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DESK STUDIES FOR PREDICTION OF EXTREME WAVE CONDITIONS FOR THE PROPOSED DEVELOPMENT OF PORT AT VADHAVAN FOR M/S JNPT

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DESK STUDIES FOR PREDICTION OF EXTREME WAVE CONDITIONS FOR THE PROPOSED DEVELOPMENT OF PORT AT VADHAVAN FOR M/s JNPT

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Synopsis:

M/s Jawaharlal Nehru Port (JNP), Mumbai in association with Maharashtra Maritime Board, Govt. of Maharashtra undertaking has a proposal to develop a major greenfield port at Vadhavan. The location of proposed port is at Lat. 19^0 55.8' N, Long. 72^0 39.6' E in Dahanu Taluka, Palghar district of Maharashtra state and is at about 110 km north of Mumbai. The layout of the port was finalised based on tidal hydrodynamic and wave tranquility studies carried out at CWPRS and port being on open coast, it requires an offshore breakwater of 10.3 km in length to protect the berthing structures against the furry of waves from the Arabian sea. The major portion of breakwater with its alignment being in deeper depths of about 15-18 m, it was essential to assess its hydraulic stability against the extreme wave climate at the port site.

The prediction of extreme wave climate is generally carried out by analyzing measured wave data using Long term statistical analysis. However, such data being seldom available, Ocean wave hindcasting studies were carried out by analyzing the storms occurred in the Arabian sea for the years 1946-2015. The data of storm tracks, synoptic charts was analysed and 95 storms are found to be of significance to the port off the coast of Vadhavan. The analysis carried out revealed that there are 57 events which have generated waves (H_s) higher than 2 m in 30 m depth off the coast at Vadhavan. The extreme value analysis by fitting the hindcast data in different distribution function viz. Gumbel, Weibull etc. reveal that waves of Significant height (Hs) of 8.1 m may occur in 30 m depth off Vadhavan having Peak period (Tp) of about 18 sec. for 1 in 100-year return period. This wave condition for predominant wave directions was transformed up to breakwater using Telemac software and it reveal that H_s on seaside will vary between 6.8 m and 7.5 m, T_p= 18 sec.

Similar to wave hindcasting studies the extreme storm surge was estimated by analyzing storms for period (1993-2015) and maximum surge of about 2 m may occur near proposed port for a return period of 1 in 100- years.

Key Words: Extreme value prediction, Wave hindcasting, Peak period, Return period, Significant wave height, Storm surge, Storm tracks, Synoptic Charts

DESK STUDIES FOR PREDICTION OF EXTREME WAVE CONDITIONS FOR THE PROPOSED DEVELOPMENT OF PORT AT VADHAVAN FOR M/s JNPT

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1. INTRODUCTION

The Government of India (GOI) through a joint venture between Jawaharlal Nehru Port (JNP) working under Ministry of Surface Transport, GOI and Maharashtra Maritime Board (MMB) of Government of Maharashtra (GoM) has a proposal to develop a major greenfield port at Vadhavan. The location of proposed port is at Lat. 19^{0} 55.8' N, Long. 72^{0} 39.6' E in Dahanu Taluka, Palghar district of Maharashtra state and is at about 110 km north of Mumbai in the state of Maharashtra. It has been proposed to develop this port as a modern all-weather port at Vadhavan and is on the open coast facing the Arabian Sea. The port is about 11 km North of Tarapur Atomic Power Station (TAPS) as shown in Fig.1 and its seaward limit extends up to about 26 m depth in the deeper part of the sea with an overall area of about 175 Sq km. The northern limit of the proposed Vadhavan Port is on the southern side of entrance to the Dahanu creek. The port is proposed to be developed on the seaward side of the headland at Vadhavan and stack yard area will be formed by creating an artificial land in the foreshore area by reclaiming about 1428 ha in the intertidal zone at Vadhavan point. The port will have entrance through the navigational channel from the Arabian Sea, wherein waves are predominant from two quadrants namely North-West & South-West. The tides are semi-diurnal in nature with macro type having tidal range of about 6 m.

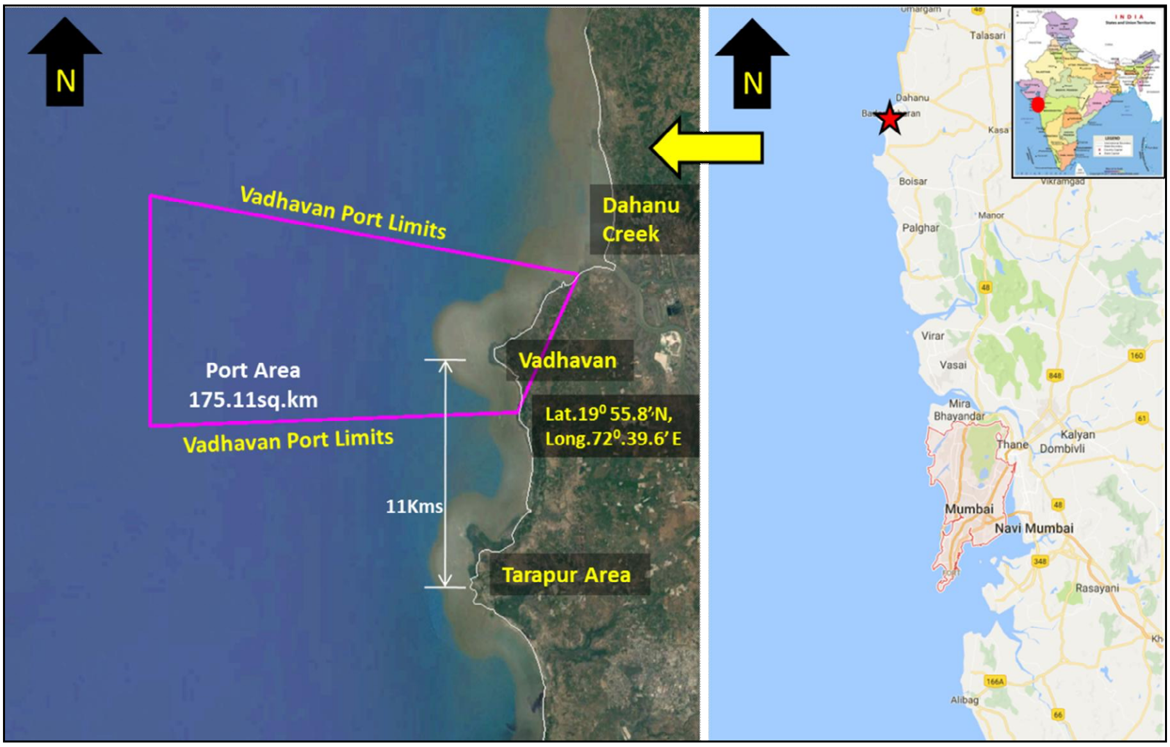

Fig.1: Location Plan of Proposed Port at Vadhavan

M/s JNP has taken up the task of planning the configuration of port layout, positioning and alignment of various structures like breakwaters, berths and operational area, harbour basin, approach channel etc. The conceptual layout plan has been proposed to be finalised through model studies.

In view of proposed port site being in the close vicinity of Tarapur Atomic Power Station (TAPS), Department of Atomic Energy requested M/s JNP to assess the impact of proposed port development on TAPS through institute like CWPRS. Accordingly, M/s JNP approached CWPRS through e-mail dated 5th march 2017 and a meeting was held at JNP on 10th March 2017 between officials of CWPRS and JNP. Based on the discussions, JNP vide their letters JNP/PPD/ Vadhavan/ 2017/422 and JNP/PPD/ Vadhavan/ 2017/426 both dated 10th March 2017 requested CWPRS to carry out the various hydraulic model studies to assess the impact of proposed development on TAPS and also to finalize the concept layout for the proposed port at Vadhavan. In response to this to decide the scope of various hydraulic model studies, a meeting was held at CWPRS on 22nd March 2017 for the preliminary layout plans submitted by M/s JNP. The studies proposed to be carried out are divided in to two parts namely:

I) Studies to finalise the layout of proposed port at Vadhavan and

II) Assess the impact of proposed port at Vadhavan on TAPS.

In this context, studies proposed to be carried out for Part-I at CWPRS are:

- Hydrodynamics and siltation
- Wave transformation and tranquility
- Shoreline changes and littoral drift
- Design of breakwaters – Wave flume studies

The studies proposed to be carried out to assess the impact of proposed port development on intake/outfall facilities of TAPS in part-II are:

- Hydrodynamic and siltation studies to assess the impact of proposed port at Vadhavan on TAPS
- Thermal model studies to assess the dispersion of hot water due to proposed port development.

Subsequent to this the various meetings were held at CWPRS to assess the progress of studies regarding finalisation of layout of breakwater from wave tranquility, tidal hydrodynamic and siltation considerations. In one of such meeting held at CWPRS on 3rd July 2017, It was informed by CWPRS offficials that for assessing hydraulic stability of breakwater, design wave condition is to be provided by M/s JNP as per TOR and proposal submitted by CWPRS dated -03rd April 2017. However, JNP officials insisted that CWPRS should take up the studies for this aspect as the hydraulic stability is being studied at CWPRS. Accordingly CWPRS based on the discussions held, agreed to take up the studies to predict extreme wave conditions and submitted the study proposal vide letter No. TC/2017/1021/1652 dated 28th August 2017.

This report describes the information about storm data used for analysis of storms occurred in past in the Arabian sea off Vadhavan which are of significance, estimation of wave heights using hindcasting technique, estimation of storm surge as well as prediction of extreme wave heights and storm surges for various return periods. The Scope of work for studies is mentioned below.

2. SCOPE OF WORK

The objective of this study is to determine extreme wave conditions on the seaward side of the proposed breakwater structure for the development of port planned at Vadhavan. It is also necessary to estimate the likely storm surge for various storms which are of significance and prediction of extreme storm surge for various return periods. The studies include:

1) Storm wave hindcasting studies
2) Extreme value analysis of storm waves
3) Storm surge analysis
4) Extreme value analysis of storm surges

3. METHODOLOGY

The determination of extreme waves and storm surge levels are essential to know the forces which are likely to be exerted on marine structures during its life and should be based on the statistical analysis of long-term measurements. Since the long-term measurements of waves and storm surge levels, which occur during the storm (cyclonic) conditions, are seldom available, the extreme value analysis for the waves and storm surge is carried out using hindcast storm waves and storm surge data (predicted values using past storm data). The extreme value analysis of these hindcast data provides the wave height and storm surge levels of various return periods required for assessing the hydraulic stability of coastal structures such as breakwaters as well as to determine the deck levels of berths/terminals etc.

The Indian coasts are typically characterized by monsoon wave climate and tropical storms. The wave climate is more severe during tropical storms in comparison to monsoon. As such, in the extreme value analysis for determining the design wave conditions for certain return periods, it is necessary to consider the storm wave climate. Several storms occur on the East and West coasts of India every year, particularly during the periods from April to June and October to January, due to typical meteorological conditions prevailing in the ocean. On the west coast, the frequency of occurrence of cyclones is low (about 2 per year); whereas on the East coast, the cyclones are more frequent (about 5 per year). The India Meteorological Department (IMD) provides the records of these storms in the form of synoptic charts (pressure distribution) and storm tracks for the moving storms. IMD also provides the information about ship observed wave data in their daily weather reports.

The hindcast storm wave data, obtained by considering the storms in the vicinity of the Vadhavan area between the years 1946 and 2015 (about 60 years) have been utilized for the studies. Extreme value analysis of hindcast storm wave data was carried out to determine the wave conditions with various return periods at the proposed Vadhavan port area. The wave conditions obtained by the Hindcast studies are in the water depth of about 30 m from the coast off Vadhavan. The predicted values of wave height for various return period viz. 100 year, 50 year, 25 year and 10 year are determined by fitting the hindcast wave data in different distribution functions, which are normally adopted for ocean wave data fitting. The wave transformation studies to determine extreme wave heights at different depths along the proposed breakwater are carried out by developing a mathematical model using Telemac software and transforming the waves from 30 m depth up to the proposed breakwater.

4. DATA FOR STUDIES

M/s JNP have entrusted the work of preparation of DPR; EIA/EMP to M/s Pentacle Consultants (I) Pvt. Ltd. and the Consultants collected the field data in January-February 2017 itself (Non-Monsoon) and this data was submitted by M/s JNP to CWPRS to carry out the model studies. However, in view of some discrepancies observed in the same data after scrutiny, CWPRS communicated the observations to JNP vide letter No. PH-III/2017/174/1085 dated 31st May 2017. This aspect was discussed in the meeting held at CWPRS on 3rd July 2017 and thereafter part of the data required to carry out the tidal hydrodynamic studies was received from the consultants only for Non-Monsoon season. The field data submitted to CWPRS is as follows:

1. Bathymetry survey of proposed port site
2. Tide data collected at 3rd pier of Dahanu Creek Bridge (one location) at the entrance of Dahanu creek for one-month duration from 10/01/2017 to 10/02/2017.
3. Wave data at location in the port limit (Lat.19^0 56' 59.82" N; Long. 72^0 37' 13.56" E) from 10/01/2017 to 05/02/2017.
4. Meteorological data viz. wind speed, direction etc. at one location
5. Geotechnical investigations – borehole data (61 locations)

The location of oceanographic field data collected is shown in Fig. 2. The field data for bed samples and its grain size analysis in the proposed port area was provided later by JNP vide their letter No. PPD/M/Vadhavan Port/2018/152 dated 23/01/2018 and e-mail dated 14/12/2017.

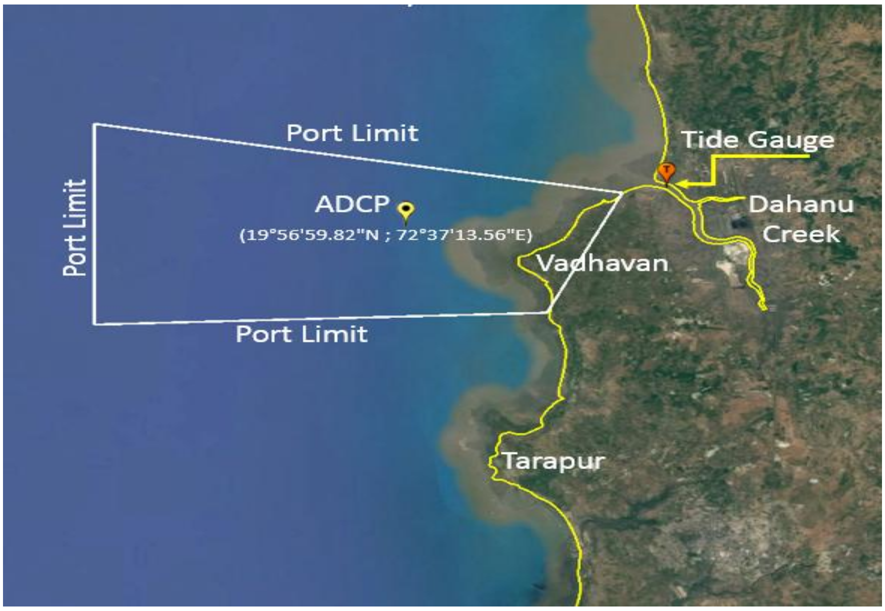

Fig.2: Locations of Oceanographic Field Data Measurements for Proposed Port at Vadhavan

The information about storm tracks, synoptic charts, type of storm, central pressure etc for the year 2009-2015 required for hindcasting studies was provided by JNP through IMD, Pune.

4.1 Bathymetry

The hydrographic survey for the proposed port area within its limit is carried out by project authorities during December 2016 to March 2017 (Ref-6) and the same is shown in Fig.3.

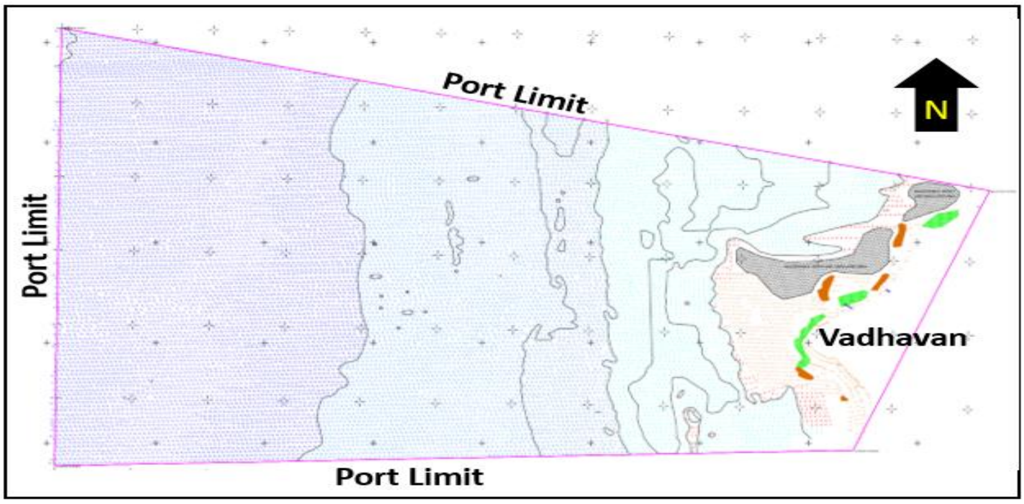

Fig.3: Bathymetry Data for Proposed Port at Vadhavan

The depths within the port limit vary between -26 m and +2 m w.r.t. CD of Vadhavan area. The data shows some patches of rocky outcrops and areas of mangrove coverage near shoreline. The bathymetry in the areas like Dahanu creek, Vadhavan, Tarapur area was provided by JNP and part of this data is based on the hydrographic charts prepared by MMB in year 2003 for Tarapur site and Vadhavan headland area while for Dahanu creek in year 2009.

4.2. Tide Levels

The tidal data was collected at 3rd pier of Bridge on Dahanu Creek for the duration of one month from 10/01/2017 to 10/02/2017 and is correlated with CD of Vadhavan area. The CD was correlated w.r.t. Benchmark established on the Light House at Dahanu. The plot of Tide data collected is shown in Fig. 4.

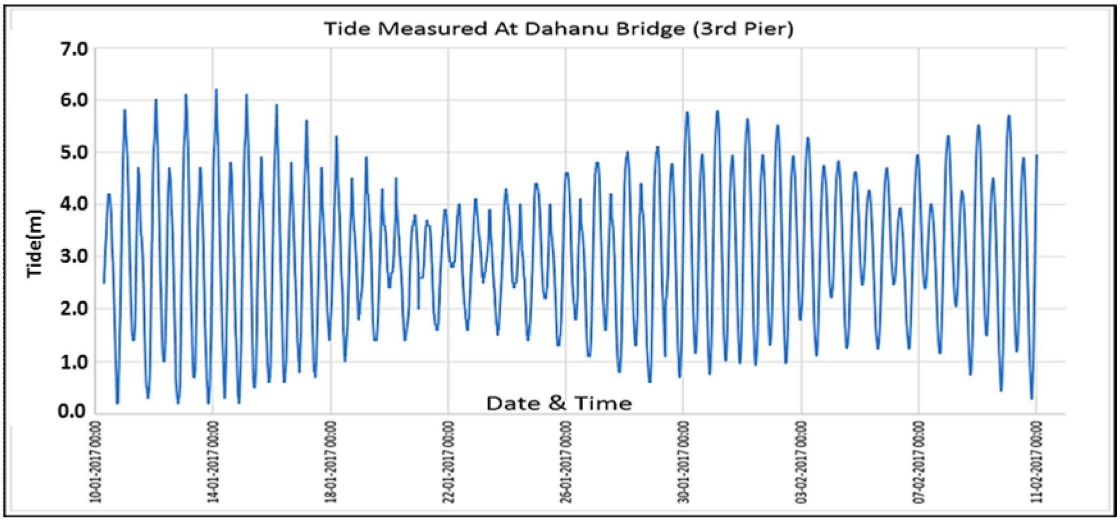

Fig.4 : Measured Tide Data at Dahanu Bridge Location (10/01/2017 – 10/02/2017)

The analysis of measured tidal data is carried out and it reveals that the tides are semi-diurnal in nature with diurnal inequality. The spring tide occurred on 14/01/2017 and tidal range was 5.87 m, while neap tide occurred on 21/01/2017 with tidal range of about 2.10 m.

4.3 Wave Data

The wave data is also measured at ADCP location and is presented in Fig.5.

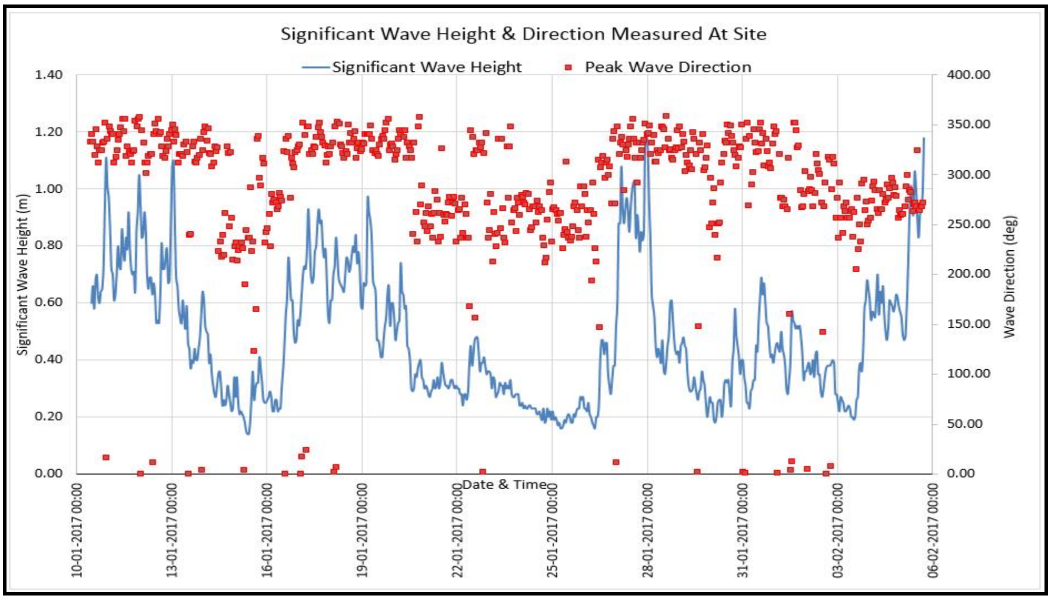

Fig.5 : Measured Wave Data at ADCP Location (10/01/2017 – 05/02/2017)

The plot shows maximum significant wave height observed during the period as 1.19 m, Tp = 5.4 sec, while minimum significant wave height observed is 0.14 m, Tp = 14.9 sec with corresponding peak wave directions as 351^0 N and 244^0 N respectively. Thus, the majority of waves during the period of observation (non-monsoon period) are approaching from North-West quadrant (Fig.6). The peak period (Tp) varies between 2.0 seconds and 16.90 seconds during the period of observation with dominant at 4.0 seconds.

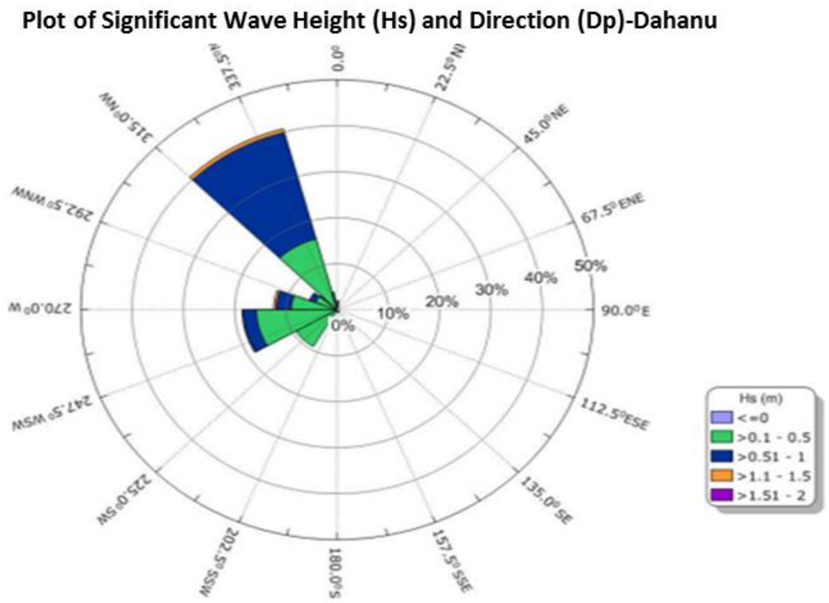

Fig.6: Wave Rose Diagram For Measured Data at ADCP Location

4.4 Grain Size Analysis of Bed Material

The bed samples at various locations (8) in the vicinity of proposed port area were collected and the grain size analysis of the same was carried out and is presented in Table-I.

Table - I
Grain Size Analysis of Bed Samples

Sr. No.	Description	Location		Sample retained on 75 Micron %	% Fines		D_{50}
		Easting	Northing		Silt %	Clay %	
1	Dandepada (A1)	252850.51 m E	2202778.18 m N	7.98	59.66	32.36	0.0100
2	Dandepada (A2)	252615.50 m E	2202745.80 m N	8.65	57.53	33.82	0.0115
3	Dandepada (A3)	252473.37 m E	2202714.44 m N	7.22	53.15	39.63	0.0050
4	Dandepada (A4)	252389.46 m E	2202644.83 m N	10.69	59.15	29.80	0.0076
5	Chinchani (B1)	254175.56 m E	2200735.42 m N	10.41	59.64	29.95	0.0150
6	Chinchani (B2)	252921.99 m E	2201004.30 m N	10.02	60.78	29.20	0.0114
7	Chinchani (B3)	252698.02 m E	2200930.75 m N	9.87	59.38	30.75	0.0113
8	Chinchani (B4)	252496.19 m E	2200560.39 m N	12.02	58.53	29.45	0.0138

The analysis reveal that bed material is clayey silt with D_{50} varies between 0.005mm and 0.015 mm. A typical grain size analysis curve plotted to determine D_{50} of bed material is shown in Fig. 7.

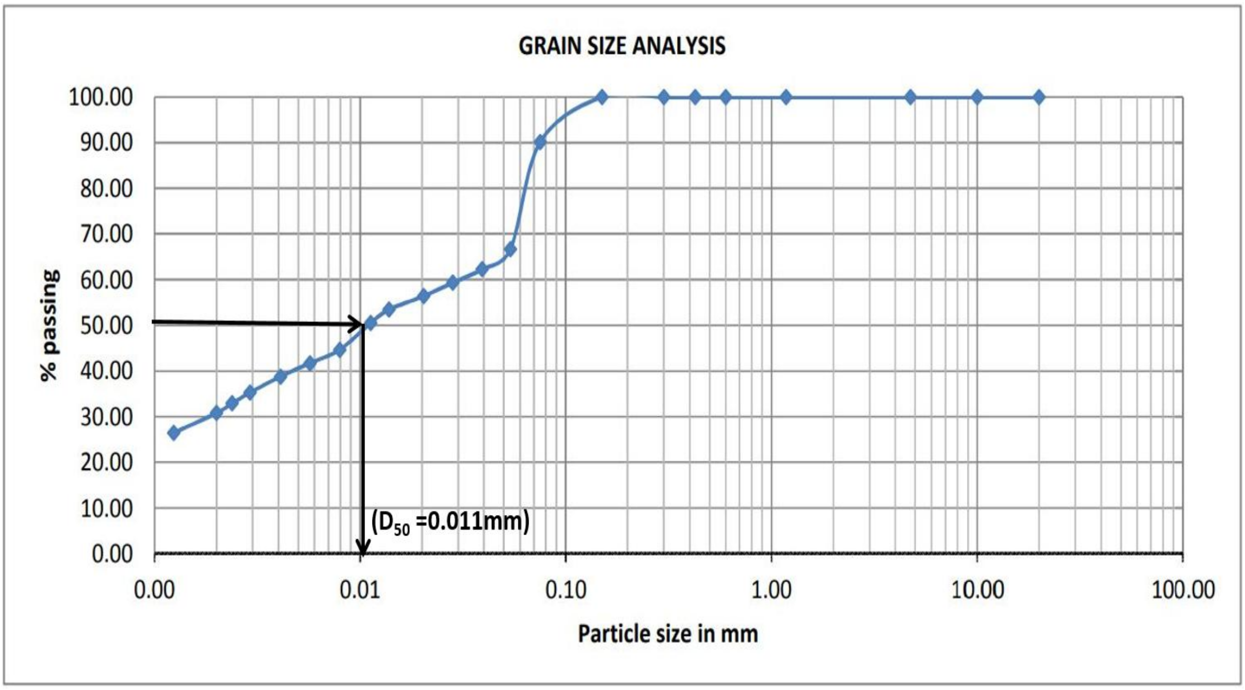

Fig.7: Typical Plot of Sieve Analysis indicating D_{50} size of Bed Sample

5. STORM WAVE HINDCASTING AND EXTREME WAVE ANALYSIS

The design wave height for any marine/coastal structure viz. breakwater/seawalls is the extreme wave height that a structure should withstand without significant damage. The determination of the design wave height is site specific and depends on the extreme wave climate at the site, life of the structure, service life of the structure, risk, cost etc. The determination of the design wave height should be based on the statistical analysis of long-term extreme wave height measurements.

5.1 Sources of Wave Data

There are three sources of wave data, which are generally used for the estimation of design wave conditions for the coastal/offshore structures:

i) Visually observed data
ii) Instrumentally recorded data and
iii) Hindcast wave data

5.1.1 Visually Observed Wave Data

Visual observations of wave data are reported by various ocean-going vessels. The ship observed visual data are compiled by the India Meteorological Department (IMD) and reported in the form of Daily Weather Reports. Some agencies also have compiled these data in the form of Wave Atlas. Visually observed data are quite vast and cover large area of the ocean where ships are regularly passing. However, these data may not be of good quality. The ship observed wave height is primarily a matter of personal judgment and estimation. Moreover, these ships are usually unlikely to ply through areas of pre-warned storms, thereby missing some of the important storm wave information. The visually observed wave heights correspond to significant wave height (H_S) and the wave period observed are close to the average wave period (T_Z). Ship based data also contain the vital information about the wave direction.

5.1.2 Measured Wave Data

Many governmental/non-governmental agencies in the world have been conducting long-term wave measurements or short-term project-oriented wave measurements for limited duration at various sites by deploying equipment like Wave Rider Buoys/ADCP etc. The quality and duration of measured wave data varies from site to site. These instrumentally recorded data though most accurate and reliable, are costly as compared to visually observed data. The directional measurement capabilities have become available only during the last couple of decades. As such, most of the earlier measured data lack of the directional information. Also, these data are very site specific.

The recent developments in the satellite remote sensing techniques have shown that the remote sensing data can be advantageously used to obtain synoptic information on wave directional spectra covering large area.

5.1.3 Hindcast Wave Data

Wave hindcasting is generally used to obtain storm wave data for extreme value analysis, since the long-term measured data are seldom available. Wave hindcasting is usually done to obtain wave data from the major storms over 30 to 50 years or longer. Measured wave data for longer duration were not available in the vicinity of Vadhavan area. As such, hindcast storm wave data were utilized to arrive the extreme wave and storm surge conditions near the proposed breakwater for development of Port facility at Vadhavan.

5.2 Data for the Wave Hindcasting Studies

For wave hindcasting studies, the storm data in the form of storm tracks and synoptic charts (pressure distribution) are required. CWPRS obtained the storm tracks and synoptic charts for the period between the years 1946 and 2015 (about 60 years) from IMD. These data were analyzed to find storms, which passed by the area of interest and are significant to Vadhavan coast.

5.3 Hindcasting of Storm Wave Data

Estimation of waves generated by the storms in the past is called 'Wave Hindcasting'. Wave hindcasting is generally used to obtain storm wave data for extreme value analysis, since the long-term measured data are seldom available. Ocean waves are generated by the wind blowing over the water surface. The parameters, which govern the wave generation, are :

1) Wind speed
2) Duration of wind
3) Distance over which the wind blows – Fetch
4) Distance between point of observation and front of fetch area – Decay distance

The methods for estimating wave conditions from the above parameters have been established by various researchers. A combined empirical- analytical procedure was developed by Sverdrup and Munk, which were revised by Bretschneider, based on empirical data. This wave prediction system is called as the "Sverdrup-Munk-Bretschneider (SMB) Method". Using the modified Bretchneider method for hindcasting of storm waves, the significant wave height (H_S) and the peak wave period (T_p) could be predicted for a particular site. The data regarding wind speed, wind duration, fetch length and decay distance is obtained from the storm tracks and the synoptic charts. The wind speed is determined from the pressure gradient and the latitude of the fetch area. The pressure gradient is determined from the isobar spacing shown on the synoptic chart.

5.3.1 Analysis of Storm Data

The storms shown on storm tracks are classified as :

Low pressure area	:	Wind Speed less than 31 km/hr
Depression	:	Wind Speed between 31 and 50 km/hr
Deep Depressions	:	Wind Speed between 51 and 61 km/hr
Cyclonic Storm	:	Wind Speed between 62 km/hr and 87 km/hr
Severe Cyclonic Storm	:	Wind Speed between 88 km/hr and 117 km/hr
Very Severe Cyclonic storm	:	Wind Speed between 118 km/hr and 220 km/hr
Super Cyclones	:	Wind Speed above 220 km/hr

From the storm data for the period between years 1946 to 2015 (about 60 years), the storms passing through the area in the vicinity of Vadhavan coast were identified. It was seen that there were few storms which crossed the coastline in the vicinity off Vadhavan during 1946 and 2015 (Fig. 8).

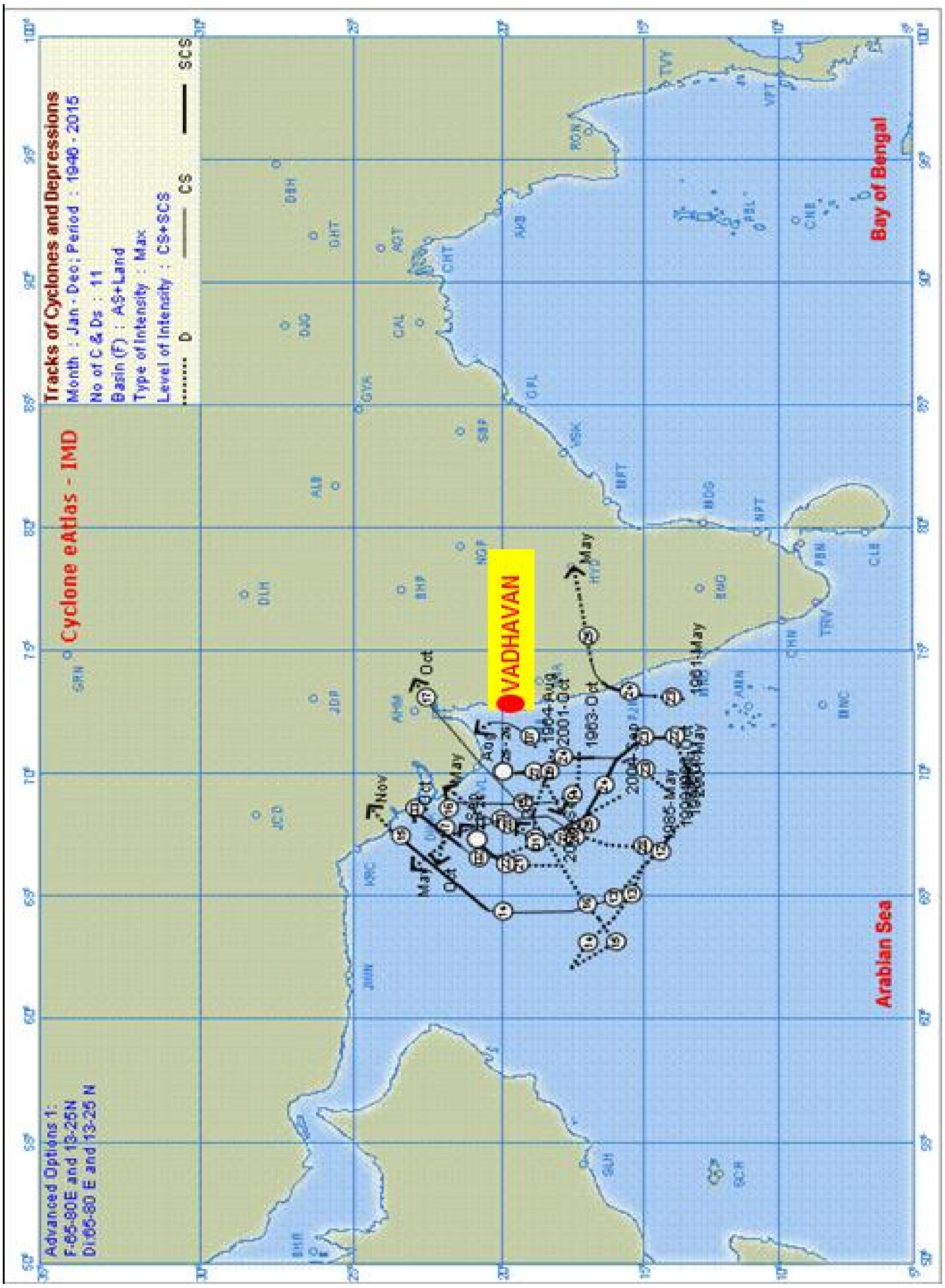

Fig. 8: Storms crossed the land on either side of Vadhavan port site

However, due to the importance of the project and to use the value for return period analysis for 100 years major storms passing off the coast of Vadhavan in the Arabian sea have been considered for the studies. In all 95 storms which are of significance to the Vadhavan coast are considered for the studies and their distribution based on its classification are listed in the Table-II and shown in Figs. 9 to 11.

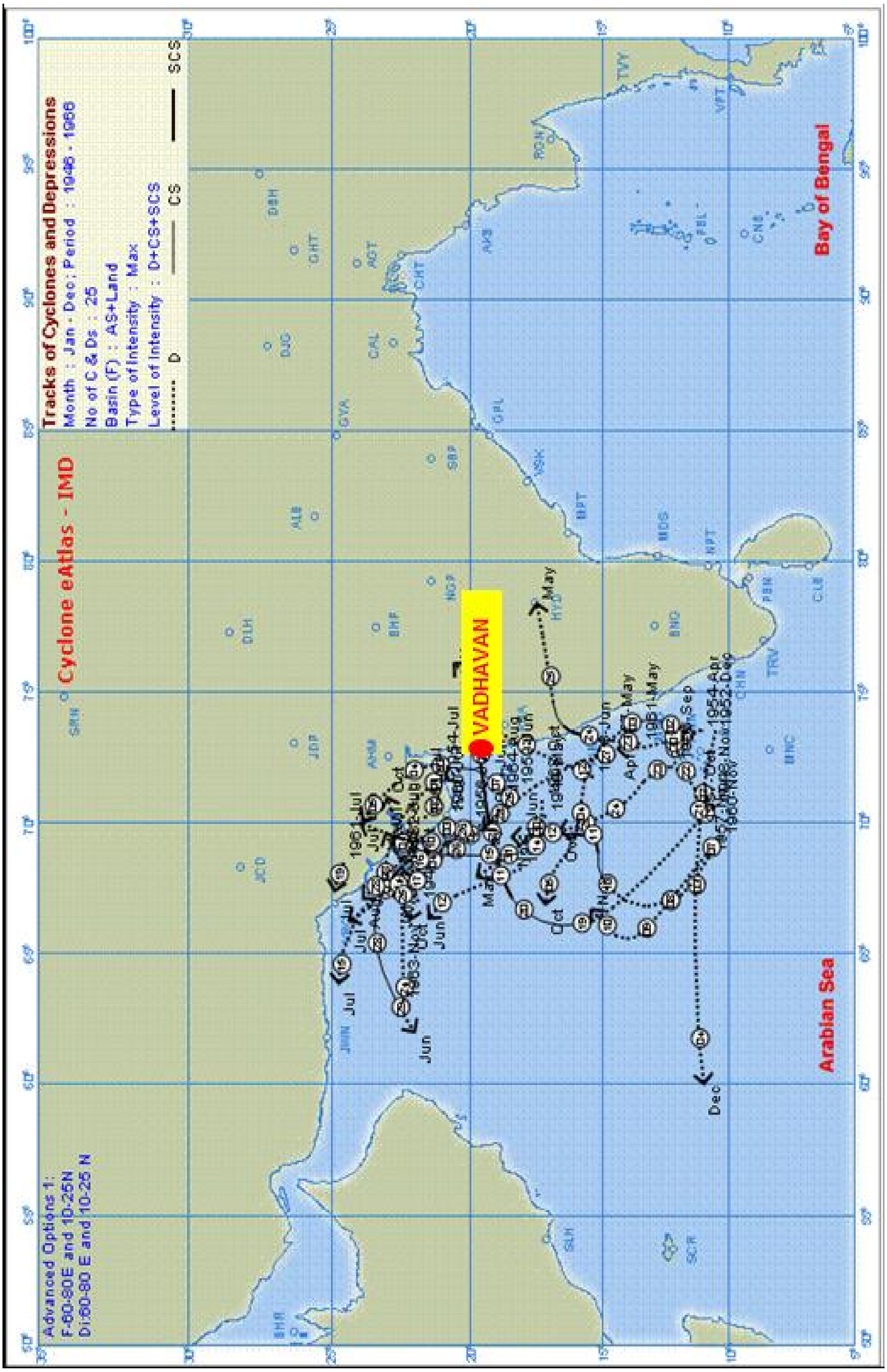

Fig. 9: Storms occurred in the Arabian Sea (1946-1966) off the coast for Port at Vadhavan

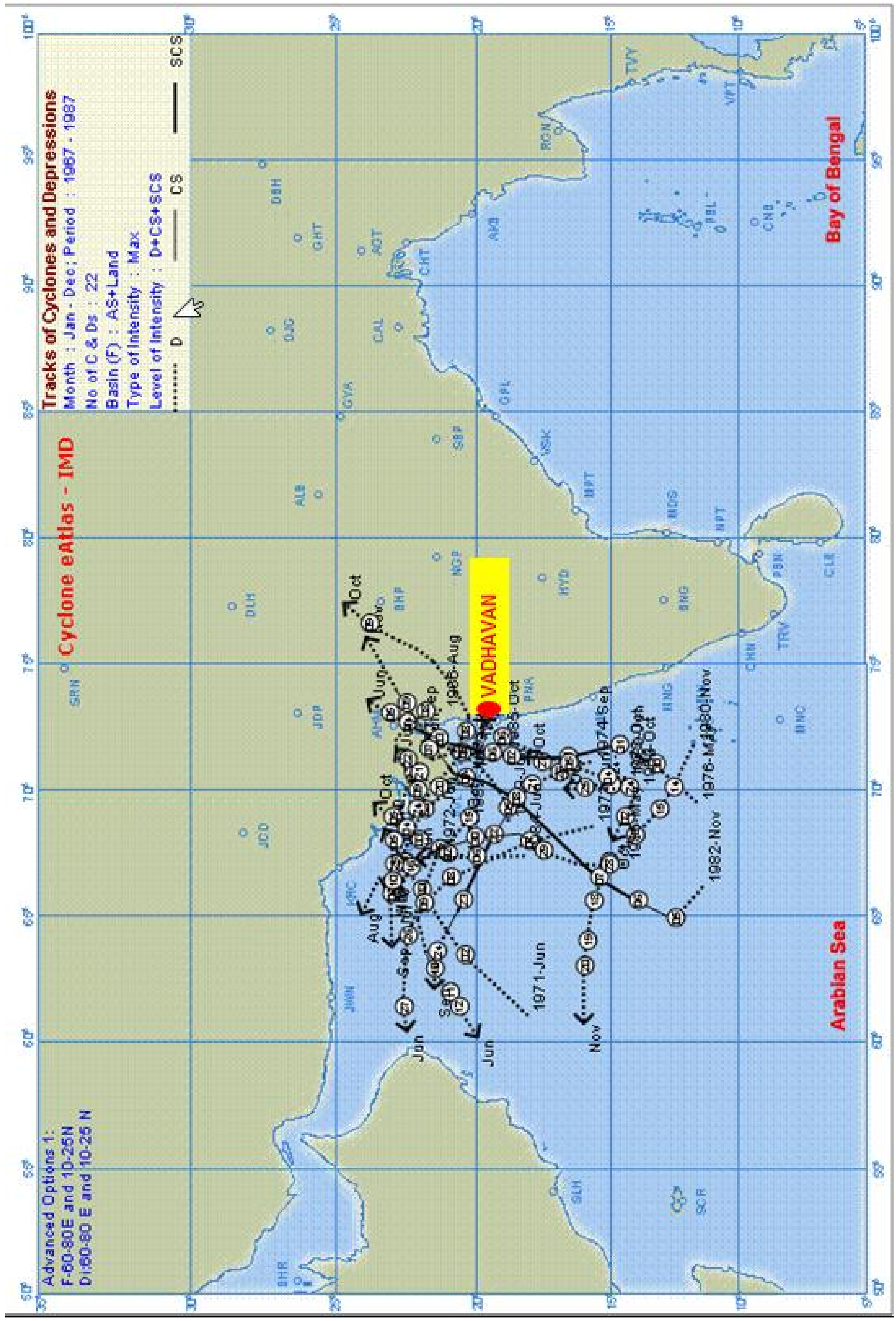

Fig. 10: Storms occurred in the Arabian Sea (1967-1987) off the coast for Port at Vadhavan

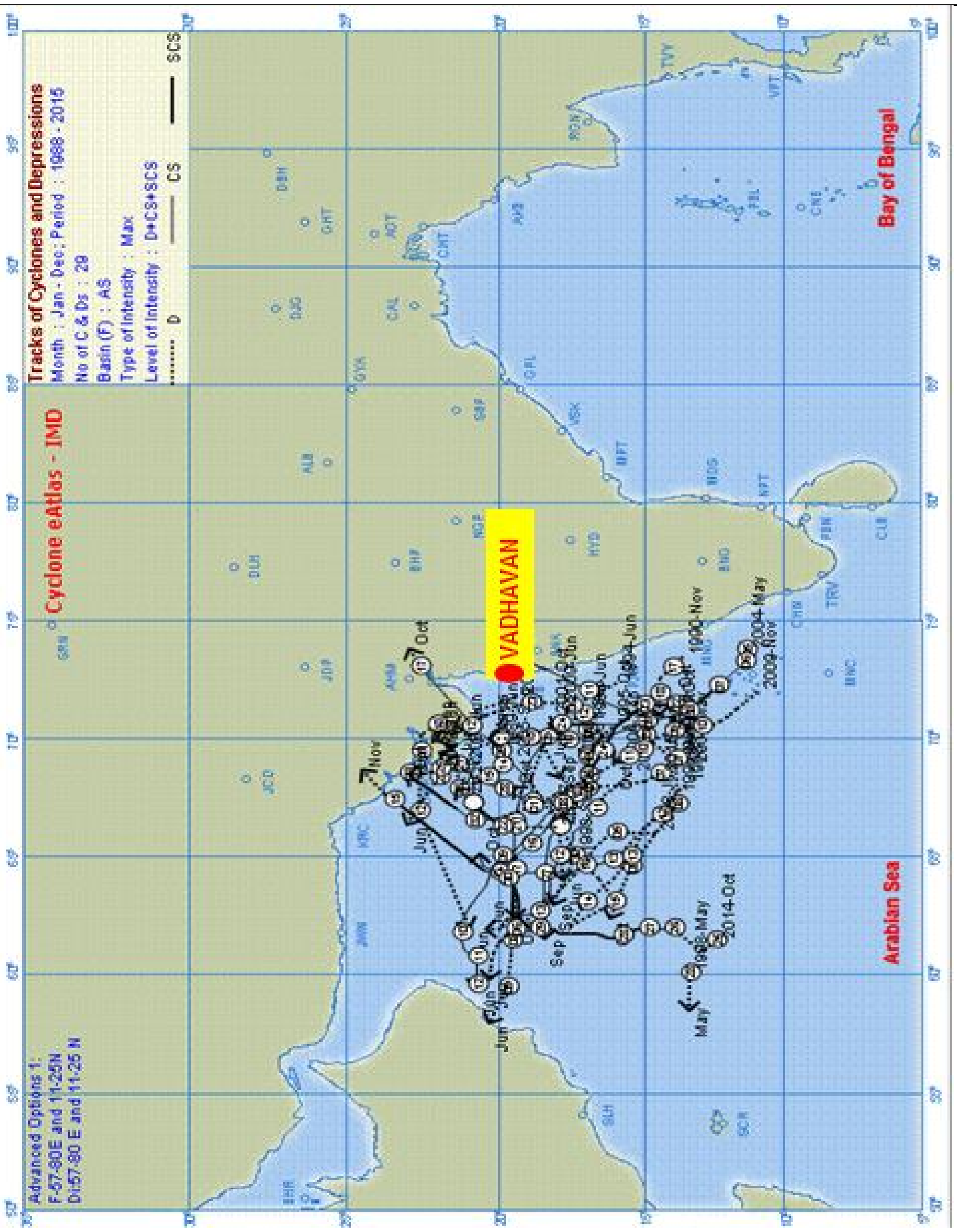

Fig. 11: Storms occurred in the Arabian Sea (1988- 2015) off the coast for Port at Vadhavan

The typical synoptic charts for storms used for analysis are given in Fig 12(A) and Fig.12(B). The break up of various storm conditions is given in Table-II, while its distribution in Fig. 13.

Table-II

Distribution of Storms of Different Types

Depressions	:	20 Nos.
Deep Depression	:	12 Nos.
Cyclonic Storms	:	31 Nos.
Severe Cyclonic Storms	:	19 Nos.
Very Severe Cyclonic Storms	:	12 Nos.
Super Cyclone	:	01 No.

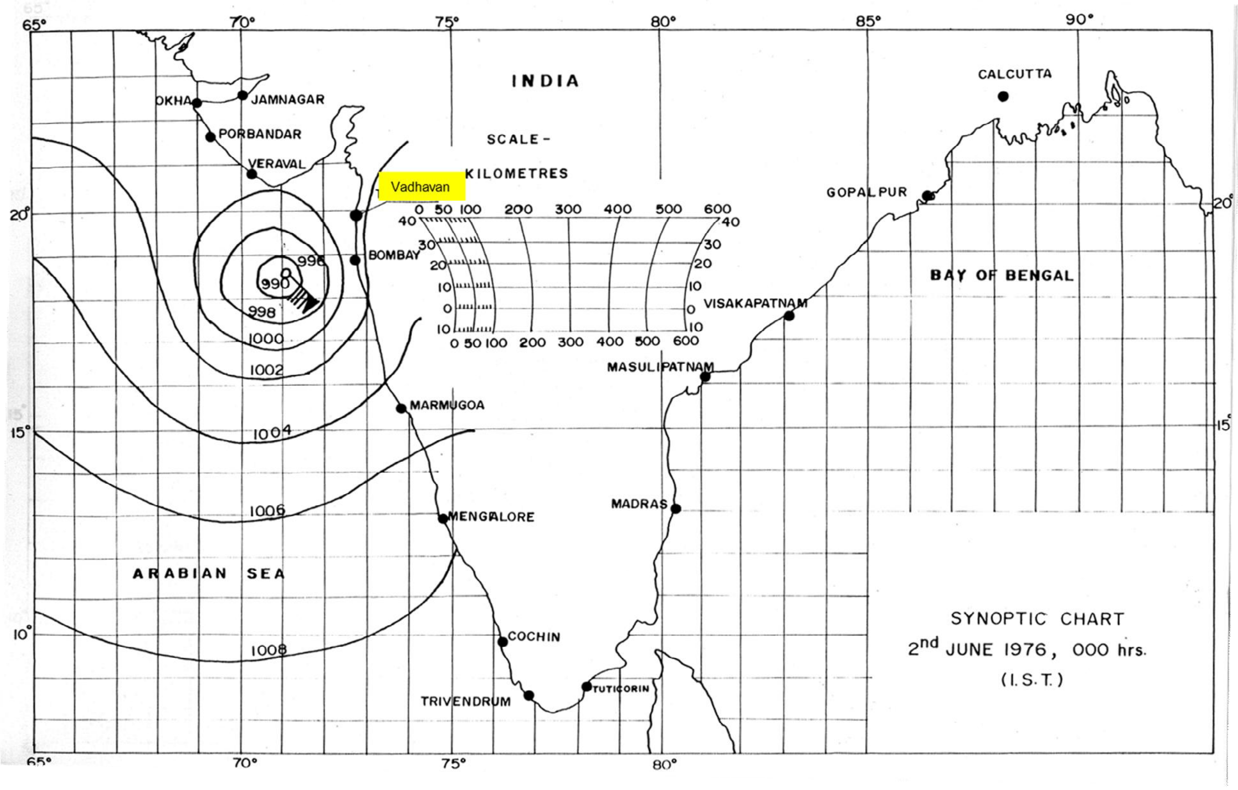

Fig. 12(A): Synoptic chart for storm occurred on 2nd June 1976

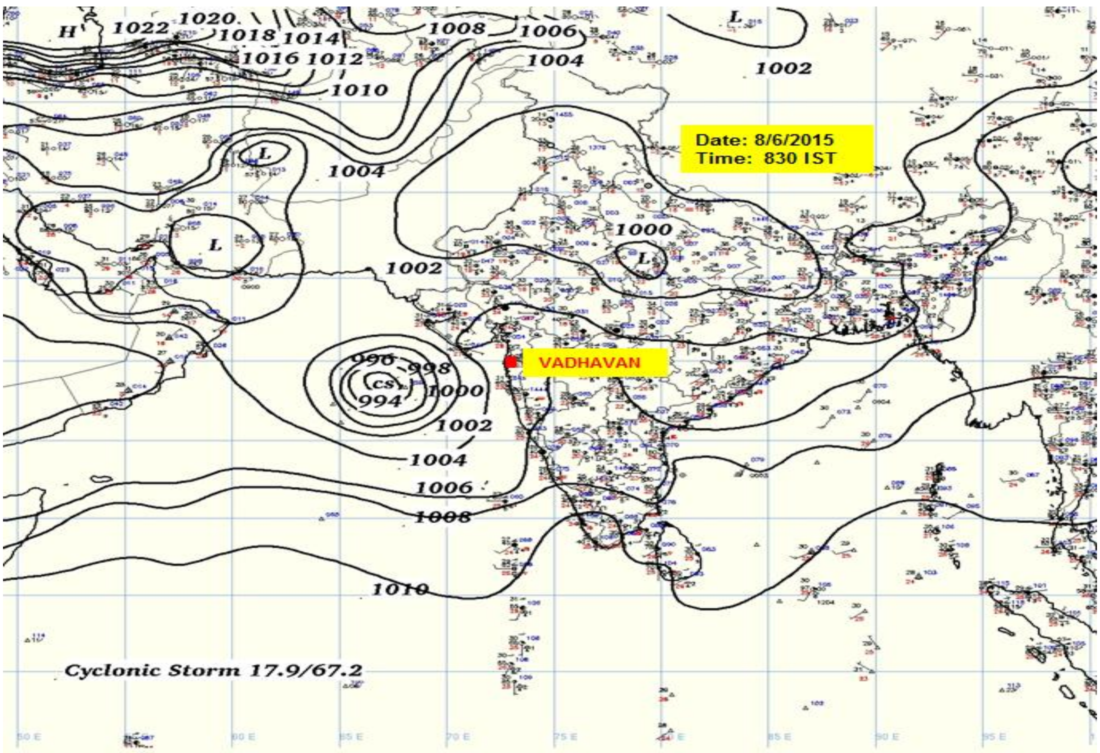

Fig. 12(B): Synoptic chart for storm occurred on 8th June 2015

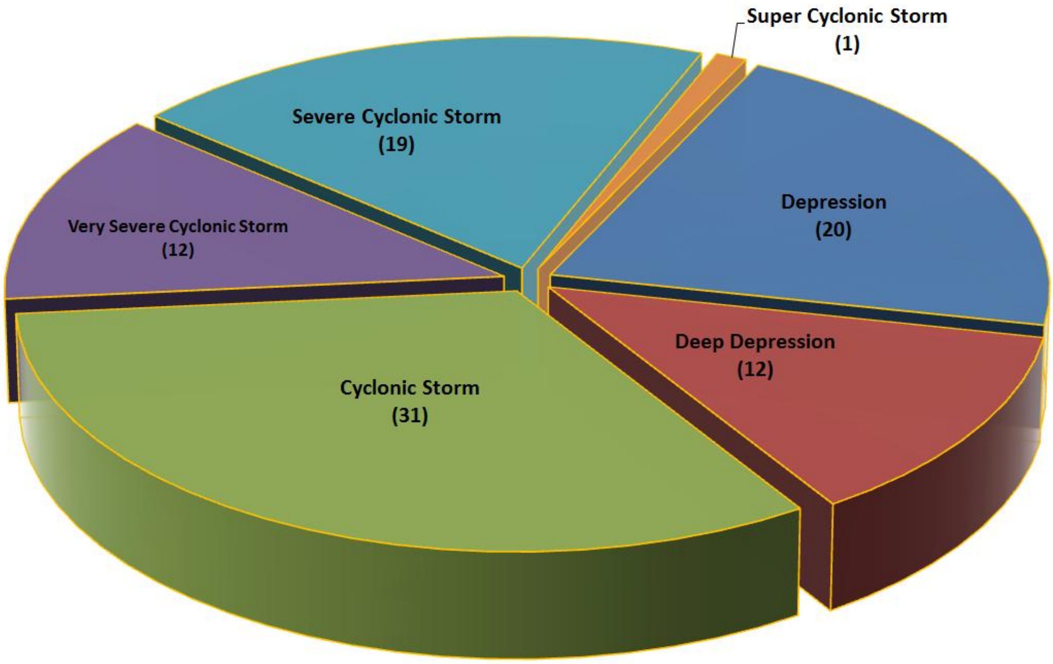

Fig. 13: Distribution of Different Types of Storm Events off Vadhavan Port (1946-2015)

It is observed that almost all the storms which are of significance for Vadhavan have occurred during the months of May to November. The month-wise and year-wise distributions of the storm events are shown in Fig.14 and Fig.15 respectively.

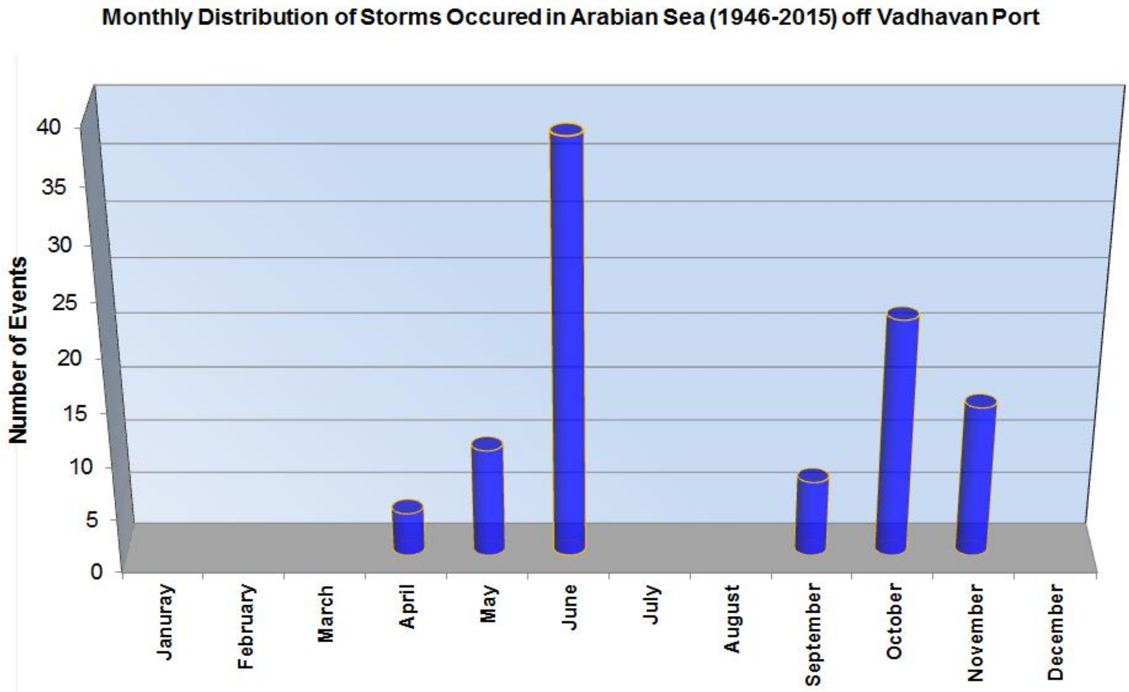

Fig. 14: Monthwise Distribution of Storm Events Ocured during 1946- 2015

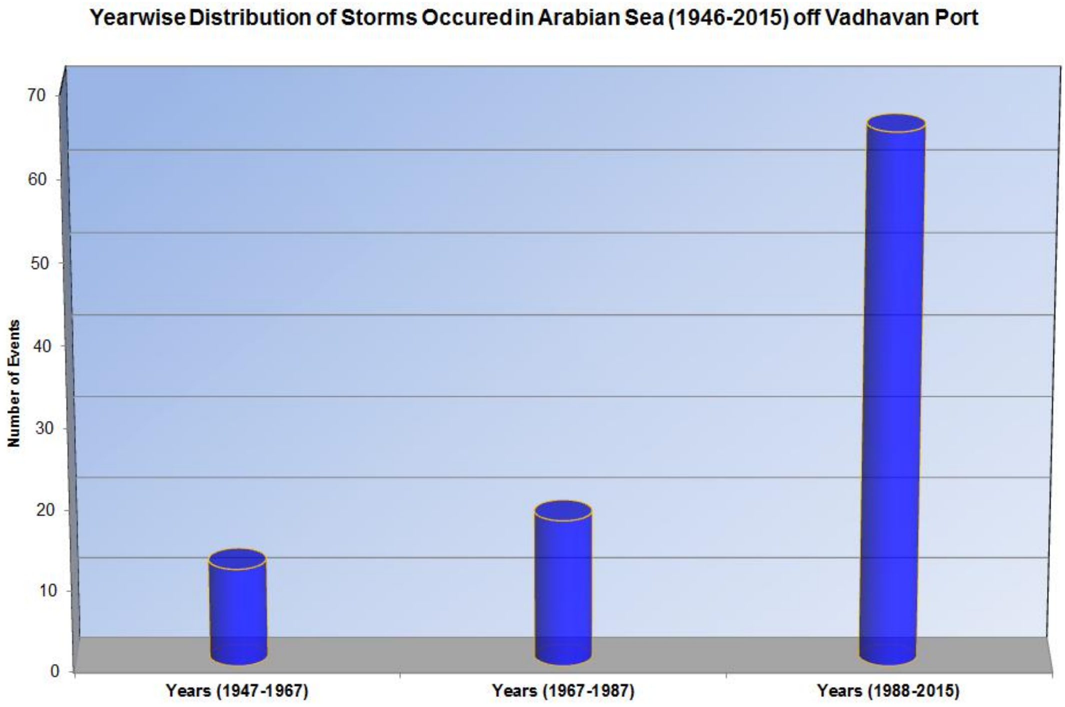

Fig. 15: Yearwise Distribution of Storm Events Ocured during 1946- 2015

Using method given in paragraph 5.3 for hindcasting of waves, the probable significant wave height (H_S) and wave period (T_p) off the coast of Vadhavan were computed. The effective fetch, duration of storm, wind speed and decay distance were taken in to account in the computations. Initially, the deep-water wave conditions at the front of the fetch were computed and then using the decay distance for each storm, the wave conditions off the Vadhavan coast in 30 m water depth were computed. Out of 95 storm events, there are 57 storms, which generate the wave height higher than 2.0 m off the coast of Vadhavan in 30 m water depth. As an example the storms which generated Significant wave height (H_S) more than 4.0 m are given in Table -III.

Table – III
Major Hindcast Storm Wave Conditions off Vadhavan Coast during the period 1946 -2015 (30 m water depth)

Sr. No.	Period of storm		Significant Wave Height In metres	Peak Wave period in Sec.	Average Wave period in Sec.	Max. Wave Height in metres.
	Date	Time				
1	16-04-1947	11.30	4.19	15.19	10.8	8.5
2	24-09-1948	2.30	4.42	12.51	8.9	9.0
3	24-09-1948	11.30	4.86	13.99	9.9	10.1
4	28-06-1959	8.30	4.11	18.14	12.9	8.3
5	21-11-1974	17.30	4.29	14.52	10.3	8.8
6	10-06-1977	8.30	4.83	17.39	12.4	9.4
7	11-06-1977	8.30	5.05	21.05	15.0	9.8

8	12-06-1977	8.30	4.84	21.74	15.4	9.5
9	01-11-1981	8.30	4.41	14.39	10.2	9.0
10	07-11-1982	8.30	4.36	18.06	12.8	8.6
11	15-11-1993	8.30	4.07	15.4	10.9	8.3
12	17-05-1999	17.30	4.57	17.51	12.4	9.0
13	26-05-2001	8.30	4.09	17.18	12.2	7.9
14	04-06-2007	8.30	6.79	12.97	9.21	10.0
15	04-06-2007	3.00	7.07	21.18	15.0	13.5
16	29-11-2011	5.30	4.36	16.84	12.0	8.7
17	29-11-2011	17.30	4.06	16.77	11.9	8.2
18	28-10-2014	11.30	4.93	17.72	12.6	9.8
19	29-10-2014	5.30	4.14	20.72	14.7	8.1
20	08-06-2015	17.30	5.09	17.46	12.4	9.8

The average wave period , T_z and the maximum wave height, H_{max} given in Table – III are computed using the following relations :

$$T_p = 1.408T_z \qquad \text{---------------------------------- (1)}$$

$$H_{max} = H_s\sqrt{\frac{ln(N)}{2}} \qquad \text{----------------------------------(2)}$$

Where , N = Total number of waves = Duration of storm / (T_z)

6. EXTREME WAVE ANALYSIS

6.1 Long Term Analysis of Ship Observed Data

The normal wave conditions for the location of the proposed port near Vadhavan are derived from the ship observed data as described in paragraph 5.1.1. From the frequency distribution of wave heights, the percentage of time per year that a certain wave height will be exceeded was computed. The cumulative percentage probability for normal wave condition is presented in Table –IV below.

Table –IV

Exceedence Probability of various Significant Wave Heights

Significant Wave Height, H_s	Probability of Exceedence
0.0 m	100 %
0.5 m	47.87%
1.0 m	28.98%
1.5 m	20.87%
2.0 m	14.33%
2.5 m	9.24 %
3.0 m	5.58%
3.5 m	2.49 %

The normal wave data has been plotted on a Log-normal graph paper as shown in Fig. 16 . For the long term analysis of this data, the duration of each data is assumed as 12 hours. The exceedence percentage for the wave height for once in one year is given as:

$$\frac{12\ Hours}{365\ Days\ X\ 24\ Hours}\ X\ 100 = 0.137\% \qquad \text{-----------------------(3)}$$

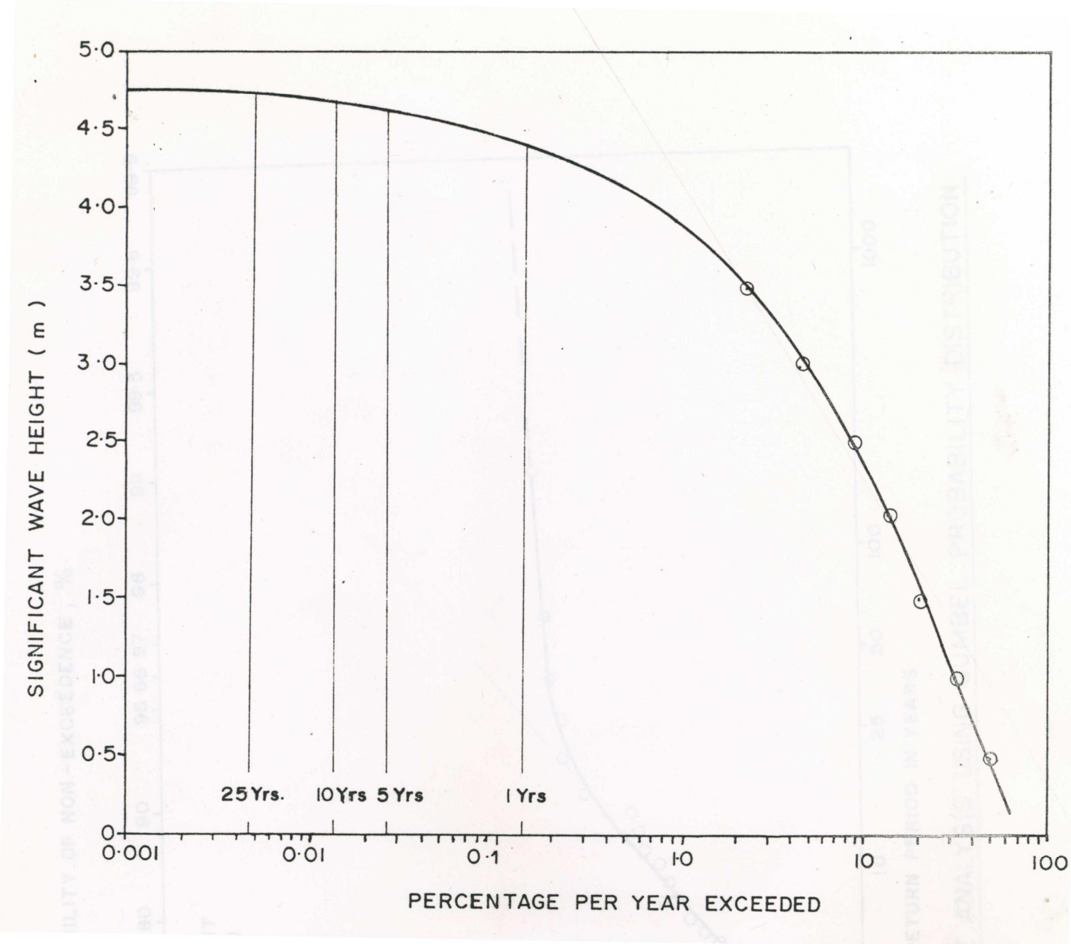

Fig. 16: Long Term Analysis of Normal Wave Data

Thus the once in one year wave height read from Fig. 16 is 4.4.m. Similarly the extreme wave heights for different return periods are determined from Fig. 16 and are given in Table-V:

Table-V

Extreme Wave Height for Various Return Periods

Return Period	Extreme Wave Height
1 Year	4.40 m
5 Years	4.60 m
10 Years	4.65 m
25 Years	4.70 m

The objective of the extreme value analysis is to provide a basis for selection of extreme wave condition. Prediction of extreme wave height over a span of 25 years, 50 years, 100 years for the structure is required for selecting the wave height for design purpose. The wave height, which occurs on an average once in 100 years, will have 100 year `return period ' (Rp).

6.2 Extreme Value Analysis of Storm Wave Data

These hindcast wave data of storms were considered for extreme wave analysis. These data over a period of about 60 years (1946 to 2015) represent the storm waves and were fitted to Gumbel, Weibull and Log-Normal distributions, since these distributions are applicable for the storm data (Herbich, 1990). The estimates of extreme wave heights for different return periods using Gumbel, Weibull and Lognormal distributions are given in Table -VI. It is seen that the wave heights predicted using Gumbel, Weibull and Log-Normal distributions do not show significant variation and as such all distribution are well fitting to data taken for analysis.

Table – VI
Predicted Wave Heights off Vadhavan Coast
(30 m Water Depth)

Return Period (R_p) in years	Predicted Significant Wave Height, Hs in meters			
	Ship Observed	Gumbel	Weibull	Log-Normal
1	4.40	3.30	3.10	3.30
10	4.65	5.70	5.90	5.70
25	4.70	6.90	6.90	6.60
50	-	7.60	7.50	7.30
100	-	8.30	8.10	8.10

Considering the facts mentioned above the distribution of Weibull which gives highest correlation co-efficient for storm data is considered as more appropriate and wave heights considered are shown in Table VII. The Peak wave period is computed from scatter data.

Table – VII
Extreme Wave Heights off Vadhavan Coast
(30 m Water Depth)

Return Period R_p in years	H_s Significant wave height (Hs) in metres	Peak Wave Period (T_p) in sec.
1	4.4	15.60
10	5.9	16.70
25	6.9	17.20
50	7.5	17.50
100	8.1	18

6. DEVELOPMENT OF MATHEMATICAL MODEL

The mathematical model study covers the simulation of wave propagation in Vadhavan port area. The studies were carried out by using TELEMAC software available at Central Water & Power Research Station (CWPRS), Pune. The wave module Tomawac is the third generation spectral wave model (Benoit et al., 1996) and it models the changes, both in the time and in the spatial domain of power spectrum of wind driven waves and wave agitation for applications in the oceanic domain, in intercontinental seas as well as coastal zone. The model uses the finite elements formalism for discretizing the sea domain; it is based on computational subroutines of the TELEMAC system, viz TOMAWAC developed by EDF R&D,LNHE, France.

Tomawac models the sea states by solving balance equation of the wave action density directional spectrum (N). In order to serve that purpose, the model should reproduce the evolution of action density directional spectrum at each node of a spatial computational grid. The model solves the action conservation equation in Cartesian or spherical spatial coordinates.

$$\frac{\partial N}{\partial t} + \dot{x}\frac{\partial N}{\partial x} + \dot{y}\frac{\partial N}{\partial y} + \dot{k_x}\frac{\partial N}{\partial x} + \dot{k_y}\frac{\partial N}{\partial y} = Q\left(x, y, k_x, k_y, t\right) \quad \text{-------(4)}$$

Where k_x and k_y are the wave number vector components and the dot over the variables symbolizes the time derivative. The term Q represents the source and sink terms that can be taken into account in this model. The source term from wind-driven wave generation, sink terms from white-capping, bottom friction, depth induced wave breaking and the non-linear quadruplet and triad interactions are included.

Tomawac model is capable of modelling random multi-directional waves based on superposition of sinusoidal waves as well as complex bottom topography and irregular shorelines. Wave induced currents are accounted for when coupled with tidal hydrodynamics. However, as phase-averaging model, this model cannot fully model phase-dependent processes such as radiation and diffraction.

7.1 Descritisation of the Domain Area

The domain area of the model for present study considered is of fan shape and extends up to about 19 Km on north and 40 Km south of Vadhavan location in the offshore region, wherein offshore boundary of model extends up to 30 m depth [with respect to Chart Datum (CD) of Vadhavan] and is about 54 km from Vadhavan headland. The model also includes entire port limits wherein breakwater, terminals as well as reclamation area near Vadhavan headland are proposed. The total area of domain is about 2406 sq.km and is shown in Fig 17(A). The latest bathymetry data made available by JNP for Vadhavan port limit, data provided by MMB for Dahanu creek and for rest of the area bathymetry data is taken from Mike –C Map available at CWPRS . The bathymetry of model is shown in Fig 17(B).

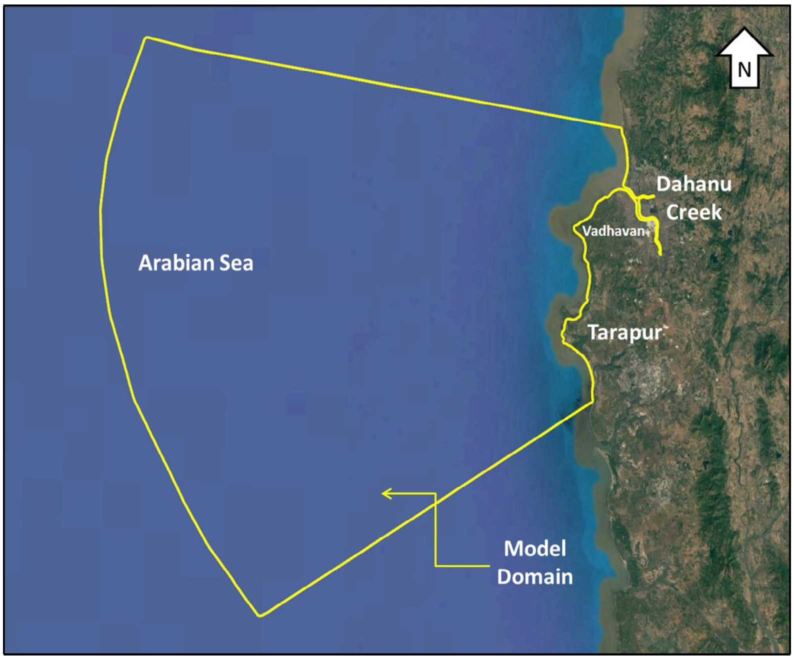

Fig-17(A): Domain Area Considered for Wave Transformation Model

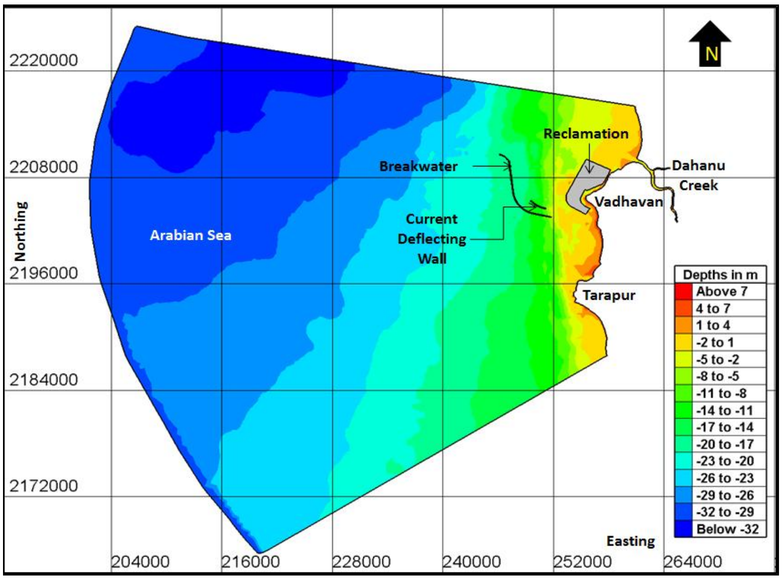

Fig-17(B): Bathymetry Layout for Wave Transformation Model

The triangular finite elements with fine resolution near breakwater and around reclamation with mesh size (50 m X 50 m), near shoreline (100 m X 100 m) were adopted for true simulation of steep slopes, effect of refraction/shoaling on wave parameters and coarser size of (200 m X 200 m) and (500 m X 500 m) in deeper depth areas to optimize number of elements to minimise simulation time. Thus mesh generated can effectively reproduce wave conditions without compromising on the quality of results.

7.2 Transformation of Waves

The 100 year return period wave height predicted at 30 m water depth off Vadhavan was considered as boundary condition for wave transformation studies to determine the wave heights near the proposed breakwater structure. During cyclonic conditions as the waves may propagate from West to Southwest direction predominantly, waves from three different directions viz. West, West-Southwest and Southwest are considered in association with local wind prevailing at Vadhavan (10 m/sec) from respective directions. The results of wave transformation studies for these wave directions are shown in Fig. 18,19 and 20. The studies were also carried out at High tide level (6.2 m) and high tide level with storm surge of 2 m.

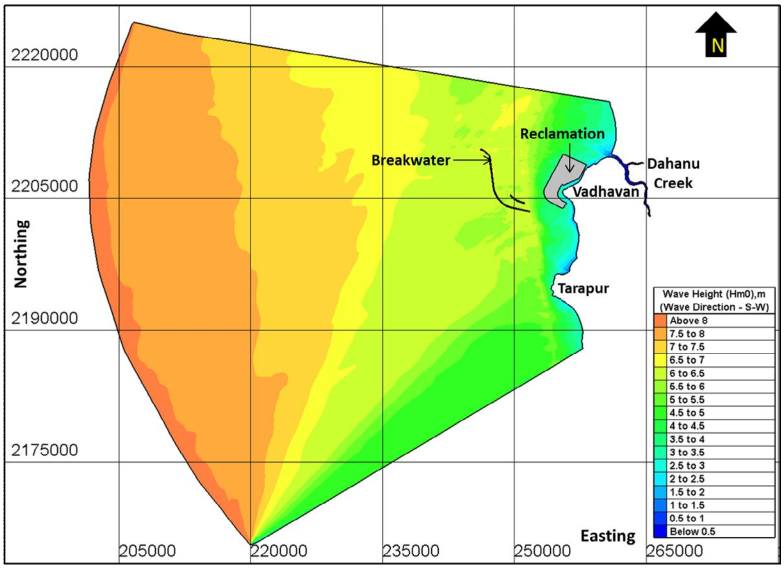

Fig.18: Plot of Significant Wave Height (Hs) for Waves from Southwest

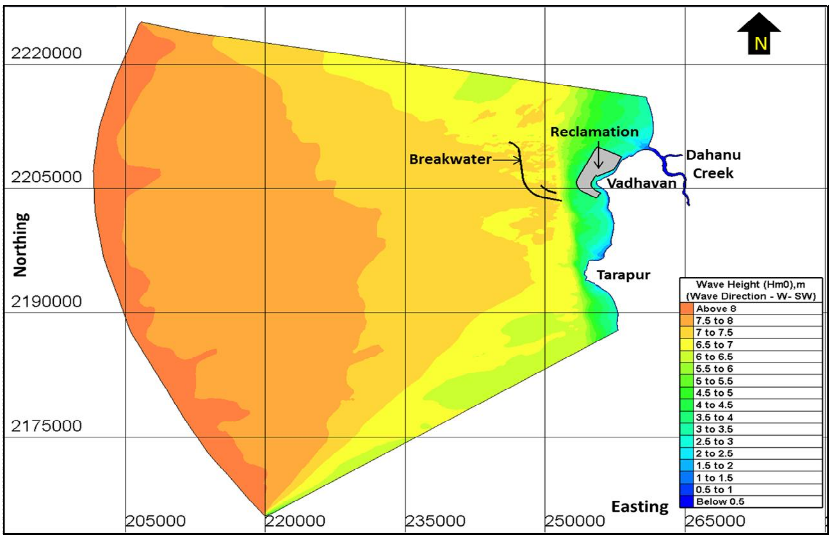

Fig.19: Plot of Significant Wave Height (Hs) for Waves from West-Southwest

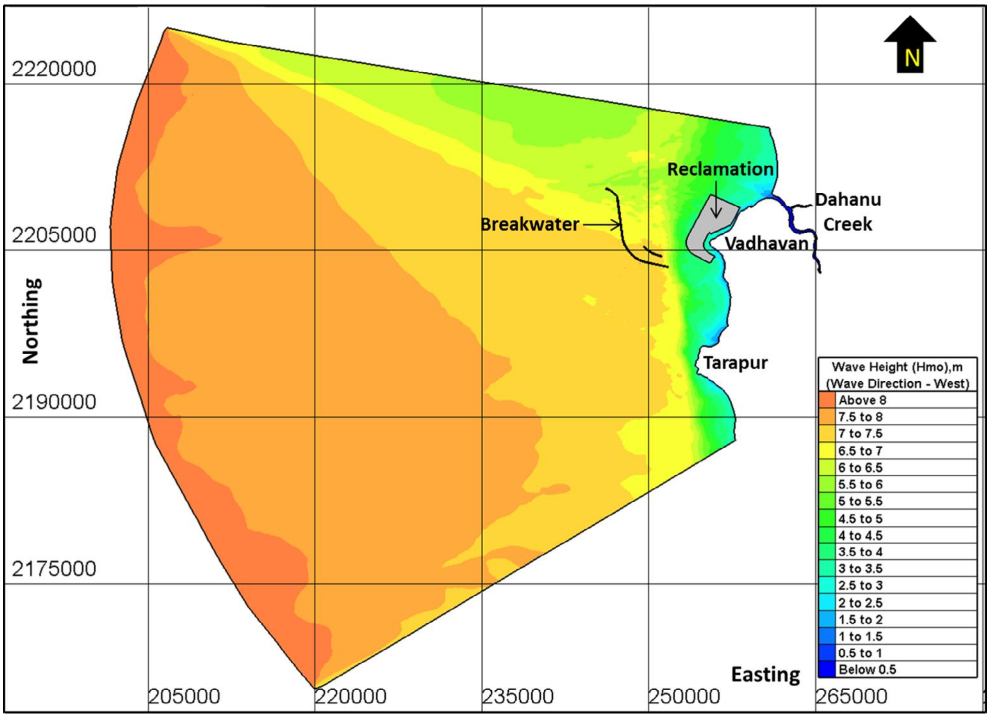

Fig.20: Plot of Significant Wave Height (Hs) for Waves from West

The wave heights derived from model studies near breakwater are given in Table-VIII, while the maxima values are given in Fig. 21.

Table-VIII

Significant Wave heights on seaside of breakwater for port at Vadhavan

Wave Direction at Boundary		SW			W-SW			West		
Portion of Breakwater	Depth w.r.t. CD (m)	Low Tide Level	High Tide Level	High Tide Level + Storm Surge	Low Tide Level	High Tide Level	High Tide Level + Storm Surge	Low Tide Level	High Tide Level	High Tide Level + Storm Surge
North- Roundhead	-19.00	6.20	6.50	6.60	6.40	7.00	7.00	5.90	6.20	6.20
Trunk - 1	-15.50	6.40	6.70	6.70	6.80	7.40	7.50	6.50	6.90	6.90
Trunk - 2	-18.00	5.70	6.10	6.10	6.10	6.90	7.00	6.10	6.80	6.80
Trunk - 3	-18.00	5.80	6.10	6.20	6.40	7.20	7.25	6.50	7.20	7.30
Trunk - 4	-17.00	5.80	6.10	6.20	6.40	7.20	7.30	6.40	7.30	7.40
Trunk - 5	-14.00	5.60	6.00	6.00	5.90	7.10	7.20	6.00	7.20	7.40
Trunk - 6	-11.00	4.90	6.00	6.20	5.00	6.70	7.00	5.00	6.70	7.10
Trunk - 7	-8.20	4.50	6.20	6.50	4.60	6.60	7.10	4.60	6.60	7.10
South- Roundhead	-6.40	3.70	6.00	6.40	3.70	6.20	6.80	3.70	6.10	6.80

The incident direction of wave at north roundhead end will be 255^0 North, while that at south roundhead end will be 260^0 North. The direction of wave attack for trunk portion may be considered as right angle to the longitudinal axis of breakwater in respective water depths.

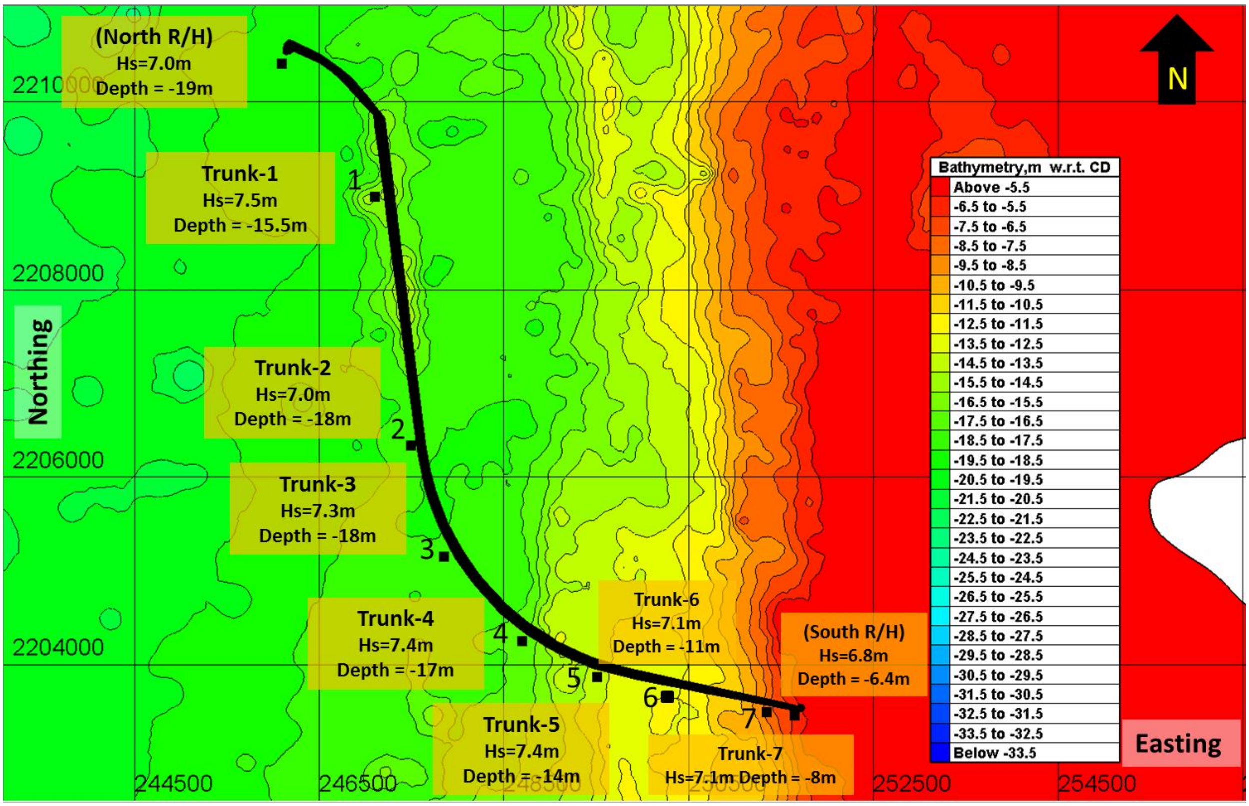

Fig. 21: Extreme Significant Wave Height (Hs) on seaward side of breakwater for Vadhavan Port for 1 in 100 year return period

8. STORM SURGE HINDCASTING AND EXTREME SURGE ANALYSIS

Storm surge is the temporary rise in the water level at the coastline during the cyclone event. This temporary rise in the water level takes place only when the cyclonic wind blows over the continental shelf and pushes the water against the coastline. Cyclones are not only associated with high winds, but are also associated with torrential rains that lead to flash flooding and abnormally high waves and storm surge. Each of these alone can pose a serious threat to life and property. Their combined effect is capable of causing enormous loss of life and wide spread destruction. Severity of the storm i.e. wind speed, pressure gradient as well as water depth, width of continental shelf etc. establishes the magnitude of the surge. The determination of the storm surge is site specific and depends on extreme storm climate in the vicinity of the site. Ideally, determination of extreme storm surge values should be based on the statistical analysis of surge values. Since the measurements of surge, which occur during the storm conditions, are not available, the extreme value analysis is carried out using past storm data for estimating the design storm surge. The India Meteorological Department (IMD) provides the records of the storms in the form of synoptic charts (pressure distribution) and storm tracks for moving storms. These storm data are useful for hindcasting the storm surge values. Surge hindcasting is usually done to obtain surge data from the major storms over 25 to 100 years or longer. Extreme value analysis was carried out for predicting the storm surge values with various return periods for the Vadhavan. In order to determine the extreme water level at the breakwater, the predicted maximum storm surge is to be superimposed over the High Water Level (HWL).

8.1 Data for Surge Hindcasting Studies

For surge hindcasting studies, the storm data in the form of storm tracks and synoptic charts (pressure distribution) as well as information about central pressure (P_0) are required. CWPRS obtained the storm tracks, information about central pressure and maxima wind speed etc for the past 25 years (1990 -2015) from IMD. Theses data were analysed to find storm surge, which has passed by the area of interest off the coastline.

8.2 Hindcasting of Storm Surge

The term `hindcasting' is popularly used in the Coastal Engineering in the context of predicting the wave conditions using the past storm data. Wave hindcasting is usually carried out to obtain storm wave data from the past storms. These storm wave data are subjected to extreme value analysis for predicting the wave conditions having various return periods. By using the same analogy, the storm surge values having various return periods can be predicted by carrying out the extreme value analysis of `hindcast storm surge data'. The parameters, which govern the storm surge, are:

1) Wind speed
2) Duration of wind
3) Distance over which the wind blows, called `fetch'
4) Isobaric pressure gradient
5) The width of the continental shelf
6) Water depth at the edge of the continental shelf
7) Water depth at the observation site

Empirical methods are available for estimating storm surge from the above parameters. The data regarding wind speed, wind duration and fetch length are obtained from the storm tracks and the synoptic charts. The wind speed is determined from the pressure gradient and the latitude of the fetch area. The pressure gradient is determined from the isobar spacing down on the synoptic chart. The width and depth of the continental shelf can be obtained from the Hydrographic Charts.

8.2.1 Storm Data

From the available data of storm tracks from 1990 to 2015, all important storms that will affect the surge value off Vadhavan have been considered for studies. From the storm data for the period between years 1990 and 2015 (25 years), the storms passing through the area in the vicinity of Vadhavan coast were identified. It was seen that there were total 41 cyclonic storm events, however the effect of some of these storms is negligible. The break up of these storm conditions is given as:

Cyclonic Storms	:	23
Severe Cyclonic Storms	:	05
Very Severe Cyclonic Storms	:	14
Super Cyclonic Storms	:	1

It is observed that almost all the storms which are of significance for Vadhavan have occurred during the months of June to November.

Synoptic charts showing the pressure distribution of the storm on the day which generates maximum storm surge were obtained from Indian Daily Weather Reports (IDWR) , available at IMD. Based on the pressure distribution of the storm, surge analysis was carried out.

8.2.2 Storm Surge Analysis

Rise in the normal water level due to storms is called as “Storm Surge”. The storm surge at or near the shoreline is due to two main components viz. (a) inverted barometric pressure effect and (b) onshore wind stress effect. The computations of the storm surge for the storms in the vicinity of Vadhavan area for each of the two components are described in the following paragraphs.

8.2.2.1 Inverted Barometric Effect

The inverted barometric effect is the tendency for the water surface to be sucked upwards in regions of low atmospheric pressure. During the storm conditions, the water surface rise is centred at the eye of the storm and depends directly on the central pressure relative to normal sea-level pressure.

The surge due to inverted barometric effect (Sa) is given by (Silvester,1974):

$$Sa = 0.01\ (P_n - P_0) \text{ in metres} \qquad \text{-----------------------------(5)}$$

Where, P_n = Pressure of the isobar at the boundary of storm, in mb

P_o = Pressure at the centre of storm, in mb.

The central pressure (P_0) is generally not mentioned on the synoptic charts. However, it can be computed using Analytical model of wind and pressure profile (Holland GJ, American Meteorologial Society, 1980). The pressure profile of a cyclone in Model is given by :

$$r^{B} ln[(P_n - P_c) - (P \quad - P_c)] - A \qquad \text{-----------------------(6)}$$

Where ,

r = Radial distance from the centre of storm in km
R = Radial distance of maximum cyclostrophic wind from the centre of storm in km
P = Pressure at radial distance `r' in mb,
P_n = Ambient pressure at the outermost isobar in mb

The set of the values of P and r can be obtained from the synoptic chart and equation (6) can be solved for P_c and A & B. Where "A" and "B" are the scaling parameter. The value of "A" is location relative to Origin of graph and "B" is the shape of the profile. However the value of the storm surge due to inverted barometric pressure computed at the center of cyclone/storm will have to be estimated at the point of interest and the reduction in the storm surge value is inversely proportional to the distance from the eye of the cyclone viz. decays at exponential rate.

A plot of synoptic chart and pressure profile for 28th October, 2014, 1130 Hrs IST cyclone to compute radius of maximum wind are shown in Fig .22(A) and 22 (B).

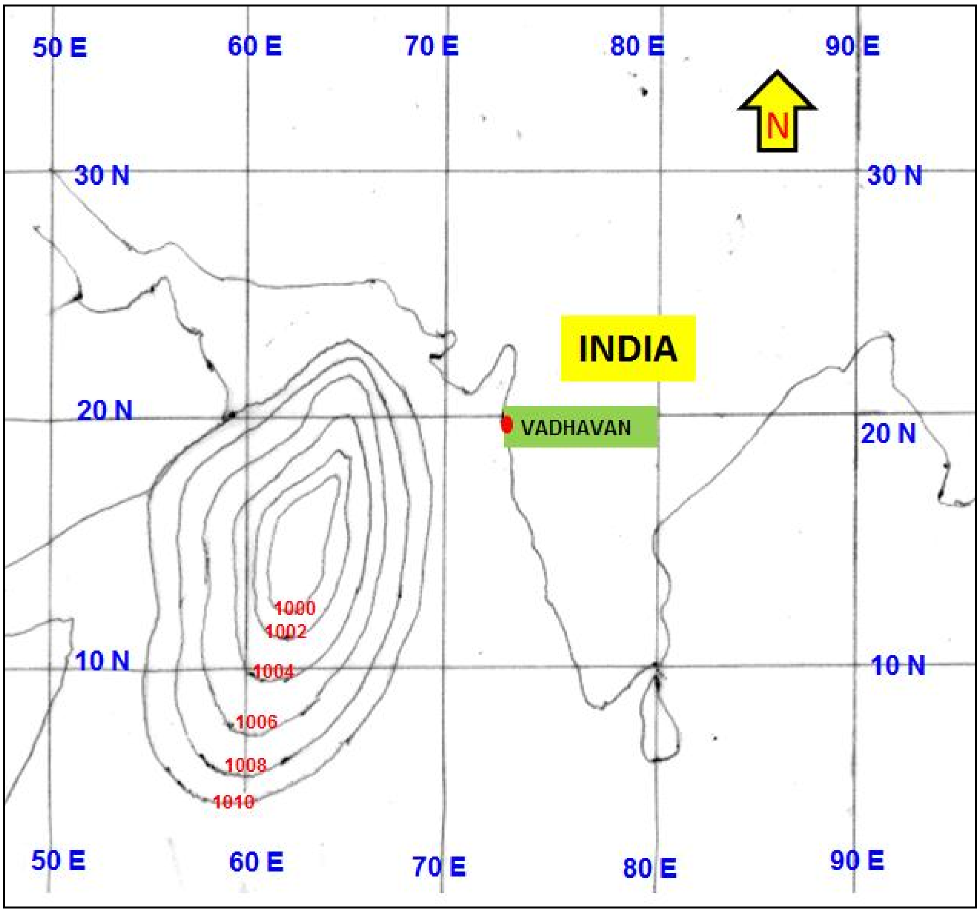

Fig. 22(A) Plot of Synoptic Chart for the Storm on 28th October 2014

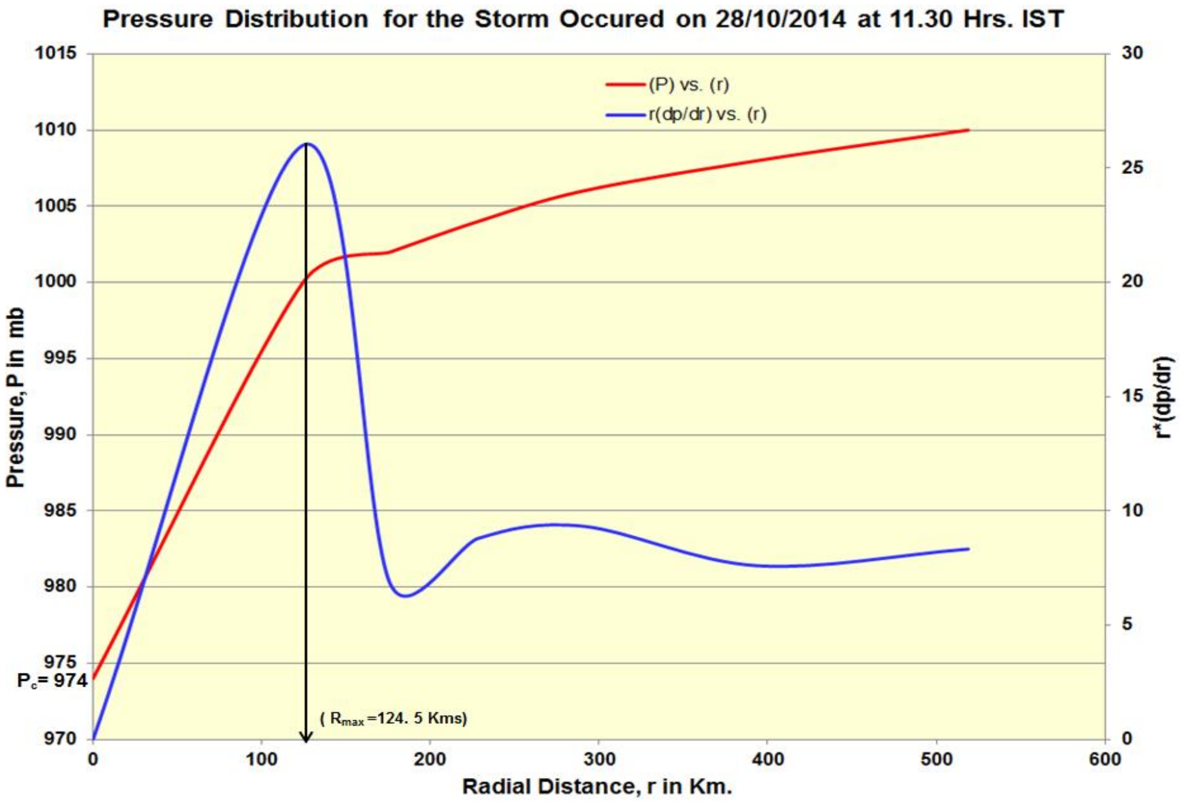

Fig. 22(B) Plot of Pressure Profile for computation of Radius of Maximum Wind

8.2.2.2 Wind Stress Effect

Generally, the larger component of any storm surge is that due to the wind stress on the water surface. The storm surge in the coastal region of an open ocean (i.e. storm surge over the continental shelf) due to static wind field is given by Silvester (1974) as :

$$S_w = \frac{KU^2L}{g(d_1 - d_2 - S_w)} \, ln\left\{\frac{d_1}{d_2 + S_w}\right\} \qquad \text{-------------------------(6)}$$

Where,

S_w	=	Storm surge due to wind stress in meters
K	=	Wind stress co-efficient
U	=	Surface wind speed in m/sec
L	=	Length or Fetch over which wind is blowing in meters. (Taken as width of the continental shelf if fetch is larger than the width of the continental shelf)
G	=	Acceleration due to gravity (9.81 m/sec^2)
d_1	=	Depth of the water at the edge of the continental shelf in m
d_2	=	Depth of the water near the coast in meters

8.2.3 Results of Storm Surge Analysis

The values of the storm surge due to inverted barometric effect (S_a) and due to wind stress (S_w) were computed for all the storms, which were of significance for the Vadhavan Coast. Total storm surge `S' was computed by adding these two components. Although these two components cannot occur simultaneously, the design storm surge is generally computed by adding these two components for all engineering purposes. There are 9 storm conditions, which generated a total storm surge of 0.75 m or higher at the Vadhavan and are given in Table -IX.

Table - IX
Major Storm Surge Conditions at Vadhavan coast during the period 1990 – 2015

Sl. No.	Period of storm		Storm Surge (Ss)		
	Year	Time in Hrs IST	Wind Stress Effect (S_w) in metre	Barometric Effect (S_a) in metre	Total Surge (S) in metre
1	04/06/2007	3.00	1.90	0.05	1.95
2	04/06/2007	8.30	1.76	0.09	1.85
3	28/10/2014	5.30	1.28	0.24	1.52
4	08/06/2015	8.30	1.29	0.03	1.32
5	29/10/2014	17.30	0.95	0.09	1.04
6	03/06/2007	8.30	0.96	0.03	0.99
7	17/05/1999	17.30	0.81	0.03	0.84
8	28/10/2014	11.30	0.77	0.04	0.81
9	26/05/2001	8.30	0.72	0.04	0.76

Besides the wind stress forcing the water shoreward, the reduction of atmospheric pressure at the centre of the storm also causes a rise in the water level, as mentioned earlier. The maximum barometric surge may be concurrent with the wind stress surge or it may precede or follow it. For engineering purposes, it is desirable to consider them as synchronous. Considering these two effects synchronous, the total surge at the Vadhavan coast during the super cyclone of 4th June, 2007 works out as 1.95m.

8.3 Extreme Value Analysis of Storm Surge Data

The objective of extreme value analysis is to predict the storm surge for the different return periods using the past storm data. Prediction of extreme storm surge over a life span of 100 years for proposed port at Vadhavan is required for determining extreme water level at the shore. The storm surge, which occurs on an average once in 100 years, will have 100 year `return period' (Rp).

The storm surge data of 41 storm events were considered for extreme value analysis. These data represent the storms over a period of 25 years (1990 to 2015) and were fitted to

Gumbel, Weibull and Log-Normal distributions, since these distributions are applicable for the storm data (Herbich,1990). The plots of Gumbel, Weibull distributions for the storm surge are given in Table - X.

Table – X
Predicted Storm Surge at Vadhavan Coast

Return Period (R_p) in years	Predicted storm Surge (S_S) in metres	
	Gumbel	Weibull
10	1.37	1.61
25	1.62	1.82
50	1.81	1.97
100	2.00	2.10

It is seen that the storm surge predicted using Gumbel, Weibull distributions are almost similar for higher return period (100 year). As such values for different return period considered are shown in Table - XI.

Table – XI
Extreme Storm Surge at Vadhavan Coast

Return Period R_p in years	Storm Surge (S_s) in metres
10	1.50
25	1.72
50	1.90
100	2.05

It is seen that the 100 – year storm surge for the Vadhavan coast is predicted as 2.05 m, say 2.0 m for practical purpose.

9. CONCLUSIONS

Based on the studies conducted following broad conclusions can be drawn:

i) The information on oceanographic data collected at Vadhavan on tides indicate that tides are semi-diurnal with macro type having high tide level as 6.2 m. Thus owing to high tidal levels there exists wide tidal flats and as such the bigger waves reach even upto the coast at high tide levels during cyclonic/stormy condition.

ii) The proposed port layout was evolved through mathematical model studies for assessing desirable flow conditions as well as achieveing tranquility conditions at various berths/terminals. The layout involves construction of breakwater in relatively deeper depths of about 15 m - 18 m alongwith reclamation in intertidal zone as a stackyard. The breakwaters being in deeper depths and in macro tidal region the assessment of hydraulic stability of breakwater structure requires prediction of extreme wave climate. Idealy the prediction of extreme wave condition needs to be carried out by analyzing measured wave data for longer duration and carrying out long term statistical analysis. However such data being seldom available, prediction of extreme wave condition is carried out by ocean wave hindcasting studies.

iii) The wave hindcasting studies for proposed port at Vadhavan is carried out by analyzing the storms occurred in the Arabian sea off the Vadhavan coast to estimate the extreme wave condition for various return periods. The storm data for year 1946 to 2009 available at CWPRS and for year 2010 to 2015 provided by M/s JNP through India Meteorological Department (IMD) reveal that there are in all 95 storms which are of significance to the development under consideration. These storm are classified as depressions, cyclonic stroms, severe cyclonic stroms, very severe cyclonic stroms, super cyclones etc. The hindcasting studies carried out reveal that in all 57 storms out of 95 considered for analysis have generated waves (H_s) higher than 2.0 m in height in 30 m depth off the coast at Vadhavan.

iv) The extreme value analysis of all these wave conditions (57) is carried out by fitting the Hindcast wave data set in various distribution functions viz Gumbel, Weibull, Log-Normal etc. The studies reveal that the Significant wave height (H_s) in 30 m water depth will have height of H_s = 8.1 m with peak period T_p = 18 sec for 1 in 100 year return period. The studies carried out and reported in CWPRS TR No 5558 of January 2018 reveal that waves from West, West-SouthWest and SouthWest are the predominant and these directions are of significance for the studies under consideration.

v) The estimation of storm surge was carried out using the data received from M/s JNP through IMD for period of 1990-2015. The analysis of cyclonic storm events indicate that there are in all 41 conditions which are of relevance to the port at Vadhavan. The storm surge is a rise in water level occured due to the effect of (a) inverted barometric pressure and (b) wind stress. The storm surge analysis of past storms (hindcasting) reveal that in all 9 storms have generated surge more than 0.75 m with maximum of 1.95 m.

vi) The storm surge data fitted in distribution function viz. Gumbel and Weibull to predict its value for different return periods reveal that storm surge of 2.0 may occur for return period of 1 in 100 year.

vii) The wave transformation studies were carried out using Telemac software for 100 year return period wave height (H_s) and peak period (T_p) to assess the wave conditions on the seaward side of proposed breakwater (alignment evolved through tidal and wave hydrodynamics). The waves incident from West, West-SouthWest and SouthWest being the predominant directions and due to non probability of waves propagating from NorthWest direction in cyclonic condition, the wave climate was determined at various depths on seaward side of the breakwater alignment (both roundheads and trunk sections) for various water levels such as low water level, High tide level and high tide level in association with extreme storm surge for 1 in 100 year return period. The studies carried out reveal that the Significant wave height (H_s) varies between 6.8 m and 7.5 m as shown in Fig. 21 with peak period (T_p) as 18 sec as the extreme wave conditions for 1 in 100 year return period. The incident direction of wave at north roundhead end will be 255^0 North, while that at south roundhead end will be 260^0 North. The direction of wave attack for trunk portion may be considered as right angle to the longitudinal axis of breakwater in respective water depths.

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