpose of applying this model to this site was to calibrate and validate the model for this area and then to utilise the output parameters from this model as input to the Boussinesq model to study the wave-device interaction. The validation of the model was done by comparing the model results with the measurements of a buoy installed at the EMEC test births.

The model computational domain is shown in Fig. 1 which is about 130 km x 110 km with a maximum water depth within the model area about 200m. The west, north, east and part of the south boundaries of the model are open boundaries where the offshore boundary conditions could be specified to drive the waves into the model domain. The offshore boundary wave conditions to be used as input to drive this model were obtained from the Danish Hydraulic Institute (DHI). DHI runs a global wave model using NCMRWF winds (National Centre for Medium Range Weather Forecast) assimilated with MSMR winds (Multi channel Scanning Microwave Radiometer) and these are used as input to the global wave model. The desired wave and wind parameters can be extracted from this global wave model for any location around the globe. The input parameters used here are extracted at a time interval of 30 minutes at three locations on the offshore boundary. The input used at the offshore boundary are the time series of significant wave height, peak wave period, mean wave direction and wave spreading indices. These boundary input varies with time. It was observed from the boundary wave input that the waves were mainly propagating from west and north boundaries for the period of simulation under consideration and hence no boundary input were used at other boundaries of the model domain. The waves predominantly travel in the directional sector of 250-360 degrees and the spectra were resolved into 16 directional bins. The number of time steps used was 3150 and the time step interval was 300 seconds (5minutes), which means the model produces output for every 5 minutes. The maximum Courant number for the computational domain was 0.9 which is well within the limit allowed to obtain accurate results [2]. The model was run in directionally decoupled formulation mode for spectral generation with instationary time formulation. The results from this model are discussed under results and discussion section.

Wave power device modeling

In order to study the wave and device array interaction, the Boussinesq wave model was used. The Boussinesq wave model has been successfully used to model the wave transmission through porous structures such as a breakwater [2], wherein some part of the incoming wave energy is reflected, some transmitted through the structures and some energy is dissipated (or absorbed) within the structure. The amount of energy reflected or transmitted depends on the thickness and porosity characteristics of the structure. This concept is somewhat similar to the process of a wave interacting with a wave device and hence is used in modelling the wave devices in the present work. This procedure can be very well applied to bottom mounted fixed type wave devices but should be used with great caution to model floating type devices. Since it cannot model the dynamic interaction between the wave and floating device or between the devices within the array and therefore the application of this wave model to rapidly moving floating devices is questionable. However, for deep draught floating structures with restricted or limited motions, the authors believe that this wave model would still produce acceptable results if the main interest is only on the wave climate around the devices. The method followed for this study differs from the study by Miller et al.[3] and Beels et al.[4] by the facts that (i) the wave devices are modelled as porous structures (ii) five such devices are placed which includes interaction between individual devices and also to the neighbouring wave climate taking account of the variation in the sea bathymetry.

The model bathymetry is shown in Fig. 2. The maximum water depth within the model domain is about 65m. In order to avoid wave breaking in the model domain a minimum water depth of 2.5m was used close to the shore. The length of the computational domain in the x-axis (east-west) is 5km and that of the y-axis (north-south) is 4.5km. The grid spatial resolution is 10m on both directions. The model area is approximately shown by a red square box in Fig.1. The wave device is represented by a structure occupying 10m width in the horizontal direction (one grid) with a length of 160m. The center to center spacing of the device is 320 m or the clear spacing between tip to tip of two devices is 160m. An array of five of these devices is marked by a red ellipse in Fig.2. The above dimensions may approximately be similar to an array of wave dragon devices [16]. In the model domain, a 50-point wide sponge layer has been set up at the internal wave generation line (west boundary) and also at the shoreline, to absorb the wave energy propagating out of the model area.

The wave parameters produced by the spectral wave model are used as boundary input into the Boussinesq model. The simulations were carried out without the

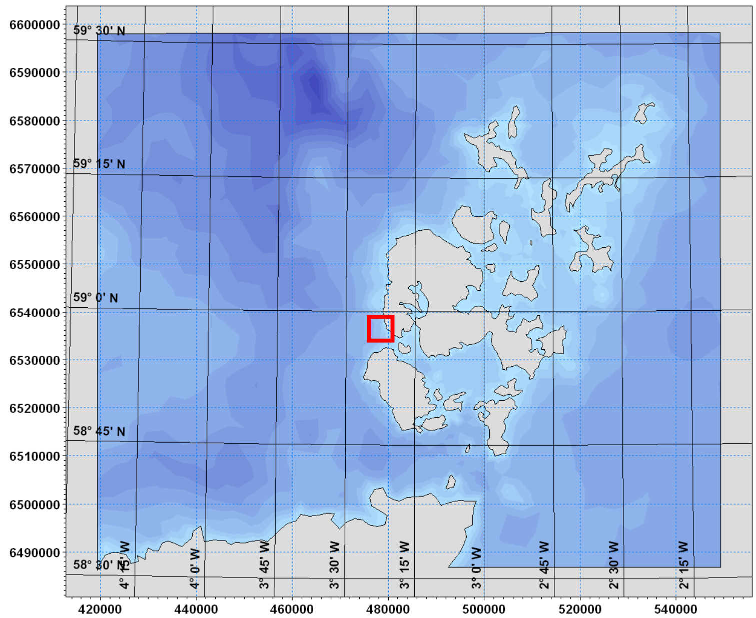

Figure 1 : Computational domain used for Spectral wave model

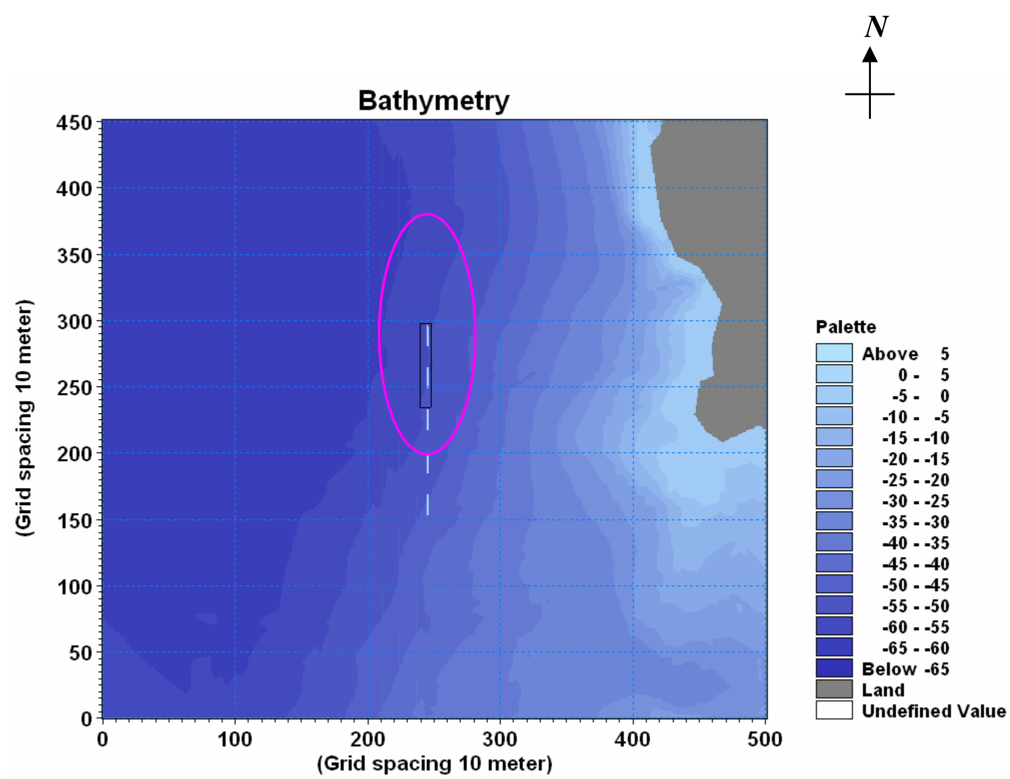

Figure 2 : Model bathymetry used for Boussinesq wave model showing wave device array.

inclusion of the deep-water terms and this also helps to keep the computational time reasonably low. The waves were generated along a generation line inside the computational domain backed up by sponge layer. The simulations were carried out for 53 minutes with a sampling interval = 0.4 sec.

Results and discussion

Wave parameters estimation

The spectral wave model produces several wave parameters in the form of an area map for the whole computational domain. It is possible to extract the required wave parameters at any particular location (or co-ordinates) from this area map. Once the relevant parameters are extracted then the wave power can easily be calculated for that location.

The results extracted from the spectral wave model at the EMEC buoy site [58° 57.913"N & 3° 23.256"W] are compared with the buoy measurements at 50m water depth in Fig. 3. The significant wave height and peak wave period extracted from the model output for the duration from 08/04/05 12:00:00 to 13/05/05 11:30:00 are shown in these plots. In general, the model results compare well with the measurements; however, at some parts differences are seen between the measurements and simulations. A possible reason for this could be that the simulations are carried out assuming that the input wave parameters are the same along the entire input or offshore boundaries. In reality, the values of the wave parameters may not be constant along the input boundary and may vary with location and time. It is possible that if the simulations had been carried out in the fully spectral formulation mode using the varying wind field over the computational domain then the results would be very close to or same as the measurements. Nevertheless during the above period of simulations, at many parts of the time series, the model results show comparable values with buoy measurements and the trend in significant wave height, wave periods and other directional characteristics (not shown here) of the model results are much similar to the buoy measurements. It is to be kept in mind that the idea behind this simulation is to use real waves as input to the Boussinesq model rather than using hypothetical sea states.

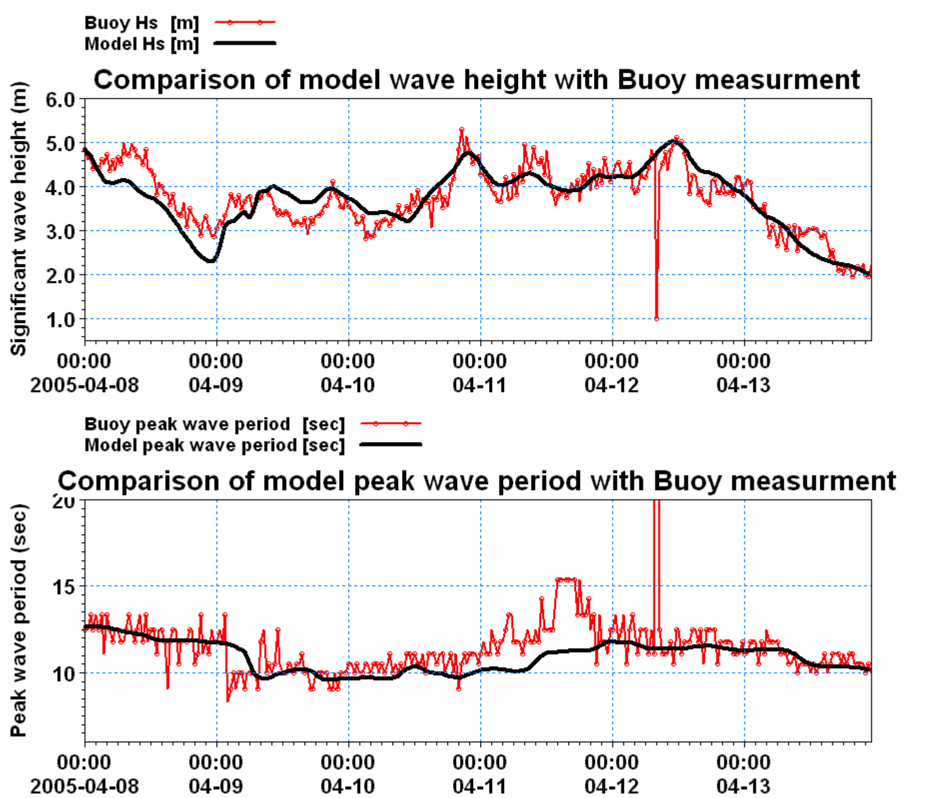

Figure 3 : Comparison of Spectral wave model results with buoy measurements at EMEC test birth location

Effect of wave devices on neighbouring wave climate

This section deals with the results obtained from Boussinesq wave model. For all the simulations, one set of significant wave height (Hs = 4m) and peak period (Tp = 10sec) selected from the output (Fig. 3, @ 10/04/05 17:00:00) of the Spectral wave model were used to generate waves in the Boussinesq model. Note that all the simulations were carried with unidirectional irregular waves. At first, the wave model was run in the absence of any devices in the model domain and then arrays of five devices were used. This would easily allow us to identify the wave climate scenarios between the 'absence' and 'presence' of the devices. The devices were modelled as solid (no energy absorption allowed) structures for one set of simulations and then porous (energy absorption permitted) structures for the next five sets. Solid devices will reflect waves to a high degree and will not allow any wave energy absorption or transmission through them. Porous structures are used to represent the wave devices with varying degree of reflection, absorption and transmission. This is achieved by changing the porosity of the structures

The significant wave height calculated for the model domain without any wave devices is shown in Fig. 4(a). This plot illustrates the change in the significant wave height over the model area after about 53 minutes of the simulation. As it is seen here, very close to the internal wave generation boundary (west) and also close to shore (east) the waves which are propagating out of the model area are completely absorbed by the sponge layers. At about 200m from west boundary the significant wave height is equal to the input wave height i.e., 4m. As the wave propagates toward the shore, a very large proportion of the energy is lost due to bathymetry effect by wave refraction, shoaling and other energy losses and the wave height close to the shore is only in the range of 1.33-1.67m.

When wave devices are placed, a large variation in the wave heights is seen over the domain as shown in Figs. 4(b) and 4(c). The contours of significant wave height plotted in Fig. 4(b) correspond to devices that are fully reflecting and no energy is absorbed by the devices. In Fig. 4(c) the devices absorb wave energy corresponding to a porosity of 0.7 and also partially reflect and transmit the energy. In these two figures, the changes in wave height, particularly the values at the downstream, clearly demonstrate the effect of the installation of devices with/without wave energy absorption. This is further explored below by considering the values at the front and rear of the devices.

The results are expressed in terms of *wave disturbance coefficients* defined as the ratio of significant wave height at a location in the model domain to a reference significant wave height at the boundary. The values of the wave disturbance coefficients along a straight line running through the centre of all devices, starting from a distance of 1000m from the west boundary to a distance 4000m towards east, are extracted from the model output and plotted in Fig. 5 for different porosity values, *n*. In each subplot five curves are plotted corresponding to the five devices. A break in these curves indicates the location of a device. Note that the top subplot shows the 'no device' case where no break in the curve is seen. The wave disturbance coefficients for the solid or 'non-absorbent' devices show a large amount of reflected waves just in front of the devices. At the location of 1000m the wave disturbance coefficients for all the devices are more or less equal to 1.0, which indicates that up to this distance the wave energy lost or gained by the incoming waves are not that significant. However, significant amount of energy is lost further away from this location as indicated by a reduction in the disturbance coefficients at and around 2000m. At the front of the devices, wave disturbance coefficients show a maximum of value of about 1.308 indicating that about 31% increase in wave height by reflection. Note that Thiruvenkatasamy and Neelamani [12] reported about the same level of reflection for a multiple OWC.

The coefficients in the downstream of the devices show a large reduction in the wave height compared to the upstream values. Immediately behind the devices a large depression is seen with coefficient values of about 0.3 at around 2500m and then the value increases to a maximum of 0.55 at 2980m, which indicate that about 45% reduction in wave height at this location. It is further observed that the values of these coefficient decrease beyond 3000m and again increases slightly. It is also to be noted that downstream of the devices the coefficient for each device is different and this can be attributed to the bathymetry variation.

A similar trend in the variation of the wave disturbance coefficients is noticed for the case where the devices are modelled using a porosity value of n = 0.5. However, since the devices absorb and transmit waves, the amount of energy reflected is reduced as indicated by a maximum value of 1.15. The wave disturbance coefficients for other values of porosity, n = 0.6, 0.7, 0.8 and 0.9 show similar tendency but with a reduction in the amount of reflection by the devices. The increase in porosity produces different patterns in the wave transmission through the devices. For example, when n = 0.5, a minimum value of 0.165 is obtained just behind the devices at about 2500m. For the same location, this value is found to be 0.24, 0.33, 0.4 & 0.47 respectively for n = 0.6, 0.7, 0.8 & 0.9. Whereas, at location around 3000m, the maximum value of this coefficient is 0.51 for n = 0.5 and almost remain constant at about 0.49 for all other porosity values.

It is worth noting that if the simulations had been performed for a uniform water depth with no structure (noted by 'no device'), then it is possible to obtain the same magnitude of wave disturbance coefficients in most of the computational area except where sponge layers were placed. But in the present case, due to variations in the bathymetry the wave disturbance coefficients showed different values at different locations. Therefore, in order to estimate the exact quantity of loss or gain in the wave height, the values of the wave disturbance coefficients obtained for devices with different porosities are divided by the coefficients obtained for 'no device' case (top subplot in Fig.5). This ratio, hereafter known as *disturbance coefficients ratio*, is then plotted in Fig. 6 and here only the middle device is considered, though similar plots can be

(a)

(b)

(c)

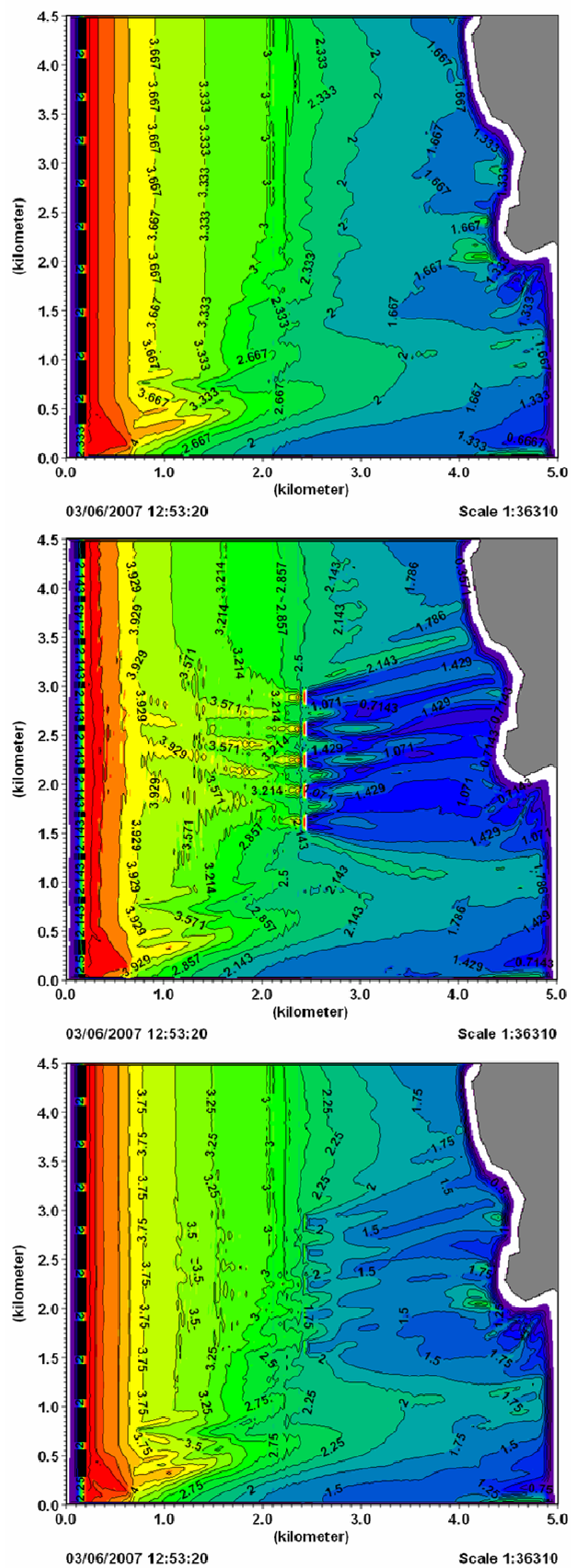

Figure 4 : Change in significant wave height; (a) no structure placed (b) solid structure and (c) structure with porosity = 0.7

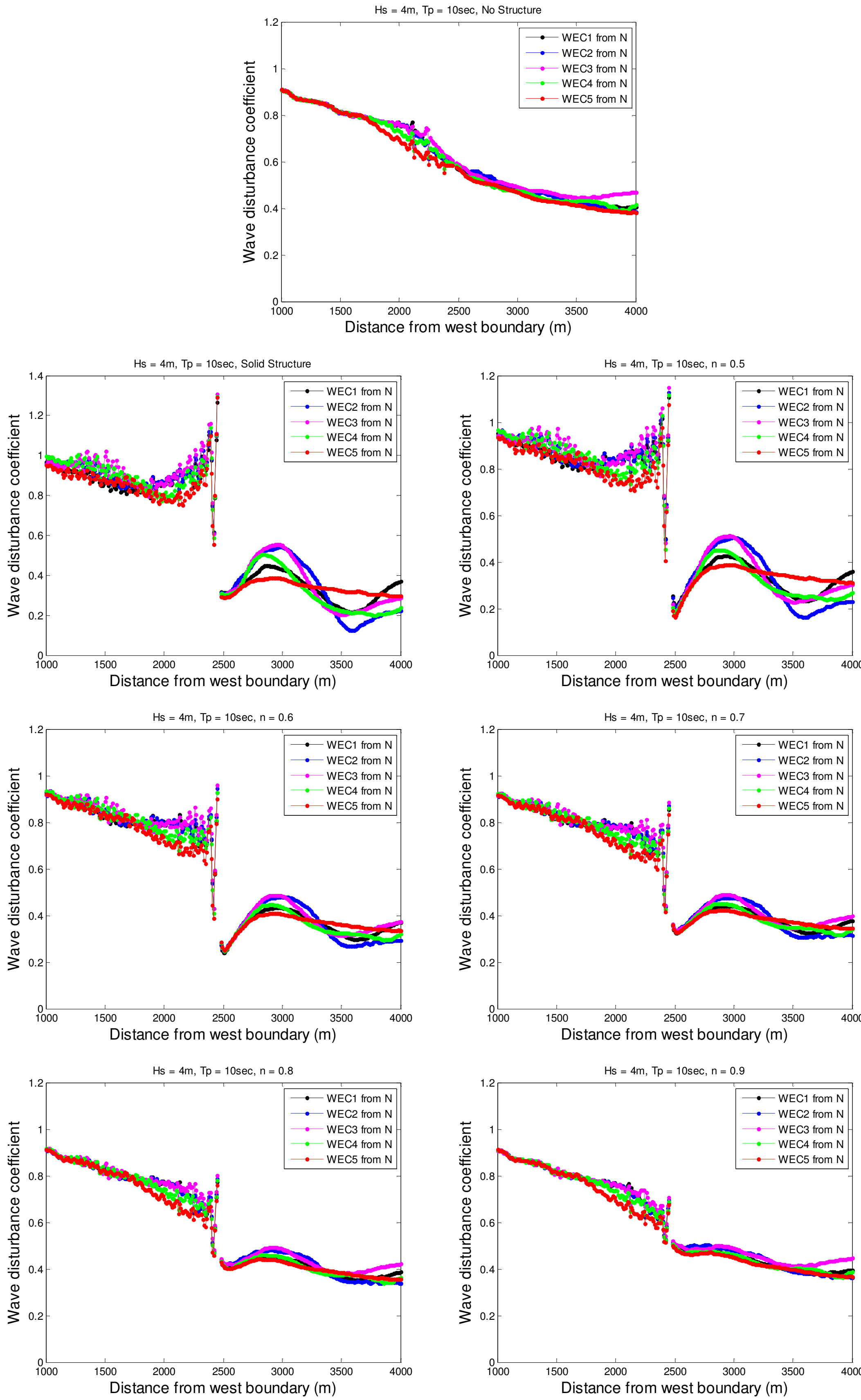

Figure 5 : Wave disturbance coefficients for different energy absorption of the devices

made for other devices as well. By this representation a value equal to one, would indicate no alteration to the wave height by the wave interaction. As expected, when the devices are 'non-absorbent' (i.e., solid structure, n = 0), this ratio is much higher in front of the middle device and on the rear of the device this ratio shows a value of 0.49 at around 2500m, reflecting that the wave heights are reduced by 51%. However, around 3000m this ratio is higher again equal to 1.12 indicating a 12% increase in wave height compared to the 'no device' case and beyond this location, a decrease in wave height is seen.

When different porosities values are applied, the disturbance coefficients ratio follow a similar trend as discussed above. It is interesting to note that for n = 0.5 & 0.6, the reduction in the transmitted wave height is comparatively lower than the 'solid structure' case. A maximum reduction of 69% and 57% are observed for n = 0.5 and 0.6 respectively. The authors believe that this is due to the process that when the device is solid or non-porous, it produces maximum reflection and at the same time allows the waves to diffract from its sides. But when the device is allowed to absorb energy, the absorption takes place all around the device, thus reducing the amount of diffracted and transmitted waves. However, for higher values of porosity, the device acts like a transparent structure resulting in less reflection and less absorption as indicated by a maximum reduction of only about 13% in wave height behind the device for n = 0.9 (Fig. 6). Another point to be noted here is that it may be possible to place a second row of devices at around 3000m for energy extraction as it appears that irrespective of the degree of wave absorption, the value

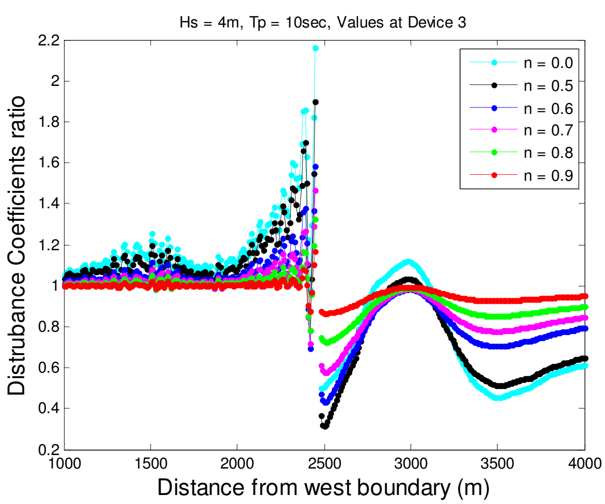

Figure 6 : Disturbance Coefficients ratio

of the disturbance coefficient ratio remains at about one. Further work will be undertaken in the future to verify this. The important observation is that whatever the porosity of the device, there is always a reduction in wave height (and hence wave energy) in the downstream of the devices which may alter the sedimentation process and other wave phenomena near the coasts.

Conclusions

The interaction of waves with an array of hypothetical wave power devices are numerically studied for different absorption and transmission levels by modelling the devices as porous structures. Two wave models have been used for this study. The spectral wave model has been used to calibrate and validate the predictive accuracy of the model to the Orkney Islands and the Boussinesq wave model has been used to study wave-device array interaction. The spectral wave model results showed good comparison with the wave measurements from wave buoy. The wave-device array interaction has resulted different levels of wave reflection, absorption and transmission in the upstream and downstream of the devices and these are presented in the form of wave disturbance coefficients for each device. The results showed that the reduction in wave heights in the downstream of the devices is in the range of 13-69%. The results also shows the presence of regions of augmented wave energy behind the array, due to diffraction and interference, whose position will depend on the wave properties and the dimensions of the array. Thus the modelling procedure could be used to determine the best location for further devices positioned behind the initial line of devices.

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