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Assessment of Efficiency of Array of Wave Energy Converters using Mike21-Bw Model, Near Bhagvati Bandar

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Abstract: *The world we live in is becoming more and more dependent on electrical energy and shortage of energy is bound to happen in the nearest future. India is the third largest in terms of power generation. Global warming and climate changes are the biggest challenge faced by mankind. Use of energy resources which are renewable and green that is producing low carbon emission is the need of the day. India has invested heavily on wind energy and solar energy. Ocean wave energy generation is renewable process with minimal carbon emission as well as less land requirement. India has a long coastline and has a tremendous scope for generation of wave energy along its coastline. Wave Energy Converter (WEC) is the device used in the wave energy extraction. For making the wave energy conversion feasible, the efficiency of a WEC is required to be assessed. For the design of WEC and assessment of its efficiency numerical models are very much useful giving the flexibility of assessing a number of alternatives at a relatively low cost. An attempt is made in this paper to estimate efficiency of an array of WECs using the Boussinesq Wave Model, namely the mathematical model MIKE21-BW. A site at Bhagvati Bandar, which is identified as hotspot for wave energy generation is considered for the installation of WECs. Numerical model experiments were carried out to find optimal configuration of an array of WECs and the findings are presented in this paper.*

Keywords: *Wave energy, Wave energy converter, Numerical modelling, Renewable energy*

I. INTRODUCTION

The world we live in is becoming more and more dependent on electrical energy and shortage of energy is bound to happen in the nearest future. Power is one of the most critical components of infrastructure which is reconcilable for the economic growth of nations. India's power sector is one of the diversified in the world. Sources of power generation in India range from non-renewable sources to renewable sources. The installed power generation capacity of country is 344.4 GW as of January 2018 and is the world's 5th largest. In 2016, India became the world's third largest power consumer, too. New sources of pollution are created by the new methods applied to produce the energy. By considering all the ill effects we have to develop renewable energy sources. India is surrounded with oceans/sea from three sides and has a long coastline. Therefore, wave energy seems to meet the future energy demands of India, if explored judiciously. The wave energy potential for Indian shore is about 170 MWh to 210 MWh per meter, which mainly found in the part of Indian Ocean (Holmukhe, 2014). A study along the coast of Maharashtra has shown that there are some potential sites such as Vengurla rocks, Malvan rocks, Redi, Ratnagiri etc. possessing an average annual wave energy potential of 5 to 8 KW/m and monsoon potential of 15 to 20 KW/m (Deshpande Sunil, 2015). The total potential along the 720 km-stretch of Maharashtra coast is approximately 500 MW for wave energy power plants (IREDA, 2014). Thomas Justin et al (2012) and Rupesh Kumar et al (2018) in their studies have shown that there are three locations near Bhagwati Bandar rich in wave energy potential. The average annual wave energy potential is 7 KW/m and average wave energy potential in the South West monsoon is 14 KW/m. Wave Energy Converter (WEC) is the device used in the wave energy extraction. For making the wave energy conversion feasible, the efficiency of a WEC is required to be assessed. For the design of WEC and assessment of its efficiency numerical models are very much useful giving the flexibility of assessing a number of alternatives at a relatively low cost. WEC can be considered as a permeable breakwater placed in a Wave flume and its transmission coefficient can be determined. Using a numerical model, it is possible to simulate a permeable breakwater by selecting appropriate porosity coefficient and width of the breakwater. From the model results, the transmission coefficient of a breakwater can be computed. Thus the wave transmission properties of a WEC for various wave and site conditions can be determined by carrying out several numerical experiments assuming the WEC as a permeable breakwater (Norgaard and Andersen (2012), Greenwod (2014). For making the wave energy conversion feasible, the efficiency of a WEC is required to be assessed. For the design of WEC and assessment of its efficiency, numerical models are very much useful giving the flexibility of assessing a number of alternatives at a relatively low cost.

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In the present paper, an attempt is made to estimate efficiency of an array of WECs using the Boussinesq Wave Model, namely the numerical model MIKE21-BW. A site at Bhagvati Bandar in India, which is identified as hotspot for wave energy generation is considered for the installation of WECs. Numerical model experiments were carried out to find optimal configuration of an array of WECs considering the wave and site conditions at the site and the findings are presented in this paper.

II. METHOD OF THE STUDY

It is proposed to carry out numerical model study to assess efficiency of array of wave energy converters (WECs) located at a site on the West Coast of India using a numerical model MIKE21-BW. The near shore wave data is analysed to derive the design wave conditions to be used as the boundary conditions for the numerical model MIKE21-BW. MIKE21-BW is a commercially available Mathematical model developed by DHI (Danish hydraulic Institute) used for studying of wave disturbance. The present work is done on the run station of Mathematical Modelling for Coastal Engineering division 2, CWPRS, Pune, Maharashtra. The model is based on time dependent Boussinesq equations of conservation of mass and momentum obtained by integrating the three-dimensional flow equations without neglecting vertical acceleration. They operate in the time domain, so that irregular waves can be simulated. These equations include nonlinearity as well as frequency dispersion. The model simulates the processes of shoaling, refraction, diffraction from breakwater tips and bed friction. It also takes into account partial reflections from the boundaries, piers and breakwater. This is done by including porosity terms in the governing equations named Continuity equation shown as (2.1) X Momentum equation shown as (2.2) and Y Momentum equation shown as (2.3) as follows:

Continuity Equation:

$$n\frac{\partial\varsigma}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0 \qquad (2.1)$$

X Momentum Equation:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)+n^2gh\frac{\partial\varsigma}{\partial x}+n^2p\left(\alpha+\beta\sqrt{\frac{p^2+q^2}{h^2}}\right)-\frac{p^2}{nh}\frac{\partial n}{\partial x}-\frac{pq}{nh}\frac{\partial n}{\partial y}$$

$$=n\frac{D^2}{3}\left(\frac{\partial^3 p}{\partial x^2\,\partial t}+\frac{\partial^3 q}{\partial x\,\partial y\,\partial t}\right) \qquad (2.2)$$

Y Momentum Equation:

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial x}\left(\frac{pq}{h}\right)+n^2gh\frac{\partial\varsigma}{\partial y}+n^2q\left(\alpha+\beta\sqrt{\frac{p^2+q^2}{h^2}}\right)-\frac{q^2}{nh}\frac{\partial n}{\partial y}-\frac{pq}{nh}\frac{\partial n}{\partial x}$$

$$=n\frac{D^2}{3}\left(\frac{\partial^3 q}{\partial y^2\,\partial t}+\frac{\partial^3 p}{\partial x\,\partial y\,\partial t}\right) \qquad (2.3)$$

Where,

$\varsigma(x,y,t)$ = water surface elevation above datum

$p(x, y, t)$ = flux density in x direction

$q(x, y, t)$ = flux density in y direction

$h(x, y, t)$ = water depth

$n(x, y)$ = porosity

g = gravity

α = resistance coefficient for laminar flow in porous media

β = resistance coefficient for turbulent flow in porous media

x, y = space coordinates

t = time

These differential equations are solved using a time-centred implicit finite difference scheme with variables defined on a space staggered rectangular grid. Output of MIKE21-BW model is in the form of wave height distribution plot in the area of study.

The BW model will be then used to simulate the wave penetration in the array of WECs with the actual bathymetry at the site for different alternatives and wave conditions. From the results, to estimate the potential of wave energy based on ratios of incident wave height to penetrated wave height and from that, to estimate the energy ratio. And by considering energy ratio, to fix the proper alignment which will give the large potential of wave energy. Finally, efficiency of array of WECs would be estimated based on several experiments by the numerical model. The MIKE21-BW model is used to simulate the wave penetration in the array of WECs with the actual bathymetry at Bhagwati Bandar for different alternatives and wave conditions. Finally, efficiency of array of WECs would be estimated based on following experiments by the numerical model. (Norgaard, 2012)

III. EXPERIMENTS

Numerical model studies were carried out to assess wave energy potential (Justin Thomas, 2012 and Rupesh Kumar, 2018) and wave energy map was prepared from the results of the studies. From the map three hotspots of wave energy were identified. Bhagvati Bandar is situated about 4.5 kms from Ratnagiri towards north at Latitude: 17.006689°N, Longitude: 73.269751°E, UTM: 43. The study area near Bhagvati Bander is shown in Fig. 1(a). The bathymetry in the study area is generated by operation of the CMAP software

Fig. 1(a). Location of Bhagwati Bandar, Ratnagiri, Maharashtra.

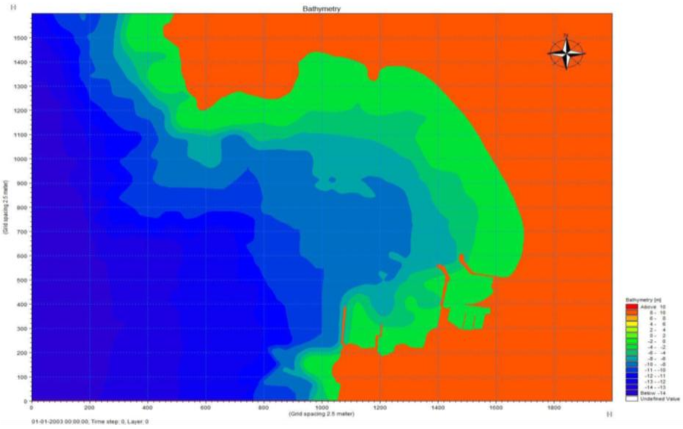

Fig. 1(b). Bathymetry of study area

A. *Model Experiment for the existing condition*

From the study area, the model region of about 800 m x 640 m is considered. The model region is discretised with rectangular grid with grid spacing of 2.5 m. The bathymetry of the model region is shown in Fig. 1(b). Wave generation file was prepared with peak time period using MIKE21 tool box. Random wave is generated at the boundaries based on a mean JONSWAP spectrum. The Model is run for two predominant wave directions i.e. West and WSW. The vector plots plotted from the results were observed to be similar for both the directions. The vector plot for West direction is shown in Fig. 2

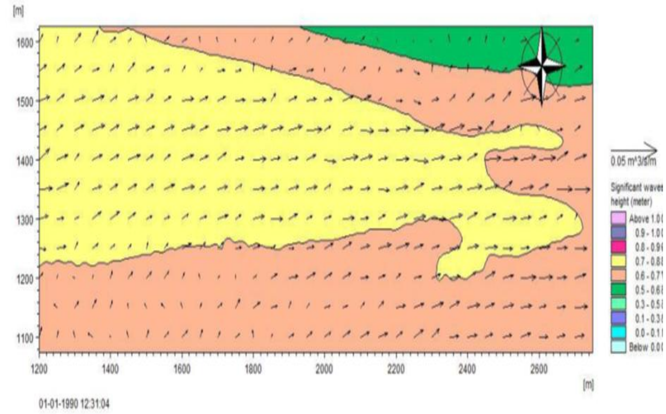

Fig. 2: Wave vectors for West direction

` From this vector plot, in general, the direction of wave approach is found to be normal to North- South direction. This information helps to locate and align the wave energy convertor.

B. *Model Experiments for the Alignment of WEC's*

A linear arrangement of two WECs is considered. The alignment of WECs was fixed by considering the predominant wave directions and plot of wave vector near Bhagvati Bandar. The wave climate analysis indicated the predominant wave directions to be West and WSW.

The wave hydrodynamics in the vicinity of Bhagvati Bandar was simulated by the numerical model for the three different alignments namely:

Alignment 1: WECs at 270°N
Alignment 2: WECs at 260°N
Alignment 3: WECs at 250°N.

The Alignment 1 with WECs at 270°N means, the wave approach direction which is normal to WECs is at 270° N. This is similarly applicable to the other two alignments. The schematic diagrams of these alignments for wave approach directions West and WSW are shown in Figs. 3(a) and 3(b).

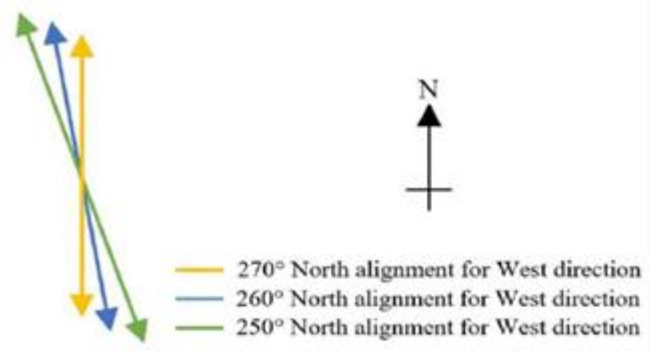

Fig. 3(a): Schematic diagram of alignments of the WECs for West direction

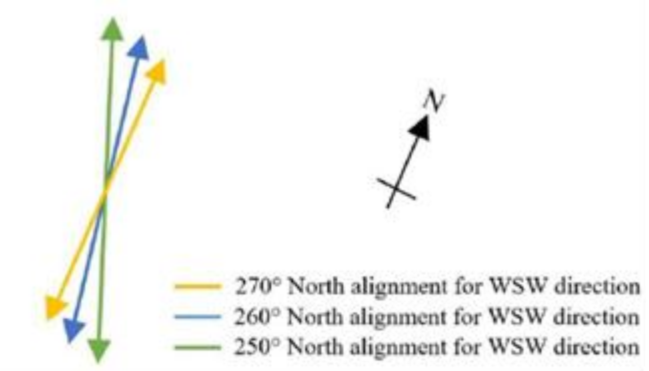

Fig. 3(b): Schematic diagram of alignments of the WECs for WSW direction

1. *Model experiment for Alignment 1: WECs at 270°N*

The bathymetry of the model region considered is the same as shown in Fig. 1(b). The porosity and the sponge layer were created using MIKE21 tool box. To study permeability of a WEC, a permeable breakwater with the transmission coefficient 0.81, and the device width equal to 24 m is considered. These permeable breakwaters act as wave energy converters (WECs). Two permeable breakwaters of 300m each at the depth of -10m, placed 100m apart are considered for the numerical study of conversion of wave energy. MIKE21-BW is used to simulate wave height and direction in the area. Wave transmission coefficient of a WEC is incorporated in the model by proper choice of porosity value, considering width of the WEC and the wave length.

The wave hydrodynamics in the vicinity of the WECs is simulated by the MIKE21-BW model for two predominant wave directions i.e. West and WSW. The corresponding plots of significant wave height distribution obtained from model results are shown in Figs. 4(a) and 4(b).

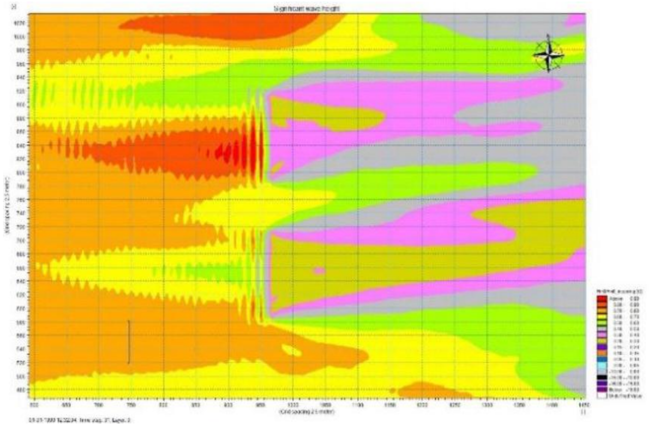

Fig. 4(a): Significant wave height (West Direction)

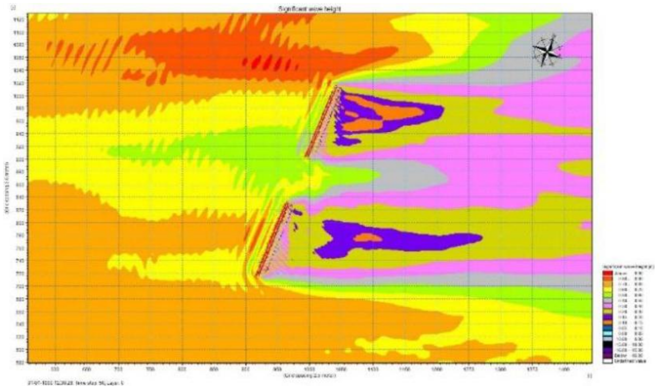

Fig. 4(b): Significant wave height (WSW Direction)

2. *Model experiment for Alignment 2: WECs at 260° N*

The Alignment 2: WECs at 2600 N is considered with the same model details described for the Alignment 1. The wave hydrodynamics in the vicinity of the WECs is then simulated for two predominant wave directions i.e. West and WSW. The corresponding plots of significant wave height distribution obtained from model results are shown in Figs. 5(a) and 5(b).

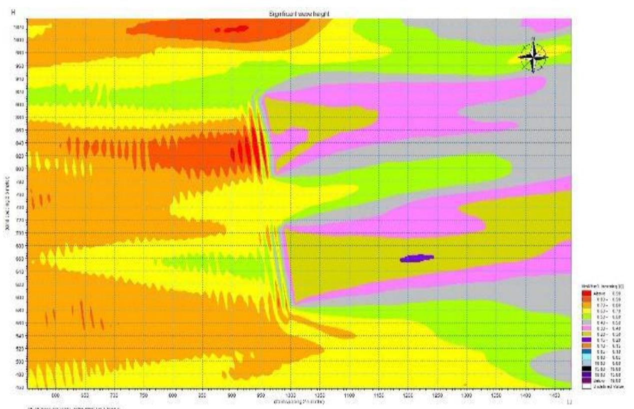

Fig. 5(a): Significant wave height (West Direction)

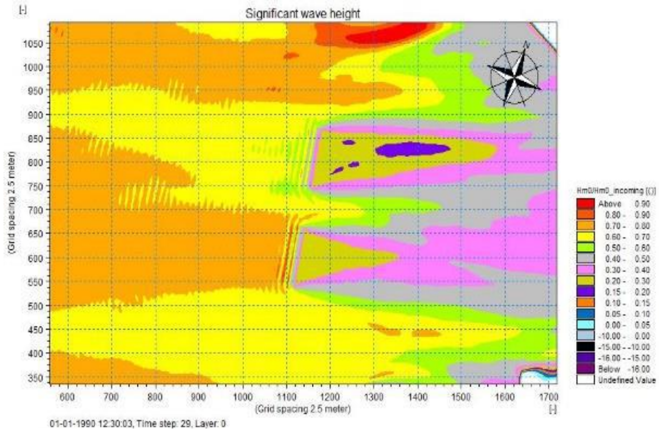

Fig. 5(b): Significant wave height (WSW Direction)

3. *Model experiment for Alignment 3: WECs at 250° N*

The Alignment 3: WECs at 2500 N is considered with the same model details described for the Alignment 1. The wave hydrodynamics in the vicinity of the WECs is then simulated for two predominant wave directions i.e. West and WSW. The corresponding plots of significant wave height distribution obtained from model results are shown in Figs. 6(a) and 6(b)..

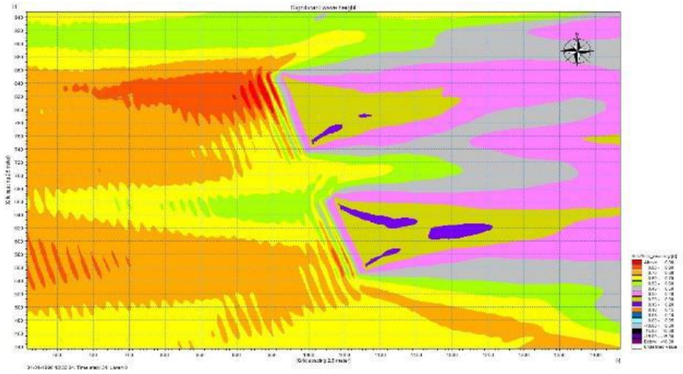

Fig. 6(a): Significant wave height (West Direction)

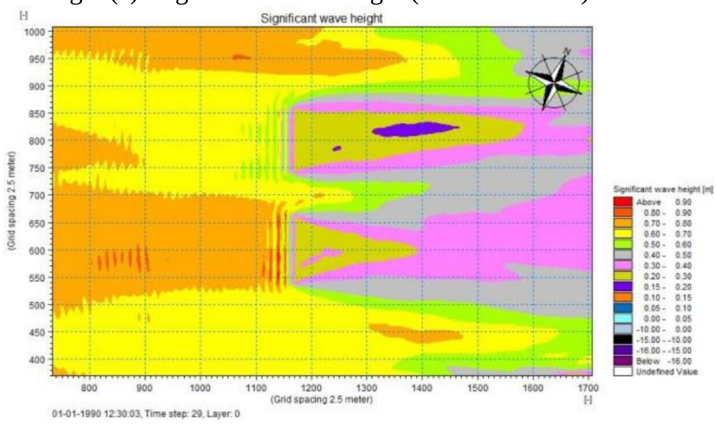

Fig. 6(b): Significant wave height (WSW Direction)

Computation of Energy Ratio(ER)

To achieve the objective of the project, it is very important that the array of WECs must be arranged in proper manner for the maximum efficiency of WECs. For the same, energy ratio was calculated from the performed experiments. The MIKE21-BW is used to simulate wave height distribution in the vicinity of the array of the WECs.

From each experiment, output file of significant wave height is used to calculate the transmission coefficient and energy ratio.

The transmission coefficient is calculated by:

$$K_t = \frac{h_t}{h_i} = \sqrt{\frac{E_t}{E_i}}$$

Hence, $(1 - K_t^2) = (Ei - Et)/Ei$ will give the ratio of wave energy intercepted to the incident wave energy. Let us denote the ratio by ER (Energy Ratio).

Where,

Kt= Transmission coefficient

hi = Incident wave height

ht= Transmitted wave height

Et= transmitted wave energy

Ei = Incident wave energy

For those six experiments, result files were generated and from that, energy ratio was calculated for the different alignment of WECs which are alien to the different angles with respect to north for the West and WSW wave direction. It is well known that as transmission coefficient decreases the efficiency of WEC increases. Also, as energy ratio increases the efficiency of WEC also increases. The following Table 1 shows the energy ratio for the West and WSW wave directions.

Table 1: Comparison of ER for the three Alignments

Direction / Alignment	Energy Ratio for WEST Wave Direction		Energy Ratio for WSW Wave Direction	
	WEC 1	WEC 2	WEC 1	WEC 2
Alignment 1 (270°)	0.78	0.76	0.74	0.72
Alignment 2 (260°)	0.88	0.86	0.79	0.78
Alignment 3 (250°)	0.80	0.79	0.86	0.85

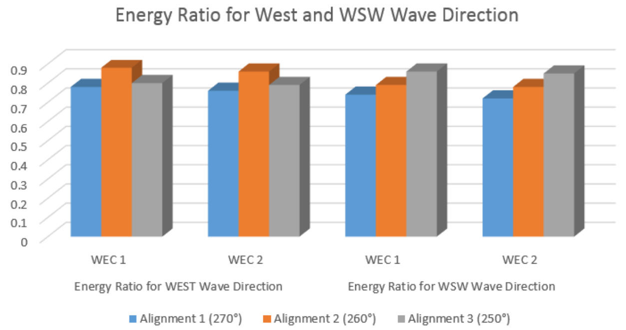

Fig. 7: Graph of Energy Ratio

From the Table 1, a graph of Energy ratio for West and WSW wave directions is drawn and shown in Fig. 7. From this graph it can be observed that energy ratio is high for Alignment 2 for the West wave direction, in which the WECs were aligned 260° N. Also, it can be observed that energy ratio is high for Alignment 3 in case of WSW wave direction, in which WECs were aligned 250° N. Also, it is observed that the efficiency for WEC2 is less than that of WEC1. This indicates that the effect of the bathymetry around the WEC is reflected in the results. Therefore, by comparing both values of energy ratio of West and WSW wave direction, the Alignment 2 for West wave direction is chosen for the further experiment, in which the array of WECs are aligned to 260° N

C. *Experiment for the Calculation of q-factor*

The operational behavior of a single device may have a positive or negative effect on the power absorption of the neighboring WECs in an array. As a result of the interaction between the WECs within an array, the overall power absorption is affected. Finally, the wave height behind a large farm of WECs is reduced and this reduction may influence the efficiency of array. The aim of this study is to develop a numerical modelling approach which is able to provide design criteria for the optimization of the layout of an array of Wave Energy Converters (WECs). From the above experiments, it is found that the WEST direction with WEC aligned to 260° is having the maximum energy ratio. The analysis of results is given in the discussion. Therefore, this alignment is chosen for the further experiments. The numerical model is run for the different arrangement of WECs in an array which was done by changing the location of WECs. Such two experiments were carried out with different arrangements of WECs. For that configuration, q factor was computed for the maximum efficiency.

The q-factor is a ratio of the total energy absorbed by an array divided by the energy absorbed by a single WEC device, multiplied by number of WEC devices in an array. If q-factor is greater than one then it shows positive effect on an array of WECs. Thus the q-factor helps to improve the efficiency of an array leading to the proper arrangement of WECs in an array.

Experiment for the linear arrangement of WCEs

As suggested in Section B, alignment of WECs to 260° N is considered in this experiment of linear arrangement of WECs in the bathymetry. The linear arrangement is shown in Fig. 8. It is suggested that in case of linear arrangement, the distance between the two consecutive WECs should be equal to the length of a WEC (Nørgaard 2012). Hence in an array, the distance between the two WECs is taken to be 300 m which is length of one WEC here. The model simulation is carried out and from the results q- factor is computed to be 0.86. The wave distribution plot for this linear arrangement is shown in Fig. 8.

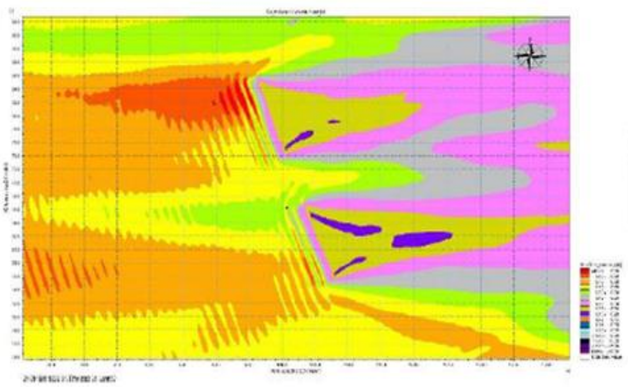

Fig. 8. : Significant wave height for linear arrangement of WECs

Experiment for the Parallel arrangement of WCEs

For this experiment the WECs are aligned to 260° with parallel arrangement in the bathometry. The parallel arrangement is shown in Fig. 9. The lateral distance between the two WECs is 300m as shown in Fig. 9. The model simulation is carried out and from the results q- factor is computed to 0.56. The wave distribution plot for this parallel arrangement is shown in Fig. 9.

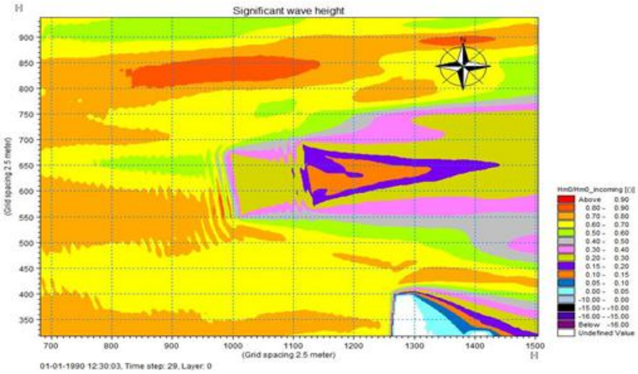

Fig. 9. : Significant wave height for parallel arrangement of WECs

From the values of q-factor computed, i.e. 0.85 for the linear arrangement and 0.56 for the parallel arrangement, the linear arrangement is preferable instead of parallel arrangement of WECs in an array. This is because the q-factor for the linear arrangement is greater than the parallel arrangement. Also, because, if value of q-factor is more than one or nearly equal to one, then it shows the positive effect for an array.

IV. CONCLUSION

The Boussinesq Wave Model MIKE21-BW is used to simulate wave hydrodynamics and to estimate efficiency of an array of WECs considering bathymetry near mouth of Bhagvati Bandar in India which is identified as hotspot for wave energy generation. Numerical model experiments were carried out to find optimal configuration of an array of WECs and the main findings are presented below.

1. The alignment of WECs was fixed by considering the predominant wave directions and plot of wave vector near Bhagvati Bandar. The wave climate analysis indicated the predominant wave directions to be West and WSW.

2. The wave hydrodynamics in the vicinity of Bhagvati Bandar was simulated by the numerical model for the three different alignments namely, Alignment 1: WEC at 270 degree with respect to north, Alignment 2: WEC at 260 degree with respect to north and Alignment 3: WEC at 250 degree with respect to north.

Alignment 1 - WEC at 270^0 N: For this alignment, simulations of wave hydrodynamics using MIKE21-BW were carried out for waves approaching from both West and WSW directions. The ratio of intercepted energy to incident wave energy computed (Table 1) indicated that the ratio is the maximum for the waves approaching from West direction.

Alignment 2 - WEC at 260^0 N: For this alignment, the model simulations were carried out for waves approaching from both West and WSW directions. The ratio of intercepted energy to incident wave energy computed (Table 1) indicated that the ratio is the maximum for the waves approaching from West direction.

Alignment 3 - WEC at 250^0 N: For this alignment, the model simulations were carried out for waves approaching from both West and WSW directions. The ratio of intercepted energy to incident wave energy computed (Table 1) indicated that the ratio is the maximum for the waves approaching from WSW direction.

3. From the ratios of intercepted energy to incident wave energy (Table 1), it is seen that Alignment 2 is preferable for wave approach from West and Alignment 3 is preferable for wave approach from WSW.
4. By considering above results of the single WEC, the alignment of two WECs in an array at 260^0 N is chosen, considering the West direction to be the predominant wave direction.
5. Further two different arrangements of array of WECs were considered namely linear and parallel. From the model results, the linear arrangement is preferable instead of parallel arrangement of WECs in an array.
6. The MIKE21- BW model which incorporates almost all the wave phenomena, is suitable and hence very much useful for such studies.
7. It is expected that, the findings of this study may be useful for similar study with the similar site conditions.

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