CHAPTER 2
2. WAVES AND WAVE TRANSFORMATION

Wave action provides the primary source of energy available in the nearshore zone for various processes. Waves contribute to form beaches, assorting bottom sediments on the shoreface and transporting bottom materials onshore-offshore and alongshore. An adequate understanding of the fundamental physical processes in surface wave generation and propagation must precede any attempt to understand the complex water motion in nearshore areas. In order to provide the physical and mathematical understanding of wave motion, various theories have been used to describe wave generation and transformation. Waves which reach coastal regions expend a large part of their energy in the nearshore region. Since the actual water-wave phenomenon is difficult to describe mathematically because of non-linearities, three-dimensional characteristics and apparent random behaviour, many theoretical concepts have been evolved for describing the complex sea waves.

2.1. Wave climate

Information on wind waves is extremely important for projects related to coastal and offshore development and for the proper management of the coastal zone. Wave climate at a shoreline depends on the offshore wave climate, caused by the prevailing winds and storm, and on the bottom topography that modifies the waves as they propagate shoreward. Ocean waves
are highly random in nature, and longer the duration of observation, more realistic would be the estimation of design parameters.

Compilation of ocean wave climate involves the long-term collection of wave data at many locations on an operational basis. Since a systematic collection of wave data for the seas around India is lacking, the information about the wave climate is limited. Under such circumstances, the following procedures are generally followed to obtain information on waves.

1. Visual information on sea and swell wave characteristics reported by ships passing in the seas around India pertain to deep water waves. This data are reported by the India Meteorological Department and form a major source of wave information till recently. The human error in the visual observation and the scarcity of data during rough weather seasons are some of the limitations in such wave information. Soares (1986) stresses that visual observations of wave height are still the main source of statistical informations available for the reasonable prediction of extreme wave conditions.

The information on waves close to wave breaking zone is lacking due to the operational difficulties involved in making the measurement close to the shore. In many of the littoral environmental observation programs, still the
visual observations are made to estimate the breaking wave parameters.

2. Wave hindcasting using meteorological conditions is another source to obtain the wave information. The estimation of nearshore wave climate from hindcasting is usually a time-consuming job and the estimate obtained may suffer in quality because of the inaccuracy of the meteorological data and the difficulty of assessing the effect of nearshore topography on wave characteristics. Computer based wave prediction models include deep water forecasts for commercial and military ship routing, nearshore forecasts for commercial and recreational interests and climatological forecasts of extreme wave conditions for ocean engineering applications such as offshore structural designs.

3. The direct source of wave climate information is the measurement of wave using instruments, which forms a more reliable one. Instrumentally measured wave data around the Indian coast are very limited. In India, wave measurements have been done using shore based stations, moored buoys, and shipborne wave recorders on board R.V. Gaveshani, O.R.V. Sagar Kanya and FOR V Sagar Sampada.

Since the wave measurements using instruments are very expensive both in manpower and facility, the ship reported data compiled for a longer periods have been advantageously used for various coastal engineering studies. In India,
effective long term data collection using instrument is not yet systematic. The instrumental measurements at many places mostly cover the duration of only an year or less.

Waves in deep water can propagate for enormous distances without much attenuation. The coastal wave climate of any region is dependent on deep water waves and their complex transformation processes. Depending upon the location the breaker direction vary between $210^\circ \text{N}$ to $300^\circ \text{N}$ along the south-west coast of Kerala. (Baba, 1988).

In the light of the general wave climate data available (N.P.O.L, 1978; Varkey et al., 1982; Chandramohan et al., 1990), the deep water waves having directions $270^\circ$, $210^\circ$ and $290^\circ$ for south-west monsoon, north-east monsoon and fair-weather seasons respectively with periods 6 and 8 sec. were selected for the preparation of refraction diagrams along the Kerala coast.

2.2. Wave theories

Wave phenomenon is complex and difficult to describe mathematically. The wave theories put forward by Airy (1845) and Stokes (1880) predict the wave motion reasonably well in the region where the water depth is large compared to wave length. The higher order wave theories (Stokes, 1880) are found satisfactory under certain circumstances in describing the waves. For shallow water regions, cnoidal wave theory (Kortweg and DeVries, 1895) is generally used to predict the
form and associated motion. At very shallow regions, the solitary wave theory (Russel, 1845; Boussinesq, 1872; Rayleigh, 1876; McCowan, 1891; Keulegan, 1948; Iwasa, 1955) can be used to describe the wave behaviour satisfactorily. The regions of validity of various wave theories are indicated by Le Mehaute (1969).

In shallow water region, particularly close to breaking zone, the use of higher order wave theories would provide more accuracy in the analysis. The appropriate wave theories for the different regions are classified according to the relative water depth as follows.

\[
\begin{array}{ll}
\text{h/L} & \text{Wave theory} \\
\text{---} & \text{--------} \\
> 0.2 & \text{Stoke's III order} \\
0.2 > \text{h/L} > 0.05 & \text{Cnoidal} \\
0.05 > \text{h/L} > \text{h_b/L} & \text{Solitary}
\end{array}
\]

where \( h \) is the water depth and \( L \) is the wave length.

2.2.1. Small amplitude wave theory

The elementary progressive wave theory referred to as the small amplitude wave theory was developed by Airy (1845). It is of fundamental importance because it is easy to apply and reliable over a large segment of the whole wave regime. While the exact wave theories are presented in series of terms, the one with only the first term is called the small amplitude wave theory. It assumes that the wave height (H) is so small that all higher order terms can be neglected. In
this way, the free surface boundary condition is linearised and the resulting approximate equation is obtained. The small amplitude wave theory with the associated boundary conditions give the phase velocity (Svendsen and Jonsson, 1976),

\[
C = \frac{gT}{2 \pi} \tanh \frac{kh}{c} \tag{2.1}
\]

\[
u = \frac{(agk)}{\sigma} \left( \cosh k(h + z) - \sinh(kx - \sigma t) \right) \cosh kh \tag{2.2}
\]

where

\[k = \frac{2 \pi L}{\lambda}
\]

\[c = \text{wave celerity}
\]

\[\nu = \text{Horizontal particle velocity}
\]

\[a = \text{wave amplitude}
\]

\[\sigma = \text{wave frequency} = \frac{2 \pi}{T}
\]

2.2.2. Finite amplitude wave theory

Once the wave amplitude becomes larger compared to wave length the assumption of small amplitude wave theory is no longer valid and it is necessary to retain higher order terms to obtain an accurate representation of the wave motion. The finite amplitude wave theory takes into account the additional parameters H/h and H/L (where H is the wave height), but it rapidly grows complicated with increasing order of approximation.

2.2.3. Stoke's higher order wave theory

Stoke's (1880) presented the approach and subsequently
many researchers extended the theory to various higher orders. Using the third order equations, Miche (1944) has given the following relationship for wave celerity.

\[ C = gT / 2 \pi \tanh kh \left( 1 + \left( \frac{2H}{L} \right)^2 K' \right) \]  

where \( K' = \frac{(5 + 2 \cosh 2kh + 2 \cosh^2 2kh)}{(6 \sinh^4 kh)} \)

2.2.4. Cnoidal wave theory

The existence of long finite amplitude waves of permanent form propagating in shallow water was first recognised by Boussinesq (1872) and the theory was developed by Korteweg and deVries (1895). The approximate range of validity of cnoidal wave theory is \( 0.2 > h / L > 0.05 \) or the Ursell parameter \( (U = HL^2 / h^3) > 25 \) (Isobe, 1985). Wiegel (1960) and Masch (1961) presented the wave characteristics in tabular and graphical form to facilitate the application.

Svendsen (1974) presented the description of cnoidal waves solving the Korteweg and deVries (Kdv) equation. The solution of this equation is expressed by a Jacobian elliptic function \( c_n \) of two variables, \( \Theta \) and a parameter \( m \) (0 \( \leq m \leq 1 \))

\[ \eta = n \min + H c_n^2 (\Theta, m) \]  
\[ \eta_{\text{min}} = (1/m)((1-E/K)-1)H \]

where

\( \eta_{\text{min}} = \text{distance of trough from the mean water level} \)
\( K = K(m) \), complete elliptic integrals of the first kind
\( E = E(m) \), complete elliptic integrals of the second kind
The value of parameter $m$ is the solution of the transcendental equation

$$U = H \frac{L^2}{h^3} = \frac{16}{3} \frac{mK^2}{m}$$  \hspace{1cm} (2.6)

If the wave motion is specified by $H$ and $L$ at depth $h$, equn. (2.6) has only one solution and hence for $K$ and $E$. For practical purposes, Skovgaard et al. (1974) have tabulated $m$, $K$ and $E$ as functions of $U$. The cnoidal solution for wave celerity, $c$ is given by,

$$C = \sqrt{gh} \left(1 + A(m)\right) \frac{H}{h}^{0.5}$$  \hspace{1cm} (2.7)

where $A(m) = \frac{2}{m} - 1 - \frac{3}{m} (E/K)$

Often as the wave is specified by the wave period ($T$) in addition to height ($H$) and depth ($h$), using $C = \frac{L}{T}$ in equn. (2.7),

$$L/h = T \left(g/h\right)^{0.5} \left(1 + A(H/h)\right)^{0.5}$$ \hspace{1cm} (2.8)

Skovgard et al. (1974) have tabulated the solution of equn. (2.7) in terms of $L/h$ with $T\left(g/h\right)^{0.5}$ and $H/h$ as parameters.

2.2.5. Solitary wave theory

Russel (1844) first recognised the existence of a solitary wave. The original theoretical developments were made by Boussinesq (1872), Rayleigh (1878), McCowan (1891), Keulegan and Patterson (1940) and Iwasa (1955). A particular simple type of cnoidal wave is obtained when $T$ tends to infinity in equn. (2.8), which implies that $L$ and hence $U$ tends to infinity. In equn. (2.6) this results in $m \to 1$ and
in equn. (2.4) \( c_n(\varnothing, m) \rightarrow \text{sech} \, \varnothing \). Hence the wave celerity in solitary wave becomes,

\[
c = (g h (1 + H/h))^{0.5}
\]  

(2.9)

In this study, the Stoke's third order, Cnoidal and Solitary wave theories have been used according to the depth of wave propagation.

2.3. Wave transformation

As waves propagate into shallow water, they get modified due to wave shoaling, refraction, bottom friction, sea bed percolation, non-rigidity of the bottom and diffraction. As the phase velocity is a function of water depth, when the wave propagates over the bottom of variable bathymetry, it bends and tries to align to the bottom contours. This is known as refraction of water waves. In wave shoaling, the wave height changes because of change in the velocity of propagation.

The roughness of the seabed and the adjoining turbulent boundary layer retard the wave motion due to bottom friction. If the seabed is permeable, the percolation of water into the sea bed further retards the wave motion. The viscosity of water causes the wave energy to dissipate termed as viscous dissipation. The presence of barriers would cause the wave to diffract leeside.

In the present study, the effect of wave refraction
and wave shoaling are considered. Assumption made in estimating the nearshore wave transformation are,

(1) The wave energy transmitted between adjacent wave orthogonals remain constant. The lateral dispersion of wave energy along the wave front, reflection of energy from the sloping bottom and the loss of energy by other processes are negligible.
(2) Waves are long crested and of constant period.
(3) Curvature of the wave front is small so that it has negligible effect on the velocity of propagation.
(4) Effect of wind, current and reflection from beaches are negligible.
(5) Changes in bottom topography is gradual.
(6) No crest breaking during propagation.

2.3.1. Shoaling

The wave power transmitted forward between two orthogonals in deep water

\[ P_o = \frac{1}{2} b_o E_o C_o \]  

(2.10)

where \( b_o \) is the distance between the selected orthogonals in deep water, \( E_o \) is the energy transmitted between two orthogonals in deep water and \( C_o \) is the phase velocity in deep water.

The power equated to the energy transmitted forward between the same two orthogonals in shallow water

\[ P = n b E \]  

(2.11)
where \( b \) is the spacing between the orthogonals in shallow water, \( E \) is the energy transmitted between two orthogonals in shallow water and \( n = 0.5(1 + (2kh/\sinh 2kh)) \)

\[
\frac{1}{2} b_0 E_0 C_0 = n b E
\]

\[
E = \frac{1}{8} \rho g H^2
\]

\[
E_0 = \frac{1}{8} \rho g H_0^2
\]

where \( H_0 \) is the wave height in deep water

\[
E = \frac{1}{2} \frac{b_0 C_0}{n b C}
\]

\[
E_0 = \frac{1}{2} \frac{b_0 C_0}{n b C}
\]

\[
H = \sqrt{E} = \frac{1}{2} \frac{b_0 C_0}{n b C}
\]

\[
H_0 = \sqrt{E_0} = \frac{1}{2} \frac{b_0 C_0}{n b C}
\]

\[
\sqrt{\frac{b_0}{b}} = K_R \text{ is the Refraction coefficient} \quad (2.13)
\]

2.3.2. Refraction

Since the phase velocity is a function of depth in shallow water, when the wave front propagates over the bottom of variable bathymetry, it bends and tries to get aligned to the bottom contours. The reduction in phase velocity in
shallow water causes refraction in a process analogous to Snell's law in geometrical optics. Then the change in direction of orthogonal as it passes over relatively simple bathymetry may be approximated by,

\[ \sin \alpha_2 = \frac{C_2}{C_1} \sin \alpha_1 \]

\( \alpha_1 \) = angle of wave crest make with the bottom contour
\( \alpha_2 \) = angle of wave crest for the next bottom contour
\( C_1 \) = wave velocity at a depth of first contour
\( C_2 \) = wave velocity for the next contour.

The spacing between orthogonals indicate the amount of concentration or dispersion of energy. Wave rays are normal to the crests and are therefore in the direction of wave advance and energy propagation. The wave power is conserved between adjacent rays, so that a convergence of rays implies a focusing of the wave energy leading to greater wave heights and progressive separation of rays represents defocussing.

For straight and parallel contours, the orthogonals would be parallel and the horizontal distance is constant between two adjacent orthogonals. Therefore,

\[ \frac{b_0}{\cos \alpha_0} = \frac{b}{\cos \alpha} \]

\[ \frac{b_0}{b} = \frac{\cos \alpha_0}{\cos \alpha} \]

\[ K_r = \left( \frac{b_0}{b} \right)^{0.5} = \left( \frac{\cos \alpha_0}{\cos \alpha} \right)^{0.5} \]

(2.5)

where \( \alpha \) is the angle between two orthogonals in shallow water and \( \alpha_0 \) is the angle between two orthogonals in deep water.

For a given topography and deep water wave characteristics, the refracted orthogonals can be plotted by
geometrical procedure (Anonymous, 1975). The graphical method of wave refraction analysis by Arthur et al. (1952), has been widely used till recently for computation of wave refraction. Studies using graphical method are many for the Kerala coast as well as other part of the country, which have been reviewed earlier (Chapter I). Many refinements have been made relating to the direct construction of refraction diagrams based on the wave crest method (Johnson, 1947) and orthogonal method. Recently computer based numerical methods for determining refraction characteristics have been used (Griswold, 1963; Harrison and Wilson, 1964; Wilson, 1966; Dobson, 1967). While these computer methods are undergoing considerable refinement, they are operational and may result in significant time saving in refraction computations over a relatively large area.

Refraction studies based on the numerical models are scanty for the Kerala coast. A study of the wave transformation using a numerical model along the Kerala coast by making synchronized measurements of deep and shallow water waves has been done by Kurian (1987). For a given bathymetry and deep water characteristics, numerical wave transformation models incorporating shoaling and refraction have been developed by many researchers. (Skovgaard et al., 1975; Griswold, 1963; Harrison and Wilson, 1964; Orr and Herbich, 1969; Jen, 1969). Most of the numerical refraction model have used the linear wave theory and a few have attempted using finite amplitude wave theories.
2.3.3. Numerical wave refraction

Fig. 2.1 shows the adjacent orthogonals O1, O2 and two consecutive wave fronts F1, F2 separated by time interval dt (Skovgaard et al., 1975). At point A, the infinitesimal distance between orthogonals and fronts are Df and Ds respectively, where,

\[ Ds = c \, dt \quad (2.16) \]

The distance s is taken as positive in the direction of wave propagation and the positive direction of f is such that Ds and Df form a right hand coordinate system. \( \theta \) is the angle between the x axis and the orthogonal, positive in anticlockwise direction.

From the triangles BCE and CDF,

Curvature of wave orthogonal = \( \frac{D\theta}{Ds} = -\left(\frac{1}{c}\right) \left(\frac{Dc}{Df}\right) \) (2.17)

Curvature of wave front = \( \frac{D\theta}{Df} = \frac{1}{Df} \left(\frac{D(Df)}{Ds}\right) \) (2.18)

Defining the following operators as

\[ \frac{D}{Ds} = \cos \theta \left(\frac{d}{dx}\right) + \sin \theta \left(\frac{d}{dy}\right) \]

\[ \frac{D}{Df} = \sin \theta \left(\frac{d}{dx}\right) + \cos \theta \left(\frac{d}{dy}\right) \]

and using eqns. (2.16) and (2.17),

\[ \frac{d\theta}{dt} = -\left(\frac{Dc}{Df}\right) \]

(2.21)

Using eqns. (2.17), (2.18), (2.19), (2.20) and (2.21), the basic equations for the wave orthogonals become,

\[ \frac{dx}{dt} = c \cos \theta \]

(2.22)

\[ \frac{dy}{dt} = c \sin \theta \]

(2.23)

\[ \frac{d\theta}{dt} = (dc/dx) \sin \theta - (dc/dy) \cos \theta \]

(2.24)
Fig. 2.1. System of wave orthogonals and fronts

Fig. 2.2. System of grids
For the calculation of wave heights along the orthogonal, Munk and Arthur (1952) have derived a second order homogeneous ordinary differential equation for the orthogonal separation factor (\( \beta \)) with distance (s) along the orthogonal as,

\[
\frac{d^2 \beta}{ds^2} + p(s) \frac{d\beta}{ds} + q(s) \beta = 0
\]  
(2.25)

Using eqn. (2.16), eqn. (2.25) can be rewritten as function of time (t) hence the use of variable t has the advantage of giving the phase of wave motion with self adjusting wave length,

\[
\frac{d^2 \beta}{dt^2} + p(t) \frac{d\beta}{dt} + q(t) \beta = 0
\]  
(2.26)

where, \( p(t) = -2(\cos \theta \frac{dc}{dx} - \sin \theta \frac{dc}{dy}) \)  
(2.27)

\[
q(t) = c((\sin^2 \theta \frac{d^2 c}{dx^2}) - (\sin 2 \theta \frac{d^2 c}{dxdy}) + (\cos^2 \theta \frac{d^2 c}{dy^2}))
\]  
(2.28)

\[
\beta = \frac{Df}{Dfst} = Kr^{-2}
\]  
(2.29)

Equns. (2.22), (2.23), (2.24) and (2.26) with (2.27) and (2.28) can be solved numerically with proper initial boundary conditions.

2.4. Construction of refraction diagram

The numerical wave transformation model explained in Chandramohan (1988) has been used for studying the wave refraction pattern for the entire Kerala coast and to identify the regions of convergence and divergence of waves.
Referring to the section 2.2, based on the wave climate of Kerala coast the three predominant wave directions, 270° for south-west monsoon period (June-September), 210° for north-east monsoon period (October-January) and 290° for fair-weather period (February-May) were selected for the construction of wave refraction diagrams. Reflection and diffraction were not considered for this coast which is straight and open.

The grid system was prepared as shown in (Fig. 2.2) with X-axis parallel to the coastline and Y-axis perpendicular to it. The Naval Hydrographic Chart Nos. 217, 218, 219, 220 and 221 were used for estimating the contour depths. Computation starts when the origin for the specified wave direction and the wave orthogonal is plotted for each successive grid points. The orientation of the grid has been made according to the orientation of the coast. (Fig. 2.2).

The wave refraction diagrams for each wave direction have been constructed for the predominant wave periods of 6 and 8 seconds from the 100 m contour line. The program listing is given in Appendix - I and the flow chart of the model used is shown in Fig. 2.3.

2.4.1. Input for the model

1. Number of grids in X direction = IXEND
2. Number of grids in Y direction = JYEND
3. Depth at nodal points = D(IXEND, JYEND)
Fig. 2.3. Flow chart of Nearshore wave transformation model.

\[
\begin{align*}
\frac{dx}{dt} &= C \cos \Theta, \quad \frac{dy}{dt} = C \sin \Theta \\
\frac{d\Theta}{dt} &= \frac{\partial c}{\partial x} \sin \Theta - \frac{\partial c}{\partial y} \cos \Theta \\
\frac{d^2 \beta}{dt^2} &= P(t) \frac{d\beta}{dt} + q(t) \beta = \Theta
\end{align*}
\]
4. Distance between the grids (metres) = SCA
5. Slope of the seabed = SLOPE
6. Starting point of wave orthogonal in X direction = X
7. Starting point of wave orthogonal in Y direction = Y
8. Deep water wave height (m) = H
9. Wave period (s) = T
10. Direction of wave crest with X axis (deg) = THETA
    (wave crest to X axis anticlockwise positive)
11. Wave theory = LINEAR/HIGHER
12. Time step = T
13. Stop computation at = BREAKING/GIVEN DEPTH

Computation stops at one of the following condition:

1. Wave steepness : H/L = 0.172 tanh kh
2. breaking depth : \( d_b = 1.28 H_b \)
3. orthogonal reaches the sides/shore/required depth.

Output: Output of the model consists of grid locations of the orthogonals at different time, deformed wave crest direction, shoaling and refraction coefficients and the net wave breaker heights.

2.5. Results

The numerical wave refraction study was undertaken to find out the distribution of wave energy along the Kerala coast. The refraction diagrams for different incoming wave directions and different wave periods are presented in (Figs. 2.4a & 2.4b), (Figs. 2.5a & 2.5b) and (Figs. 2.6a &
2.6b). The pattern of wave refraction according to the different seasons are described below.

South-west monsoon period (Wave direction: $270^\circ$, Wave period: $6\ S$ and $8\ S$)

The refraction diagram for the predominant wave periods $6\ S$ and $8\ S$ for the wave direction $270^\circ$ with respect to north are presented in (Fig. 2.4a) and Fig. (2.4b) respectively.

(Fig. 2.4a) shows convergence of wave orthogonals only at Vypin, north of Cochin. The divergence of wave orthogonals is observed south of Ezhimala, south of Cannanore, at Quilandi, Quilon, Varkallai and Puvar. The remaining stretch of the coast experiences nearly uniform wave energy for this direction of wave approach and wave period.

Waves approaching from $270^\circ$ with respect to north and with $8\ S$ period, show more convergence of energy along the coast than waves of $6\ S$ period (Fig. 2.4b). Convergence of wave energy is observed at Kasargod, south of Cannanore, North of Quilandi, south of Beypore, at Ponnani, Vypin, north of Alleppey, north of Karunagappalli and at Neendakara. The divergence of wave orthogonals is seen south of Ezhimala, Andhakaranazhi and Quilon. Along the rest of the coastal stretch, it is seen that the wave energy is uniformly distributed.
Fig. 2.4a. Wave refraction diagram for Kerala coast - Direction: 270°, Period: 6 s
Fig. 2.4b. Wave refraction diagram for Kerala coast - Direction: 270°, Period: 8 S
North-east monsoon period (Wave direction : 210°, Wave period : 6 S and 8 S)

The wave orthogonals approaching the coast at 210° with respect to north for the wave periods 6 S and 8 S are presented in (Fig. 2.5a) and (Fig. 2.5b) respectively.

The refraction diagram for the wave period of 6 S (Fig. 2.5a), shows convergence of wave energy north of Kanjangad, at Vypin and at Purakkad. The divergence of wave orthogonals is seen along the coast south of Ezhimala, between Cannanore and Mahe, Quilandi and further south and Quilon. It is seen that remaining stretch of the coast is subjected to uniform distribution of wave energy.

(Fig. 2.5b), for the 8 S waves shows, convergence of wave energy along south of Kasargod, Kanjangad, north of Ponnani, Azhikod, Vypin, north of Alleppey, Purakkad and Neendakara and divergence of wave orthogonals near Cannanore upto Badagara, Mahe, south of Nattika, Andhakaranazhi and north of Karunagappalli. The wave energy is uniformly distributed along the other parts of the stretch of this coast.

Fair-weather season (Wave direction : 290°, Wave period : 6 S and 8 S)

The refraction of wave orthogonals for the direction 290° with respect to north for wave periods 6 S and 8 S are presented in (Fig. 2.6a) and (Fig. 2.6b).
Fig. 2.5a. Wave refraction diagram for Kerala coast - Direction: 210°, Period: 6 s
Fig. 2.5b. Wave refraction diagram for Kerala coast - Direction: 210°, Period: 8 S
Fig. 2.6a. Wave refraction diagram for Kerala coast - Direction: 290°, Period: 6 s
Fig. 2.6b. Wave refraction diagram for Kerala coast - Direction: 290°, Period: 8 S
The refraction diagram for wave period 6 S (Fig. 2.6a), shows convergence of wave orthogonals along north of Bekal, south of Ponnani, at Vypin and Purakkad. The divergence of wave orthogonals are observed from Ezhimala to Mahe, at Quilandi, Nattika, Andhakaranazhi, from Quilon to Varkallai and at Puvar. The remaining stretch of the beach is subjected to more or less uniform wave energy.

(Fig. 2.6b), for the 8 S period shows that the waves approaching the coast with a direction 290° with respect to north converge at south of Bekal, Kanjangad, just north of Cannanore, south of Quilandi, south of Beypore, south of Ponnani, Azhikod, Vypin, north of Alleppey, north of Purakkad and at Neendakara. Divergence of the wave energy is observed at North of Ezhimala, Cannanore to Tellichery, Nattika, Andhakaranazhi north of Karunagappalli, along Quilon to Varkallai and at Puvar. The remaining part of the coast experiences direct attack of waves without appreciable refraction.

2.5.1. Variation of breaker parameters

Based on the numerical wave refraction study, the shoaling coefficient (Ks), refraction coefficient (Kr) just before wave breaking, and the variation of breaker height ($H_b$) for the entire Kerala coast were estimated and presented in (Figs. 2.7a & 2.7b), (Figs. 2.8a & 2.8b) and (Figs. 2.9a & 2.9b).
South-west monsoon period (Wave direction: $270^\circ$, Wave period: 6 S and 8 S)

The shoaling coefficient ($K_s$) for 6 S waves approaching from $270^\circ$, (Fig. 2.7a), shows relatively large values (>0.95) at Ezhimala, Cannanore, Quilandi, Cochin and between Quilon and Trivandrum. $K_s$ shows values around 0.9 at all the other places.

For 8 S waves approaching from $270^\circ$ (Fig. 2.7b), the value of the shoaling coefficients ($K_s$) is less than 1 at most of the places. But in some places it shows values greater than 1 (Ezhimala, Cannanore, Mahe, Quilandi, Nattika, Vypin and at South of Alleppey).

The value of the refraction coefficient ($K_r$) is very important because the wave energy distribution along the beach depends on $K_r$. From (Fig. 2.7a) it is clear that for waves approaching the coast from this predominant directions of $270^\circ$ with period 6 S, the $K_r$ values at the breaking point are greater than 1 north of Ezhimala, at Vypin, Andhakaranazhi, Alleppey and north of Quilon. The $K_r$ value is very low along south of Ezhimala and along south of Quilon.

The refraction coefficient ($K_r$) presented in (Fig. 2.7b), for 8 S period waves, shows values greater than 1 north and south of Ezhimala, Kanjangad, south of Beypore, south of Bekal, between Vypin and south of Alleppey and Quilon. $K_r$ values are low around 0.6 north of Quilon and at Varkallai. The lowest value of 0.5 is observed near Puvar.
FIG. 2.7a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT. WAVE DIRECTION = 270° WAVE PERIOD = 6 SEC.
FIG. 2.7b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 270° WAVE PERIOD = 8 SEC.
The breaking wave heights \( (H_b) \) along the Kerala coast, evaluated from \( K_s \) and \( K_r \) for unit deep water height for 6 S waves are presented in (Fig. 2.7a). Increase in net wave height \( (>1 \text{ m}) \) is observed at Quilandi, Vypin, North of Alleppey and Quilon. The highest breaker height of 1.5 m is observed near Vypin. Breaker height is around 0.8 m along the remaining stretch of the Kerala coast. Low breaker height is observed at Calicut beach.

The breaker height distribution \( (H_b) \) for 8 S period waves (Fig. 2.7b) shows that the breaker heights are more than the deep water wave height at Kasargod, Kanjangad, north of Ezhimala, south of Bekal, Quilandi, south of Beypore, Ponnani, Nattika, Vypin, Andhakaranazhi, Alleppey and Quilon. Along the rest of the coast, the breaker heights are less than \( (0.6 \text{ m} - 0.9 \text{ m times}) \) the deep water wave height. Lowest breaker height is observed near Puvar.

North-east monsoon season (Wave direction : 210°, Wave period : 6 S and 8 S)

(Fig. 2.8a), shows that for waves approaching from 210° with respect to north with period 6 S, the shoaling coefficient \( (K_s) \) is greater than 1 at Quilandi, north of Nattika, Vypin and at Alleppey. At all the other places it is around 0.95.

The shoaling coefficient values \( (K_s) \), for the 8 S waves (Fig. 2.8b), are greater than unity at Cannanore,
FIG. 2.8a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 210° WAVE PERIOD = 6 SEC.
FIG. 2.8b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT
WAVE DIRECTION = 210° WAVE PERIOD = 8 SEC.
Quilandi, Ponnani, north of Nattika, Vypin, north of Alleppey, and north of Quilon. Along the remaining stretch of the coast, the values are around 0.95.

The refraction coefficient (Kr) for 6 S period waves shows values greater than 1 at Kasargod, Ezhimala, Cannanore, Quilandi, Vypin, south of Alleppey and Quilon. All the other places, it ranges between 0.5 to 0.9.

The refraction coefficient (Kr) estimated for 8 S period waves shows that the values are greater than 1 at Ezhimala, Cannanore, south of Chawaghat, North of Nattika, Vypin, north of Alleppey, Purakkad and Quilon.

The breaker height parameter (Hb) computed for the waves approaching from 210° with 6 S period, indicates high values at Vypin and Quilon. Between Andhakaranazhi and Alleppey, the values show a minimum breaker height for this period and direction (0.6m). At other places, it is 0.75 of the deep water wave height. The highest breaker height of 1.4 m is observed north of Cochin.

For the direction of approach of 210°, waves with period 8 S show net breaker height (Hb) greater than 1 at Ezhimala, Cannanore, Vypin, north of Alleppey, Purakkad and north of Quilon. At Vypin, the wave breaker heights get amplified and show values around 1.3m for the deep water wave of 1m. At places between Nattika and Andhakaranazhi, Hb shows values around 0.5m while at Kasargod it is 0.9 m.
Fair-weather period (Wave direction: 290°, Wave period: 6 S and 8 S)

The refraction coefficients and the breaker heights estimated for the predominant wave approaching from 290° with 6 S period are presented in (Fig. 2.9a). The shoaling coefficient shows high values (>1) at Ezhimala, north of Nattika, Cochin and Quilon. Along the remaining stretch of the beach, the value is around 0.94.

From (Fig. 2.9b), for 8 S period waves, it is seen that the shoaling coefficient (Ks) is greater than 1 at Ezhimala, Cannanore, Mahe, Quilandi, Ponnani, north of Nattika, Azhikode, Cochin, Andhakaranazhi and Alleppey. At all other locations, it is around 0.95.

The refraction coefficient (Kr) for 6 S period shows low values along the entire stretch of the Kerala coast with an average value of about 0.75. High values of refraction coefficient (0.9) are observed south of Kasargod, Quilandi, Alleppey and a maximum value of 1.1 at Quilon.

The variation of refraction coefficient (Kr) estimated for 8 S period waves shows values higher than those for 6 S period waves. Kr shows high values (>1), at Cochin, south of Andhakaranazhi, south of Alleppey (Purakkad), Karunagappalli and at Neendakara. The maximum value of Kr (1.4) is observed near Neendakara and low value (0.5) near Ezhimala. Along the remaining stretch of the coast, the value is around 0.9.
FIG. 2.9a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 290°  WAVE PERIOD = 6 SEC.
FIG. 2.9b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT. 
WAVE DIRECTION = 290° WAVE PERIOD = 8 SEC.
The breaker height estimated for the predominant wave direction of 290° with period 6 s, shows that the wave height is getting reduced and the breaker height never exceeded the deep water wave height of 1 m. It shows an average value of about 0.8 m along the stretch of the Kerala coast with low values at Ezhimala (0.5 m) and Quilandi (0.6 m). Low values of about 0.7 m have been observed between Calicut and Nattika and shows a maximum value of 0.9 m at Quilon.

The breaker height distribution ($H_b$) for 8 s period waves shows higher values for the stretch of the coast from Cochin to Quilon. $H_b$ is greater than 1 m at Cochin, Alleppey, Purakkad and Neendakara. It shows high values north of Alleppey (1.4 times the deep water wave height) and at Quilon (1.3 times). At the southern end of the Kerala coast, $H_b$ is only 0.4 times the initial deep water wave height for this wave direction and period.