1. INTRODUCTION

Rapidly increasing maritime activities, both commercial and scientific have forced the man to move far beyond the coastal water into deep water. The international trade and demand for resources have progressively increased this dependency on sea. It has, therefore became necessary to know wave climate for the smooth operation and design of coastal / offshore structures. The design and operational efficiency of any marine structure depends mainly on environmental parameters such as waves, wind and current and surge. Wave is the most influential parameter in the design of any marine structure. The underestimation of design wave condition will lead to failure of structure, while overestimation results in uneconomical design. The operational condition of marine structure is governed by normal wave condition, while the stability of the structure is governed by storm wave condition. The waves in the ocean are formed due to blowing of wind over the surface of sea. The wind may be locally generated over a smaller area or due to formation of storm over the larger area in deep sea. The waves generated in the sea due to wind are random in nature i.e. wave height and period of every individual wave is different.

India has a long coastline, which measures about 7500 Km. Out of total length, about 3000 Km is on west coast, 2700 Km on east coast, while remaining includes Andaman and Lakshadweep group of islands. The width of continental shelf on west coast extends up to 150 Km, while on east coast it extends up to 50 Km. The Indian coasts are characterised by monsoon wave climate and tropical storms. The monsoon wave climate is less severe in comparison to storm waves. 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 in the oceans. 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).

Ideally, the determination of extreme waves and storm surge levels 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 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 waves and storm surge levels of various return periods required for the design of breakwaters and determination of safe-grade elevation.
2. WAVE CLIMATE AND SOURCES OF WAVE DATA

Wave climate refers to the general condition of sea state at a particular location. The parameters in wave climate are wave height, period and direction. In random wave data analysis significant wave height ($H_s$) is usually employed as a height parameter. The other parameters are Peak period ($T_p$), Average period ($T_z$) etc. The direction of waves occurring at particular location is normally expressed in the form of wave rose diagram. The wave direction is expressed as sixteen point sector of bearing system i.e. ESE, SW, N etc.

The wave statistics is generally classified as short term, long term and extreme wave statistics. (Goda, 1990). The short term statistics deals with statistical properties of individual waves over a short duration (about 20 minutes record). The long term statistics deals with data of about one year (total no. of Significant wave heights $H_s$ about 3000), while extreme value analysis deals with 30 to 50 years of storm wave data. The short term / long term wave statistics is more useful for operational condition of any structure, while extreme value statistics is applicable for design of marine structures. The common wave data sources are visually observed data, instrumentally measured data and hindcast storm wave data.

2.1 Visually observed wave data

Visually observed wave data is measured by ocean going ships, which are unlikely to ply through pre-warned storms. The data is recorded by visual observation and is not much accurate as the measured wave height is going to differ from person to person. This data is available with India Meteorological Department (IMD) and is published in daily weather report. This visually observed data of wave height corresponds to significant wave height and the wave period is close to average zero crossing wave period.

2.2 Measured Wave Data

The various governmental as well as non-governmental organizations are measuring the wave data in the ocean on long-term basis or for a particular project for a limited duration of time by deploying Wave Rider Buoy. The quality and duration of data measured varies from site to site. Now-a-days satellite remote sensing can be advantageously used to measure directional spreading of wave spectra.

2.2.1 Methods to Analyse Measured Wave Data

A) Deterministic Approach

In this approach, the engineers works on various wave theories making the use of classical wave hydrodynamics. The wave phenomenon considered is based on regular wave theory, hence the solution to the problem obtained is approximate one. The various wave theories are
i) Airy’s linear wave theory  
ii) Non-linear stokes wave theory  
iii) Cnoidal wave theory etc.

The first order wave theory (Airy’s) is valid only for small waves in deep water. However, for many practical purposes higher order wave theories give better results. These wave theories are mainly for regular waves and applicable to swells. In olden days, before the development of hydro-servo mechanism for generating random waves, the stability of the structure was assessed under regular waves. The Cnoidal wave theory is more suitable for structures situated in shallow water. However, ocean waves are random, as such these theories don’t hold well.

B) Probabilistic Approach

The analysis of ocean waves is well understood by probabilistic approach and is carried out normally by using the following methods.

i) Statistical Method

The statistical method is based on mean, root mean square value (RMS), which is the basic measure of central tendency. The Rayleigh distribution is a probabilistic approach and is expressed in mathematical form as

\[ P(H > \hat{H}) = \frac{n}{N}; \text{ where } \frac{n}{N} = e^{-\left(\frac{\hat{H}}{H_{rms}}\right)^2} \]

\[ H^\hat{ } = H_{rms} \times \sqrt{\ln \frac{N}{n}} \]

\[ H_{rms} = \sqrt{\frac{1}{N} \sum H_j^2} \]

By plotting a graph of wave height versus cumulative percentage of occurrence on Rayleigh plotting paper, the various wave height/period parameters are calculated as follows.

\[ H_s = 4 \times H_{rms} \]

\[ H_{max} = H_s \times \sqrt{\left(\ln (N)/2\right)} \]

Where, \(N=\) Total no of waves in a wave train

\[ T_p = 1.408 \times T_z; \text{ Where, } T_p= \text{ Peak wave period} \]

\[ T_z= \text{ Av. Zero crossing period.} \]

ii) Spectral Method

The spectral method gives the distribution of wave energy as a function of frequency. The various parameters evaluated are significant wave height \((H_s)\), Peak frequency \((F_p)\), Spectral width parameter, Groupiness etc. The following methods are generally used.

a) Auto-correlation method  
b) Fast Fourier transform
The above mentioned methods are highly mathematical and involve development of computer programs, as such they are not discussed in this paper. There are various types of spectral shape developed by many researchers after studying various sea conditions. There are different types such as Pierson-Mosckowitz, Jonswop, TMA, Scott etc. The most commonly used spectrum is Pierson-Mosckowitz spectrum and the expression is,

\[ S(f) = C_1 * f^{-m} * \exp\left\{ -C_2 * \left( \frac{f}{f_p} \right)^{-n} \right\} \]

Where, \( C_1 = \alpha * g^2 * (2*\pi)^{-4} \); \( C_2 = 5/4 \); \( m = 5 \); \( n = 4 \)

\( \alpha = \) Phillips constants = 0.0081

### 2.3 Hindcast 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, called 'fetch' and
4) Distance between point of observation & face of fetch called as 'decay distance'

Simplified 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 SMB 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. The details of the SMB method are described in the Shore Protection Manual -1984.

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 Storms** - Wind Speed between 62 km/hr and 87 km/hr
- **Severe Cyclonic Storms** - Wind Speed between 88 km/hr and 117 km/hr
Very Severe Cyclonic Storms - Wind Speed between 118 km/hr and 220 km/hr
Super Cyclones - Wind Speed above 220 km/hr

A typical study of storm wave hindcasting for Chennai site on east coast carried out using the information derived from the storm track/synoptic charts are described below:

3.0 WAVE HINDCASTING ANALYSIS FOR CHENNAI SITE

Chennai is one of the city with major port on the east coast of India. From the storm data for the period between years 1951 and 2008 (58 years), the storms passing through the area in the vicinity of Chennai coast were identified. It was seen that there were total 141 such storm conditions, during 1951 to 2008, which were of significance to the Chennai coast. It is observed that most of the storms which are significant for Chennai have been occurred during the months of October to December.

Using SMB method for hindcasting of waves, the probable significant wave height ($H_s$) and wave period ($T_p$) off the coast of Chennai were computed. First, 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 coast near Chennai at 40 m water depth were computed. Out of 141 storm events, there are 128 storms, which generated the wave height of 2.0 m or higher at 40 m water depth. The Severe cyclone of 18\textsuperscript{th} November 1977 generated the highest waves with significant wave height ($H_s$) of 9.0 m.

![Fig. 1: Typical Storm Tracks near Chennai](image)

16 data sets generated wave heights ($H_s$) of the order of 7.0 m or more, which are given in Table-1.
Table – 1 : Major Hindcast Storm Wave Conditions off Chennai Coast during the period 1951-2008 (40 m water depth)

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Period of storm</th>
<th>Significant Wave Height in metres</th>
<th>Peak Wave period in Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td>Year</td>
<td>Time</td>
</tr>
<tr>
<td>1</td>
<td>18-Nov</td>
<td>1977</td>
<td>1730</td>
</tr>
<tr>
<td>2</td>
<td>28-Nov</td>
<td>1962</td>
<td>1730</td>
</tr>
<tr>
<td>3</td>
<td>3-Dec</td>
<td>1993</td>
<td>0830</td>
</tr>
<tr>
<td>4</td>
<td>26-Nov</td>
<td>2008</td>
<td>0830</td>
</tr>
<tr>
<td>5</td>
<td>3-Nov</td>
<td>1966</td>
<td>0830</td>
</tr>
<tr>
<td>6</td>
<td>7-Dec</td>
<td>1967</td>
<td>1730</td>
</tr>
<tr>
<td>7</td>
<td>26-Nov</td>
<td>1974</td>
<td>0830</td>
</tr>
<tr>
<td>8</td>
<td>11-Nov</td>
<td>1984</td>
<td>0830</td>
</tr>
<tr>
<td>9</td>
<td>22-Oct</td>
<td>1969</td>
<td>0830</td>
</tr>
<tr>
<td>10</td>
<td>1-Nov</td>
<td>1979</td>
<td>0830</td>
</tr>
<tr>
<td>11</td>
<td>7-May</td>
<td>1990</td>
<td>0830</td>
</tr>
<tr>
<td>12</td>
<td>28-Nov</td>
<td>1988</td>
<td>0830</td>
</tr>
<tr>
<td>13</td>
<td>16-Nov</td>
<td>1976</td>
<td>0830</td>
</tr>
<tr>
<td>14</td>
<td>20-Nov</td>
<td>1958</td>
<td>1730</td>
</tr>
<tr>
<td>15</td>
<td>21-Nov</td>
<td>1964</td>
<td>0830</td>
</tr>
<tr>
<td>16</td>
<td>11-Nov</td>
<td>1977</td>
<td>0830</td>
</tr>
</tbody>
</table>

3.1 Extreme Value Analysis of Wave Data

3.1.1 Method and data set

The extreme value analysis or long-term analysis deals with the storm waves. The objective of the extreme value analysis is to provide a basis for selection of design wave conditions. It is required to predict storm wave height over a long time span of 50 years or 100 years. The wave height which occurs on an average once in 100 years, will have a 100 year 'return period' or a 'recurrence interval'. The return period $R_p$ is basic parameter in extreme value analysis, wherein for a specified return period $R_p$, the wave height $H$ is predicted such that it is expected to occur once on the average during time span of $R_p$. The statistical analysis for determination of various return period wave heights from the data set involves (Burcharth and Liu, 1994):

- Choice of several theoretical distributions for extreme wave height distribution
- Fitting of the extreme wave heights to distributions
- Comparison of the fitting goodness among the distributions
- Estimation of wave height corresponding to a certain return period.
Generally there are three kinds of data sets for extreme wave analysis: (1) Observations of wave heights equally spaced in time (2) Largest wave height in each year and (3) Largest wave height in each individual storm exceeding a certain level.

Goda (1990) and Burcharth and Liu (1994) have recommended second or third type of data sets since they are directly concerned with the selection of design wave height. In practice, wave data are typically obtained either from direct observations or from wave height hindcast based on meteorological information. At least 10 years of data are required, but preferably a longer series of data such as 30 to 50 years is necessary to account for meteorological fluctuations.

When storm wave data are obtained using wave hindcasting, one may content with having a data of storm waves exceeding a certain level. Such a data is called as 'censored' data. In case of censored data, the ratio of the number of analysed data points \( N \) to the total Number of data points \( N_f \) during the period of analysis is important. This ratio is called the censoring parameter and denoted as \( \nu = \frac{N}{N_f} \). Another key factor is the mean rate of storm waves or number of storm waves per year. The mean rate is denoted as \( \lambda \) which is equal to \( \frac{N_f}{K} \), where \( K \) is the length of time period considered for analysis in years.

### 3.1.2 Distribution functions

The commonly employed distribution functions in extreme wave analysis are:

1) Gumbel or Fisher - Tippett type I (FT-I) distribution
2) Weibull distribution
3) Log-Normal distribution

These three distributions fit the extreme wave data well and no theoretical justification is available as to which distribution is to be used (Burcharth and Liu 1994). The distribution functions in the forms of the non-exceedance probability or cumulative probability are expressed as:

- **Gumbel**: 
  \[
  F = F(H < x) = \exp[- \exp\left\{-\frac{(x - B)}{A}\right\}]
  \]

- **Weibull**: 
  \[
  F = F(H < x) = 1 - \exp[-\left\{(x - B) / A\right\}^k]
  \]

- **Log-Normal**: 
  \[
  F = F(H < x) = (2\pi)^{-0.5} \int_0^x (1/At) \exp\left\{-\frac{(\ln t - B)^2}{2A^2}\right\} dt
  \]

where \( A, B \) and \( k \) are the distribution parameters to be fitted and are called as the scale, location and shape parameters respectively. \( H \) is a characteristic wave height, which could be significant wave height \( H_s \), or maximum wave height \( H_{\text{max}} \), depending on the data set. \( F \) is the non-exceedance probability.
3.1.3 Fitting methods and procedure

The data must be fitted to some distribution function to enable estimation of the various return period wave heights. Four generally applied methods of data fitting are:

1. Graphical method using specially devised plotting paper on which the data from a particular distribution are plotted on straight line.
2. Least squares method.

The graphical method was generally used in the past when calculation was a tedious job. Presently, the least squares method replaces the graphical method, since calculation is now an easy job due to aid of computers and the least squares method is refined version of graphical method. In the present studies least square methods was used. In both the methods, the extreme wave data are first rearranged in descending order. The mth data point is denoted as \( x_m \). The plotting probability \( P_m \) is assigned to \( x_m \) and the reduced variate \( y_m \) is calculated from the distribution function as

\[
y_m = F^{-1} \left( 1 - P_m \right)
\]  

(4)

The procedure to calculate plotting probability is detailed in the next paragraph.

For Gumbel and Weibull distributions, the formulae for reduced variate are

Gumbel : \[ y = -\ln(-\ln F) \]  

(5)

Weibull : \[ y = \left[ -\ln(1 - F) \right]^{1/k} \]  

(6)

In graphical method, the wave height values \( x_m \) are plotted against the plotting probability \( P_m \) (or reduced variate \( y_m \)) on the corresponding probability graph paper i.e., Gumbel distribution paper, Weibull distribution paper or Log-Normal distribution paper. Extrapolation of wave characteristic for higher return periods is then possible. It should be noted that the plotting probability \( P_m \) is related to Return Period \( R_p \) as

\[
P_m = \frac{1}{\lambda} R_p
\]  

(7)

In least squares method one should proceed as below:

Having the ordered data points \( x_m \) and the reduced variate \( y_m \), the scale parameter \( A \) and location parameter \( B \) are obtained by regression analysis using the relation

\[
x_m = Ay_m + B.
\]  

(8)
The shape parameter $k$ cannot be estimated by this method. Goda (1990) has given four values (0.75, 1.0, 1.4 and 2.0) of $k$ to fit the data to four alternative Weibull distributions. Once the extreme wave data are fitted to a distribution function and the parameters are estimated, the return value $H$ corresponding to a return period $R_p$ is calculated as

$$H = Ay + B$$  \hspace{1cm} (9)

Where,

$$y = F^{-1}[1 - 1/(\lambda R_p)]$$  \hspace{1cm} (10)

$\lambda$ is average number of storms per year or $N_T / K$, where $K$ stands for the time duration of the period from which the data is collected in terms of years.

### 3.1.4 Plotting position formulae

The problem of assigning a plotting probability to each ordered data point is discussed by Goda (1990) in detail. Studies have indicated that the plotting probability differs from one probability function to another. The following plotting probability formulae are recommended by Goda (1990) for the respective distribution functions:

- **Gumbell**: Gringorten Formula
  \[ P_i = (i - 0.44) / (N + 0.12) \]  \hspace{1cm} (11)

- **Weibull**: Petruaskas and Aagaard Formula
  \[ P_i = [i - (0.49 - 0.50/k)] / [N + (0.21 +0.32/k)] \]  \hspace{1cm} (12)
  \[ P_m = 1 - [m - (0.30 + 0.18/k)] / [N + (0.21 + 0.32/k)] \]  \hspace{1cm} (13)

- **Log-Normal**: Blom Formula
  \[ P_i = (i - 0.375) / (N + 0.25) \]  \hspace{1cm} (14)

The order $i$ is assigned in the ascending fashion. The ascending order $i$ is related to the descending order $m$ as

$$i = N - m + 1.$$  \hspace{1cm} (15)

The plotting position formulae except Petruaskas and Aagaard formula are invariant to the change of the ascending order $i$ to the descending order $m$. In the case of censored data, the plotting position should be assigned by using the total number of data points $N_T$ that have occurred in the time period considered. The descending order number $m$ remains unchanged, but the ascending order $i$ should be changed to

$$i^* = i + N_T - N.$$  \hspace{1cm} (16)
Thus in case of extreme wave analysis the determination of total number of storms (NT) occurred during period K is important. It may be possible to obtain NT from the meteorological data.

3.2 Results of Wave Hindcasting Analysis

In the present studies the extreme wave data at the site of Chennai were fitted to Gumbel, Weibull and Log-Normal distribution functions. The hindcast wave data of 128 storms were considered for extreme wave analysis. The plots of Gumbel, Weibull and Log-Normal distributions are shown in Figs respectively. The estimates of extreme wave heights for different return periods using Gumbel, Weibull and Log-Normal distributions are given in Table-2. It is seen that the wave heights predicted using Gumbel, Weibull and Log-Normal distributions are in agreement with each other.

![Fig 2: Hindcast Storm Wave Data Off Chennai on Gumbel Distribution](image)

![Fig 3: Hindcast Storm Wave Data Off Chennai on Weibull Distribution](image)
Table – 2: Predicted Wave Heights off Chennai Coast
(40 m Water Depth)

<table>
<thead>
<tr>
<th>Return Period $R_P$ in years</th>
<th>Predicted Significant Wave Height, $H_s$ in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gumbel</td>
</tr>
<tr>
<td>5</td>
<td>7.4</td>
</tr>
<tr>
<td>10</td>
<td>8.2</td>
</tr>
<tr>
<td>25</td>
<td>8.8</td>
</tr>
<tr>
<td>50</td>
<td>9.1</td>
</tr>
<tr>
<td>100</td>
<td>9.2</td>
</tr>
</tbody>
</table>

Averages of these three values for each return period are shown in Table-3. The 100 - year return-period significant wave height off Chennai coast in a water depth of 40 m is predicted as 9.3 m.

Table – 3: Predicted Extreme Wave Heights off Chennai Coast
(40 m Water Depth)

<table>
<thead>
<tr>
<th>Return Period $R_P$ in years</th>
<th>$H_s$ in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>7.4</td>
</tr>
<tr>
<td>10</td>
<td>8.1</td>
</tr>
<tr>
<td>25</td>
<td>8.7</td>
</tr>
<tr>
<td>50</td>
<td>9.0</td>
</tr>
<tr>
<td>100</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Fig 4: Hindcast Storm Wave Data Off Chennai on Log Normal Distribution
4.0 STORM SURGE HINDCASTING AND EXTREME SURGE ANALYSIS

Storm surge is the temporary rise in the water level at the coastline during the cyclone. 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 widespread 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 surges, 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. Surge hindcasting is usually done to obtain surge data from the major storms over 30 to 50 years or longer. In order to determine the extreme water level at the shore, the predicted maximum storm surge is to be superimposed over the Highest Astronomical Tidal Water Level (HATWL).

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 shown on the synoptic chart.
chart. The width and depth of the continental shelf can be obtained from the Hydrographic Charts.

**4.1 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.

### 4.1.1 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 \( S_a \) is given by (Silvester, 1974):

\[
S_a = 0.01(P_n - P_0) \text{ in metres} \quad ........... \quad (3)
\]

Where,
- \( P_n \) = Pressure of the isobar at the boundary of storm, in mb
- \( P_0 \) = 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 Hydromet-Rankin Vortex Model for the cyclones [Herbich, 1990]. The pressure profile of a cyclone in Hydromet-Rankin Model is given by :

\[
\frac{P_r - P_0}{P_n - P_0} = e^{-R/r} \quad ........... \quad (4)
\]

Where,
- \( R \) = Radial distance of maximum cyclostrophic wind from the centre of storm in km
- \( r \) = Radial distance from centre of storm in km
- \( P_r \) = Pressure at radial distance ‘r’ in mb

The set of the values of \( P_r \) and \( r \) can be obtained from the synoptic chart and equation (4) can be solved for \( P_0 \) and \( R \). A typical pressure profile for 18\textsuperscript{th} November, 1977 cyclone is shown in Fig. 5.
4.1.2 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 at the shoreline of an open ocean (i.e. storm surge over the continental shelf) due to static wind field is given by Silvester (1974) as:

\[
S_w = \frac{kU^2L}{g(d_1 - d_2 - S_w)} \ln \left( \frac{d_1}{d_2 + S_w} \right) \quad \text{......... (5)}
\]

Where,

- \( S_w \) = Storm surge due to wind stress in meters
- \( k \) = Wind stress co-efficient
  - 0.000003 for open ocean,
  - 0.0000033 for enclosed/semi enclosed water bodies
- \( U \) = 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

4.2 Storm Surge Analysis at Chennai coast

From the available data of storm tracks from 1951 to 2008, important storms that passed in the vicinity of around 800 km of Chennai have been considered for studies. A total of 141 No. of storms were of significance for generation of surge at Chennai coast. In the analysis, it was assumed that the storms pass over the site, i.e. the landfall point of the storm was assumed to be near Chennai.
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. Total storm surge \(S\) was computed by adding these two components. 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 Chennai coast during the severe cyclone of 17\(^{th}\) November, 1977 works out as 2.04 m. There are 13 storm conditions, which generated a total storm surge of 0.0.8 m or higher at the Chennai coast are given in Table - 4.

**Table-4 : Major Storm Surge Conditions at Chennai coast during the Period 1951-2008**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Period of storm</th>
<th>Storm Surge ((S))</th>
<th>Wind Stress Effect ((S_w)) in metre</th>
<th>Barometric Effect ((S_a)) in metre</th>
<th>Total Surge ((S)) in metre</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17-Nov 1977</td>
<td></td>
<td>0.85</td>
<td>1.19</td>
<td>2.04</td>
</tr>
<tr>
<td>2</td>
<td>28-Nov 1962</td>
<td></td>
<td>0.69</td>
<td>0.91</td>
<td>1.60</td>
</tr>
<tr>
<td>3</td>
<td>27-Nov 1988</td>
<td></td>
<td>0.47</td>
<td>0.63</td>
<td>1.10</td>
</tr>
<tr>
<td>4</td>
<td>5-Nov 1973</td>
<td></td>
<td>0.43</td>
<td>0.58</td>
<td>1.01</td>
</tr>
<tr>
<td>5</td>
<td>27-Nov 1966</td>
<td></td>
<td>0.46</td>
<td>0.55</td>
<td>1.01</td>
</tr>
<tr>
<td>6</td>
<td>8-Dec 1981</td>
<td></td>
<td>0.42</td>
<td>0.58</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>7-Nov 1969</td>
<td></td>
<td>0.42</td>
<td>0.53</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td>28-Oct 1956</td>
<td></td>
<td>0.40</td>
<td>0.54</td>
<td>0.94</td>
</tr>
<tr>
<td>9</td>
<td>10-Dec 1962</td>
<td></td>
<td>0.37</td>
<td>0.51</td>
<td>0.88</td>
</tr>
<tr>
<td>10</td>
<td>18-May 1997</td>
<td></td>
<td>0.38</td>
<td>0.48</td>
<td>0.87</td>
</tr>
<tr>
<td>11</td>
<td>30-Apr 1966</td>
<td></td>
<td>0.39</td>
<td>0.47</td>
<td>0.86</td>
</tr>
<tr>
<td>12</td>
<td>24-Nov 1978</td>
<td></td>
<td>0.39</td>
<td>0.46</td>
<td>0.85</td>
</tr>
<tr>
<td>13</td>
<td>21-Sep 1972</td>
<td></td>
<td>0.36</td>
<td>0.47</td>
<td>0.83</td>
</tr>
</tbody>
</table>
4.3 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 50 years, 100 years of proposed site at Chennai 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’ ($R_p$).

The storm surge data of 141 storms were considered for extreme value analysis. These data represent the actual storms over a period of 58 years (1951 to 2008) 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 and Log-Normal distributions for the storm surge are shown in Figs. 6, 7 & 8 respectively. The estimates of extreme storm surge for different return periods using Gumbel, Weibull and Log Normal distributions are given in Table-5.

![Fig 6: Hindcast Storm Surge Data at Chennai on Gumbel Distribution](image)

![Fig 7: Hindcast Storm Surge Data at Chennai on Weibull Distribution](image)
Table – 5 : Predicted Storm Surge at Chennai Coast

<table>
<thead>
<tr>
<th>Return Period $R_p$ in years</th>
<th>Predicted Storm Surge ($S_S$) in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gumbel</td>
</tr>
<tr>
<td>5</td>
<td>0.85</td>
</tr>
<tr>
<td>10</td>
<td>1.01</td>
</tr>
<tr>
<td>25</td>
<td>1.26</td>
</tr>
<tr>
<td>50</td>
<td>1.50</td>
</tr>
<tr>
<td>100</td>
<td>1.80</td>
</tr>
</tbody>
</table>

It is seen that the storm surge predicted using Gumbel, Weibull and Lognormal distributions are almost similar. Averages of these three values for each return period as shown in Table–6 are considered for the design purpose.

Table – 6 : Predicted Extreme Storm Surge at Chennai Coast

<table>
<thead>
<tr>
<th>Return Period $R_p$ in years</th>
<th>Storm Surge ($S_S$) in metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>25</td>
<td>1.2</td>
</tr>
<tr>
<td>50</td>
<td>1.4</td>
</tr>
<tr>
<td>100</td>
<td>1.6</td>
</tr>
</tbody>
</table>

It is seen that the 100 - year and 50 - year return period storm surge for the Chennai coast are predicted as 1.6 m & 1.4 m respectively. As such, these storm surge values may be considered in the estimation of extreme water level at the shore.
REFERENCES


