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Assessment of Wave Energy Potential along South Maharashtra Coast

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Abstract: In this paper, the spatial and temporal assessment of wave energy potential, along the Ratnagiri coast, on the west coast of India, is presented. The wave energy potential is estimated from the available measured data, where high wave energy is observed, and numerical model studies using third generation spectral wave model MIKE 21 SW. The wave energy potential estimates from both these approaches match well. The model is calibrated with the measured wave data near Ratnagiri. Annual average wave energy potential of the location of measurement, using measured waves and from the numerical model is estimated to be 7 kW/m and 6kW/m respectively. The spatial and the temporal distribution of the wave energy is obtained from the numerical models and the regions of high energy were identified. Annual average energy potential of three more locations is obtained which is in the range of 5.92 to 6.9 kW/m. Seasonal variation of the wave energy is estimated with the help of monthly average wave energy values and found that high seasonal variation prevails in the study area. Around 88% of the wave energy occurs during the south west monsoon. Average wave energy during southwest monsoon is almost three times of the annual average wave energy. At the selected points energy potential is comparable with that of measurement location, thus three more locations where extraction of wave energy is feasible, are identified.

Keywords: *Coastal engineering, Wave energy estimation, Numerical modelling, Wave Transformation, MIKE 21 SW, Renewable energy*

1. Introduction

Wave energy is a relatively untapped renewable energy resource which has the potential to satisfy world's energy demands. Uneven heating of earth's surface gives rise to winds, which give energy to waves. Energy is concentrated in this process, as a result ocean waves are more energy dense than wind. Also waves have the advantages of easy predictability and less requirement of land area compared to the wind energy. The development of the wave power generation project needs a detailed analysis of the wave energy potential at the site over the year, in every season. Various attempts were made to analyze global wave energy potential. Mork et al. assessed global wave energy resource from the dataset used in the default calibrated wave database contained in the standard World Waves package. It has been found that the largest power levels occur off the western coasts of the continents due to the Coriolis force and the ratio of the minimum monthly to annual average power levels confirms that seasonality is much higher in the northern hemisphere [1]. NOAA WaveWatch III (WW3) global model outputs were used to quantify the global wave energy resources by Gunn and Williams. Total wave power incident on the coastlines were found to be in the range 2.11±0.05 TW [2]. To get a detailed knowledge about the wave energy prevailing at a place, location specific estimations are essential. Henfridsson et.al. (Baltic Sea) [3], Muzathik et.al (peninsular Malaysia) [4], Lenee-Bluhm et.al (US Pacific Northwest) [4] and Vicinanza et.al (Italian offshore) [5], and other researchers attempted assessment of the wave energy potential of various locations all over the world, with some success.

Since wave data measurements like in situ measurements only provide data at a particular location, it became necessary to use numerical models to understand the spatial and temporal variation of wave power. Third generation spectral wave models were used in these scenarios to calculate wave energy resource in the near shore regions. Waters et.al, [6] studied and calculated the occurrence of extreme wave energy flux during the study period by obtaining wave climate at 13 locations along the Swedish coast to identify the wave energy potential of the coast and found that average wave energy varies in the range of 2.4 kW/m to 5.2 kW/m. Rusu and Soares [7] studied measured wave data to understand prevailing wave climate in the Portuguese near shore to identify average energetic conditions. For the numerical modelling the authors used WAM model for the entire North Atlantic basin and SWAN for wave transformation in the coastal environment. From the simulations, authors concluded that the locations showing maximum significant wave height may not necessarily be the location with maximum wave energy, due to the importance of group velocity in the calculation of wave energy. Folley and Whittaker, [8] analysed near shore wave energy resources for north Atlantic coast of Scotland and reduction of wave energy potential, when waves travel from deep water to near shore at depth of 10m, using SWAN model. It is found that the reduction in gross wave power, when waves travel from offshore to near shore is mainly because of refraction. The result is that winter and autumn account for the major share of the annual energy and average annual wave energy varies from 13 to 25 kW/m. Wave energy potential of the Black Sea was calculated by Aydogan et.al [9]. Wave properties were calculated using 3^{rd} generation spectral wave model MIKE21 SW for years 1996-2009 by using wind data from European Centre for Medium-Range Weather Forecasts (ECMWF).

Wave energy potential along Indian coast is estimated by various studies. Ravindran and Koola, [10] reviewed wave energy programme in India in 1991. The average annual wave power potential along the Indian coast varies from 5 kW/m to 10 kW/m and at the selected location for wave power plant installation it is found to be 13 kW/m. Raju and Ravindran [11] studied wave energy potential along the Indian coast using the GEOSAT altimeter data. The study concluded that the average wave power on west coast of India is more than that of east coast of India and also it is less cyclones prone compared to east coast. Kumar et.al [12] calculated wave energy potential at four shallow water locations around the Indian coast and the locations are Ratnagiri, Honnavar, Puducherry and Vishakhapatnam. The study found out that, expression used for calculating energy period (T_e), $T_e = 0.9 \times T_p$ is not valid for waves having spectral wave periods more than 8 seconds, where T_p is the spectral peak period. Another observation is that the 85% of annual average wave energy in Ratnagiri occurs during summer monsoon from the south westerly waves (250^0-270^0). The range of the wave power was found that 0.2-84.3 kW/m and average value is 7.6 kW/m. Kumar and Anoop, [13] estimated wave energy potential and studied it's variation for Indian coast at 19 locations, 11 on west coast and 8 on east coast for a period of 34 years, using ERA-Interim data, which incorporates WAM results. They analysed wave power on the basis of spatial distribution, monthly variation, seasonal variation and annual variations. Based upon the monthly variability index (ratio of the difference between the maximum and minimum monthly mean wave power and the annual mean wave power), they have concluded that Vizhinjam is more suited for installation of wave energy power plant. The wave energy potential at Ratnagiri was also investigated. From the statistical analysis of data and empirical formula, wave power maps were prepared, on a large domain. The major site for wave energy assessment and installation in India is at Vizhinjam near Trivandrum. Ratnagiri is also a location on the west coast with high wave energy potential [12, 13].

The present study analyses the wave energy potential on the coast near Ratnagiri in greater detail. Wave energy potential along Ratnagiri coast was analysed using a third generation spectral wave model, MIKE21 SW and from the measured waves for the year of 2014. A method to assess wave energy potential from simultaneous wind and wave data of one year, i.e. 2012, is evolved. For the calculation of wave energy from measured waves, deep water approximation of the wave energy equation has been used. The wave power map of Ratnagiri coast at depths less than 20 m was prepared.

From the simulation with the calibrated numerical model, wave characteristics and wave energy were obtained. The spatial and the temporal variation of the wave energy potential for the year 2014 are reported in this paper. Three additional locations, along with the site of wave data measurement, are selected and the wave energy potential at the locations is assessed using the simulated result. Average wave power roses for the selected location and the seasonal variation of wave energy are presented. The results are analysed to obtain the distribution of wave energy potential for different sea states. Wave energy map of the nearshore region along the Ratnagiri coast is presented in the paper.

2. Measured Wind and Wave Data

Wind data was collected from Earth System Science Organisation – Indian National Centre for Ocean Information Services, Hyderabad (ESSO-INCOIS). Wind is measured using a moored buoy located at, Longitude 69.004 Latitude 14.999 off Ratnagiri. The moored buoy records wind speed and wind direction which was used for wind forcing in the numerical modelling. Wave climate in Arabian Sea can be classified into three seasons, pre-monsoon (February-May), southwest monsoon (June-September) and northeast monsoon (October – January). The wave climate is observed with high wave activity during the SW monsoon and relatively calm condition with long period waves prevail during rest of the year.

Wave measurements were carried out off Ratnagiri coast by ESSO-INCOIS, from May 2007. Wave data is measured using moored Datawell directional waverider buoy deployed at the location near Ratnagiri (Longitude 73.263 Latitude 16.977). The obtained data include wave parameters like significant wave height, mean wave period, peak wave period, peak wave direction etc.

The measured wave data have been analysed to get a detailed idea about the near shore wave climate prevailing in the region. Wave data was used to calibrate the model and for the calculation of wave power using empirical formula at the measurement location. The measured wave data was used to calculate the correlation coefficient to understand the calibration in detail.

3. Numerical Model Simulation

3.1 Numerical Model

The present study describes the model set up using MIKE 21 modelling system developed by DHI. MIKE 21 SW is a new generation spectral wind-wave model based on unstructured meshes. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas. In this study fully spectral formulation was used as it is more reliable but consumes more time for running model. In the present model a formulation in terms of the wave direction, θ and the relative angular frequency σ has been chosen. The action density, N (σ, θ), is related to energy density E (σ, θ) by

$$N = \frac{E}{\sigma} \qquad (1)$$

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \approx (0.49) H_s^2 T_e \qquad (2)$$

Where H_s, is the significant wave height and T_e is the energy wave period. Since energy wave period was not available with the measured data, it was calculated using the zero cross period using the following relation

$$T_e = 1.18Tz \qquad (3)$$

The constant 1.18 was suitable for a JONSWAP spectrum having peak spectral shape 3.3 [20]

3.2 Model Setup

In order to study wave energy potential in Ratnagiri coast, a large domain including the wind data measurement location is selected. The selected stretch for calculation of wave energy potential extends from 14˚2' N to 18˚21' N in latitude and in the southern side it starts from 74˚23' E to 68˚42' E. as shown in the figure. 1. The study area considered extends from Kumta in Karnataka to Murud in Maharashtra (India). Unstructured flexible triangular mesh is used to resolve the region of interest with fine resolution with optimum number of elements. The mesh for entire region is shown in figure. 2 and the near shore portion of the mesh, with 13702 nodes and 26544 elements is shown in figure. 3

Figure 1 *Location map of study area (courtesy Google Earth)*

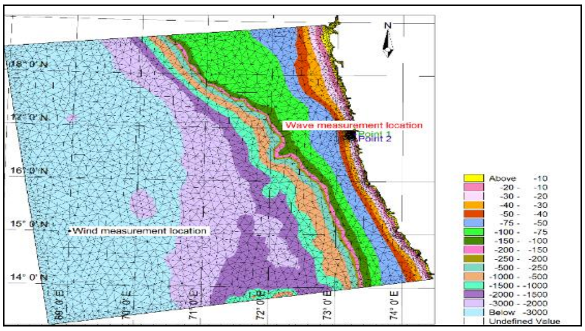

Figure 2 *Bathymetry and mesh for entire region*

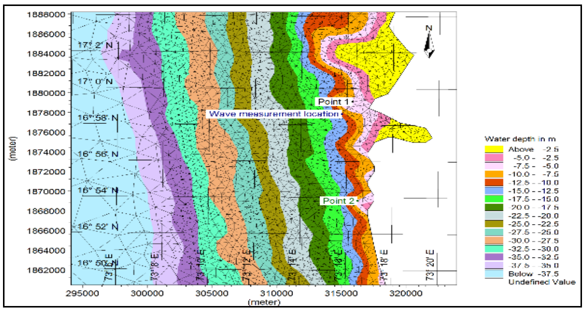

Figure 3 *Bathymetry and mesh in the region near Ratnagiri*

Wind is the basic input parameter for wave simulation. Successful wave hind cast depend on accurate wind data. The time series of the wind data measured at measurement location (Longitude 73.263 Latitude 16.977) is the input. At the measurement location, wave energy was present because the model is not a global model. The wave energy is present at the model west boundary, where wind forcing applied is estimated using the simultaneous observation of wind and waves in 2014 and the INCOIS wave data available near the boundary. The wind forcing was augmented by the existing wave energy. When wave height time series from the global model near shore is not available the near shore wave climate can be obtained by this method. The model was calibrated against measured wave data at the 15 m depth near Ratnagiri (Longitude 73.263 Latitude 16.977.). The time period chosen for the calibration was from 15 June 2014 to 15 July 2014, as this time period is the most energy dense period. White capping is used as the calibration parameter. For white capping parameter 2, the comparison of simulated and the measured wave height time series is shown in figure 4.

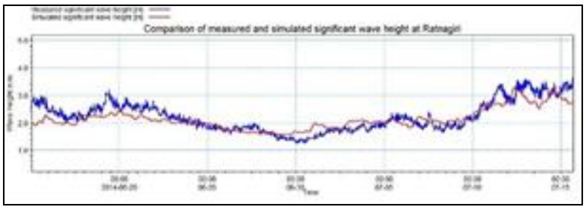

Figure 4 *Comparison of measured and simulated significant wave height time series (15/6/14 to 15/7/14)*

The correlation in the measured and simulated wave height time series is 0.86. The yearly wave parameters were simulated using the calibrated model. The correlation in the measured and simulated wave height time series for the entire year is 0.9. This validated the numerical model.

4. Results and Discussions

4.1 Numerical Model Results

The wave vector plot showing the spatial distribution of wave height and wave direction at 9/07/2014 at 3:45 for the region near Ratnagiri is shown in figure.5. For wave power calculations a total of 4 points were selected. One of them is at the wave measurement location in order to compare the wave power obtained from simulation and wave power calculated using the empirical formula. The points selected are having the geographical coordinates as mentioned in table 1.

Table 1: *Location details of the selected points investigated*

Location	Longitude in decimal degree	Latitude in decimal degree
Point 1 near Mirye	73.243079	17.037105
Point 2 near Ratnagiri	73.270554	16.988229
Point 3 wave measurement	73.263	16.977
Point 4 near Ranpar port	73.274885	16.897091

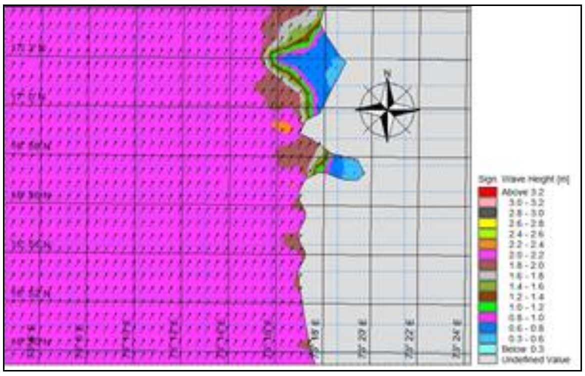

Figure 5 *Wave height and direction vectors in the region near Ratnagiri*

Using the wind time series and wave as input model was run for the entire year. Fig. 5 shows a typical wave height plot with direction vectors in the region near Ratnagiri at a certain time. The model results were used to calculate the wave power potential of the south Maharashtra coast. The wave power map for the area of interest near Ratnagiri was obtained. The changes in the wave power potential at different locations are accurately depicted.

Wave power values are extracted for the selected points from the simulated model. Wave power values of measured waves are calculated based upon equation 2.2. The obtained wave power was analysed and the annual average values of wave power were estimated as given in table.

4.2 Discussion

The measured wave power (7.05 kW/m) exceeds compared to the simulated wave power (5.92 kW/m) at the same location. This difference can be accounted for the different methods used for wave power calculations. Since we used deep water approximation for the calculation of wave power potential of measured waves, exact match of results cannot be ensured while using near shore equation based upon spectral moments. From the simulation results, it can be observed that the point 2 has the highest wave energy potential among the selected points followed by point 4, point 1 respectively. The values match with the previous estimates done for Ratnagiri.

Total wave contribution of average wave power for the corresponding sea states tables 2 (A-D) were prepared A) Using measured data B) At Pawas C) Using Simulated wave power at the wave measurement location and D) at Ratnagiri , considering significant wave height and energy wave period . In these tables, each cell is divided into 0.5m×1s ($\Delta H_s \times T_e$) bins. The value in each cell gives the contribution of wave power potential corresponding to the particular sea state in a year. Adding the values in each cell together will provide the total wave power occurring at each point. This table provides a better idea about the dominating sea states along the Ratnagiri coast. From the tables 2(A – D), it can be observed that wave heights ranging from 1.5 to 2.5 m and having an energy wave period of 6 to 8 seconds contribute most of the wave energy. These waves are mainly found during southwest monsoon season, which acknowledges the fact that most of the wave energy along the west coast of India occurs during the southwest monsoon only. Seasonal variation of wave energy of the study area is estimated by calculating the average wave power values for each month, which is plotted to understand the difference between monsoon months and non-monsoon months as shown in the figure 6. Percentage of wave power occurred during southwest monsoon is calculated and given in table 3. Average annual wave power and average wave power occurred during monsoon is calculated and given in table 4. Average wave power during southwest monsoon is almost three times of the annual average wave power. This indicates that wave power is having high seasonal variation along Ratnagiri coast, which will affect the efficiency of the wave power plant during non-monsoon season.

Percentage of wave power occurred during southwest monsoon is calculated and given in table 3. Average annual wave power and average wave power occurred during monsoon is calculated and given in table 4. Average wave power during southwest monsoon is almost three times of the annual average wave power. This indicates that wave power is having high seasonal variation along Ratnagiri coast, which will affect the efficiency of the wave power plant during non-monsoon season

Table 2: *Input contribution of wave power in kW/m for sea state, for wave heights from 0.5m to 3.5 and higher and wave periods from 5 s to 11 s.*

2 (A): *Measured Wave data data*

T_e \ H_s	0.5m	1m	1.5m	2m	2.5m	3m	>3.5m
5s	0	0	2	4	0	5	0
6s	0	0	322	677	25	0	0
7s	0	6	140	0	10	13	11
8s	0	1	213	0	0	6	44
9s	0	0	0	0	0	0	74

2 (B): *Pawas*

T_e \ H_s	0.5m	1m	1.5m	2m	2.5m	3m	>3.5m
5s	9	1	0	0	0	0	0
6s	46	26	97	61	0	0	0
7s	17	35	187	345	302	86	0
8s	3	7	126	150	162	40	0
9s	0	0	32	10	100	131	18
10s	0	0	0	0	24	161	264

2 (C): *Simulated at Location of wave measurement*

T_e \ H_s	0.5m	1m	1.5m	2m	2.5m	3m	>3.5m
5s	9	1	0	0	0	0	0
6s	46	26	97	61	0	0	0
7s	17	35	187	345	302	86	0
8s	3	7	126	150	162	40	0
9s	0	0	32	10	100	131	17
10s	0	0	0	0	24	161	249

2 (D): *Ratnagiri*

T_e \ H_s	0.5m	1m	1.5m	2m	2.5m	3m	>3.5m
5s	0	0	7	15	0	5	0
6s	0	0	395	544	112	0	10
7s	0	8	121	0	14	13	0
8s	0	6	184	0	0	0	41
9s	0	0	0	0	0	0	61
10s	0	0	0	0	0	0	84
11s	0	0	0	0	0	0	23

Model was calibrated and found that using the model with no bottom friction and white-capping parameter 2 gives satisfactory results. For calculating calibration results quantitatively, correlation coefficient was used, which gave a fairly good value of 0.86. The comparison of measured wave height time series and the simulated wave height time series showed very good match

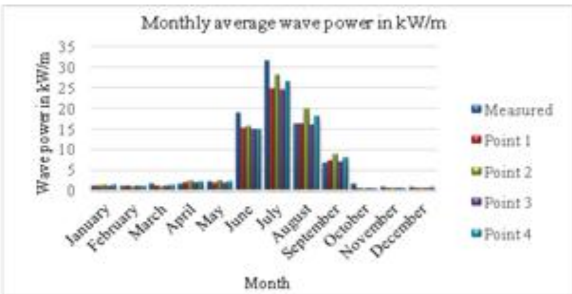

Figure 6 *Variation of monthly average wave power for the selected locations*

Table 3: *Percentage of wave power occurred during southwest monsoon*

Location	Total wave power occurred in kW/m	Wave power occurred during June to September in kW/m	Percentage of wave power occurred during June to September
Measured	84.006	73.406	87.38%
Point 1	71.498	62.93	88.01%
Point 2	82.123	72.291	88.03%
Point 3	70.532	62.085	88.02%
Point 4	76.503	66.917	87.47%

Table 4: *Comparison of average wave power values during monsoon and complete year*

Location	Average value of wave power occurred during monsoon 2014 in kW/m	Annual average wave power in kW/m
Measured	18.35	7.05
Point 1	15.73	6.0
Point 2	18.07	6.9
Point 3	15.52	5.92
Point 4	16.73	6.42

The results obtained were analysed for seasonal variation of wave power potential. From the simulation results, four locations which are high in wave energy potential were identified and wave energy potential was extracted from the simulated model in the time intervals of 15 minutes interval spanning the entire year 2014. The wave energy potential values indicated that the average annual wave energy occurring along the Ratnagiri coast is in the range of 5.92 to 6.9 kW/m. Wave energy was calculated using empirical formula for measured waves for the entire year 2014 and the average wave energy value was found to be 7.05 kW/m. The wave power occurring along Ratnagiri coast is mainly in the west and west south west direction. The waves with , wave heights ranging from 1.5 to 2.5 m and having an energy wave period of 6 to 8 seconds, contribute most of the wave energy. Monthly average wave power has been calculated (fig. 6), which shows seasonal variation of wave energy. Most of the wave energy occurred along the Ratnagiri coast was during south west monsoon season i.e. from June to September.

Seasonal variation is high along Ratnagiri coast. Around 88% of the total annual wave energy, occurs during southwest monsoon. Average wave energy during south west monsoon was around 15.5 to 18 kW/m and annual average wave energy was found to be varying from 5.9 to 7 kW/m. These results matched with the analysis of 2014 years data very well, thus with limited data and considering the sea state at the boundary, the wave power potential was estimated accurately.

At the 4 identified locations, the simulated average wave power potential in monsoon and annual period is in the range of 15.5 to 18 kW/m and 6 to 7 kW/m. The available wave power is in good agreement. The wave power availability of the Locations 1, 2 and 4 compares favorably to the wave power availability in the Location 3 which is a proposed wave power extraction site. Considering the wave power assessment, wave power extraction is feasible at all the locations. Hence the wave power map is useful in indicating new probable wave energy extraction sites.

The wave energy potential calculated using the available measured data and the simulated wave data match well.

5. Conclusions

The four locations at which the wave energy potential assessed, shows that wave energy potential for all the locations is comparable. The wave power availability of the Locations 1, 2 and 4 compares favorably to the wave power availability in the Location 3 which is a proposed wave power extraction site. Considering the wave power assessment, wave power extraction is feasible at all the locations.

The sites with high wave energy potential are within 4 kilometers from each other. The extraction of wave energy at any of these locations is feasible considering the wave energy potential. If two wave caissons are installed at the two identified sites, with one catering for waves approaching from the west and the other for waves approaching from WSW, a continuous wave energy extraction may be ensured. Thus there is sufficient wave energy potential at four locations near Ratnagiri. The feasibility of installation of wave energy converters may be fruitfully explored.

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