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CoMEM

Impact assessment of a new wave energy converter, Anaconda

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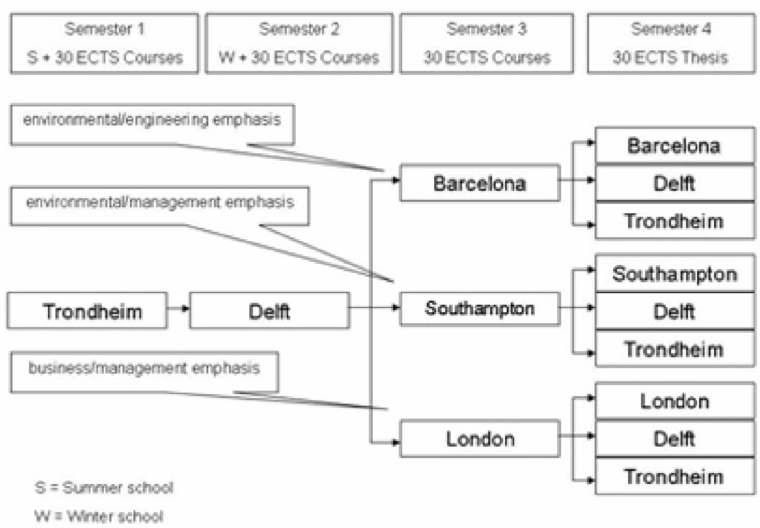

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UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

IMPACT ASSESSMENT OF A NEW WAVE ENERGY CONVERTER, ANACONDA

Mojtaba Mahmoodian

A dissertation submitted in partial fulfillment of the degree of

MSc in Coastal and Marine Engineering and Management

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Summary

Marine renewable energy as a infinite source of energy can be a reliable alternative for fossil fuels particularly in the UK with high potential wave energy in the Britain marine environment. Wide variety of wave energy converters has been developed in last decades and presenting more economical and reliable technologies is also under process. The 'Anaconda' a full-rubber Wave Energy Converter (WEC) operates in a completely new way, transferring energy from water waves to bulge waves in a giant water-filled submerged rubber tube, aligned head-to-sea. Initial researches have shown that it offers advantages of low capital and operational costs, because of its extreme simplicity and the unique durability of rubber.

Besides the importance of the design process of a wave energy converter, it is very vital to decide about the grouping of the devices in a wave farm. To have an optimum power output from the wave farm and minimum environmental impacts on marine environment and shoreline, it is necessary to evaluate the layout and the configuration of wave farm by laboratorial tests or computer simulations.

In this study MIKE 21 as a coastal and marine engineering software was used for modelling a wave farm of Anacondas. Optimum configuration which could result in the highest possible power output from the wave farm is investigated.

Results of this study showed considerable decrement in the near-shore wave height after setting up a wave farm of 21 Anacondas about 3km offshore. While some physical characteristics of Anaconda is under investigation yet, assumptions about radiation rates were taken into account and different results for different scenarios were presented.

The effect of different offshore incident wave height on the ratio of near-shore wave height decrement also showed that the higher the incident wave height the higher is the impact on shoreline. However the extent and intensity of the impact was constant for various offshore incident wave heights.

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To my Father and Mother

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1 Introduction

1.1 Background

Renewable energy is recognised as a pollution-free source of power generation in the world and it is under rapid development in different fields such as wind, wave, solar and etc. One of the main sources of renewable energy can be derived from ocean waves.

Numerous wave energy converters have been invented and designed for locations from the shore to deep water. These devices should be deployed in an arranged array to be more efficient and cost effective. The effect of each device on its surroundings will affect the efficiency of other devices in the wave farm. Therefore the device spacing and geometric configuration has effect on power output of each individual device. Wave-device and wave-wave interaction also makes the prediction of output wave characteristics more complicated.

'Anaconda' as a new floating wave energy converter has recently introduced by scientists as the potentially most-efficient wave energy converter. In this dissertation a brief introduction of Anaconda and its outstanding advantages are presented.

Investigations on the analysis of motion of floating bodies in the sea have been carried out by many researchers. These studies have mainly focused on three categories: ship movement analysis (Korsmeyer 1993), floating of huge structures (Lee 1997) and cylindrical devices with heave motion (Newman 1977 and Smith 2006).

'Anaconda' does not fall among the above categories. A flexible floating rubber tube with length of 150m and diameter of 7m is a specific shape that its physical performance in the sea is rather complicated.

May be the most similar marine device to the Anaconda is Pelamis. Pelamis is a long wave energy converter made by steel with the diameter of 3.5m and the length of 140m. Limited investigations have been carried out on the analysis of floating motion of Pelamis (Rainey 2007).

After analysis of the motion of a wave energy converter and evaluating a site about quantifying the amount of available wave power, the effect upon the wave climate by wave energy extraction from the wave farm should be investigated.

Simulation of a wave farm of Pelamis began by Mendes et al. (2006) and followed by Crom (2008) in Portugal. In the UK the modelling of a wave farm of undetermined wave energy converters has been done recently by Millar et al (2007) using SWAN software in the Wave Hub project.

Child and Venugopal (2007) did a theoretical work on interaction of waves with an array of floating wave energy devices. The problem was formulated in terms of a group of oscillating vertical cylinders oscillating in the ocean, whose motion is damped by power take-off.

V. Venugopal and G.H. Smith (2007) also have recently modeled an array of bottom mounted wave energy converters (WECs) farm by using MIKE 21.

1.2 The objectives of the research

First objective of this study is to figure out an optimum configuration of a wave farm with the maximum possible power output and minimum cost. Simulation of three different configurations is carried out for this purpose.

Another objective of this dissertation is to show how the wave climate around an array of floating wave energy converter (Anaconda) is modified. It is shown in this study that a wave farm of Anacondas can considerably reduce the downstream wave height and thus the wave properties before and after the installation of a wave farm can be evaluated. The presence of a wave farm 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 and bathymetry etc.

The result of this study can be applied in the planning of various coastal and marine structures and for many environmental issues. Change in wave characteristics may also cause interruption for leisure time activities such as surfing and water sports in some coastal areas.

1.3 The structure of the dissertation

After a brief description about available wave energy and the impact of wave energy converters in the following sections, in chapter 2 the ‘Anaconda’ as a wave energy converter is introduced. Also the advantages of Anaconda and its potential benefits compare with other wave energy converters are presented. In chapter 3 previous works on simulation of wave farms are explained and computer models that have been used for this purpose are introduced.

A comprehensive introduction of MIKE 21 is presented in chapter 4. Capability of MIKE 21 and its different modules are discussed in this chapter for better understanding of the software utilisation areas.

Simulations by using MIKE 21 BW to fulfill the main objectives of this research are explained in chapters 5 and 6. A step by step method to find an optimum configuration of a wave farm of 21 Anacondas is presented in chapter 5. The method is applied for three different configurations and the optimum configuration is selected for more study in the next chapter.

In chapter 6 the impact of setting up a wave farm on wave climate around the wave farm and near-shore is investigated. Sensitivity to change in radiation rate and the effect of different offshore incident wave height on the impact on wave climate are also evaluated.

Ultimately conclusions of the study and recommendations for further studies are presented in chapter 7.

1.4 Wave energy

Ocean waves arise from transferring the energy from the sun to wind and then water. Solar energy causes wind which blows over the ocean surface, converting wind energy to wave energy. This wave energy can travel thousands of kilometers with little energy loss. Furthermore, waves are a huge source of power with a predictable intensity that is accurately predictable several days before their arrival. Wave energy is more predictable than wind or solar energy. Fig. 1.1 presents wave power levels in kW/m of wave crest. Kilo Watt per meter (kW/m) is the typical units for measuring wave energy. Estimates show approximately 8,000-80,000 TWh/yr or 1-10 TW of wave energy in the entire oceans, and on average, each wave crest transmits 10-50 kW/m, Muetze (2006).

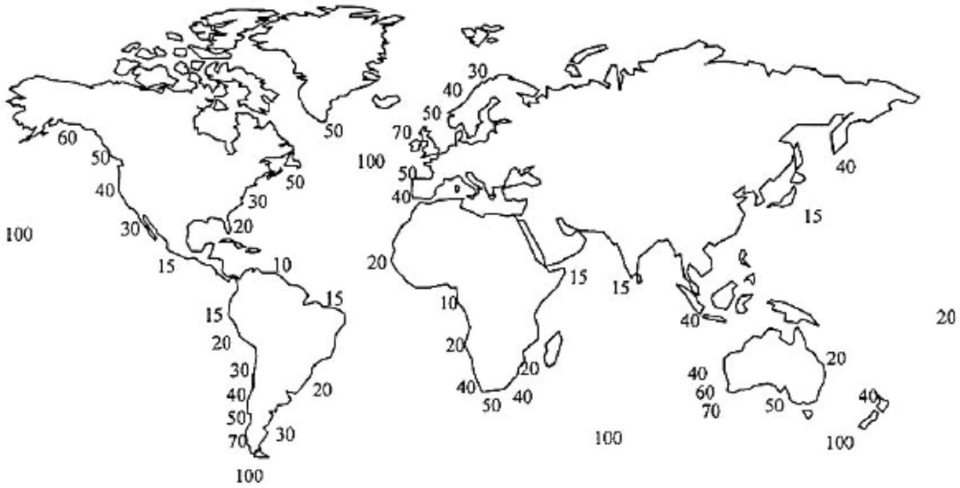


Figure 1-1: Approximate global distribution of wave power levels in kW/m of wave front, Muetze (2006)

In the UK many investigations focus on the potential for future exploitation of the marine energy resource. Also development of new and improved devices for efficient and sustainable power generation and supply has been planned by comprehensive studies in the country.

There are huge investments on marine renewable technology by the UK government and private sectors to accelerate the sector's development and cement the UK's lead in renewable marine power (The Carbon Trust, 2007). In contrast one of the most critical obstacles to develop WEC technology in USA is the lack of research support to motivate coordinated efforts in advancing the technology (Beyene and Wilson 2008).

To increase knowledge and understanding of the extraction of energy from the sea in order to reduce investment risk and uncertainty, researches should carry out in different branches of marine renewable energy (Supergen Marine Energy Research, 2007).

In this study, group simulation of Anaconda as a new wave energy converter is experienced and considerations about planning a wave farm of Anacondas are presented.

1.5 Impacts of Wave Energy Converters

Limited amount of data is available on the environmental impacts of wave farms that are under operation. Compare with other form of renewable energy sources such as sunlight or wind, wave energy conversion is expected to have less environmental impacts. The main impacts will appear after installation of a wave farm due to operational activities to maintain the devices. Muetze (2006) has examined the potential environmental impacts of wave energy converters (Table 1.1, PA: Buoy type wave energy converter (Point Absorber), OWC: Oscillating Water Column).

Table 1-1: List of Environmental Impacts of Wave Energy Converters, Muetze (2006)

(X = POSSIBLE IMPACT, XX = MORE IMPACT THAN OTHER DEVICE)

Problem Area	*Impacts*	*PA*	*OWC*
Animals	Underwater noise emissions	X	X
	Above water noise emissions		X
	Accidents:		
	· Animal collisions with device	X	X
	· Animals swept into chambers		X
	Food chain changes due to change in environment	X	X
	Electromagnetic fields and vibrations affect mammal sonar and fish reproduction	X	X
	Sedimentation and turbidity around device affects fish reproduction	X	XX
	Unnatural reef (possibly desirable)	X	X
Fauna and Seabed	Loss of seabed due to cabling and structural foundation	X	XX
	Sedimentation structural changes	X	XX
	Fauna changes due to foundation/hard substrates	X	XX
	Fauna influenced by electromagnetic fields	X	X
Coastline	Current and sediment changes for shoreline devices		X
	Decreased shoreline wave intensity due to offshore devices (possibly desirable)	X	X
Visual Impact	Above water visual intrusion		X
Pollution	Oil leakage	X	X
	Debris from ship collisions	X	X

Some of the potential environmental effects can be: wave hydrodynamics (the transport of sediments along the shorelines), noise, appearance of artificial habitats (attachment surfaces for a variety of algae and invertebrates), navigational hazards, change of migration route for marine mammals, visual effects and impacts on some forms of recreation, such as surfing, scuba diving and jet skiing

In this study the focus would be on the effect of wave farm on wave characteristics such as wave height and wave energy.

2 Anaconda; A new wave energy converter

Anaconda is a new wave energy converter system based on bulge waves traveling along a distensible rubber tube. The Anaconda is named after the long and enormous South American snake that hunts for its prey in water. It is the largest snake that spends most of its time in water environments.

The rubber tube, typically 7 m diameter and 150 m long, filled with water and closed at both ends, is oriented in the direction of wave travel. The waves excite a bulge in the tube, and the bulge moves just in front of the wave rather like a surf-board, picking up energy and increases progressively in size. The initial sea wave that caused the bulge wave, runs along the outside of the tube at the same speed as the bulge wave, squeezing the tube more and more and causing the bulge wave to get bigger and bigger. The energy from the sea is concentrated by the traveling bulge and at the end of the tube the energy can be extracted to drive a turbine and produce electricity.

2.1 Theory of bulge waves and Anaconda performance

Figure 2.1 shows how bulge wave is produced and moves along a floating tube in the sea. In the picture the waves come from the left. The arrows show the flow direction of water inside the tube. The bulge wave in the tube and the waves in the sea have the same velocity; and the wave energy is gradually transferred to the tube.

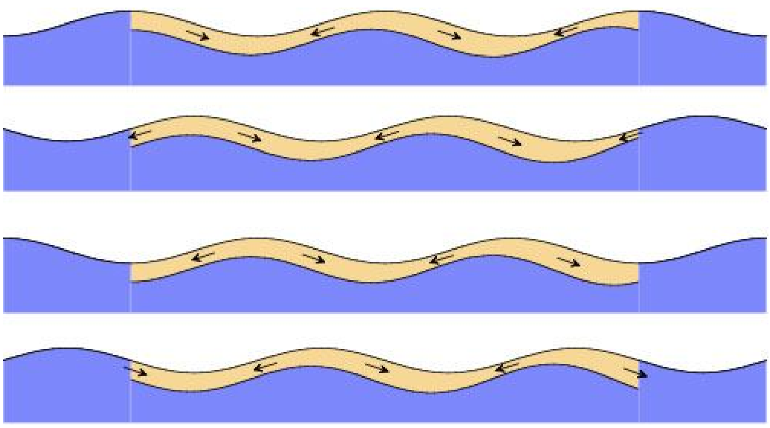


Figure 2-1: Bulge waves, http://www.bulgewave.com

The wave squeezes the tube at the bow and starts a bulge running. But as it runs the wave runs after it, squeezing more and more, causing the bulge gets bigger and bigger. The bulge moves in front of the wave where the slope of the water (pressure gradient) is highest. In fact the bulge surfs on the front of the wave.

A good example of bulge waves in a distensible tube is the pressure pulse which travels along the arteries.

Squeezing a filled rubber tube will make a local bulge in it and this bulge can propagate along the tube at a speed of 'c' given by:

$$c^2 = \frac{Eh}{d\rho} \tag{2.1}$$

Where:

E is the tensile modulus of the rubber, d the diameter of the tube, h its wall thickness and ρ is the density of water.

The speed of the bulge can be controlled by choosing the dimensions of the tube and the properties of the rubber.

The bulge wave is a wave of pressure, associated with a longitudinal oscillation of fluid, forwards and backwards within the tube. The water flows forwards when the pressure is high, and the water is flowing backwards when the pressure is low. A resonant interaction will happen when the bulge in the tube travels at the same speed as the wave and the bulge grows linearly along the tube and carries energy.

In resonance, the energy in the bulge grows as the square of the distance from the bow. Off resonance, the bulge grows initially and after reaching a maximum, decreases; this cause fluctuations in the power output.

The pressure oscillation at the end of a tube one wavelength long is three times the incoming sea wave. The energy in the tube is proportional to the tube area. The captured energy is related to the energy per meter of wave front in the sea by "capture width" (CW) parameter. In fact the device collects all the energy in the sea from a wave frontage equal to the capture width.

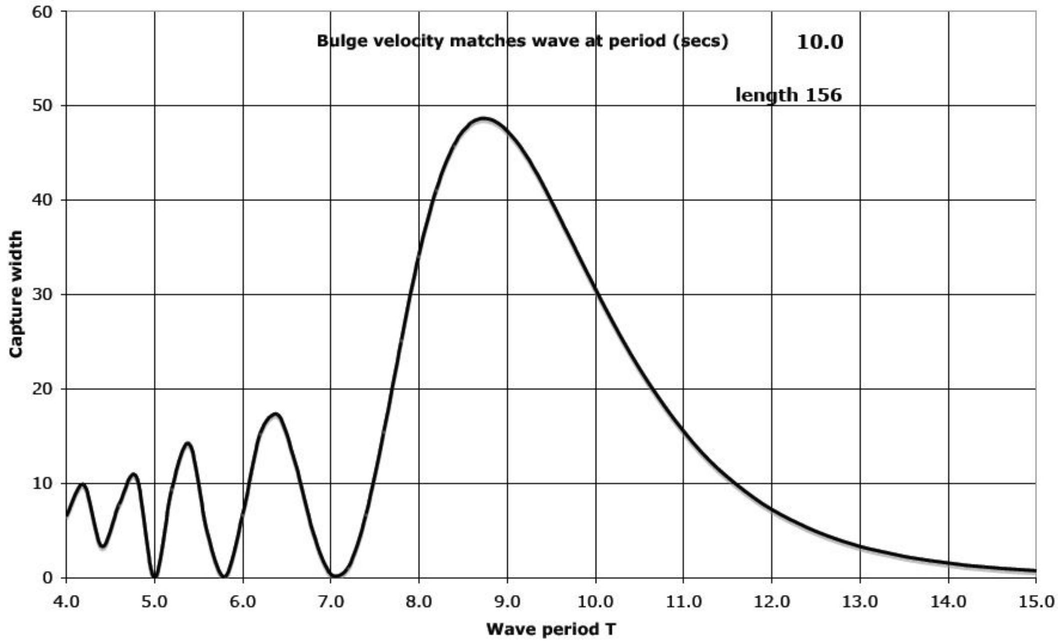


Figure 2-2: Theoretical capture width vs. wave period for tube 7 m diameter, 156 m long (Farley and Rainey 2006)

In figure 2.2 the predicted capture width for different wave period has been illustrated. The maximum capture width is about 50 m. as an average over the wave spectrum in the sea, the mean capture width equal to 20 m can be expected for a tube 7m diameter and 156m length (Farley and Rainey 2006).

In typical Atlantic conditions, the wave energy in the sea is 50 KW/m, so the energy captured in 20m width would be about 1 MW.

Comparing with other wave energy converters, the bulge wave tube has the highest capture width. This advantage can give a privilege to Anaconda in economic competition with other wave energy converters.

2.2 Advantages compare with other wave energy converters

As a renewable energy production system, the Anaconda makes a valuable contribution to environmental protection by encouraging the use of wave power. In comparison with other wave energy converters the Anaconda appears to have the following advantages:

• Simple system (No possibility of breaking due to no hinges and joints)

• Low maintenance costs

• Good capture width

• Good life time

• Based on preliminary estimates, it will be cheaper per kilowatt delivered

High durability of rubber in sea condition is a unique property of Anaconda. Rubber tubes can live very long in the sea because of its remarkable durability in aggressive sea water. An excellent example of using rubber in the sea environment is the hovercraft with its rubber skirt. Skirts of this type last many years despite of their harsh treatment and the extremely hostile environment.

Flexibility of rubber gives another advantage to Anaconda. Basically, rigid wave energy converters are matched to wave frequency which is determined by structural size. Whereas with the Anaconda the similar resonance can be achieved by making the velocity of the bulge wave along the tube matches the speed of the water waves outside.

The flexibility of rubber also gives Anaconda a significant advantage in handling and safety in transportation. Anaconda is easy to transport and to set up, as it can be rolled up and transferred as deck cargo, and even if it breaks free from its moorings it doesn't have a serious danger for ships.

A good potential competitive for Anaconda can be Pelamis. Made by Ocean Power Delivery, Pelamis has been the front runner in wave power converters in recent years (www.oceanpd.com). Pelamis is a long articulated metal structure consists of 4 sections, which oscillates laterally in the waves (figure 2.3).

Figure 2-3: A prototype of PELAMIS, 3.5m diameter and 140m long, (www.oceanpd.com)

The power take-off is from hydraulic jacks at the articulated joints (Rainey 2007). The average capture width in Atlantic seas is just 5.5 m (for Anaconda the average capture width is 20m), so in a 50 kW/m sea the mean power collected is about 280 KW. Pelamis has been sold to Portugal at a cost of £ 1.8 M. Therefore the capital cost of generating one kilowatt of electricity from Pelamis is £6500. Other wave energy converters have proved that are more expensive than the cost incurred with Pelamis. In addition to capital cost, maintenance costs are significant in offshore structure cases (as experienced in offshore wind turbines). An economical and competitive wave power can have a price of £ 2000 per average kilowatt delivered with small maintenance cost. Therefore the capital cost needs to come down by a factor of two or three (from £6500 to £2000)

Hydraulic rams, hinges and articulated joints are not used in the Anaconda and it is much lighter than other wave energy devices (made of metal). This reduces capital and maintenance costs and the risk of breakdowns.

The capital cost per megawatt for Anaconda is estimated to be about £2-3 million which is much less than the existing wave power converters. A full-scale 100-tonne Anaconda (150 meters long and 7 meters in diameter) will produce 1 megawatt (in Atlantic Ocean condition) at a cost of 6p or less per kilowatt hour.

3 Modelling a wave farm

As using wave energy and setting up wave farms is a new technology which is recently going to be implemented in prototype projects, the modelling of wave farms is also completely new subject in coastal engineering. A few common softwares have been already used for this purpose. In this section a brief history of wave farm modelling is presented. The main study for modelling floating wave energy converters has been carried out by L. Mendes et al. (2006) and I. Le Crom (2008) in Portugal on simulation of a Pelamis wave farm.

In the UK the modelling of wave farm using SWAN has been done recently by Millar et al (2007) in Wave Hub project. Venugopal and Smith (2007) also have modeled a bottom mounted wave energy converter (WEC) farm by using MIKE 21.

3.1 Using REFDIF and SWAN in Modelling of wave farms

In this section two main European projects for installing wave farms in the South and the North of Europe is explained.

3.1.1 "Maritime Pilot Zone" off Portuguese Coast

Following development of Pelamis and installation of the first large scale sets of this wave energy converter; the study about its environmental impacts was carried out by Portuguese researchers.

Mendes et al (2006) modeled a wave farm off Portugal coast using REFDIF model. The case study was in "maritime pilot zone" located at the West coast off S. Pedro de Muel, Portugal, between 30 m and 90 m water depth, with an area of about 300 km^2 (Figure 3.1). The study continued by Crom et al (2008) by using SWAN for modelling a wave farm at the same area. In the paper published by Crom et al (2008), the comparison between the results of the two models has been presented.

In this section after a brief introduction of REFDIF and SWAN models, the comparison between the obtained results by Mendes et al (2006) and Crom et al (2008) is explained.

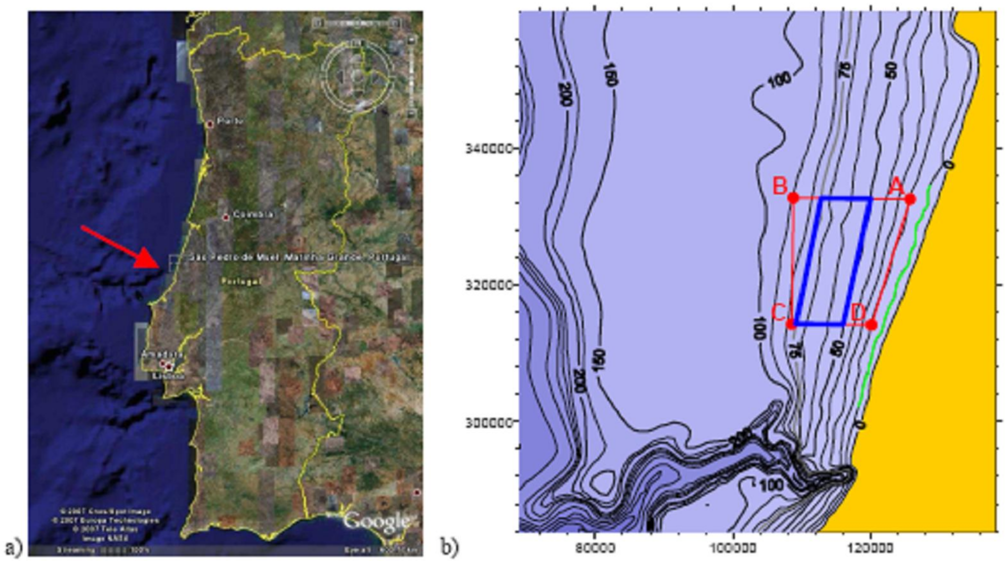


Figure 3-1: Maritime Pilot Zone in Portugal, modelling by using REFDIF, Mendes (2006)

The REFDIF model:

The REFDIF model is a numerical model based upon the large angle parabolic approximation of the mild slope equation. It simulates the propagation and deformation of regular waves over a bathymetry with variable depths.

This model takes into account refraction, diffraction (only on the direction perpendicular to the incident wave direction), shoaling, wave currents and wave breaking and some nonlinear effects. In the REFDIF model the equations are solved by a finite difference method, using a regular grid for the discretisation and an implicit iterative line by line scheme in the direction of wave propagation. Application of REFDIF in large coastal areas has been well adopted. Two types of the lateral boundary conditions exist in this model: total reflection boundaries or open boundaries. A field of monochromatic waves at the entrance boundary can be specified.

Some of the main limitations of REFDIF model are:

- The model can be applied only to regular waves
- The model can be applied only to mild slope bottoms, i.e., slope of 1:3 or less
- Because it cannot deal with the back-scattering of waves, the model does not take into account the wave reflection phenomenon. Also, diffraction is only

taken into account considering the normal wave direction and as a result it cannot be used in sheltered areas.

In a model made in REFDIF, the orientation of the grid should guaranty that the wave direction inside the grid does not exceed ±60º of the incident wave direction, due to the use of the large angle parabolic approximation.

Input data in a REFDIF model includes:

I) Incident wave characteristics such as: wave height, wave period and wave direction

II) Grid characteristics

III) Bathymetry

Outputs of the model are the wave height, H, and the wave direction in each point of the domain.

Some modifications were implemented by Mendes in the REFIDF model in order to model the wave propagation over a set of wave farms located on the computational domain. Basically, the model must extract certain energy amount along the area where the set of wave farms are installed. Based on the characteristics of those wave farms, the values of the energy dissipation can vary.

The SWAN model:

SWAN (Simulating Waves Near-shore) is a third generation numerical wave model developed by Delft University of Technology (TUDelft) to specifically model near-shore wave climate transformation, commonly-used in shallow and intermediate water. It simulates wave propagation in time and space, accounting for refraction due to variations in seabed, blockage, reflection or transmission due to obstacles, shoaling, blocking and reflection due to opposing currents.

Wave energy can be dissipated in the model due to active processes such as white capping, bottom friction, wave–wave interaction, diffraction and depth induced wave breaking. These parameters are represented by numerical coefficients that need to be determined for the cases being modelled.

Outputs of the SWAN model are significant wave height, wave periods, average wave direction and directional spreading.

In the study by Crom et al (2008), ten wave farm configurations were tested, with the same number of devices, 270, the same installed peak power, 202.5 MW, the same orientation (maximum length of wave farm perpendicular to the incident wave direction). The differences between configurations were reflected to the arrangement of the wave farms in the exploration zone.

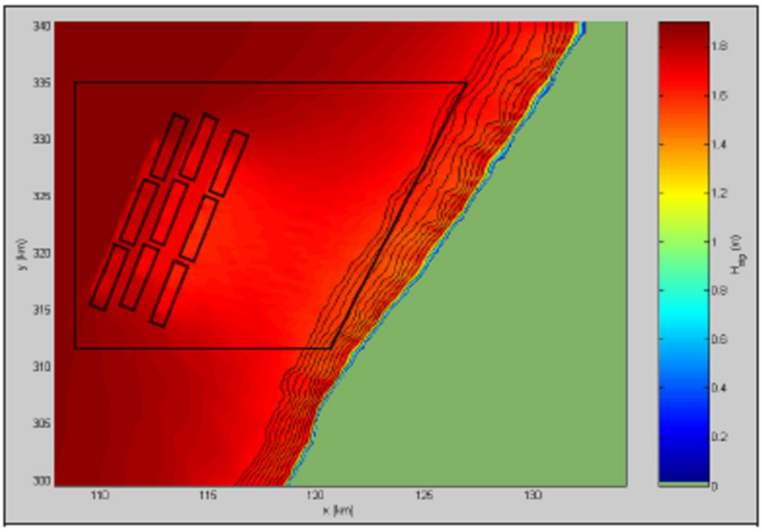


Figure 3-2: Output of SWAN model for one of the wave farm configurations off Portugal coast, I. Le Crom et al (2008)

The results showed that the large scale installation of WECs in the maritime Pilot Zone will have a measurable effect on the shoreline wave climate (Figure 3.2).

The farer the wave farms from the coast the greater will be the space for the waves to regenerate before reaching the coast, attenuating the change of the wave height.

The energy transmission was higher than 89.5% of the incident energy, therefore despite of the choice of the worst conditions (very clean swell, no wind, worst Hs/Te combination in terms of absorption and frequency of occurrence), the impact of a large scale installation was relatively low.

In the north-south extension of the coastline adjacent to the pilot zone, reduced mean wave heights equal to 8 cm (5%) has been achieved in the model.

In the most affected region of the coastline the absolute reduction of significant wave height varied from 15 to 22 cm maximum (with maximum relative change of 11.8%), within an extension of 20 km. Average reductions in the zone was 19 cm (10%). Such situation had been caused by significant wave height between 1.5 to 3 m and wave period between 6 and 9 s (which are the most frequent conditions) at the location.

In all the models ran by Crom et al(2008), the changes in wave periods and directions were very small. The study was an initial approach to analyse the effect of large scale wave energy deployment in the near-shore and the following limitations of the study were remarked:

- The study did not take into account reflection by the devices
- The uniform reduction of the energy density for each frequency of the wave spectrum (as modelled by SWAN) is not representative of the real mechanism of wave propagation
- No calibration of the physical phenomena was done
- Physical phenomena used in the study were represented by numerical coefficients that need to be tuned to the cases being modelled. Most of them were set to the SWAN default values because no additional data was available
- The model results were not compared to any inshore measurements within the zone of influence of the Pilot Zone, and monitoring will have to be implemented in order to assess the effect of the devices on the coast, as well as to justify the choices of the methodology (grid size, transmission coefficient, spatial representation of the WECs, etc) and to improve the characterisation of the zone (bathymetry, fully developed waves conditions, etc).

Comparison between REFDIF and SWAN results:

The results of the spectral model SWAN were compared with the results obtained with the monochromatic model REFDIF by Portuguese researchers (Crom et al (2008)) in the “Maritime Pilot Zone” project. Globally REFDIF showed an impact more important and narrower than the results obtained using SWAN. Some phenomena such as the non linear wave-wave interactions, the growth of the waves by the wind and the white capping can be taken into account by the SWAN model while the REFDIF can not consider them. Redistribution of the energy over the spectrum would be possible by using those phenomena and therefore a more realistic representation of the regeneration of the waves after the obstacles will be concluded in the SWAN model.

3.1.2 "Wave Hub" Project off the UK Coast

'Wave Hub' is a sub-sea electrical grid connection point, proposed for installation on the seabed 20 km off the north coast of Cornwall on the UK's southwest peninsula where the water depth is 50–60m (Figure 3.3).

Based on the purposed plan arrays of wave energy converters (WECs) will occupy the site over an area of 3000m-1000m. Although it is not yet known which devices will be initially installed at the site, all potential WECs have the objective of converting the energy of the waves into electrical power.

Halcrow (2006) and Millar et al (2006) have had comprehensive investigations on the impacts of this project on wave climate and shoreline.

Halcrow modeling scenarios were developed in consultation with the British Surfing Association (BSA) and Surfers Against Sewage (SAS) to satisfy as best as possible the needs and concerns of the surfing community. Numerical modelling was used in the simulation by Halcrow to simulate monochromic incident waves and the wave farm in wave hub project.

Millar et al (2006) used the SWAN wave model, to model a wave farm in the area and estimate the potential impact of the wave farm on the coastline.

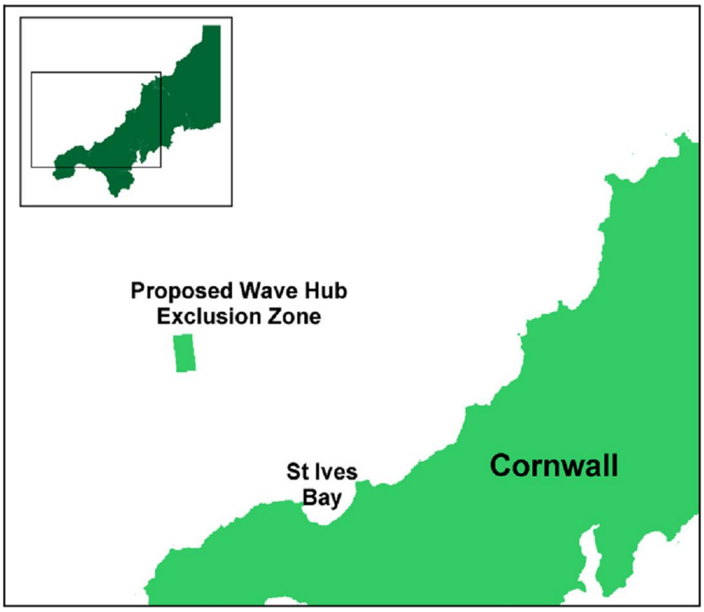


Figure 3-3: Wave Hub project, South-West of the UK, Millar (2007)

The simulated wave farm by Millar was consisted of arrays of WECs deployed at the Wave Hub site. In the model, wave farm was represented as a 4km partially transmitting obstacle, aligned approximately parallel to the incoming wave crests at the wave hub site. Different energy transmission rates (0%, 40%, 70% and 90%) by the obstacle were assumed in the model because it was not known exactly how much wave energy will be absorbed by the WECs. Each of the energy transmission percentages were set for specific reasons:

- 0%— presenting complete absorption of all incoming wave energy at the obstacle (an unachievable scenario). The largest possible shoreline effect could be expected with this scenario (Figure 3.4).
- 70%— presenting an array of densely spaced, high efficiency WECs (as an optimistic target achievable for a wave farm developer).
- 90%— presenting lower efficiency, widely spaced WECs (a more realistic scenario at the Wave Hub site).
- 40%—Included in the research to enable the representing of trends (although it was extremely improbable that this could be possible in reality)

In Millar's model it was assumed that the frequencies are unchanged. When waves approach such an obstacle in SWAN, the only change to the wave characteristics is a

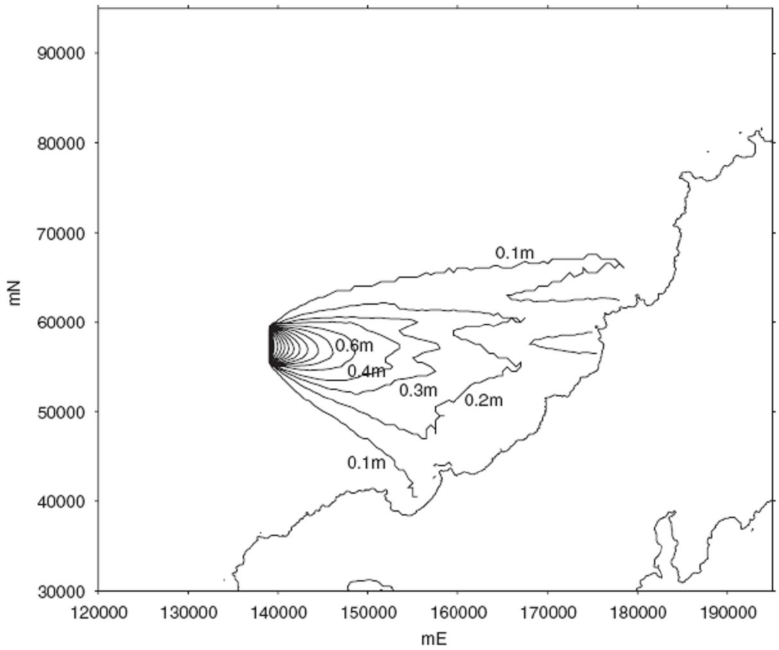


Figure 3-4: Changes in significant wave height, due to the Wave Hub for 0% energy transmission, unachievable scenario (Reference state: Hs=3.3m, Tm=11s and D=1 degree), Millar (2007)

reduction of wave height along the length of the obstacle; also the energy density for each frequency had reduced by 75%.

For modelling of a partially transmitting obstacle in SWAN, the definition of a transmission coefficient should be considered. Transmission coefficient defines as the ratio of the transmitted significant wave height over the incident significant wave height. Similarly 'wave energy transmission' or simply 'transmission' is also defined as the wave energy passing through the obstacle over the incident wave energy.

Millar's study has shown that the proposed Wave Hub development will potentially affect the wave climate off the north coast of Cornwall, but it is likely that these effects will be small. The following results were concluded from Millar (2006) study. The results presented how the effects on the wave climate vary with location and wave direction:

- At the shoreline, changes in significant wave height due to the Wave Hub decrease linearly with increasing wave energy transmission through the Wave Hub site.

- By considering a realistic scenario for a wave farm developer (90% wave energy transmission), an average change in significant wave height at the shoreline of 1 cm or less over the 11 months of sea states can be expected.
- For 90% energy transmission, the maximum change in shoreline significant wave height is 4 cm. This small change will be an infrequent event as it depends on shoreline location and specific offshore wave conditions.

Final and general conclusion by Millar et al (2006) was: there is little cause for concern that effects introduced by the Wave Hub will be felt by shoreline users of the sea. Although this result was slightly different from the results obtained by Halcrow (2006), but general agreement between model results was shown (ASR Ltd Marine Consulting and Research, 2007).

Following the Millar et al (2006) work, more studies continued by Smith (2006). In her study SWAN was used to allow an assessment of how large and how far offshore wave farm developments should be before significant changes in the shoreline wave climate occur, causing morphological and ecological impacts and affecting shoreline leisure users.

3.2 Using MIKE 21 in Modelling of wave farms

The only study that has used MIKE 21 for modelling of a wave farm has been done by Venugopal and Smith (2007) in the University of Edinburgh. They have simulated the wave devices as porous structures with different porosity levels, with the inclusion of partial reflection and partial transmission. The main objective of their work was to investigate the change in wave height in the upstream and downstream of the devices for different levels of wave absorption.

Two modules of MIKE 21 were used in that study. (i) Spectral Wave (SW) and (ii) Boussinesq wave (BW).

MIKE 21 SW (spectral wave model) was employed for the estimation of various phase averaged wave parameters for the case study area (Orkney Islands). These wave parameters were then used as input to the MIKE 21 BW (Boussinesq model) to study wave-device array interactions. The results of the spectral wave model (MIKE 21 SW) also showed good comparison with the wave measurements from wave buoy.

The Boussinesq wave model is used to simulate the wave transmission through porous structures such as a breakwater. The idea is that when a wave hit a structure some part of its 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 varies based on the thickness and porosity characteristics of the structure. Venugopal used this concept to model wave devices using MIKE 21 BW.

The aim of Venugopal study was to apply the wave modelling to a case where diffraction and refraction are the predominant effects. For this reason an array consisted of a series of bottom mounted devices were considered rather than floating devices where radiation effects might be dominant.

The model bathymetry and the array of the devices is shown in Figure 3.5.

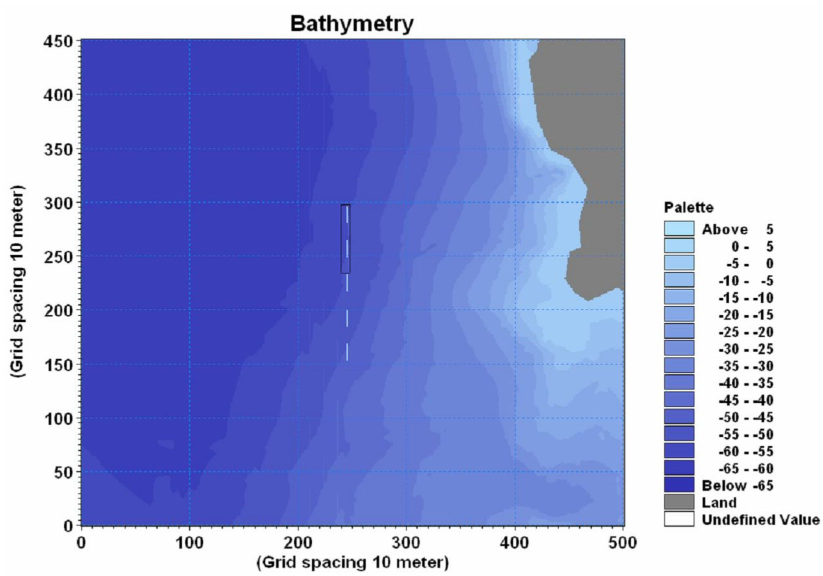


Figure 3-5: Model bathymetry and wave energy devices, Orkney Island, Venugopal and Smith, 2007

The maximum water depth within the bathymetry domain was about 65m. A minimum water depth of 2.5m was introduced close to the shore in order to avoid wave breaking in the model domain. The computational model dimension was selected 4.5km to 5 km and the grid spatial resolution was selected 10m on both directions. The wave device was introduced to the model as a structure occupying

10m width in the horizontal direction (one grid) and a length of 160m. The space between tip to tip of two devices was 160m. The above dimensions are approximately similar to an array of wave dragon devices. An array of five of these devices was considered in the model.

To absorb the wave energy propagating out of the model area it is necessary to introduce sponge layers in the model. A 50-point wide sponge layer was set up behind the internal wave generation line (west boundary) and also at the shoreline.

The results of MIKE 21 BW model were 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. Therefore it was possible to illustrate how the variations in wave absorption by the devices affect the degree of wave reflection and transmission around the devices.

The model was run for three conditions (Figure 3.6):

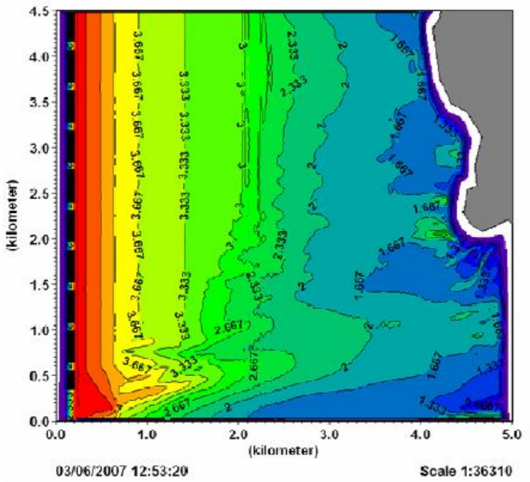
(a) No structure placed (Porosity = 1)

(b) Solid structure (Porosity = 0)

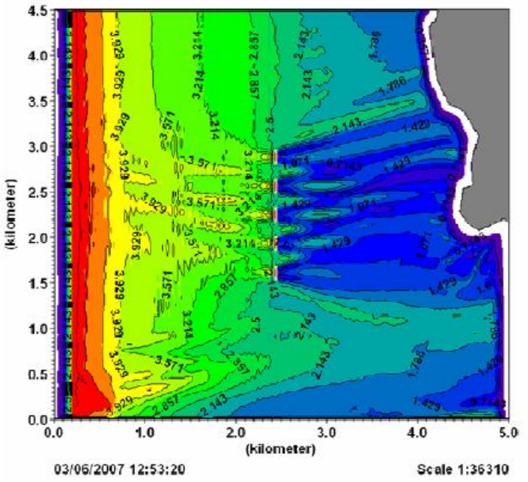
(c) Structure with porosity = 0.7

Different levels of wave reflection, absorption and transmission in the upstream and downstream of the devices were resulted in the simulations. In the downstream of the devices reduction in the range of 13-69% in wave heights was observed.

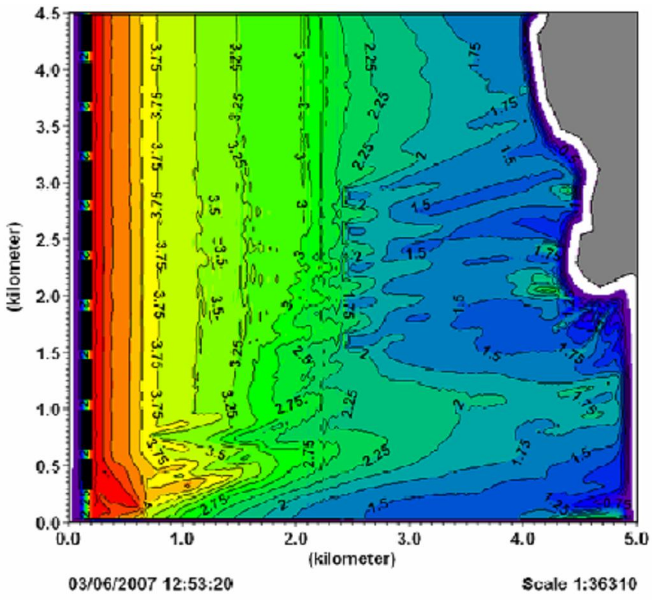
The results also showed that some regions behind the array have had increased wave energy, due to diffraction and interference. Position of these regions depended on the wave properties and the dimensions of the array.



(a)



(b)



(c)

Figure 3-6: MIKE 21 BW output, Change in significant wave height; (a) no structure placed (b) solid structure and (c) structure with porosity = 0.7, Venugopal 2007

The main differences between Venugopal study and this thesis study are:

i) Venugopal has modeled bottom mounted WECs, whearas in this thesis floating WECs will be modeled

ii) WECs direction in Venugopal study was parallel to incident wave crest, but in this thesis the WECs direction is normal to incident wave crest

Venugopal and Smith (2007) concluded that “MIKE 21 can be very well used for modelling of 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, this wave model would still produce acceptable results if the main interest is only on the wave climate around the devices”.

Hence the research in this dissertation can be a new beginning and effort to simulate floating wave energy converters by using MIKE 21.

4 Introduction to MIKE 21 (2D Modelling of Coastal Waters and Seas)

MIKE 21 is a professional engineering software package for the modelling and simulation of flows, waves, sediments and ecology in rivers, lakes, estuaries, bays, coastal areas and seas. MIKE 21 is well known as a tool that provides a design environment for engineering, coastal management and planning applications.

MIKE 21 is also used for environmental applications together with ECO Lab software.

Applications of MIKE 21 can be listed as follows:

► Design data assessment for coastal and offshore structures

► Optimisation of port layout and coastal protection measures

► Cooling water, desalination and recirculation analysis

► Environmental impact assessment of marine infrastructures

► Water forecast for safe marine operations and navigation

► Coastal flooding and storm surge warnings

► Inland flooding and overland flow Modelling

4.1 MIKE 21 Modules

MIKE 21 consists of the following modules which can be used for different purposes and in wide variety of projects (MIKE 21, user guide, 2008):

<u>PP - Pre- and Postprocessing:</u> The PP module offers an integrated work environment providing convenient and compatible routines to ease the tasks of data input, analysis and presentation of simulation results.

<u>HD – Hydrodynamics</u>: The HD module simulates the water level variations and flows in response to a variety of forcing functions. It includes a wide range of hydraulic phenomena and can be used for any 2D free-surface flow in which stratification can be assumed vertically well-mixed.

<u>AD - Advection-Dispersion</u>: Simulates the transport, dispersion and decay of dissolved or suspended substances. Typically used in cooling water and sewage outfall studies.

ST - Sand Transport: Advanced sand transport model with several formulations for current and current/wave generated transport, including 3D description of sediment transport rates. Used for morphological optimisation of port layouts, impact of shore protection, stability of tidal inlets, etc.

MT - Mud Transport: A combined multifraction and multilayer model that describes erosion, transport and deposition of mud (cohesive sediment) or sand/mud mixtures.

Coastal Morphology: An integrated system, which combines the wave, flow and sediment transport models into a fully dynamic morphological model.

PT - Particle Tracking: Simulates transport and fate of dissolved and suspended substances. Used for risk analysis, accidental spillage, monitoring of dredging works, etc.

SA - Spill Analysis: Simulates the spreading and weathering of suspended substances and is used for only forecasting oil spill, evaluating spill scenarios for contingency plans, etc.

SW - Spectral Waves: A 3rd generation spectral wind-wave model that simulates the growth, decay and transformation of wind generated waves and swell in offshore and coastal areas.

NSW - Near Shore Spectral Wind-Waves: The model describes propagation, growth and decay of short period and short crested waves in near shore areas.

PMS - Parabolic Mild Slope Waves: A linear refraction-diffraction model used to study wave disturbance in open coastal areas. Also (with some limitations) for computing wave fields in coastal areas with structures.

EMS - Elliptic Mild Slope Waves: Efficient model used to study wave dynamics in coastal areas and, for instance, harbour resonance in response to linear and monochromatic wave forcing.

BW - Boussinesq Waves: A tool for studies and analysis of wave disturbance in ports, harbours and coastal areas with full surf and swash zone dynamics.

4.2 MIKE 21 BW

4.2.1 General

The two modules included in the MIKE 21 BW (1DH and 2DH Boussinesq Wave Modules) are based on the numerical solution of time domain formulations of Boussinesq type equations. Nonlinearity as well as frequency dispersion has been included in the Boussinesq equations.

Basically, the frequency dispersion is introduced in the momentum equations by taking into account the effect of vertical accelerations on the pressure distribution. By using a flux-formulation with improved linear dispersion characteristics, both modules solve the Boussinesq type equations.

These enhanced Boussinesq type equations make the modules (1DH and 2DH) suitable for simulation of the propagation of directional wave trains travelling from deep to shallow water. The maximum depth to deep-water wave length is $h/L0 \approx 0.5$. For the classical Boussinesq equations the maximum depth to deep-water wave length is $h/L0 \approx 0.22$.

Wave breaking and moving shoreline has been included in the model by extension of the model into the surf zone.

MIKE 21 BW is capable of reproducing the combined effects of almost all important wave phenomena of interest in port, harbour and coastal engineering. These include:

- Shoaling
- Refraction
- Diffraction
- Wave breaking
- Bottom friction
- Moving shoreline
- Partial reflection and transmission
- Non-linear wave-wave interaction
- Frequency spreading
- Directional spreading

Phenomena, such as wave grouping, surf beats, generation of bound subharmonics and super-harmonics and near-resonant triad interactions, can also be modelled using

MIKE 21 BW. Thus, details like the generation and release of low-frequency oscillations due to primary wave transformation are well described in the model. This is of significant importance for harbour resonance, seiching and coastal processes.

The present release of MIKE 21 BW includes two modules:

- 2DH Boussinesq Wave Module
- 1DH Boussinesq Wave Module

The 2DH module (two horizontal space co-ordinates) solves the enhanced Boussinesq equations by an implicit finite difference technique with variables defined on a space-staggered rectangular grid.

The 1DH module (one horizontal space co-ordinates) solves the enhanced Boussinesq equations by a standard Galerkin finite element method with mixed interpolation for variables defined on an unstructured (or a structured) grid. In addition, surf zone dynamics and swash zone oscillations can be simulated for any coastal profile in this module.

The simulation of partial reflection from and transmission through piers and breakwaters can be done by using porosity value in MIKE 21 BW. Sponge layers are applied when full absorption of wave energy is required (usually in the boundaries). Finally, MIKE 21 BW also includes internal generation of waves.

4.2.2 Application Areas

A major application of MIKE 21 BW is determination and assessment of wave dynamics in ports and harbours and in coastal areas. The disturbance of waves inside harbour basins is one of the most important factors when engineers are to select construction sites and determine the optimum harbour layout in relation to predefined criteria for acceptable wave disturbance, ship movements, mooring arrangements and handling downtime.

With inclusion of wave breaking and moving shoreline MIKE 21 BW is also capable to study many complicated coastal phenomena, e.g. wave induced-current patterns in areas with complex structures.

Another application of MIKE 21 BW is prediction and analysis of the impact of ship-generated waves (also denoted as wake wash). Essential boundary conditions (at open or internal boundaries) for the models can be obtained from 3D computational fluid dynamic (CFD) models, experimental data, full-scale data and/or empirical relationships.

5 Using MIKE 21 BW for the Modelling a wave farm of Anacondas

In this chapter the method used to model a wave farm of Anacondas is explained. After discussion about the procedure for setting up the model, the results for selecting an optimum configuration is presented. Simulating of the Anaconda as a floating device in MIKE 21 BW is a completely new issue which is discussed in this chapter in detail.

5.1 Setting up the model in MIKE 21 BW

"Setting up the model" is actually another way of saying transforming real world events and data into a format which can be understood by the numerical model MIKE 21 BW. Thus generally speaking, all the data collected have to be resolved on the spatial grid selected.

Before the MIKE 21 BW can be set up the following input data must be prepared

- Spatial and temporal resolution
- Bathymetry map
- Sponge layer map (for wave absorbing)
- Porosity layer map (for partial wave reflection)
- Internal wave generation data (for incident offshore waves)

5.1.1 Selecting model spatial and temporal resolution

When selecting the model area (or profile) one must consider the area of interest, the alignment of the model grid relative to the main direction of approach of the incident wave trains and the position and types of model boundaries to be used.

The choice of the grid spacing and time step depends on the wave conditions for which simulations are to be performed and the water depth in the area of interest. The following criteria should be taken into account during setting up the model.

- The ratio of the maximum water depth to the deep water wave length of waves with the shortest wave period must not become larger than 0.22, if the deep water correction terms are excluded, and 0.5, if these terms are included.
- The grid spacing is restricted by the resolution of the shortest wave length or the surface roller, if wave breaking is included.

- The time step is restricted by the resolution of the shortest wave period.
- The Courant number should be kept equal or less than unity to avoid instability problems.

In practice the choice of the grid spacing and time step is often a compromise between low computer costs and high accuracy. The MIKE 21 BW Model Setup Planner is an efficient tool for the setup of the model. Figure 5.1 shows the inputs and the outputs of MIKE 21 BW Model Setup Planner that has been used in this study. Ultimately, the following parameters where determined for Modelling in this study:

Minimum wave period, T_{min}= 7.5 Sec

Spatial Resolution (or grid spacing), d_x= 7m

Temporal Resolution (or time step), d_t= 0.1 Sec

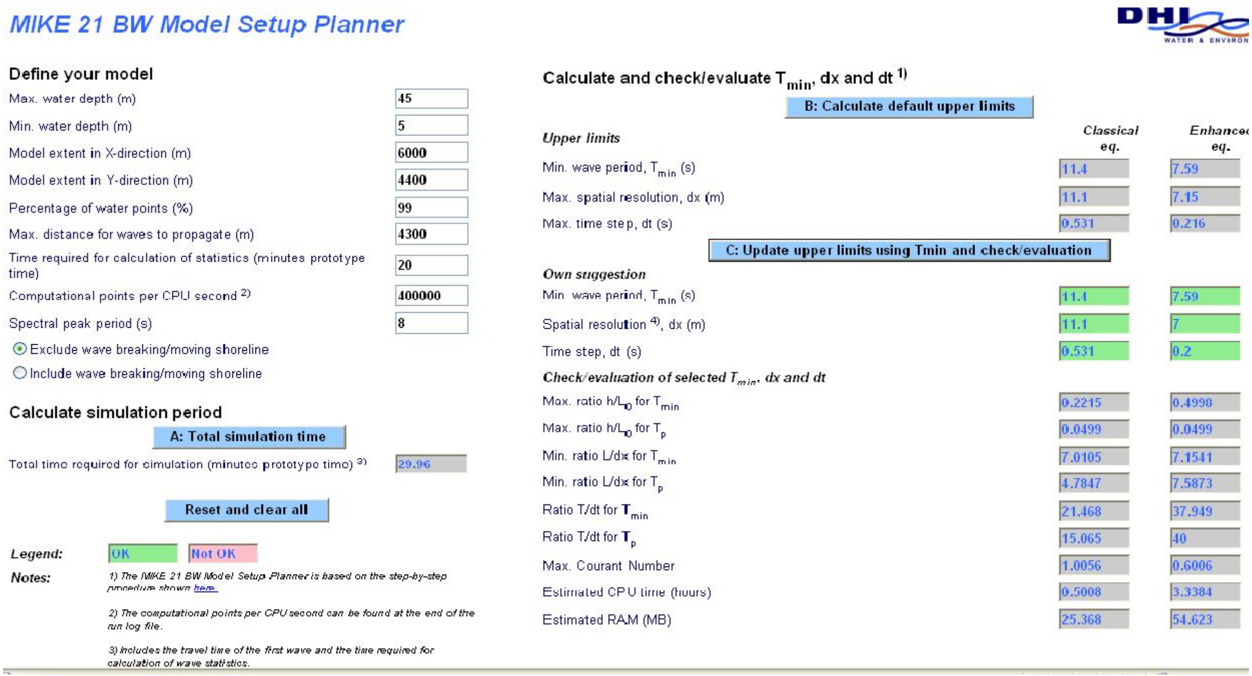


Figure 5-1: The MIKE 21 BW model setup planner, input data and output results

5.1.2 Bathymetry

The bathymetry should be specified as a data file containing the water depth covering the model area. Describing the water depth in the model is one of the most important tasks in the modelling process. Providing MIKE21 BW with a suitable bathymetry is essential for obtaining reliable results from the model.

In this study an idealized bathymetry was assumed for the simulation. The area for wave farm deployment has the depth of 45m. The depth decreases gently shoreward. The minimum depth was set equal to 5 meter to avoid wave breaking. Figure 5.2 shows the bathymetry and its cross section in the model.

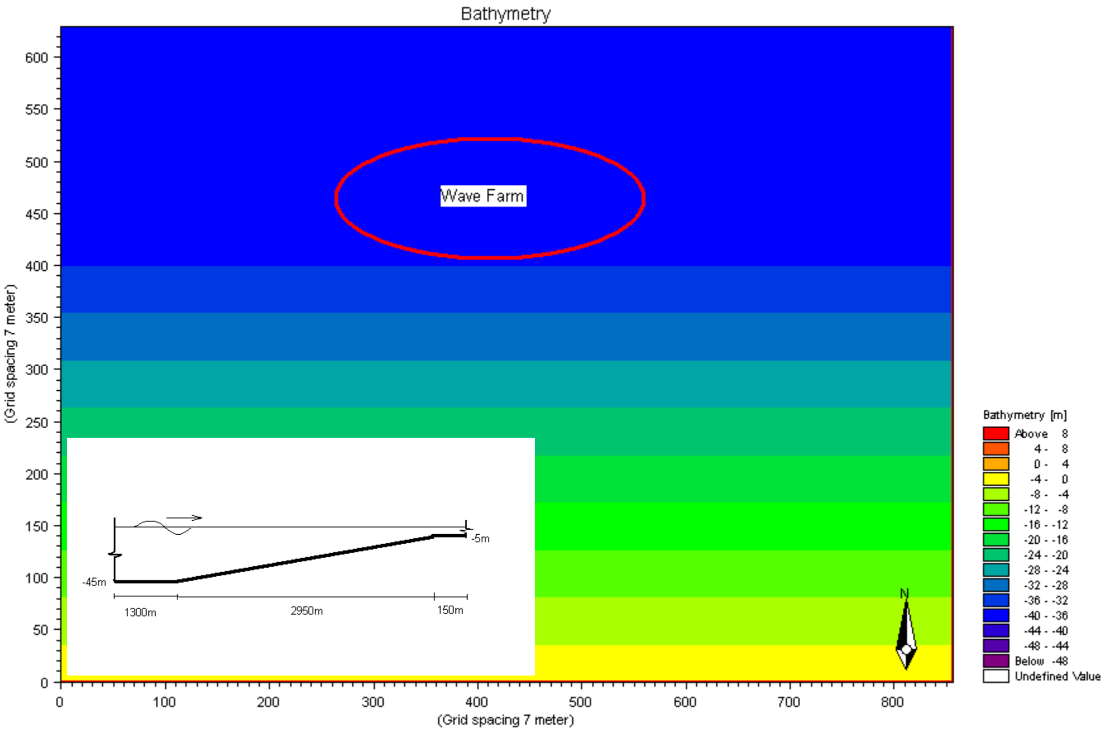


Figure 5-2: The bathymetry and the cross section of the area used in this study

Bed levels (water points) are specified as negative values when they are below the bathymetry datum and positive values when they are above it. Note that simulations are carried out using the still water level (SWL) as reference. SWL = bathymetry value + shift of reference level.

5.1.3 Sponge layer

In practical for all MIKE 21 BW applications, maps should be prepared for efficient absorption of short and long period waves. Sponge (or absorbing) layers are used as wave absorbers. These may be set up along model boundaries to provide radiation boundary conditions, which absorb wave energy propagating out of the model area. Sponge layers may also be used along shorelines.

In this study two sponge layers are used in top and end (North and South) of the model to absorb waves leaving the model.

In the primary models in this study, sponge layers were also used in left and right (West and East) of the area as sponge-absorbing boundaries. But the results showed that sponge layer can not act perfectly when incoming wave direction is not perpendicular to sponge layer direction. In that case some reflection from lateral sponge layers was detected. This undesired reflection could not be eliminated by increasing sponge layer width from 20-girds to 50-grids.

This problem is shown in Figure 5.3. The output of a model with an idealized bathymetry in this figure shows that reflection from East and West boundaries has observable effect on wave characteristics.

Therefore it was decided to define the lateral (West and East) boundaries as land boundaries without any sponge layers. Figure 5.4 shows the output of a model with the same condition as the model in Figure 5.3, but in the absence of sponge layers in the lateral sides. The results of this model show no reflection from boundaries and it is reliable.

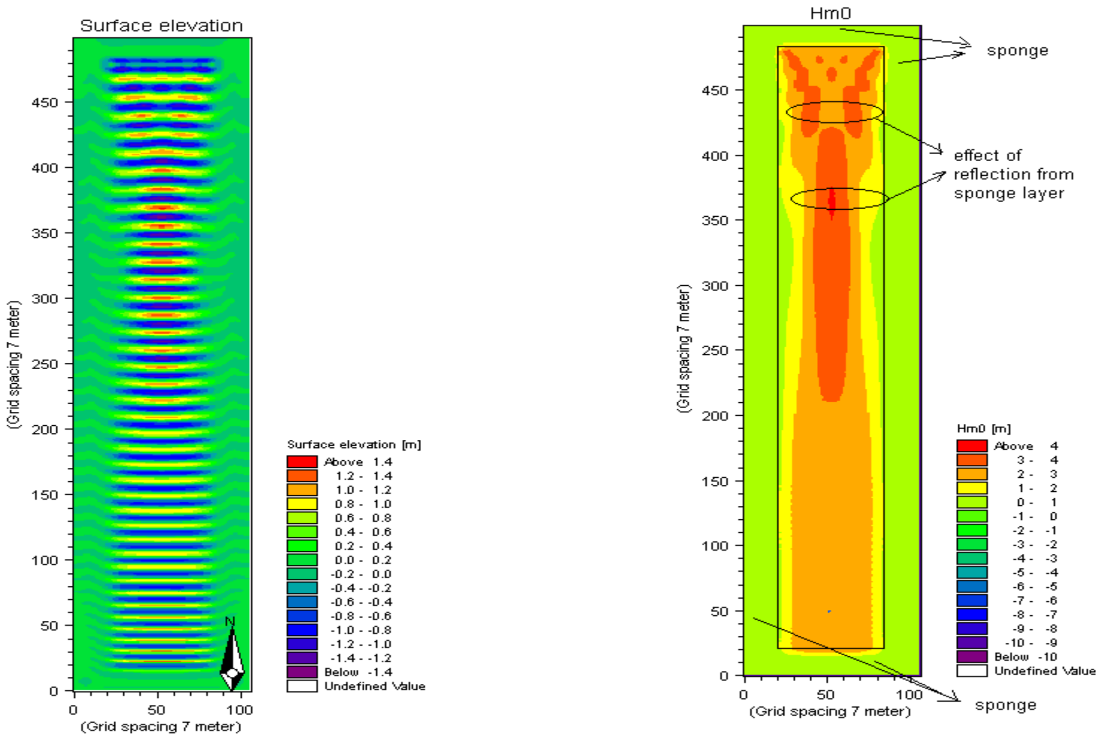


Figure 5-3: Output of a simple model, Sponge layer have used around the model (north –south-east-west)

It should be considered that using land value in lateral boundaries also can cause reflection when wave direction is not parallel to the boundaries. Therefore to solve this problem, in the simulations of this study, the width of the model (in x- direction) was increased to prevent the effect of reflection from these boundaries. Therefore before waves hit the lateral boundaries they have already reached to the end of the model.

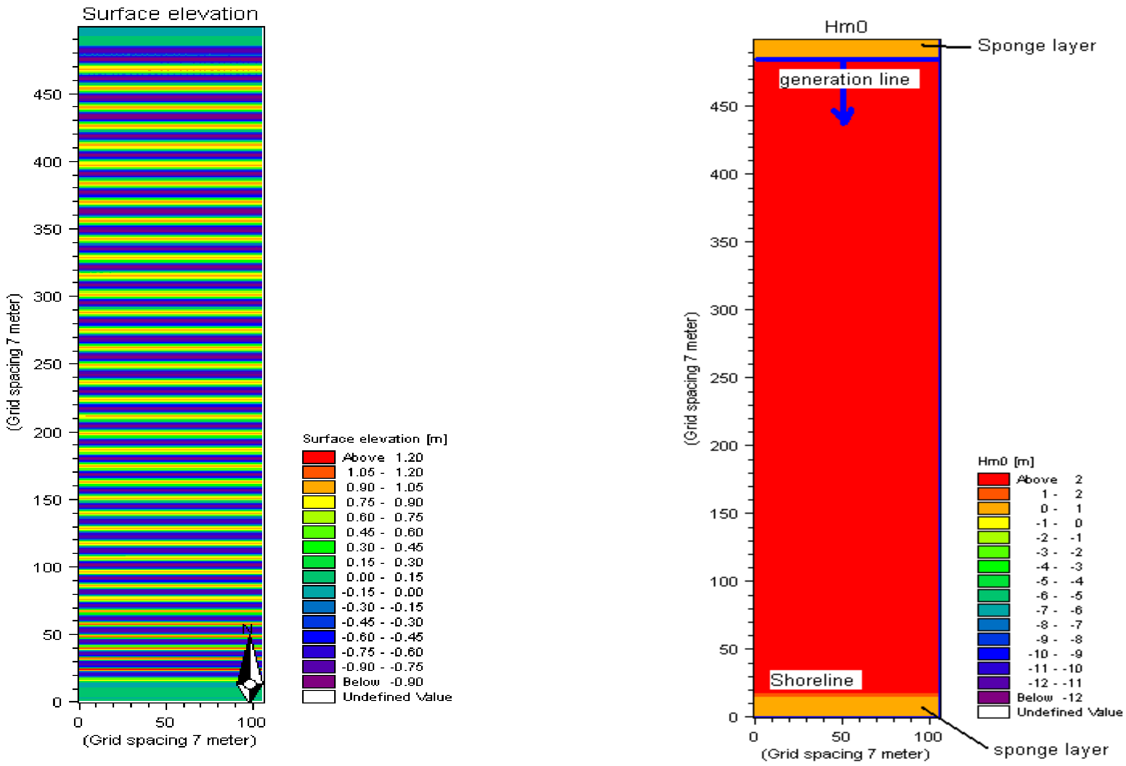


Figure 5-4: Output of a simple model, Sponge layer just have used in top and bottom of the model (north and south)

5.1.4 Porosity layer

For simulation of partial wave reflection and/or wave transmission through various types of structures a porosity layer map should be created. The porosity layer map includes a porosity value, which is set to unity at open water points (no dissipation) and between 0.2 and 1 along structures where it is necessary to include the dissipation effect of porous flow. If a porosity value is backed up by a land value (> 0), partial reflection will take place. Conversely, (partial) transmission will take place if land points do not back up the porosity values.

5.1.5 Internal wave generation data

In most applications, the model is forced by waves generated inside the model domain, i.e. using internal wave generation. Internal wave generation is performed by adding the discharge of an incident wave field along one or more generation lines. One of the advantages of using internal generation is that sponge layers can be placed behind the generation line, to absorb waves leaving the model domain (radiation type boundary).

The format of the internal wave generation data depends on type of waves such as regular, irregular or directional. For generation of regular wave data, the MIKE 21 Toolbox Regular Wave Generation tool and for irregular and directional waves MIKE 21 Toolbox Random Wave Generation can be used.

Incoming Waves: In this study generation line for creating offshore incident waves is placed in the North part of the model (Figure 5.5). A 20-gird sponge layer (147m) also is set behind the generation line.

Radiated Waves: For simulation of radiated waves from each Anaconda it is necessary to place a generation line at the end of each Anaconda to generate directional-monochromic waves (see also section 5.2). In Figure 5.5 the position of these lines is illustrated.

5.2 Simulation of the Anaconda in MIKE 21 BW

Simulation of structures in the MIKE 21 BW software is usually carried out by using porosity layer scheme. For example for simulation of a breakwater first its porosity values should be determined based on its reflection and/or transmission coefficient. Using ‘creating porosity’ function in MIKE 21 BW toolbox, the porosity values can be calculated. Based on the wave condition and some structural characteristics, the porosity value curve related to reflection and transmission coefficient is obtained from MIKE 21 BW toolbox. Figure 5.6 shows an example of porosity values based on reflection and transmission coefficients.

If a porosity value is backed up by a land value (> 0), partial reflection will take place. Conversely, (partial) transmission will also take place if land points do not back up the porosity values.

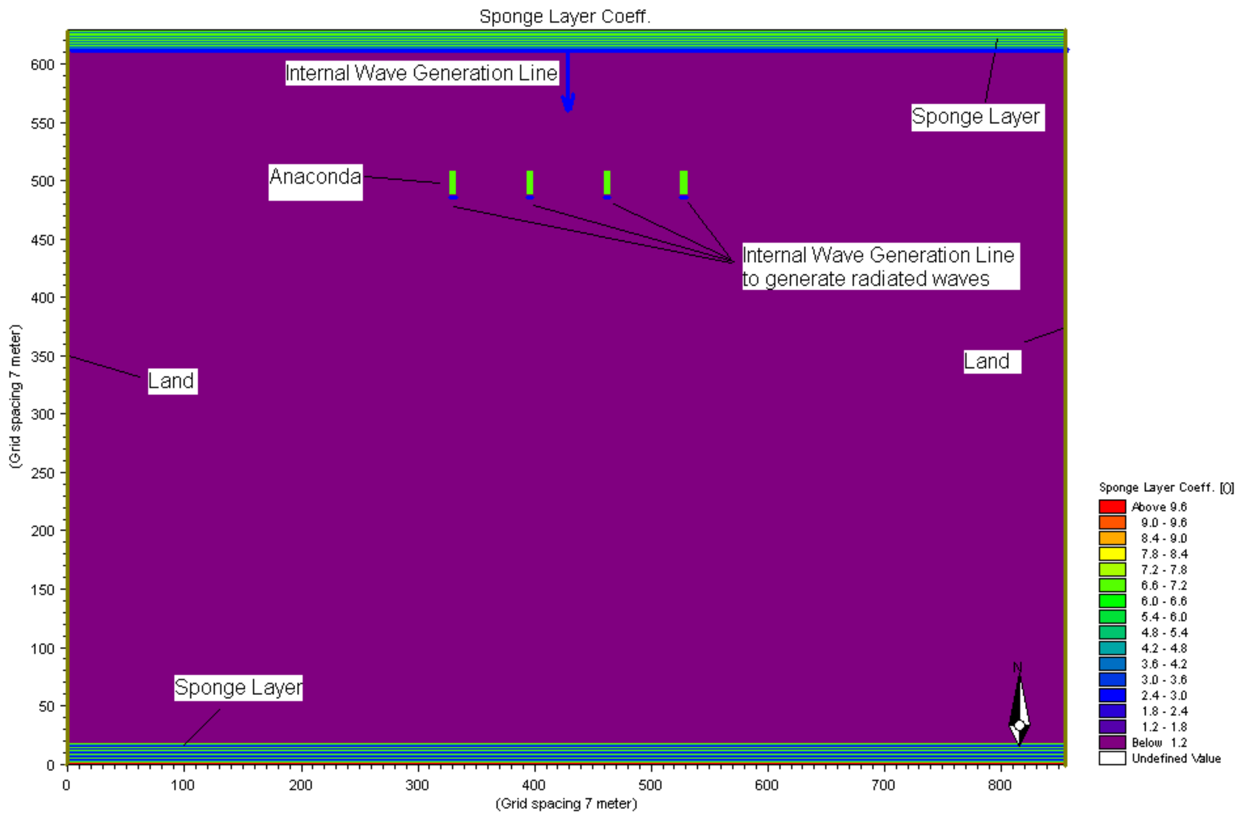


Figure 5-5: Position of sponge layers and Wave generation line in a typical model in this study

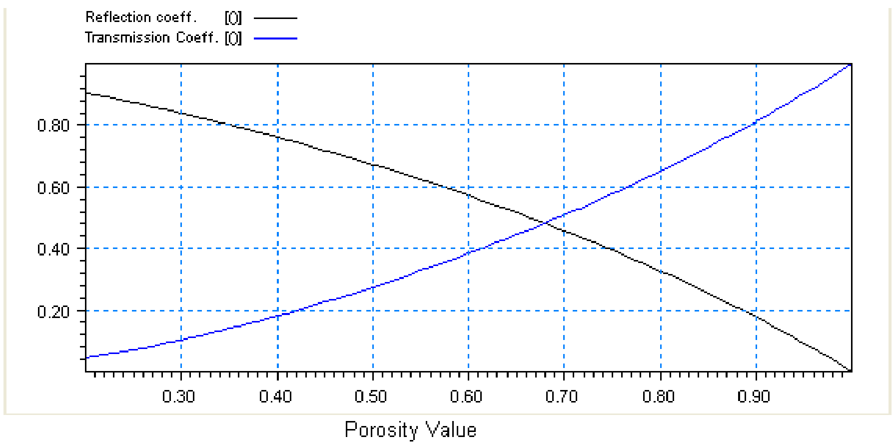


Figure 5-6: An example of porosity value versus reflection coefficient and transmission coefficient, output of MIKE 21 BW toolbox

Performance of Anaconda in the sea is not such as a breakwater or some bottom mounted wave energy converters. Anaconda is a floating flexible device; therefore there is no remarkable reflection. In fact reflection can be negligible in the case of Anaconda interaction with waves.

It is known that Anaconda captures all energy from a bond equal to its capture width. Hence no energy will transmit and will pass through each individual Anaconda.

Considering the above characteristics of the Anaconda, the idea of using sponge layer instead of porosity layer for simulation of the Anaconda seems more reliable. Sponge layer as it was mentioned in section 5.1.3 is a layer which can absorb energy gradually.

A sponge layer with the following characteristics was considered for simulation of an Anaconda with 7 meter diameter and about 150m length:

- Width: 21m (3 grids)
- Length: 147m (21 grids)

The width of the Anaconda in the model was assumed equal to 21m to correspond with the capture width of about 20m (see section 3.1).

For such a sponge layer, sponge values vary from 1 to 7. This layer can absorb all energy from incoming wave in a width of 21 meter.

Another challenge in the simulation of the Anaconda is its floating action. MIKE 21 BW does not have any option for Modelling of floating structures; therefore simulation of an Anaconda needs special considerations.

Every wave energy absorber in the sea generates (radiates) waves. In the other words "absorption of waves means generation of waves, J. Falnes". Therefore in this study it was decided to simulate Anaconda floating action by adding a radiated wave generation line at the end of each Anaconda.

Investigations about the wave radiation characteristics of Anaconda are now under process in the laboratory researches. By oscillating the Anaconda in a still water and detecting the results it would be possible to have precise data about the Anaconda floating performance, but this investigation has not finished yet. Therefore for this study some assumptions such as percentage of Radiation, characteristics of radiated waves about the Anaconda should be considered.

To generate more realistic radiated waves, it is assumed that the Anaconda generates monochromic directional waves. Figure 5.7 shows some input parameters for creating radiated waves data by using MIKE 21 BW toolbox.

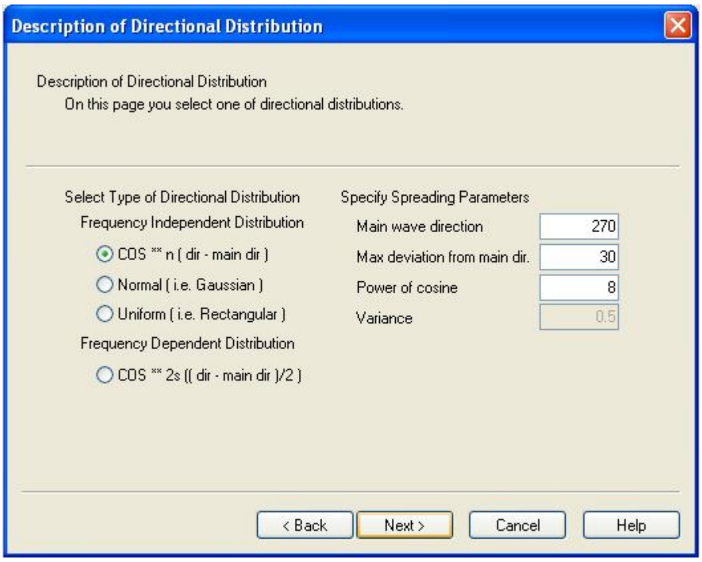


Figure 5-7: Input parameters for creating radiated wave data, MIKE 21 BW toolbox

5.3 Calibrating and Verifying the Model

Purpose: After setting up the model and preparation of all input data it is highly recommended to calibrate and verify the model. The purpose of the calibration is to tune the model in order to reproduce known/measured wave conditions. The calibrated/tuned model is then verified by running one or more simulations for which measurements are available without changing any tuning parameters. This should ensure that simulations can be made for any wave conditions similar to the calibration and verification wave conditions with satisfactory results.

Calibration parameters: After performing the calibration run for the first time, the simulation results should compare to the measurements (or other information). In many cases, differences between the two can be detected. The purpose of the calibration is then to tune the model so that these differences become negligible. The following model specifications can be changed in order to reduce the differences:

- Wave conditions
- Porosity
- Bed resistance
- Bathymetry
- Wave breaking
- Moving shore line

In this study because the condition is an idealised situation and measured data are not available, verification is done by using theoretical formula and tables.

To check the model bathymetry, boundary conditions, numerical parameters and input wave data, the output of the first models were checked with shoaling diagram. Shoaling was checked by excluding other parameters (wave breaking, bottom friction, filtering and etc.) from the model.

First results showed that some modification in the bathymetry and numerical parameters is required to fulfill shoaling diagram. Particularly checking validity of MIKE 21 BW for the following criteria should be considered:

- The ratio of the maximum water depth to the deep water wave length of waves with the shortest wave period must not be greater than 0.22, if the deep water correction terms are excluded, and 0.5, if these terms are included.

This criterion sometimes limits increment in depth of the model. For example having wave period of T=8sec (wave length, L=100m), limits the depth to a maximum of 50m in the bathymetry layer.

Figure 5.8 shows that how the output of the final model corresponds with the shoaling diagram. The data for illustrating shoaling diagram is the general data that have been extracted from wave table (Appendix A1).

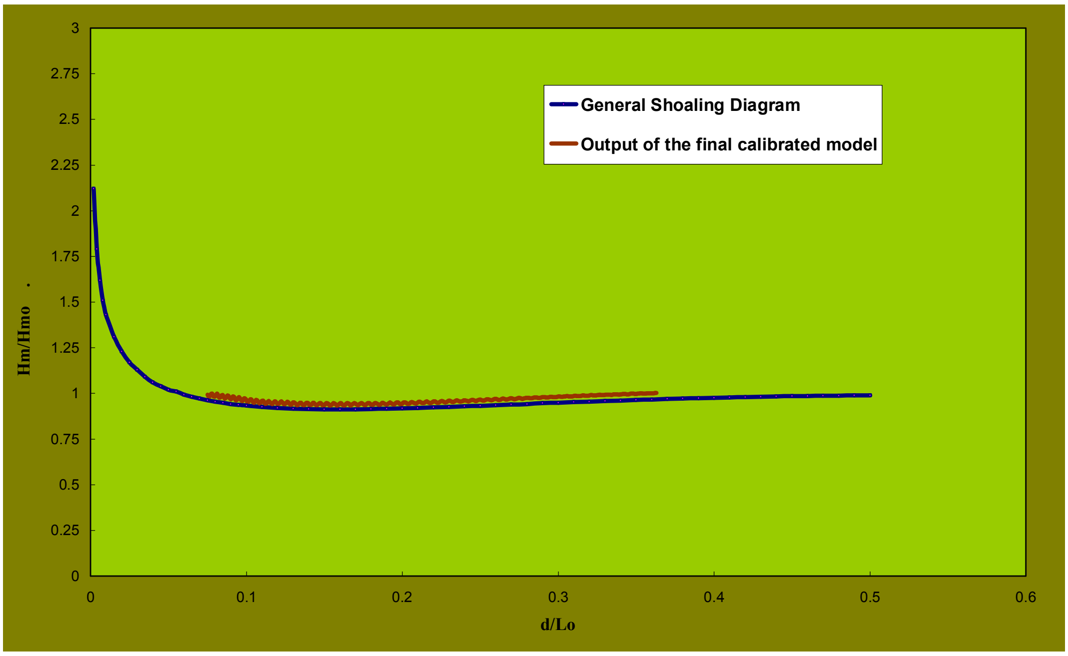


Figure 5-8: Comparing of the model output with general shoaling diagram

5.4 Configuration for grouping the Anacondas

As it was mentioned before, Anaconda dimension and technology is some how identical to Pelamis technology. Therefore for making a wave farm of Anacondas, initial configuration was assumed to be set similar to Pelamis wave farms. Based on Pelamis Power Ltd recommendation, in Modelling of a Pelamis wave farm in Portugal, placing the devices in three rows has been suggested (Mendes et al (2006) and Le Crom et al (2008)). Figure 5.9 shows the Pelamis wave farm configuration.

To find out effectiveness of this configuration for an Anaconda wave farm, three models with different configurations were studied in this research. The main difference between configurations is the distance between each two Anacondas in a row (distance in x-direction). Three configurations were named as follows:

- Configuration A: distance between two Anacondas d= 147m (equal to the length of one Anaconda)
- Configuration B: distance between two Anacondas d= 294m (two times of the length of one Anaconda)

- Configuration C: distance between two Anacondas d= 441m (three times of the length of one Anaconda)

The procedure for simulation is carried out in a step by step approach. First, each model was set up with just one row of Anacondas to assess the wave characteristics after passing the first row. Then the most effective and optimum place for the second and third rows is selected.

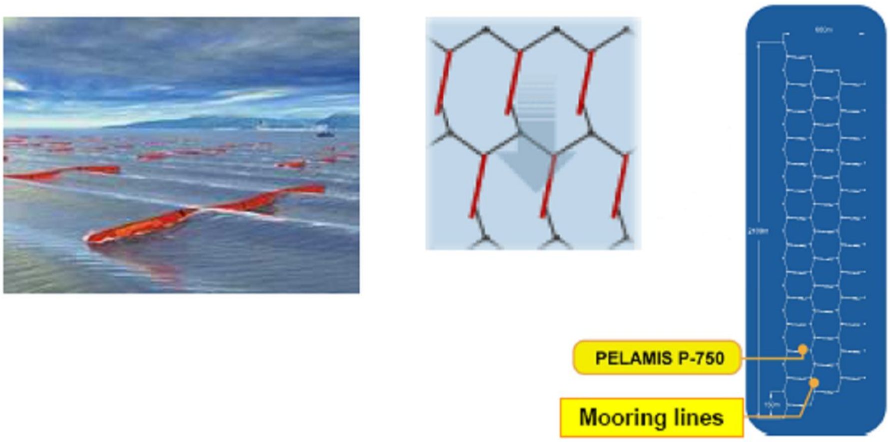


Figure 5-9: Pelamis wave farm configuration, Mendes 2006

5.4.1 Configuration A

Four Anacondas were set in one row in the initial model. Each Anaconda was presented as a sponge layer (see section 5.2) consisting of 3-grid width and 21-grid length in the model (therefore dimensions of Anaconda in the model would be: $3 \times 7 = 21m$ width (capture width) and $21 \times 7 = 147m$ length). Also the distance between Anacondas was set equal to d=147m (Figure 5.10).

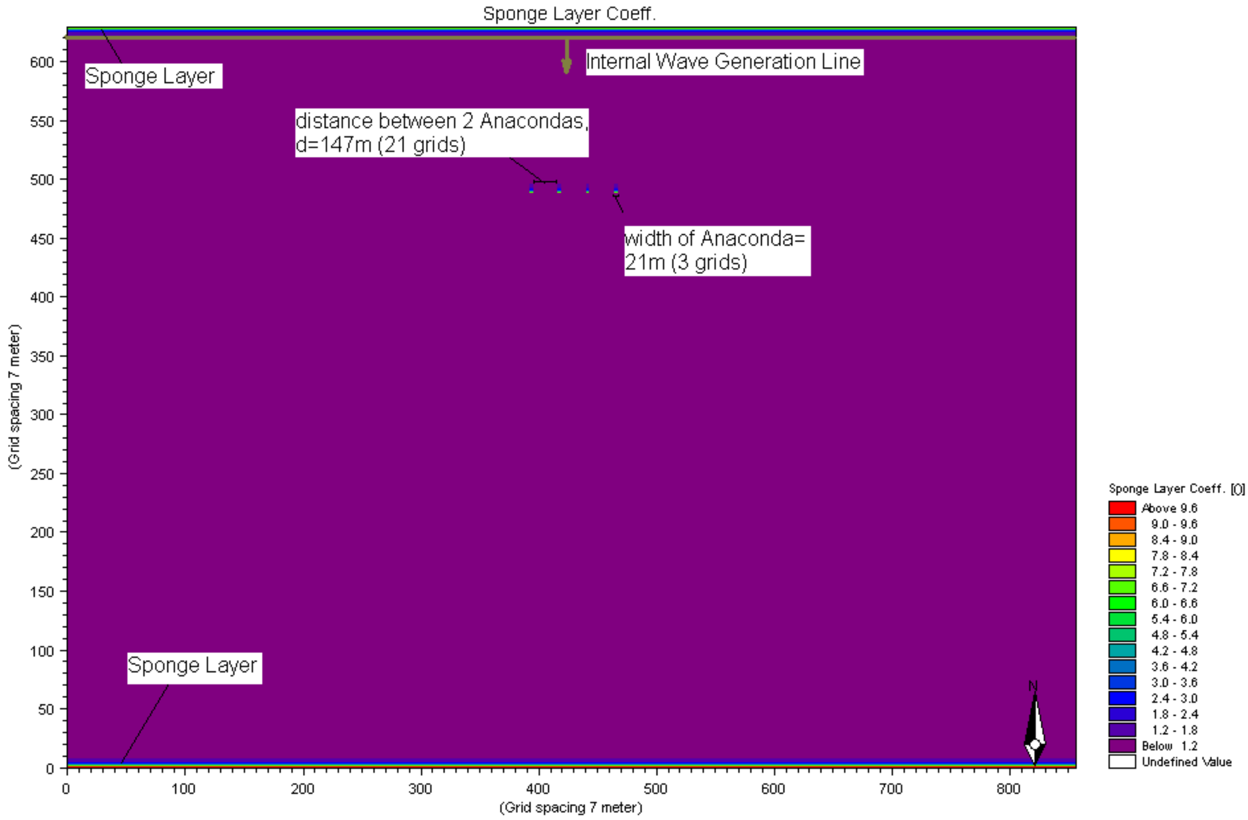


Figure 5-10: Sponge layer, input of the model with 4 Anacondas in one row, Configuration A, d=147m

The simulation is carried out for an incident wave height equal to 2m (significant wave height = 2.8m) and wave period of 8sec. For simulation of radiated waves from each Anaconda, an internal generation line producing directional waves was set at the end of each Anaconda. Characteristics of these radiated waves are:

- Wave height = 0.77 (assuming 15% of incident wave energy will be back to the sea as radiated waves, $E_2 = 0.15E_1 \Rightarrow H_2^2 = 0.15H_1^2 \Rightarrow H_2 = \sqrt{0.15 \times (2)^2} = 0.77m$)
- Wave Period= 8 Sec
- Frequency Spectrum: Monochromic Waves
- Maximum Deviation from main direction= 30 degree

Figure 5.11 shows the changes in significant wave height in the model area after 880 seconds (8800 time steps). It can be concluded from the results that the significant wave height just after passing the first row of Anacondas, in its maximum amount (indicated as ellipsoids in the figure 5.11), is around 2.8m. Therefore the incident significant wave height for the second row can be same as first row if we put the second row of Anaconda in places with maximum wave height.

Considering the figure 5.11, it is clear that placing the second row of Anacondas co-linear to the first row is more effective than placing them in the middle axes of the first row Anacondas.

This is because the output wave from the first row is greater after passing the Anacondas (ellipsoids in Figure 5.11) than wave height in the middle axes of them (between ellipsoids in Figure 5.11).

Therefore in the next step, the second row of Anacondas consisting of 3 Anacondas is placed co-linear to the first row.

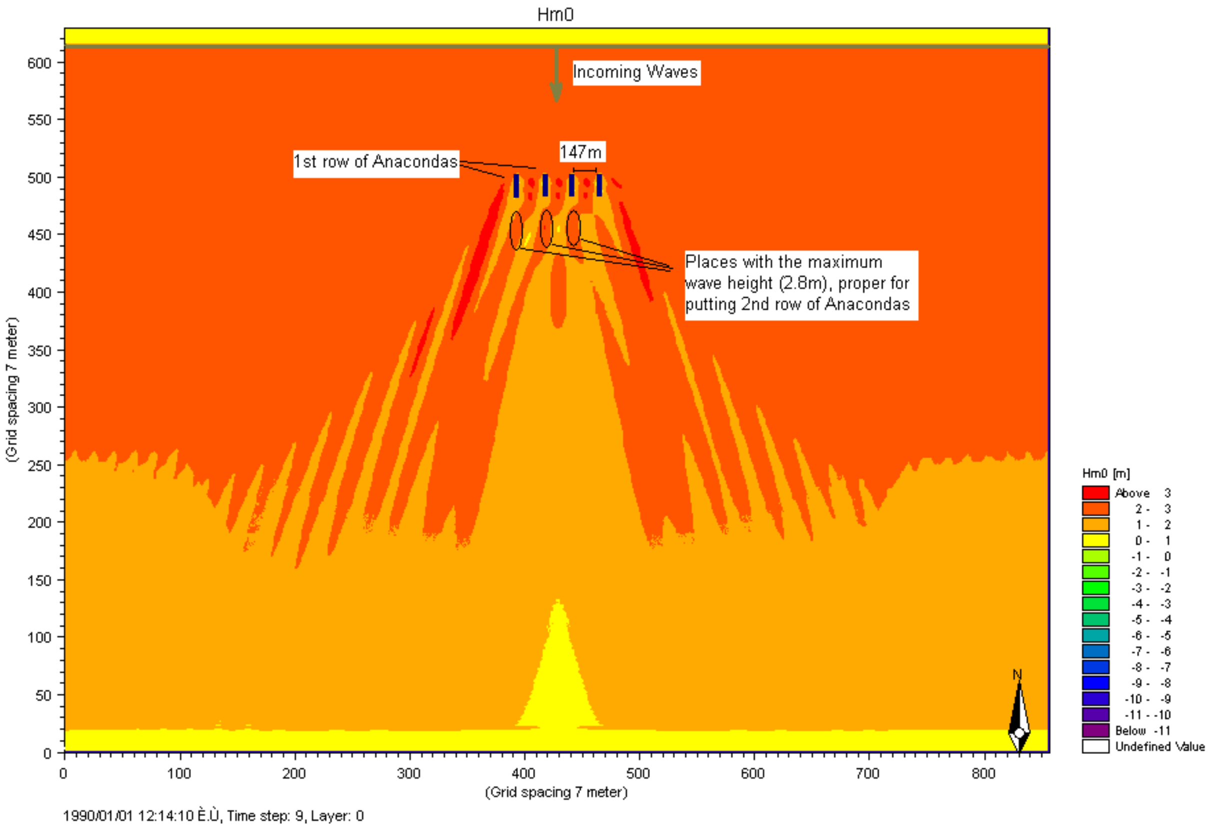


Figure 5-11: Significant wave height, output of the model with 4 Anacondas in one row (Configuration A, d=147m)

From previous stage the optimum place for second row of Anacondas in y direction was selected (Figure 5.12). Because of economical concerns (cost of cables, etc.), the second row should be as close as possible to the first row. Considering this, the distance from the end of the first row of Anaconda was selected equal to 161m (23 grids).

The second model was run with two rows of Anacondas, consisting of totally 7 Anacondas. Figure 5.12 shows the position of Anacondas in the model.

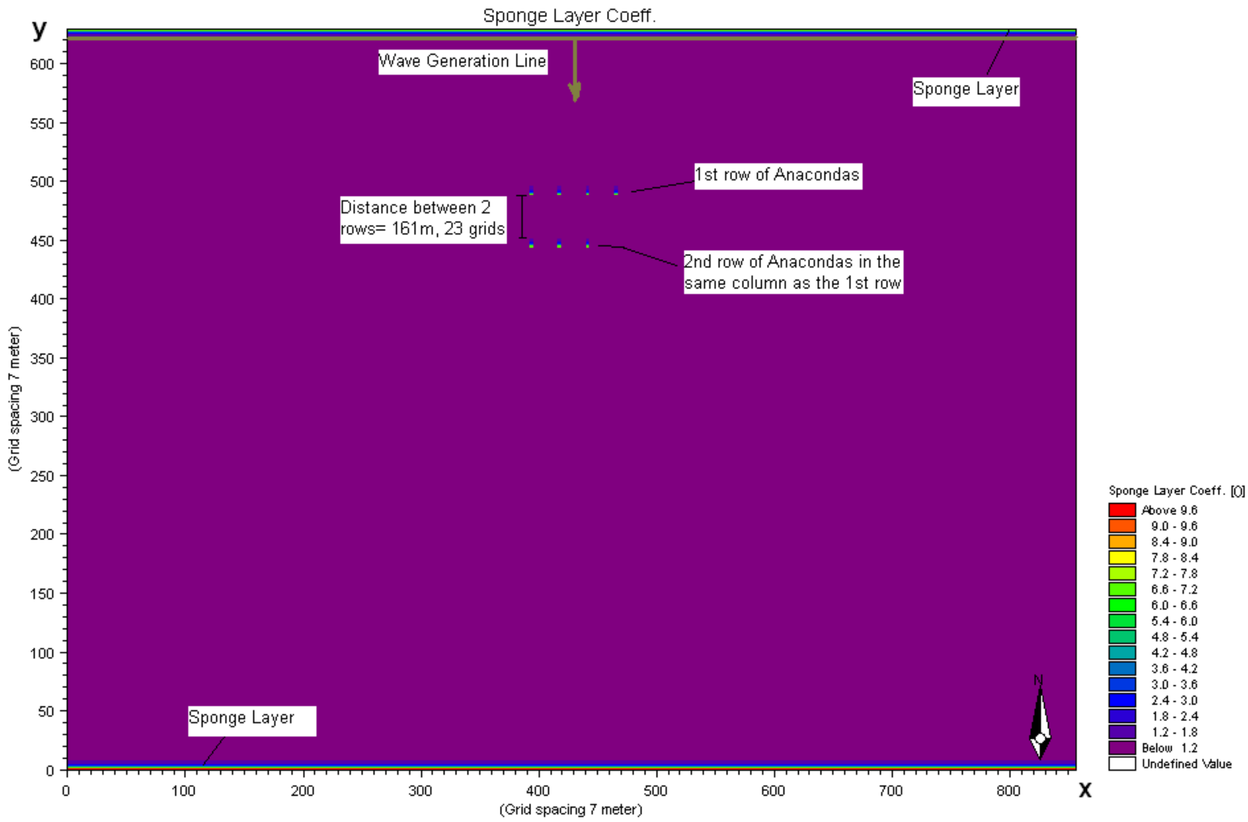


Figure 5-12: Sponge layer, input of the model with 7 Anacondas in two rows, Configuration A, d=147m

The model was run for an incident wave height equal to 2m (significant wave height 2.8m) and wave period of 8 seconds. Same as the previous model, for simulation of radiated waves from each Anaconda, an internal generation line producing directional waves was set at the end of each Anaconda. While the incident wave height was similar for Anacondas in the first row and Anacondas in the second row, therefore characteristics of these radiated waves for Anacondas in both rows are identical.

Figure 5.13 shows the significant wave height in the area after 880 seconds (8800 time steps). As it can be concluded from this figure, the significant wave height after passing the second row has decreased considerably. The significant wave height after second row, in its maximum amount (indicated as ellipsoids in the figure 5.13), is around 1.7m, while this amount is equal to 2.8m before waves enter the wave farm. This result shows a remarkable decrement in wave height after passing the second row of the anacondas. This conclusion leads us to do not put another row of Anacondas as the third row in this case. Because the wave height after the second row is too small, it will decrease the amount of wave energy extraction by Anacondas in the third row.

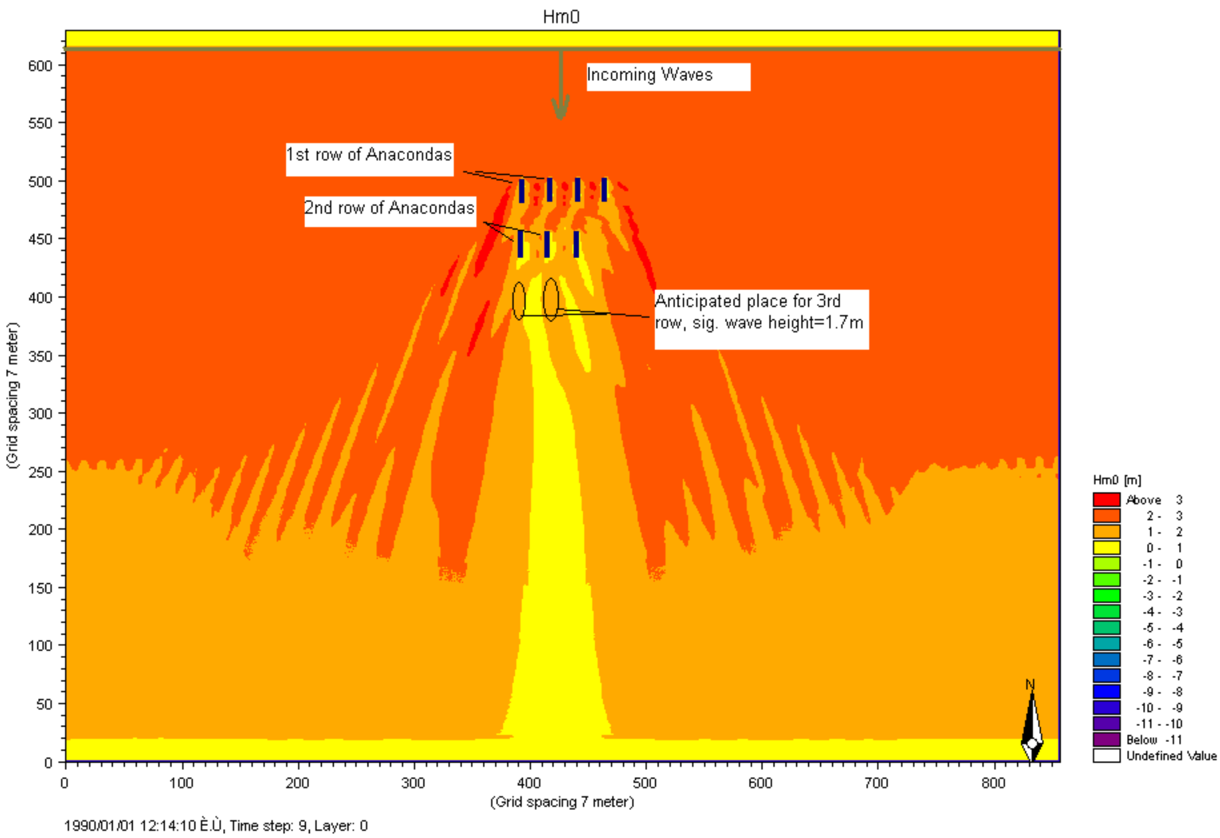


Figure 5-13: Significant wave height, output of the model with 7 Anacondas in two rows (Configuration A, d=147m)

5.4.2 Configuration B

Configuration B is created by doubling the distance between each two neighboring Anacondas (in x-direction). Initially the model is run just with one row of 4 Anacondas. The procedure for finding the optimum place for the second row of the Anacondas is same as explained method in the section 5.4.1.

First simulation with one row of 4 Anacondas is performed for an incident wave height equal to 2m (significant wave height 2.8m) and wave period of 8sec. For simulation of radiated waves from each Anaconda, an internal generation line producing directional waves was put at the end of each Anaconda. Characteristics of these radiated waves are:

- Wave height = 0.77 (assuming 15% of incoming wave energy will be back to the sea as radiated waves, $H_2 = \sqrt{0.15 \times (2)^2} = 0.77m$)
- Wave Period= 8 Sec
- Frequency Spectrum: Monochromic Waves
- Maximum Deviation from main direction= 30 degree

Figure 5.14 shows the significant wave heights as the output of running the model. Also the optimum place for placing the second row of the anacondas has been illustrated in the Figure. To have the maximum possible wave energy for the second row it is necessary to set Anacondas in places with greater wave heights.

As it can be concluded from this Figure, the significant wave height after passing the first row of Anacondas, in its maximum amount (indicated as ellipsoids in the figure 5.14), is around 3.2m, while this amount is equal to 2.8m before waves enter in the wave farm. Therefore the incident significant wave height for the second row can be higher than the first row if we put the second row of Anaconda in places with maximum wave height.

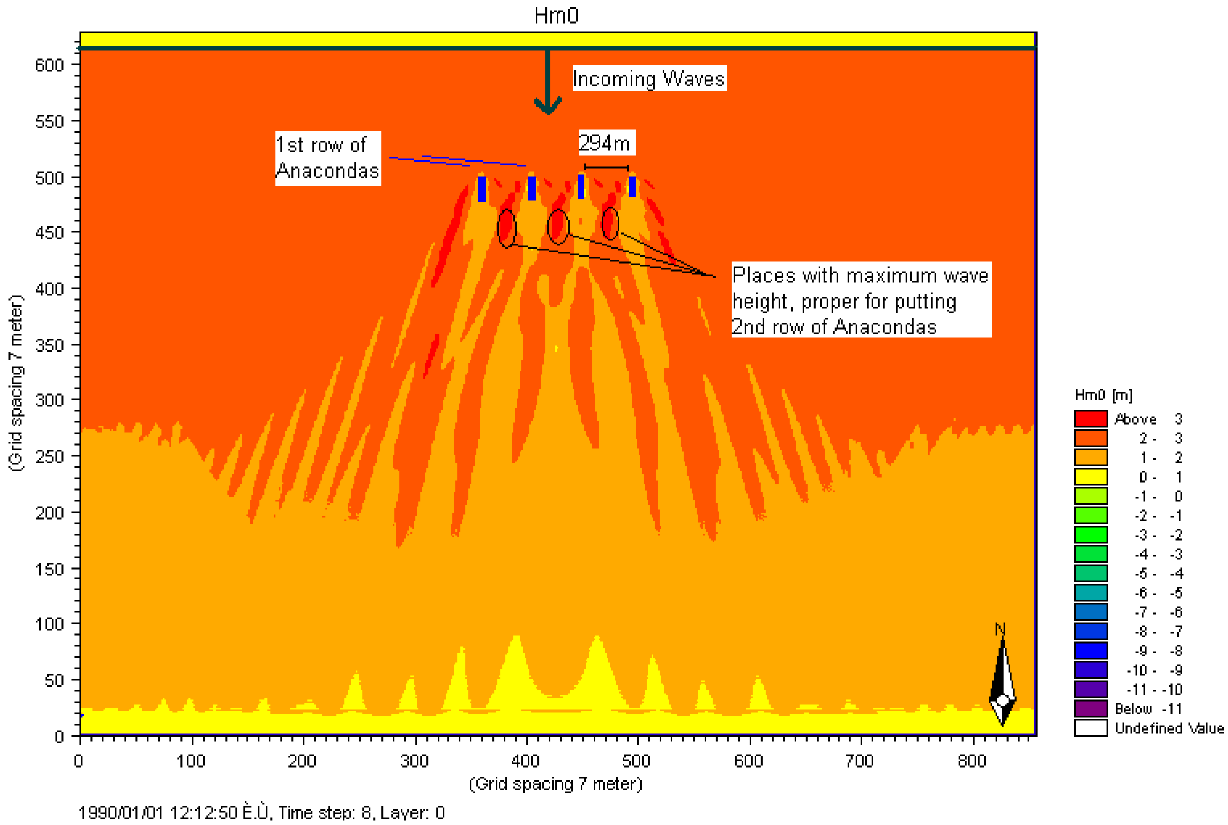


Figure 5-14: Significant wave height, output of the model with 4 Anacondas in one row (Configuration B, d=294m)

Consequently, in the next simulation, the second row of 3 Anacondas is placed in the middle axes of the column lines of the first row. The distance between the two rows is also set equal to 98m (which is optimum possible distance in this case).

The model with two rows of Anacondas was run for an incident wave height equal to 2m (significant wave height 2.8m) and wave period of 8 seconds. Same as the previous model, for simulation of radiated waves from each Anaconda, an internal generation line producing directional waves is placed at the end of each Anaconda. While the incident wave height is different for Anacondas in the first row and Anacondas in the second row, therefore input parameters for these radiated waves for Anacondas in first and second row are set differently. Table 5.1 presents radiated wave characteristics for Anacondas in the first and the second rows.

Table 5-1: Input wave characteristics in the model of two rows of Anacondas (Configuration B)

Position of the row	Incident wave height* (m)	Wave height of Radiated Waves (m)	Wave Period (Sec)	Frequency Spectrum for radiated waves	Max. Deviation from main direction for radiated waves
Anaconda in first row	2	$H_2 = \sqrt{0.15 \times (2)^2}$ =0.77**	8	Monochromic Waves	30 Degree
Anaconda in 2nd row	2.25	$H_2 = \sqrt{0.15 \times (2.25)^2}$ = 0.87**	8	Monochromic Waves	30 Degree

*: incident wave height=significant wave height/ $\sqrt{2}$

**: Assuming 15% radiation,

Figure 5.15 shows the significant wave height in the area after 880 seconds (8800 time steps). As it can be concluded from this figure, the maximum significant wave height after passing the second row has not changed considerably. The significant wave height after second row, in its maximum amount (indicated as ellipsoids in the Figure 5.15), is around 2.9m, while this amount is equal to 2.8m before waves enter the wave farm. This result shows a small increment in the maximum wave height after passing the 2 rows of the Anacondas.

Considering the above result, in this case it is possible to add more Anacondas in another row (the third row). In section 5.5 this results will be evaluated and explained more.

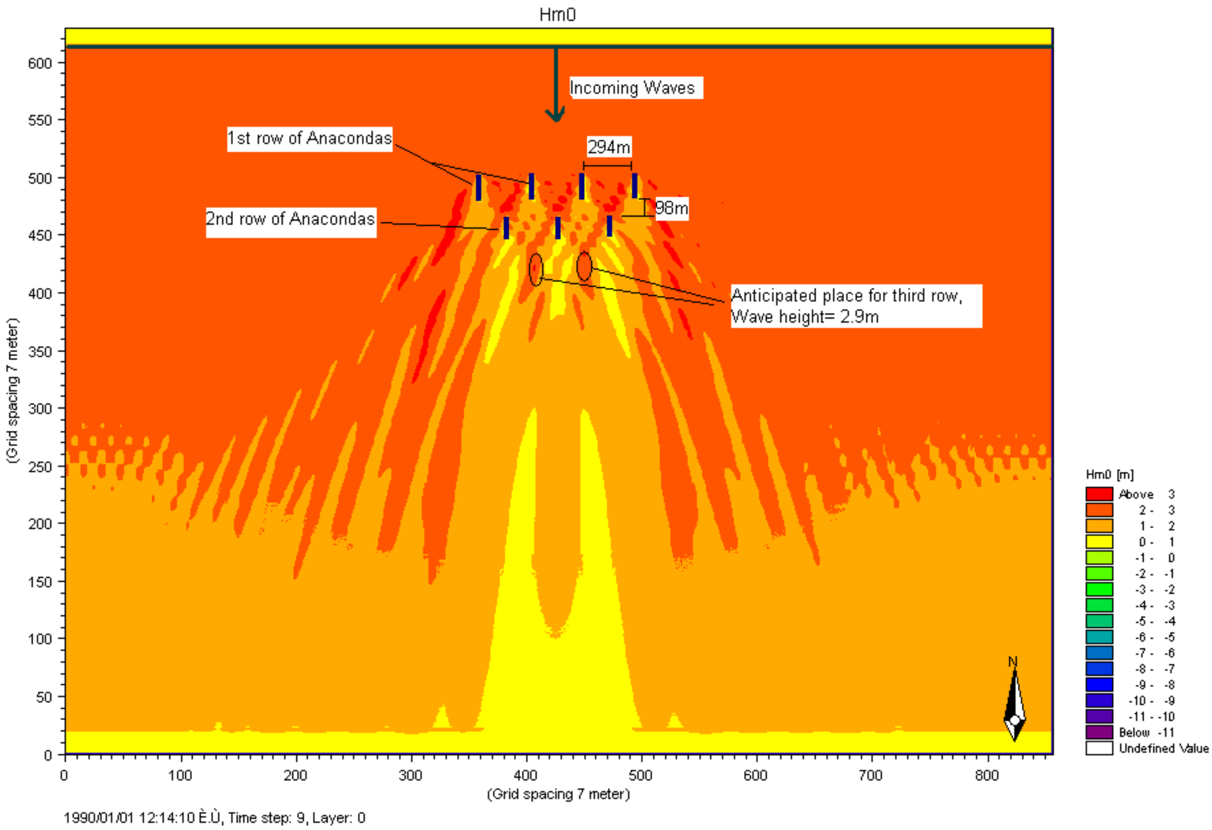


Figure 5-15: Significant wave height, output of the model with 7 Anacondas in two rows (Configuration B, d=294m)

5.4.3 Configuration C

For simulating the effect of increasing the distance between Anacondas, a wave farm with the distance between each two neighboring Anacondas equal to $3 \times 147 = 441m$ (three times of an Anaconda length) is modelled.

The procedure was done in a step by step approach same as sections 5.4.1 and 5.4.2. Figure 5.16 shows the significant wave height as the output of the model with one row of Anacondas.

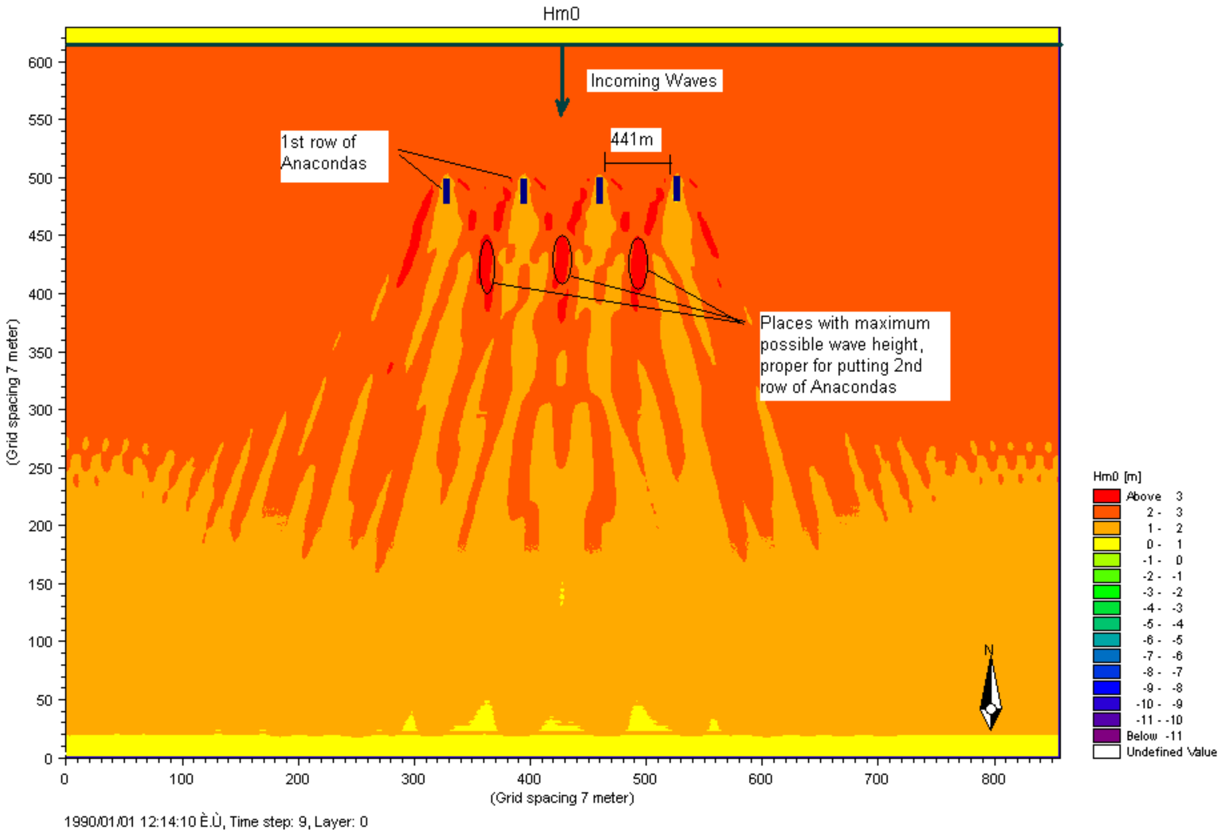


Figure 5-16: Significant wave height, output of the model with 4 Anacondas in one row (Configuration C, d=441m)

The second model with two rows of Anacondas also was simulated. The result is illustrated in the Figure 5.17. Maximum possible significant wave height after passing the first row is 3.3m while this parameter is 3m after waves pass the second row.

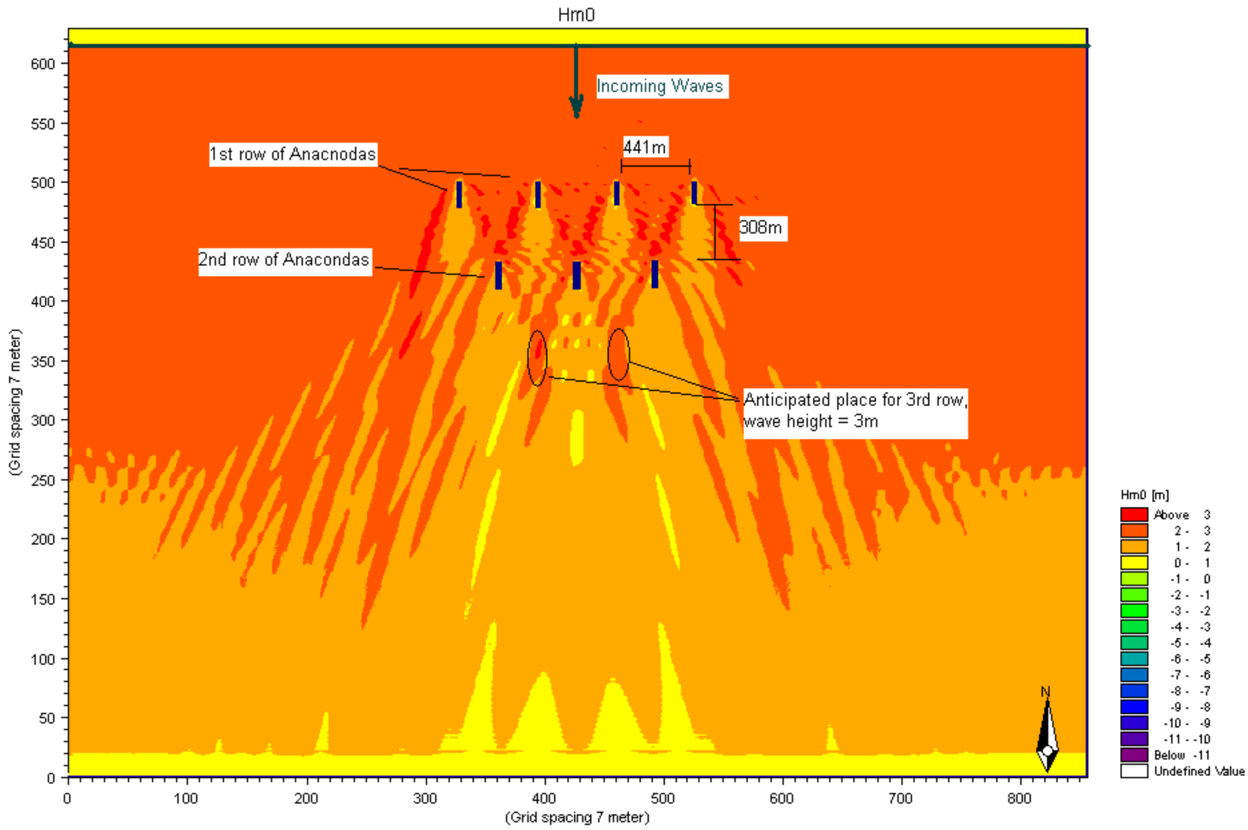


Figure 5-17: Significant wave height, output of the model with 7 Anacondas in two rows, (Configuration C, d=441m)

5.5 Suggestion for the optimum configuration of the Anacondas in a wave farm

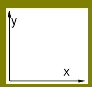
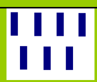
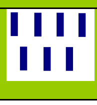
In previous sections of this chapter the investigation on the optimum way for grouping the Anacondas in a wave farm was discussed. In this section the results are compiled up to conclude the recommended configuration for setting up a wave farm for Anacondas.

Table 5.2 shows the sum up of the modelling of three different configurations (A, B and C). Using wider space between Anacondas in a row has considerable effect on the maximum amount of wave height passing each row. Setting up Anacondas in three rows would be possible if the distance between each row of Anacondas is selected suitably. The closer the Anacondas the lesser will be the output wave height. Therefore by choosing wider wave farm the amount of energy extraction can be higher. However the distance between Anacondas can be limited by:

- cost of cables
- the available area in the sea

For wider wave farm, more cost and expenses for connecting Anacondas to the electrical network is anticipated. Furthermore by increasing the width of the wave farm, more area is needed for installation process, which obviously increases interruption for shipping activities.

Table 5-2: Results of modelling three different configurations of Anaconda wave farm

Configuration	Schematic Figure 	Dist. between 2 Anacondas (x-direction), (m)	Dist. between 2 rows of Anacondas (y-direction), (m)	Incoming sig. wave height, (m)	Max. Sig. wave height after passing the 1st row, (m)	Max. Sig. wave height after passing the 2nd row, (m)
A		147	161	2.8	2.8	1.7
B		294	98	2.8	3.2	2.9
C		441	308	2.8	3.3	3

Considering all effective aspects on Anacondas configuration in a wave farm (i.e., economy, power output and area limitation), configuration B (with 294m distance between Anacondas in a row) can be considered as an optimum configuration and is selected for more studies in the next chapter.

It is recommended to evaluate each case individually by using the same procedure that was presented in this chapter, because based on significance of different parameters (economy, power output and the available area) the optimum configuration may change case by case.

6 The impact of a wave farm of Anaconda on shoreline

In this chapter the effect of a wave farm of a group of Anacondas on wave characteristics is investigated. It is predictable that by setting up a wave farm in an area, some amount of wave energy is extracted from offshore waves and as a result of that near-shore wave energy and wave height are decreased.

Change in wave climate in shoreline will affect sediment transport and consequently accretion or erosion leads to the change in shoreline. Besides the coastal morphology issues, the results from this study can also be applied in the planning and design of various coastal structures and for some marine environmental studies.

Another application of this study would be in assisting the prediction of wave scenario near wave farm sites where leisure time activities such as water sports and surfing may take place.

6.1 Results of simulation of a wave farm with 21 Anacondas

The aim of this section is to plan a wave farm with a capacity of about 20 MW electricity production. From the conclusions of the results from the previous chapter, to have an optimum configuration, the distance between Anacondas in a row is selected equal to 294m (two times of the Anaconda length) same as configuration B discussed in chapter 5. The distance between rows also was set equal to 98m (optimum place obtained in section 5.4.2).

Offshore incident waves are regular waves with the following characteristic:

- Wave height, H_1= 2m (significant wave height = 2.8m)
- Period, T_1=8 Sec

Assuming that 15% of wave energy is radiated back to the sea, radiated wave characteristics would be:

- Wave height for the 1st row, H_2 = 0.77 ($H_2 = \sqrt{0.15 \times (2)^2} = 0.77m$)
- Wave height for the 2nd and the 3rd row, H_2 = 0.87 ($H_2 = \sqrt{0.15 \times (2.25)^2} = 0.87m$)
- Wave Period, T_2= 8 Sec
- Frequency Spectrum: Monochromic Waves

- Maximum Deviation from main direction= 30 degree

The wave farm is deployed in three rows. The difference between radiated wave height in 1st row and radiated wave height in 2nd and 3rd rows is because of different incident wave height for each row (see section 5.4.2).

The bathymetry is an idealized and calibrated bathymetry identical to the bathymetry map explained in section 5.1.2 (Figure 5.2). Anacondas are also simulated by using sponge layers (3×21 grids) based on explanations in section 5.2. At the end of each Anaconda one directional wave generation line is placed to generate radiated waves. Figure 6.1 shows the configuration of the wave farm.

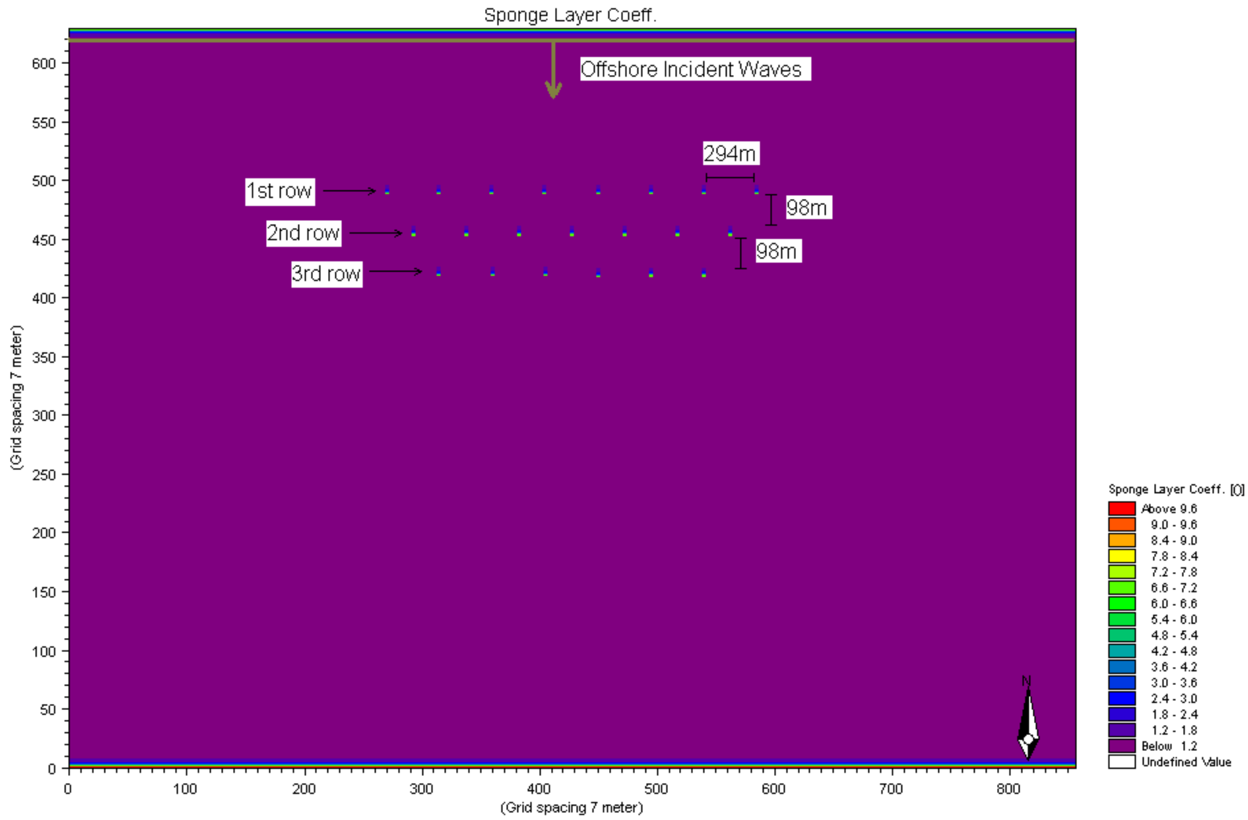


Figure 6-1: Configuration of 21 Anacondas in 3 rows, used in the simulation

In Figure 6.2 significant wave height at the end of simulation period is presented.

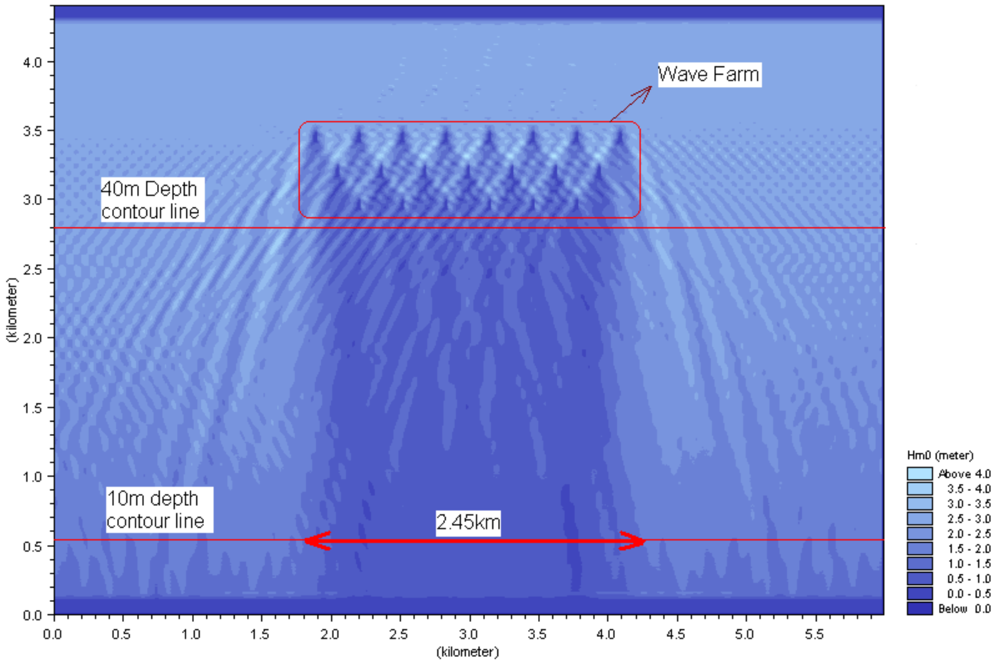


Figure 6-2: Significant wave height, simulation of wave farm of 21 Anacondas in three rows

From this figure it is clear that 2.45km of shoreline was found to be affected (from kilometer 1.8 to 4.25). This width is approximately equal to the width of the wave farm ($294 \times 7 + 21 \times 8 = 2226m$)

By checking the condition with a simulation without a wave farm, the effect of installation of the wave farm on near-shore wave height can be evaluated better. Running the model in the absence of the wave farm will result an average significant wave height of 2.56m along 10m depth bathymetry line, whereas the simulation with the presence of the wave farm results significant wave height of 1.19m in the impacted area. This results show that installing a wave farm decreases near-shore significant wave height by 53%.

Figure 6.3 illustrates the trend in the significant wave height along different bathymetry line at the end of the simulation period.

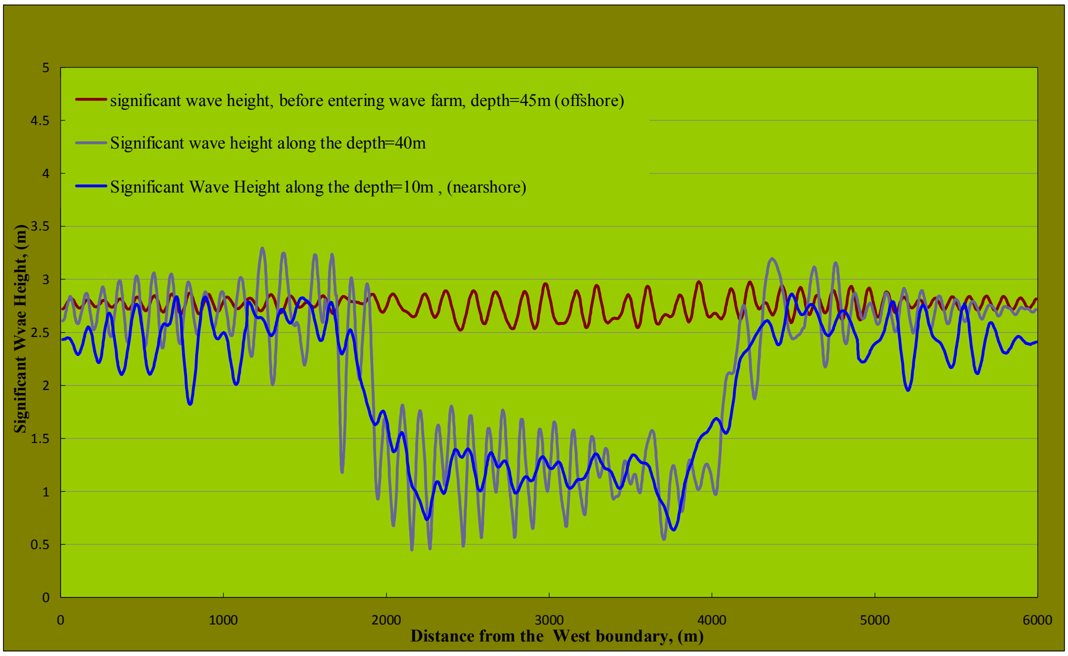


Figure 6-3: The significant wave height along different bathymetry line at the end of simulation period

In this figure significant wave height just before and after entering the wave farm has been illustrated. The plot for the depth of 45m shows the significant wave height prior to waves enter the wave farm. Fluctuations in this plot represent the effect of radiation of waves from Anacondas offshore side. Other two plots in Figure 6.3 refer to the depth contour line of 40 and 10m.

The average of significant wave height shoreward has not changed considerably. This parameter is 1.25m along 40m bathymetry line, whereas it is equal to 1.30m along 10m bathymetry line. These averages have taken from values between 1.8 km and 4.25km from the west boundary.

This small increment (1.25m to 1.30m) is the result of shoaling effect. A limitation of MIKE 21 BW is incapability to model wind effects. Whereas, in reality wind may regenerate waves and it would be possible that near-shore wave height become much higher than wave height just after passing the wave farm.

Higher domain fluctuations in the significant wave height plot along the depth of 40 m (grey plot) are observed compare with the plot along the depth of 10m (blue plot).

This result shows that some considerations about the rough wave condition around wave farm should be taken into account before setting up a wave farm of Anacondas. This rough wave region behind the wave farm may create problems for some ships and sea transportation and activities.

6.2 Sensitivity to change in radiation rate

As it was already mentioned, the physical performance and characteristics of Anaconda have not been fully investigated yet. One of the potentially effective parameters about Anaconda's impact on wave climate can be its radiation rate. Radiation rate is defined in this study as the ratio of radiated wave energy to absorbed wave energy.

The result of radiation rate of 15% was presented in previous section. To investigate the effectiveness of the change of radiation rate on shoreline wave characteristics, two more scenarios were simulated (simulation A and C).

Simulations A and C have radiation rates of 5 and 25 percent respectively. Table 6.1 shows the detail of all three simulations. Except radiation characteristics, other input parameters such as configuration, bathymetry and incident offshore wave characteristics were kept constant.

Table 6-1: Characteristics of three simulated models for evaluation of sensitivity to radiation rate

Simulation	Offshore Incident wave height, (m)	Radiation rate of Anacondas, (%)	Wave height of the radiated wave for the 1st row, (m)	Wave height of the radiated wave for the 2nd and 3rd row, (m)
A	2	5	0.44	0.49
B	2	15	0.77	0.87
C	2	25	1	1.15

The radiated waves from Anacondas were set as directional monochromic waves with maximum deviation from main direction equal to 30 degree and a period of 8 Sec (same as incident offshore wave period).

Figure 6.4 illustrates the significant wave heights along 10m bathymetry line. This result shows that change in radiation rate has very little effect on near-shore wave height.

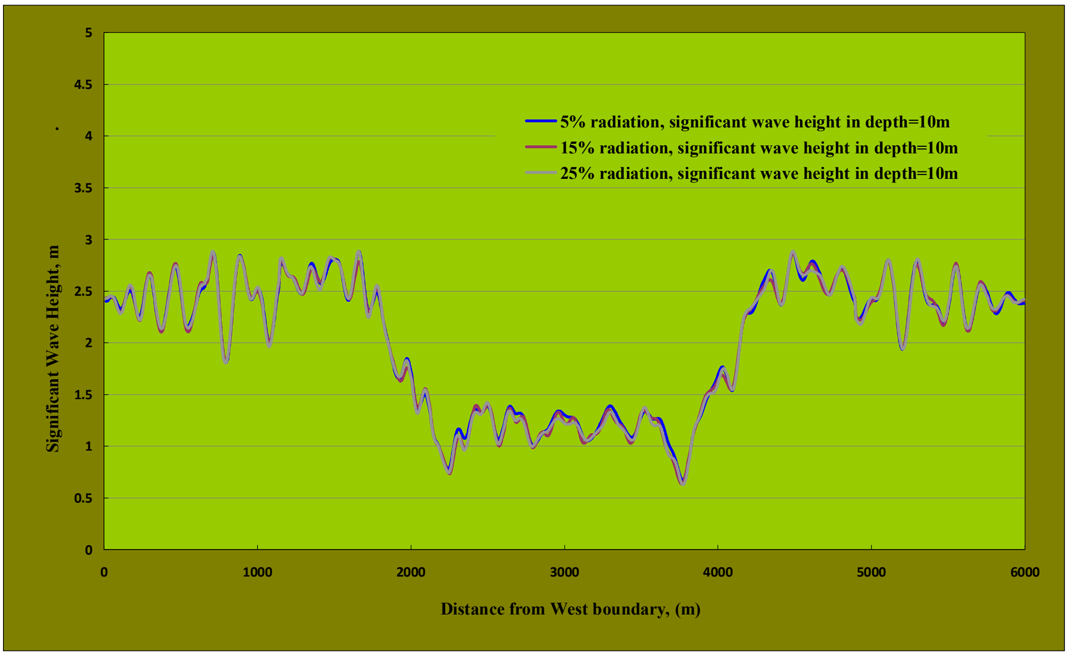


Figure 6-4: Comparison of the effect of different radiation ratio of Anaconda on significant wave height along 10m bathymetry line

To investigate more about this, another simulation was carried out with a same wave farm configuration and without offshore incident waves. In the other word the model is consisted of a group of 21 Anacondas oscillating in a still water condition. For this simulation the radiated wave characteristics for all Anacondas are set as follows:

- Wave height = 1m
- Wave period = 8 Sec
- Wave type: Directional Monochromic wave

Figure 6.5 shows the surface elevation in the area of interest at the end of simulation period. Also in Figure 6.6 the significant wave height along 40m and 10m bathymetry lines are illustrated.

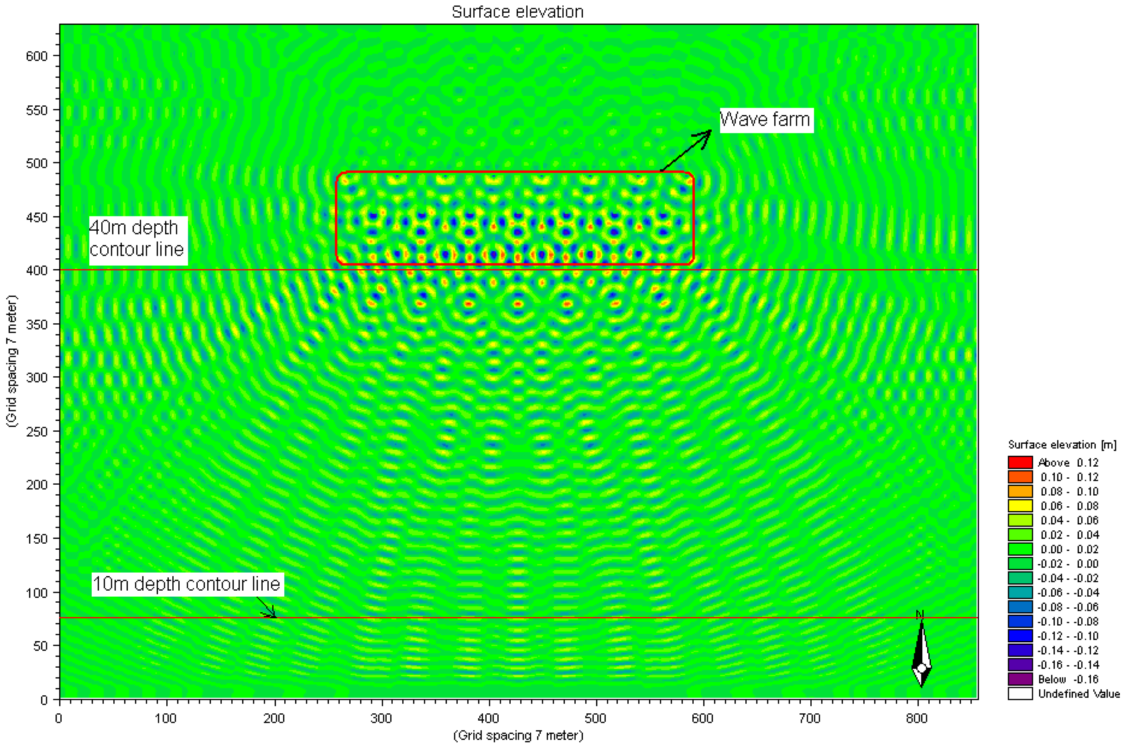


Figure 6-5: Surface elevation in the area at the end of simulation, wave farm in still water (no incident waves)

It can be concluded that radiated waves propagating from Anacondas neutralize each other so that when they reach to the shoreline the added up effect is negligible. The average of significant wave height in 10m depth contour line is equal to 5.5cm. This parameter is 10cm just after the wave farm along 40m depth contour line.

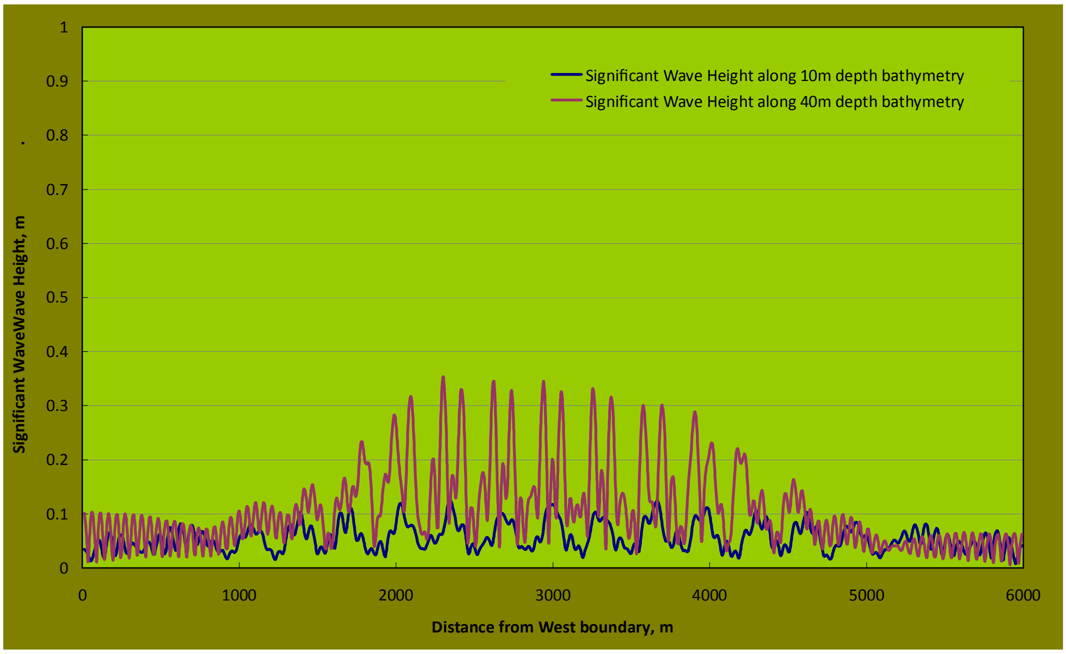


Figure 6-6: Significant Wave Height along 10m bathymetry line at the end of simulation, wave farm in still water condition

6.3 The effect of different incident wave height on the impact

In a real ocean condition the offshore incident wave height is not constant. It changes with time (seasonally, monthly or even daily). The performance of a wave farm and the amount of extracted energy depends on offshore incident wave height.

To consider the effect of variation of offshore incident wave height on the wave farm impact on shoreline, more simulations were performed. Table 6.2 shows the characteristics of the three simulations for this purpose.

Table 6-2: Simulations with different incident wave condition

Simulation	Offshore Incident wave height, (m)	Offshore Significant Wave height, (m)
I	1.5	2.12
II	2	2.8
III	2.5	3.5

All incident waves in the above table were regular wave with a period of 8 Sec. Radiation rates for all three simulations were kept constant (15% of incident wave energy for each row in each simulation). Figure 6.7 shows the significant wave height along 10m bathymetry line for all three simulations. The comparison of the results in this Figure shows that by increasing the incident wave height the fluctuation patterns in the plots are approximately identical for all three simulations, but the plots are shifted up for the greater incident wave heights. However, the length and intensity of the impact is constant. In all three cases, percentage of decrement in significant wave height is between 53% and 55%. The detail of the result is presented in Table 6.3.

Table 6-3: Output result of near-shore significant wave height for various offshore incident wave heights

Simulation No.	Offshore Incident Wave Height (m)	Average Sig. Wave Height before entering the wave farm, (m)	Average Near-shore Significant Wave Height, (m)	Decrement in near-shore Sig. Wave Height (%)
1	1.5	1.92	0.85	55
2	2	2.56	1.19	53
3	2.5	3.2	1.45	54

In Figure 6.8 the relation between incident wave height and the average significant wave height along 10m depth between 1.8km and 4.25km from the West boundary is presented. The greater offshore incident wave height results greater near-shore significant wave height. It can be concluded from this figure and the regression line that change in this relation is linear.

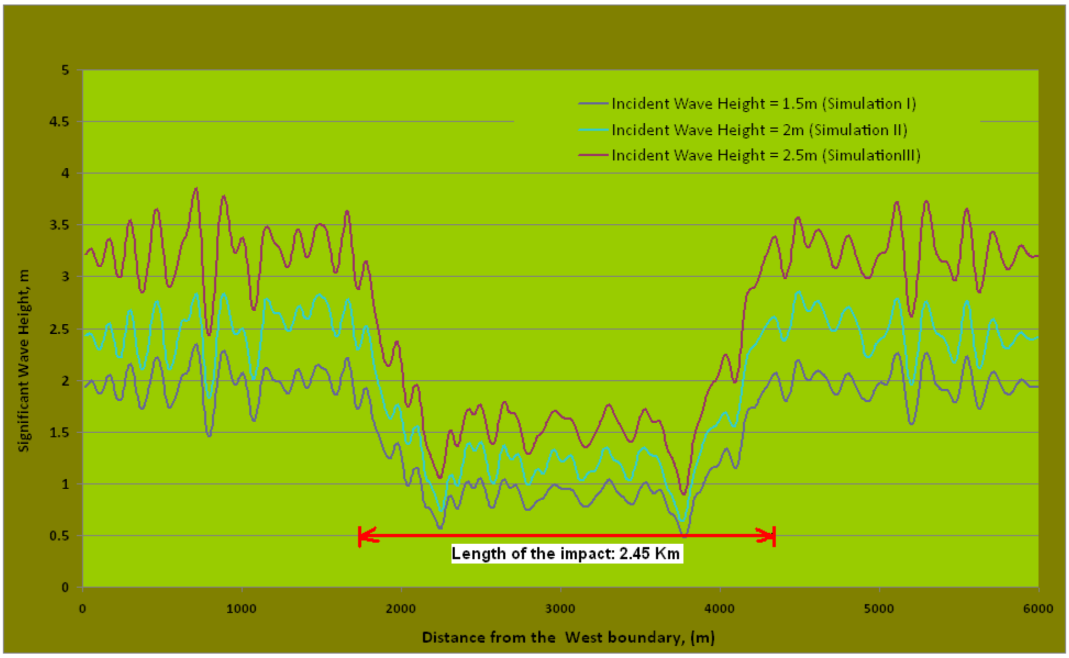


Figure 6-7: Significant wave height along 10m bathymetry line for different incident wave height

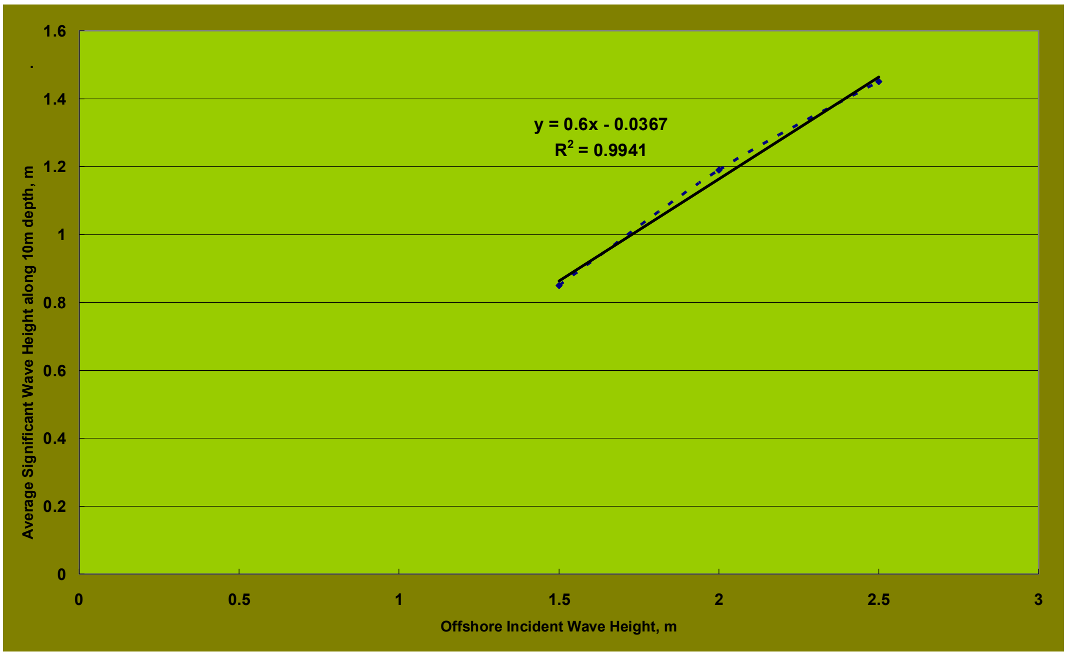


Figure 6-8: The relation between incident wave height and the average significant wave height along 10m depth between 1.8km and 4.25km from the West boundary

7 Conclusion and Recommendation

The research focused on two main subjects:

- Planning an optimum configuration of a wave farm of Anacondas
- Impact assessment of a wave farm of Anacondas on wave climate

Previous study has been done for bottom mounted Wave Energy Converter using MIKE 21 (Venugopal and Smith, 2007), whereas in this research MIKE 21 is used to study floating wave energy converters.

In this chapter first the conclusions from the obtained results are discussed and then recommendations for further studies are presented.

7.1 Conclusions

- Modelling of Anaconda was done by using Sponge layer as it absorbs all incoming wave energy along its capture width. Utilisation of sponge layer rather than porosity layer for simulation of a structure was a new approach for modelling a structure in MIKE 21 BW. This can be a new beginning for simulation of wave energy converters which reflection/transmission are not dominant parameters in their physical performance.
- Modelling of floating action of Anaconda was carried out by adding a wave generation line to the device to simulate radiated waves from them. Radiation rate defined as the ratio between radiated wave energy and absorbed wave energy and radiated wave height was calculated based on the assumption that the radiation rate of Anaconda is 15%.
- By a step by step approach of simulation, optimum configuration of a group of Anacondas was determined. In this approach each row of Anacondas is placed in a position with greater possible wave height.
- The distance between Anacondas in a row, affects the optimum positioning of the adjacent row of Anacondas in the wave farm. In this study for a specific calibrated bathymetry the optimum configuration for a wave farm consisting of 21 Anacondas was specified. It is well recommended that the optimum configuration for each case can be selected by using the same approach.

- Installing a wave farm of Anacondas about 3km offshore resulted remarkable decrease in the near-shore significant wave height. Even though the length of the impact was approximately equal to the length of the wave farm, it is concluded that the 53 percent decrease in wave height occurs along 10m bathymetry line after installing the wave farm (significant wave height along 10m depth was 2.56m in the absence of the wave farm while it was 1.19m in the presence of the wave farm). This considerable impact on near-shore wave height is due to the wider capture width of Anaconda compared with other types of wave energy converters. On one hand, the wider capture width of a wave energy converter has an advantage of extracting greater power from the sea, but on the other hand it has a greater impact on wave climate than the wave energy converters with narrower capture width.
- Small increment between significant wave height just after waves passing the wave farm and near-shore significant wave height (10m depth) was observed. This increment is due to shoaling. In reality existence of winds can regenerate waves and increase waves heights before approaching the shoreline.
- Significant fluctuations around and downstream of the wave farm were detected. This shows that some considerations about the rough region around wave farm should be taken into account before setting a wave farm of Anacondas. The rough wave condition behind the wave farm may create problems for some ships and sea transportation and activities.
- Some physical characteristics of Anaconda such as radiation rate are uncertain. To investigate about the effect of different radiation rate of Anacondas on shoreline wave climate, simulations with three different radiation rates were carried out (simulation A, B and C with radiation rate of 5%, 15% and 25% respectively). The result suggested that the various radiation rates have negligible effect on near-shore wave height.
- Simulation of a wave farm in still water condition also confirmed that the effect of radiated waves on shoreline wave characteristics is very small. Superposition of these waves resulted in an average of near-shore significant wave height of 5.5cm.

- Wave farms with various offshore incident wave heights (1.5, 2 and 2.5 meter) were simulated to analyse the effect of various incident wave heights on the shoreline. Results showed that the greater the offshore incident wave height the greater the near-shore significant wave height. A linear relation between the offshore incident wave height and the near-shore significant wave height was determined in this study.

7.2 Recommendations for further studies

- MIKE 21 as a software for simulation of coastal areas and structures needs more considerations for use in marine renewable energy projects. Certain limitations of this software reduce its capability in simulating wave energy converters. Possibility of simulation in deeper water and simulation of floating structures and decreasing the possibility of blow up or instability increases the applicability of this software.
- More study on effectiveness of sponge layer should be carried out by the software producer (DHI Ltd). The performance of sponge layers when are used in lateral boundaries is questionable. They can absorb wave energy perfectly when wave crest is parallel to sponge layer direction, but reflections were detected in this study for oblique waves.
- Wind effect can not be modeled using MIKE 21 BW. Hence wave regeneration by winds cannot be simulated using this software. This problem may be solved by linking MIKE 21 BW to MIKE 21 SW.
- More investigation and some laboratory tests are necessary for better understanding of Anaconda's floating action. Though the rate of radiation does not have significant effect on the shoreline, but it is necessary to consider it as it creates fluctuations around the wave farm.
- The safety of shipping and sea activities close to an Anaconda wave farm should be investigated further. Fluctuations and rough wave condition around the wave farm may limit the minimum distance between Anacondas.

- MIKE 21 BW has capability to simulate the wakes (wave generated by ship motion). By using this capability it may be possible to study the effect of motion of bulge wave inside the Anaconda on the surrounding wave climate.
- A step by step procedure was introduced in this study to find optimum configuration for a wave farm. It is recommended to evaluate setting up a wave farm in each case individually by using the same procedure, because based on significance of different parameters (economy, power output and the available area) the optimum configuration may change case by case.
- To decrease the impact of an Anaconda wave farm on near-shore wave climate it is recommended to place the wave farm far from the shoreline so that waves can be regenerated by winds before reaches the shore.

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Appendix A1- Wave Table

Appendix A2- Addressing the input and output files

Input files that have been used for the simulations in this study are addressed below:

Item	Location in the report	Location in the CD	
		Folder name	File name
Configuration A	Section 5.4.1	Optimum configuration	Configuration A.bw
Configuration B	Section 5.4.2	Optimum configuration	Configuration B.bw
Configuration C	Section 5.4.3	Optimum configuration	Configuration C.bw
Simulation A	Section 6.2	Radiation Rate	Simulation A.bw
Simulation B	Section 6.2	Radiation Rate	Simulation B.bw
Simulation C	Section 6.2	Radiation Rate	Simulation C.bw
Still Water condition	Section 6.2	Radiation Rate	Still Water condition.bw
Simulation I	Section 6.3	Various Incident Waves	Simulation I.bw
Simulation II	Section 6.3	Various Incident Waves	Simulation II.bw
Simulation III	Section 6.3	Various Incident Waves	Simulation III.bw