

MODULE VI

WIND-WAVE MODELLING

1.0 WAVE PREDICTION: WIND-WAVES

Most of the design requirements start from the design of wave height and wave period. The extreme wave height plays a major role for the life time design of structures and the wave period plays a significant role in number of design components, for instance, deciding on the mooring system for safe offshore unloading. Always, there are many contradicting discussions on the wave parameters and the user may not be clear of the terminology used for obtaining the wave parameters. For example, to achieve a good tranquillity inside the harbour, what is the approach to be undertaken? How to obtain an extreme wave climate, an operational wave climate and whether, are these related to sediment transport and tranquillity studies. The design requirements vastly diverge for different types of systems under design and it necessitates the definition of the requirement.

In this section, the wind-wave prediction is addressed from the simple crude way of approximation to the complex numerical prediction which needs lot of effort. Both the extreme way of prediction is still being commonly adapted from the preliminary proposal stage to the detailed design.

The first part covers only wind-waves and the numerical prediction also covers swell. The definition of swell is that those waves travelling away from wind band direction, are called as swell. The period of swell can be 8s to 25s even though the general perception is that swells are very long waves.

1.1 Historical Wave assessment

- It is possible to estimate wave parameters, H_s and T_z from local geography & wind information.
(H_s - Significant wave height & T_z is mean zero crossing period)
- And also from Historical representation of wave records.

1.1.1. Oceanography Maps

- * Gives most probably H and T over 50 or 100 year storm.

1.1.2. Wave scatter diagrams

- * Information about different sea states, H_s and T_z , over say 1-year period.
- * Indicates also the number of occurrences hence will be useful for fatigue studies.

1.1.3. Wind/ wave rose diagram

- * Wind: Information about percentage exceedance of wind speed, U from various wind direction, θ_w
- * Wave: Information about percentage exceedance of H_s from various directions, θ_m
- * Wave height exceedance diagram used to model the extreme conditions of storm for fatigue or foundation settlement problems.

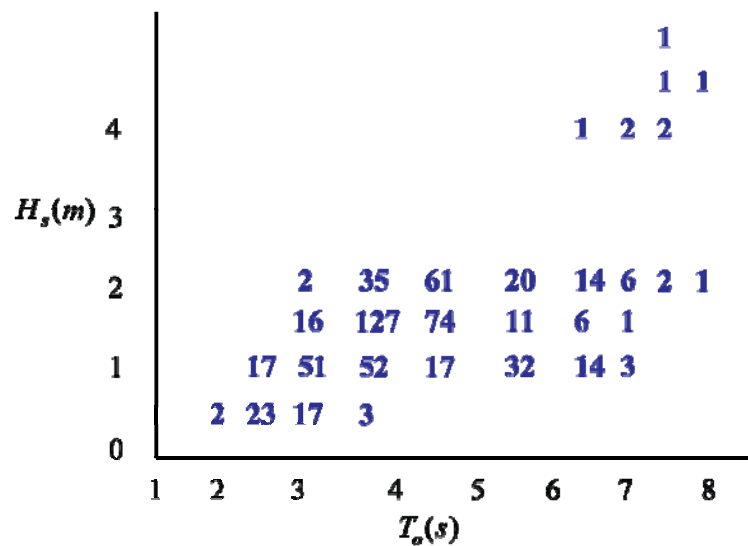
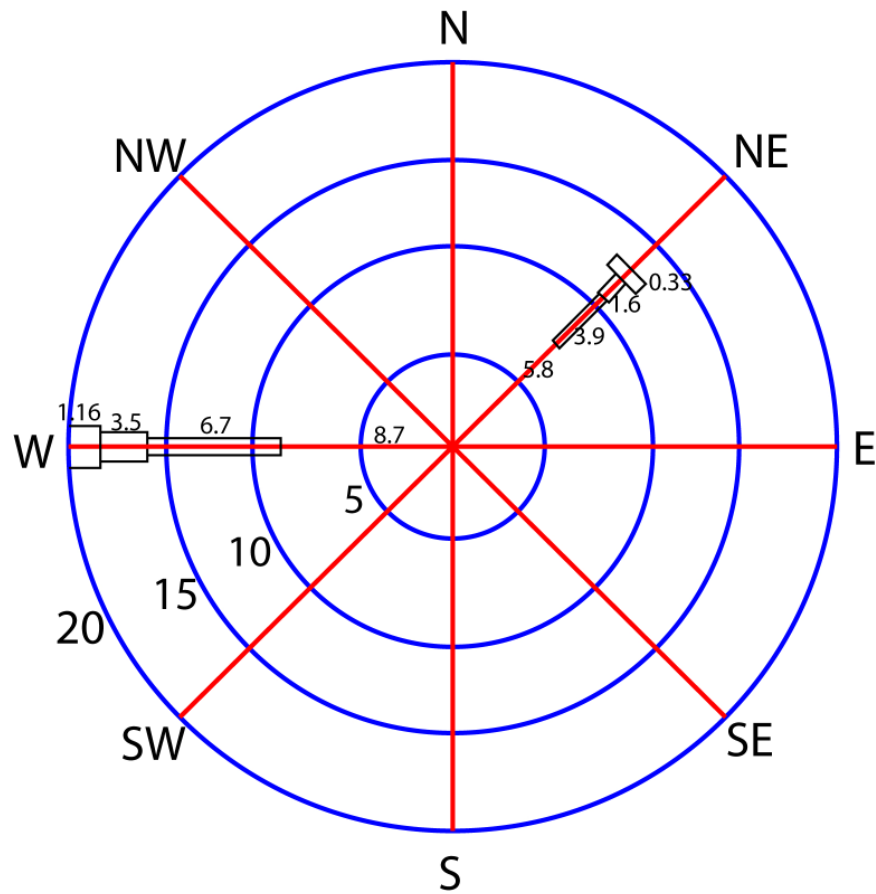


Fig.1. Wave scatter diagram.



Wind speed in knots

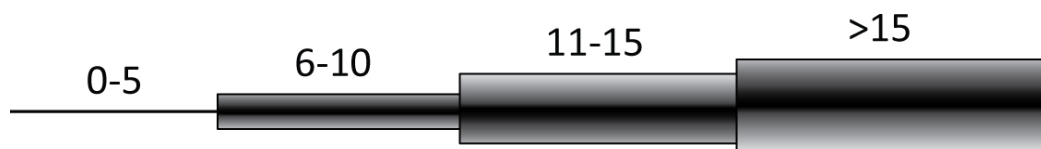


Fig.2. Wind rose diagram

1.2. Principle of Wind-wave generation

- * Wind transfers energy to the sea.
- *Complex process - to address, many theories have been evolved.
- * As wind blows over the water surface, the surface forms wrinkles due to pressure and shear effects, and hence, small ripples are formed.

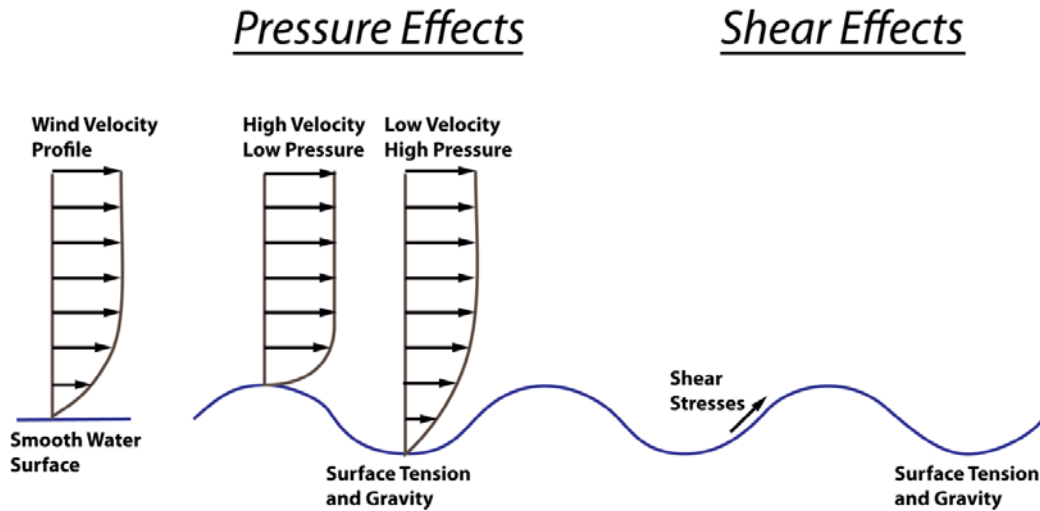


Fig. 3. Shear and Pressure differences along a wave.

Pressure effect:

From the Bernoulli's theorem, the pressure increases if the velocity drops and vice versa.

Above the crest, the wind velocity increases and hence pressure decreases.

Above the trough, the wind velocity decreases and hence pressure increases.

This makes pressure variation and makes surface wrinkles.

Shear effect: Water surface is stretched due to wind shear. Friction forces between air and water induce shear forces and push water particles to make small hills and hence, a down-hill on its upstream.

- Question for re-think: Water is a frictionless medium!

* These ripples grow if the wind continuously blows over the surface.

* Let, wind of constant mean velocity blow over the ocean.

Due to pressure and shear effects, ripples are formed on the water surface.

Initially, high frequency, short-waves formed.

Wave break and transfer to low-frequency components.

As well, nonlinear wave-wave interaction shifts energy to low frequency.

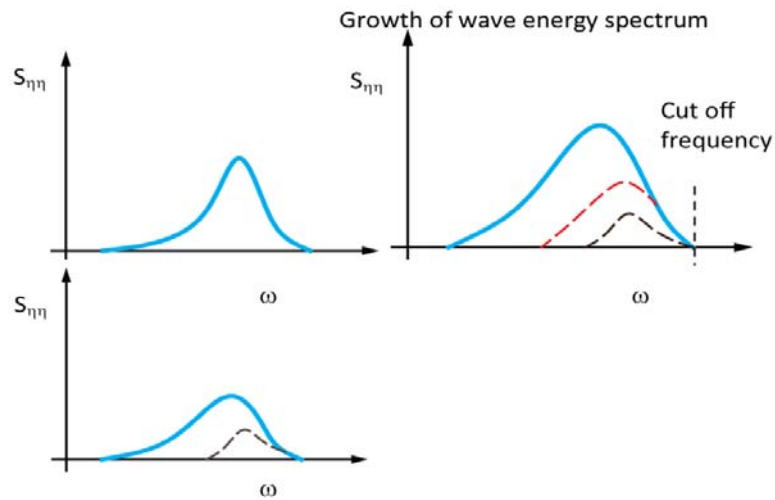


Fig.4. Spectral wave growth.

So, energy continuously transfers from high frequency to low frequency until the phase velocity of wave (C) is equal to the wind velocity (U), i.e., $C = U$. In more general, we can take, $C_g = U$.

Beyond, $C_g > U$, wind doesn't supply energy to waves directly. That means, waves reach an equilibrium at certain extent. This equilibrated sea state is called as '*fully developed sea*'.

Two physical constraints may restrict the above process:

Before the wave attains its equilibrium, if the wind stopped blowing, the sea state can be called 'under developed' from its potential. This sea is called '*duration limited*'.

On the other hand, if there is constraint in the space for wave propagation for the wave to grow, then also, waves would have stopped growing. This sea is called '*fetch limited*' sea.

* Hence, main factors governing wave growth from the ripples stage:

wind speed,

wind duration and

fetch (length over which wind blows).

Wind is the exciting force in this case and gravity is the restoring force. Hence, the sea is developed as an vertically oscillating component influenced by the gravity, g . Hence, the wind-waves are also called as gravity waves.

From the above discussion, Fully developed Sea = $f(U, g)$

Duration limited Sea = $f(U, t_d, g)$

Fetch limited Sea = $f(U, L_F, g)$

where, t_d is the duration of wind and L_F is the fetch.

Fully developed Sea state:

* Once it is known that any sea state has an equilibrium sea state for the given wind climate, then, it is obvious to seek a solution to arrive at the wave characteristics such as significant wave height and mean wave period directly.

Table1. Equilibrium sea state

Wind speed	Fully developed sea state after	
	Fetch (km)	Duration (hrs)
10 m/s	>	>
15 m/s	>	>
20 m/s	>	>
30 m/s	>	>
40 m/s	>	>
50 m/s	>	>

* Many theories predict reasonably well.

* Spectral models such as PM (Pierson-Moscowitz, 1964) spectrum, exists.

1.2.1. Wave Spectral Model: Pierson-Moskowitz spectrum (Pierson and Moskowitz, 1964)

For a fully developed sea, following the Pierson-Moskowitz formulation, the estimates for significant wave height ($H_{mo}=H_s$) and peak wave frequency (f_p) are derived as follows:

$$H_{mo} = \frac{0.21U^2}{g} \quad (1)$$

$$f_p = \frac{0.87g}{2\pi U} \quad (2)$$

where U is the wind speed in m/s, and g is the gravitational constant. The above formulae were derived for wind speeds between 10 and 20 m/s and it was assumed that the sea was neither fetch limited nor duration limited.

1.2.2. SMB wave prediction curves

Sverdrup and Munk (1947) developed a wave prediction procedure based on wave energy growth concepts with empirical calibration using a limited amount of field data. This procedure was improved by Bretschneider (1952, 1958) by calibrating using vast field data. The method is known as the SMB method after the three authors. Consider a dimensional analysis of the basic wave prediction relationship,

$$H_s, T_s = f(U, L_F, t_d, g)$$

Depending on whether the wave generation is fetch or duration-limited, the fetch or the duration term on the right side would control the estimation.

$$\frac{gH_s}{U^2} = 0.283 \tanh \left[0.0125 \left(\frac{gX}{U^2} \right)^{0.42} \right]$$

$$\frac{gT_s}{2\pi U} = 1.2 \tanh \left[0.077 \left(\frac{gX}{U^2} \right)^{0.25} \right]$$

$$\frac{gt}{U} = K \exp \left[\left\{ A \left(\ln \left(\frac{gX}{U^2} \right)^2 \right) - B \ln \left(\frac{gX}{U^2} \right) + C \right\}^{0.5} + D \ln \left(\frac{gX}{U^2} \right) \right]$$

where, $K = 6.5882$; $A=0.0161$; $B=0.3692$; $C=2.2024$; $D=0.8798$

The above relation has been presented in the form of empirical equations and dimensional plots and is shown in Fig. 6 (US Army coastal Engineering Research Centre, 1977).

For a fetch-limited wave condition, the solid lines can be used to predict the significant wave height and period. For a duration-limited wave condition, the dashed line can be used. Note that the parameters, fetch, duration, significant wave height and wave period were non-dimensionalised in terms of wind speed. The curves tend to become asymptotic to each other and horizontal lines on the right hand edge. This limit is the fully developed sea condition.

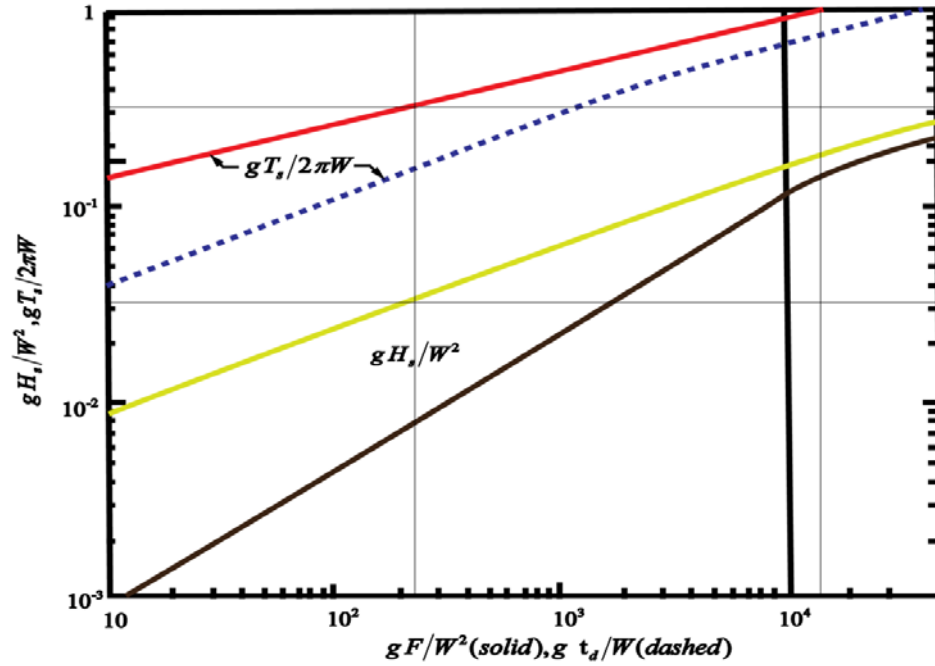


Fig.5. SMB wave prediction curves [Bretschneider, 1952, 1958] (Note: W is the wind speed, t_d is the duration of wind and F is the fetch).

1.2.3. SPM: Deep water wave prediction

A parametric model based on Jonswap studies has estimated wave characteristics under fetch limited and duration limited wind conditions.

For fetch limited condition:

$$\frac{gH_{m0}}{U_A^2} = 0.0016 \left(\frac{gL_F}{U_A^2} \right)^{1/2}$$

$$\frac{gT_p}{U_A} = 0.286 \left(\frac{gL_F}{U_A^2} \right)^{1/3}$$

For duration limited condition:

$$\frac{gt_d}{U_A} = 68.8 \left(\frac{gL_F}{U_A^2} \right)^{2/3}$$

Here, the wind is adjusted to U_A from U_{10} as, $U_A = 0.71U_{10}^{1.23}$. It has to be noted that the above expressions have empirical coefficients and hence, it is sensitive to units. Wind speed is given in terms of m/s.

1.3 Extreme Sea states

Maximum significant wave height generated by a tropical cyclone in deep water,

$$H_{\max} = 0.2 (P_n - P_c)$$

where, $(P_n - P_c)$ is the pressure drop from the environment to the cyclone centre in hPa (Hsu, 1991). However, the wave height attenuates quickly outside this region and in most cases, it may not be of any interest.

1.4. Wind-wave Modelling

All the above efforts in predicting wave heights is based on the fact that either the domain is unbounded or in the defined boundedness. However, in most of the field situations, one needs to predict (forecast) wave climate for operational reasons, such as to establish a navigational route (this is million dollar industry); to establish a time window for the erection of jacket structure; or, to evaluate the number of operational days in an offshore jetty. Such a near accurate estimate could not be made with the historical methodologies.

Assisting the above objectives, world wars learned to evade countries through sea route. This made huge investment in operational wave prediction models by the Navy. Even though, it is unfortunate for the improvement in the scientific achievements, there was sudden surge in the funding to the research developments of theoretical modelling aspects after the world wars I & II.

Jeffrey's theory (1924, 1925) laid a foundation even in 1920's. It addresses whether variation in pressure (Fig.4) can result in a flux of energy from the wind to the waves.

$$\frac{\partial E}{\partial t} = \frac{1}{\rho_w g} \overline{\rho_a \frac{\partial \eta}{\partial t}} \quad (3)$$

*Pressure component correlated with $\frac{\partial \eta}{\partial t}(\text{slope})$ will result in an energy flux to the wave

(i.e., the component of pressure in quadrature with the water surface)

* So, there should be a phase shift between η & p for positive energy flux, higher pressure on the windward side of the wave.

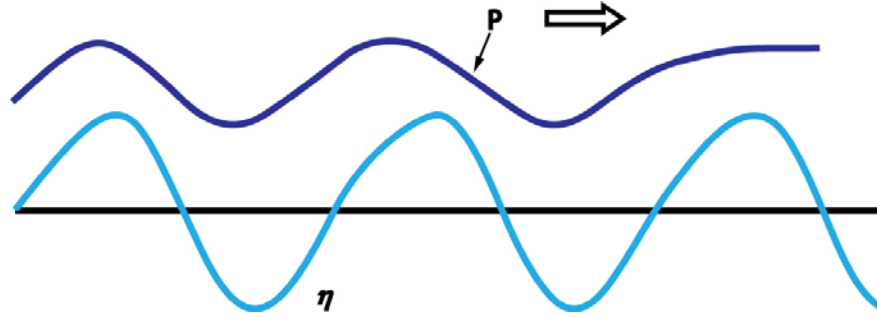


Fig.6. Air pressure variation above the wave surface.

From Potential flow formulations,

$$\frac{\rho}{\rho_a g} = -ae^{-kz} \left(1 - \frac{U}{C}\right)^2 \sin(kx - \omega t) - z \quad (4)$$

Here, 'p' is in out of phase with 'η'

From (1), this leads to no flux of energy from the air to the water.

“This is counter to our intuition”

Also, (2) shows, p exponentially decrease with 'z' above water surface.

1.4.1. Jeffrey's sheltering theory

-energy transfer by form drags associated with flow separation (on leeward side)

$$p = S \rho_a (U_\infty - C)^2 \frac{\partial \eta}{\partial x} \quad (5)$$

S= sheltering coefficient <1

U_∞ - wind speed (no boundary layer is considered)

From (3) & (5),

$$\frac{\partial E}{\partial t} = \frac{1}{2\rho_a g} S \rho_a (U_\infty - C)^2 (ak)^2 C \quad (6)$$

Note, $E \propto a^2$ (phase speed)

$$\alpha(U_{\infty} - C) \quad (\text{So no energy flux if } U_{\infty} = C)$$

α wave slope, ak (due to flow separation assumption)

S depends on $U_{\min}^3$ (minimum wind to keep the wave sustain against the losses)

After nearly three decades from the initial work of Jeffrey, the work of Philips (1957, 1960) and Miles (1957) make milestones in transferring the understanding of energy transfer mechanism to mathematical formulation.

Philips (1957, 1960): Key to their study is the pressure effect. The main cause of the wave growth is hypothesized as a resonant interaction between forward moving pressure fluctuations and free waves propagating at the same speed as the pressure fluctuations.

Miles (1957) hypothesized on the air flow patterns above the free surface that develops due to wavy surface. It specifies a development of a secondary air circulation around an axis parallel to wave crest by the wind velocity profile. This forms from the basis that, if one closely follows the wind velocity profile shown in Fig. 3 just above the free surface, below one point, the wind velocity becomes lesser than wave phase velocity. Below this point, air flow is reversed relative to the forward moving wave profile. However, above this point, air flow direction is same as wave propagating direction. This result in a relative flow circulation in a vertical plane. This causes an out of phase pressure distribution on the wave surface with the surface displacement, η . If we refer back potential flow formulation (Eq.4), there is a momentum transfers to the wave at particular wave components.

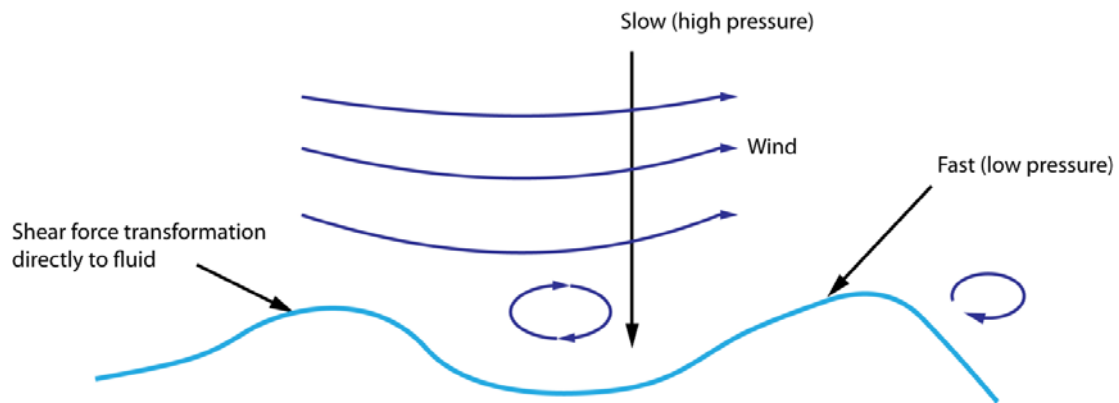


Fig.7. Pressure and shear effects on a wind generated wave.

Many other theories evolved but Philips & Miles' theories dominate others to address the initial knowledge on the development of the wind waves. One of the significant findings from other theories which is absorbed in the theoretical modelling is that the ripples on the free surface create more friction and hence, frictional forces can be enhanced if the wind blows over the surface compared to over a very calm sea.

1.5. Wave Evolution Modelling

To define a mathematical model for the description of the evolution of wind waves from the physical processes which influences this evolution.

Now, let us see, how the evolution of wind wave's can be described.

From Jeffery's theory (1924, 1925), it can be understood that the flux of energy averaged over a period of time and hence, modelling the rate of change of wave energy is an ideal modelling parameter than the wave profile and its' velocity components.

In 50's, the governing equation for the wave propagation has been formulated.

$$\frac{dE}{dt} = 0 \quad \text{for no wind condition, i.e., only wave propagation is considered.}$$

If there is wind, we can include the input wind energy as a source function.

$$\frac{dE}{dt} = S_{in}, \quad \text{where, } S_{in} \text{ is the input source function (addition of energy)}$$

If there is only addition of energy without the provision of any extraction, numerically the energy spectrum will grow without attaining the equilibrium state. Hence, the energy extraction process through wave breaking and friction are modelling through negative source function, called dissipation source.

$$\frac{dE}{dt} = S_{in} + S_{dis}, \quad \text{where, } S_{dis} \text{ is the dissipation source function (sink)}$$

By looking at the above source functions, S_{in} will pump the energy on the higher frequency band upto the limit of $U = C_g$, where the resonant interaction ceases to transfer energy to the water surface. And, the dissipation function again takes away the energy from higher frequency band relative to the S_{in} . In overall, for a given wind speed, the energy spectrum will not grow towards lower frequency bands with the above definitions. The waves grow, transfer of energy from high to low frequency bands, due to nonlinear wave-wave interaction. Hence, another source function modelling nonlinear wave-wave interaction has been included to complete the wind-wave modelling equation.

$$\frac{dE}{dt} = S_{in} + S_{dis} + S_{nl}$$

Even with the present day capabilities of super computers, it is uneconomical to solve fully the nonlinear wave-wave interaction term. Hence, only resonant interaction terms by four wave-wave interaction has been modelled by Hasselmann (1985). This reduced order has been included in the recent state-of-the art models, WAM and WaveWatch III as Discrete Interaction Approximation (DIA) term.

For nearshore wave prediction, an additional nonlinear wave-wave interaction term, called triad interaction, has to be included to consider the three wave resonant interaction in coastal waters.

Fig. 8 shows the energy distribution contribution of various source function with reference to the given spectrum.

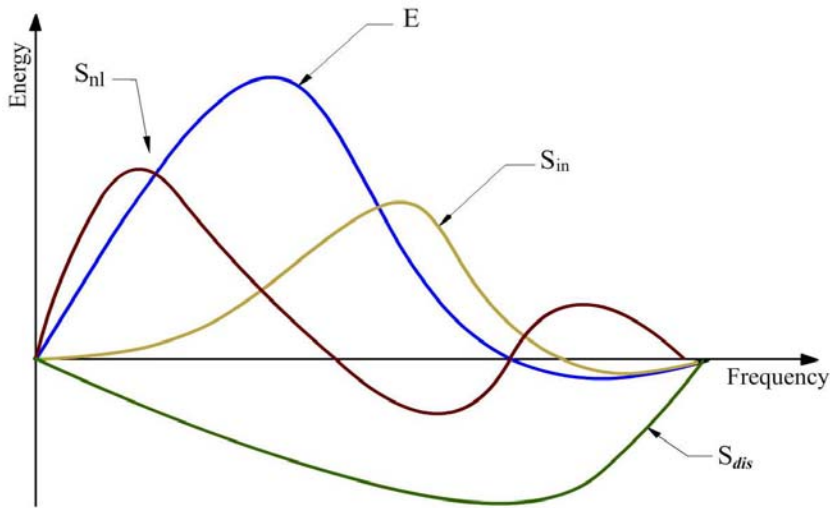


Fig.8. Distribution of energy by various source functions.

1.5.1. Wave dissipation

- *Some aspects on incorporation of wave breaking dissipation in numerical models
- * Least understood physical processes in the wave evolution.
- * Spectral representation of energy transfer rate over a wide spatial scale - is it justifiable?

Approximate theories of wave dissipation

- * *Pressure-Pulse or 'whitecap' model*
- * *Steepness (Instability) or quasi-saturated model*
- * *Probability model*

Concept of theoretical development: Processes which are weak-in-the mean (even if strongly nonlinear locally) yield quasi-linear (to lowest interaction order) source function.

$$S_{dis} = \gamma \cdot F(k, \theta)$$

where, $\gamma = f(F(k, \theta), U)$.

Evaluation of γ involves the detailed hydrodynamics of breaking waves and the representation of individual breaking events in a spectral form.

Simplified concept of evaluating γ in spectral balance equation is based on the analysis of spectrum which is stationary (when local).

$$\frac{\partial F(k)}{\partial t} = S_{in} + S_{dis} + S_{nl} = 0$$

Hypothesis I: White-cap model

- * Whitecaps as random distribution of perturbation forces
- * Whitecap scales (space & time) are small compared to waves

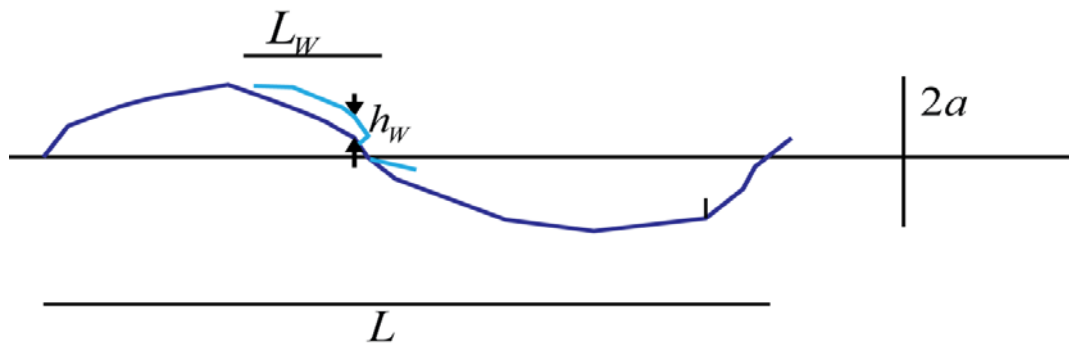


Fig.9.Whitecapping on the wave crest.

It is assumed that,

1. Extent of the white-cap is proportional to the length of the wave.
2. 'white-caps' and underlying wave are in geometric similarity (Duncan, 1981).

i.e., $L_w/L = \text{constant}$; $h_w/a = \text{constant}$

3. Downward pressure on the upward moving water (negative work on the wave).

$$p_w = \rho_w g h_w \approx \rho_w g a$$

Komen et al.(1984).

$$S_{dis} = -C_{ds} \left(\frac{\hat{\alpha}}{\hat{\alpha}_{PM}} \right)^m \left(\frac{\omega}{\bar{\omega}} \right)^n \omega F(k)$$

where, C_{ds} , m & n are fitting parameters.

$C_{ds} = -2.36 \times 10^{-5}$, $m = 2$ & $n = 1$. Here, m is insensitive to sea state.

Hypothesis II: Quasi saturated model (Philips, 1985) and Donelan (1989)

* Whitecapping is local in wave-number space.

$$S = -\gamma F(k, \theta)$$

$$\text{where, } \gamma = C_{ds} \omega k^8 F^2(k)$$

Both these two hypothesis are deterministic. But wave breaking is an un-predictable. It is better to represent in probabilistic sense.

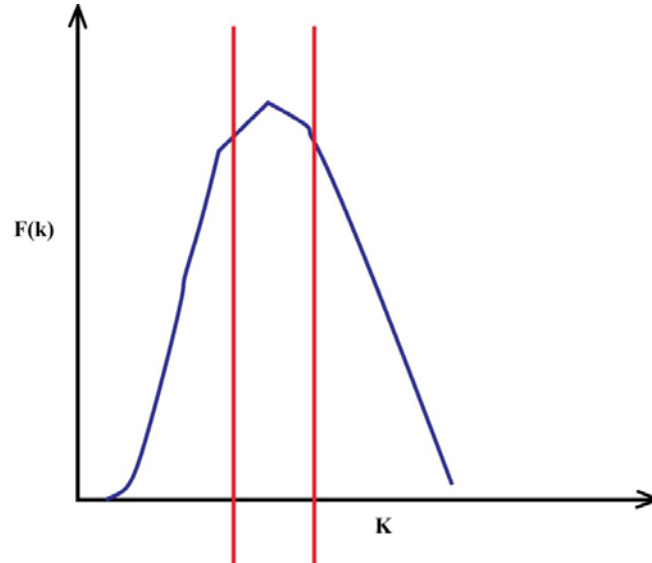


Fig. 10. White capping representation in the wave number space.

Hypothesis III: Probability model

* Concept: wave breaks while exceeding Stokes' limiting criterion.

i.e., Crest particle acceleration $> g/2$.

If expected loss of energy per wave cycle is $a_b \omega g/2$, then

$$\Delta E = \frac{1}{2} \rho_w g \int_{a_b}^{\infty} (a - a_b)^2 p(a) da$$

where, a & ω are based on joint probability density function of wave height and frequency.

1.5.2 Nonlinear wave-wave interaction Modelling

- * Four wave-wave interaction (Quadruplet interaction) in deep waters
- * In addition, Triplet interaction in shallow waters.

2.0 NUMERICAL WIND-WAVE MODEL

The development of numerical wave modeling within spectral approach has been started since early sixties. The spectral energy balance concept was the basis for the solution of wave energy transport equation. The first generation wave models were based on linear formulation and the spectral shape was prescribed. The adopted formulation of wind-wave momentum transfer over predicted the wave environment. Successively, second generation models evolved with the addition of non-linear wave-wave interaction terms. However, the complete formulation of non-linear energy transfer was not implemented due to the complexity in solving the integration as well as the computer power restrains. The complex wave-wave interaction terms were solved by the method of discrete interaction approximation [Hasselmann and Hasselmann, 1985] which laid foundation for the third-generation models. The wind input source term was defined by Janssen (1989). Now, more than two decades after the implementation of third-generation models, the improvement to the numerical wave modeling efforts has been slowly dawning.

A third-generation wave model, WAM model (WAMDI, 1988; Komen et al., 1994) estimates the evolution of the energy spectrum for ocean waves by solving the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. Hasselmann (1963) proposed an equation for the energy balance of the wave spectrum which is the basis for the exact theory of wave spectrum dynamics.

$$\frac{\partial F(f, \theta; x, t)}{\partial t} + \nu \cdot \nabla_x F(f, \theta; x, t) = S \quad (1)$$

where $F(f, \theta; x, t)$ is the wave energy spectrum in terms of frequency f and propagation direction θ at the position vector, x and at time t ; v is the group velocity. The second term on the left-hand side is the divergence of the convective energy flux, $v \cdot F$, and S is the net source function which takes into account all physical processes which contribute to the evolution of the wave spectrum. The source function is represented as superposition of source terms due to wind input, non-linear wave-wave interaction, dissipation due to wave breaking, and bottom friction.

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} \quad (2)$$

The amalgamation of these source terms signifies the current state of understanding of the physical processes of wind waves, namely the inputs from the processes of wind field, non-linear interaction, dissipation and bottom friction balance each other to form self similar spectral shapes corresponding to the measured wind wave spectra. Except for the non-linear source term, which uses the discrete interaction approximation that simulates an exact non-linear transfer process formulated by the four-wave resonant interaction Boltzmann equation and characterizes the third-generation model, all the other source terms are individually parameterised to be proportional to the action density spectrum, F .

The wind input source function was adopted from Snyder et al. (1981) and Komen et al. (1984). The non-linear source function S_{nl} is represented by the discrete interaction operator parameterisation proposed by Hasselmann et al. (1985),

$$S_{nl}^{di}(k_4) = \sum_{\gamma=1,2} A_{\gamma} \omega_4 \left[n_1^{\gamma} n_2^{\gamma} (n_3^{\gamma} + n_4^{\gamma}) - n_3^{\gamma} n_4^{\gamma} (n_1^{\gamma} + n_2^{\gamma}) \right] \quad (3)$$

where A_{γ} are coupling coefficients and the action densities

$$n_i^{\gamma} = F(k_i^{\gamma}) / \omega_i^{\gamma}, \quad i = 1, 2, 3; \quad \gamma = 1, 2 \quad (4)$$

are evaluated at discrete wave numbers $k_i^{\gamma} = T_i^{\gamma} k_4$. The discrete wave numbers are related to the reference wave number k_4 through fixed linear transformations, T_i^{γ} . These discrete interactions have been tested for fetch and duration-limited wave growth. In the finite depth hind cast studies, the depth dependent angular refraction term is generally ignored.

Quadruplet wave-wave interactions

A general perturbation theory for the nonlinear resonant interaction of waves in a random sea was developed by Hasselmann [1962, 1963]. He found that a set of four waves, called quadruplet, could exchange energy when the following resonance conditions are satisfied:

$$k_1 + k_2 = k_3 + k_4$$

$$\omega_1 + \omega_2 = \omega_3 + \omega_4$$

where ω_j is the frequency and k_j the wave number vector ($j=1, \dots, 4$). The frequency and wave number are related through the dispersion relationship. The four interacting wave components (expressed above) form the quadruplet. The above resonance conditions define not only the frequencies of spectral components that can interact nonlinearly but also their propagation directions, since the wave number is a vector expression. Hence, all components of the spectrum are potentially coupled and energy can be exchanged, not only between components of different frequency, but also among components propagating in different directions. The nonlinear energy transfer is represented by:

$$\begin{aligned} \frac{\partial n_j}{\partial t} = & \iiint G(k_1, k_2, k_3, k_4) \times \delta(k_1 + k_2 - k_3 - k_4) \times (\sigma_1 + \sigma_2 - \sigma_3 - \sigma_4) \times [n_1 n_3 (n_4 - n_2) + \\ & + n_2 n_4 (n_3 - n_1)] dk_1 dk_2 dk_3 \end{aligned} \quad (5)$$

where $n_j = n(k_j)$ is the action density at wave number k_j and G is a coupling coefficient.

The nonlinear energy transfer conserves both the total energy and momentum of the wave field, merely redistributing it within the spectrum. As a consequence of the symmetry of the resonance conditions with respect to the pairs of wave numbers (k_1, k_2) and (k_3, k_4) , the quadruplet interactions also conserve the wave action. The absolute value of the rate of change of the action density is equal for all wave numbers within the quadruplet:

$$\frac{dn_1}{dt} = \frac{dn_2}{dt} = -\frac{dn_3}{dt} = -\frac{dn_4}{dt} \quad (6)$$

This property states that the absolute value of the change in action density $|\Delta n_j|$ is the same for all components in a resonant set of wave numbers.

The quadruplet wave-wave interactions dominate the evolution of the spectrum in deep water, transferring wave energy from the spectral peak to lower frequencies – thus moving the peak frequency to lower values - and to higher frequencies – where the wave energy is

dissipated by whitecapping. A full computation of the quadruplet wave-wave interactions is extremely time consuming and not convenient in any operational wave model.

2.1 Features of WAM : A Third Generation Ocean Wave Prediction Model

Functionality of WAM

The following wave propagation processes are implemented in the model:

- Cartesian or spherical propagation
- Deep and shallow water
- Without or with depth and current refraction
- Dissipation of white-capping
- Wave generation by wind
- Nonlinear wave-wave interaction

Features of WAM

- Based on the spectral energy balance equation
- Nonlinear transfer of energy
- Dissipation due to wave breaking
- Bottom dissipation, and
- Refraction for finite-depth water

Inputs

Wind source, Bathymetry and Current data

Outcome

- Significant wave height;
- Mean wave direction
- Mean frequency
- Friction velocity
- Wind direction
- Wave peak frequency
- Drag coefficient
- Normalized wave stress
- Two-dimensional spectra

2.2 Wave Propagation Over Constant Depth Bathymetry

The wave generation over a basin of constant water depth was considered. A water depth of 250m was assumed over a region of $20^\circ \times 20^\circ$. The grid resolution was $1/12^\circ \times 1/12^\circ$. In this case, the model was run for different combinations of wind and current fields. These were

1. Constant wind blowing over the entire region in the absence of current field
2. Constant wind in addition to in-line current field
3. Constant wind over opposing current field

A constant northerly wind of 10 m/s was assumed to blow over the entire region. An initial wave was set up with the same wind condition. The simulation was then carried out for forty-eight hours and the steady state was reached. In the second case, with the above wind field, a constant in-line current of 5 m/s was assumed to be present. In the last case, a constant opposing current field of 5 m/s was assumed. The current direction in the second condition was the same as the wind direction while, in the last condition, it was 180° out-of-phase with the wind direction.

The simulated wave field was analysed for estimated spectral parameters such as significant wave height, H_s and peak wave period, T_p . Fig. 11 shows the evolution of wave field in the virtual constant depth basin under the action of constant wind field over period of forty-eight hours. The wave parameters such as significant wave height and mean wave period approached asymptotic values at the end of the propagation period. The estimates were compared to the values from the analytically derived equations for the constant wind field. The comparison of wave characteristics from WAM with the wave spectral model and SMB prediction curves is presented in Table 2 for the constant wind condition. Table 3 presents the variation in wave conditions in the presence of in-line and opposing current field.

The spectra for the three cases are shown in Fig. 12. It can be seen that the in-line current field reduces the wave height and shifts the peak frequency towards higher harmonics. The opposing current field however made the waves steep by focusing on the narrow band of frequencies. The frequency components were shifted towards lower harmonics.

Table 2. Variation of simulated wave estimates under the action of constant wind and current fields

S.No.	External forcing	WAM	Wave spectral model	SMB
1.	Significant Wave height	2.14	2.14	2.14
2.	Peak wave period	7.44	7.4	7.69

Table 3. Comparison of simulated and analytically derived wave estimates in a constant northerly wind of 10 m/s

S.No.	External forcing	H_s (m)	T_p (s)
1.	Wind	2.14	7.44
2.	Wind + Inline current	2.07	5.09
3.	Wind+Opposing current	2.10	13.19

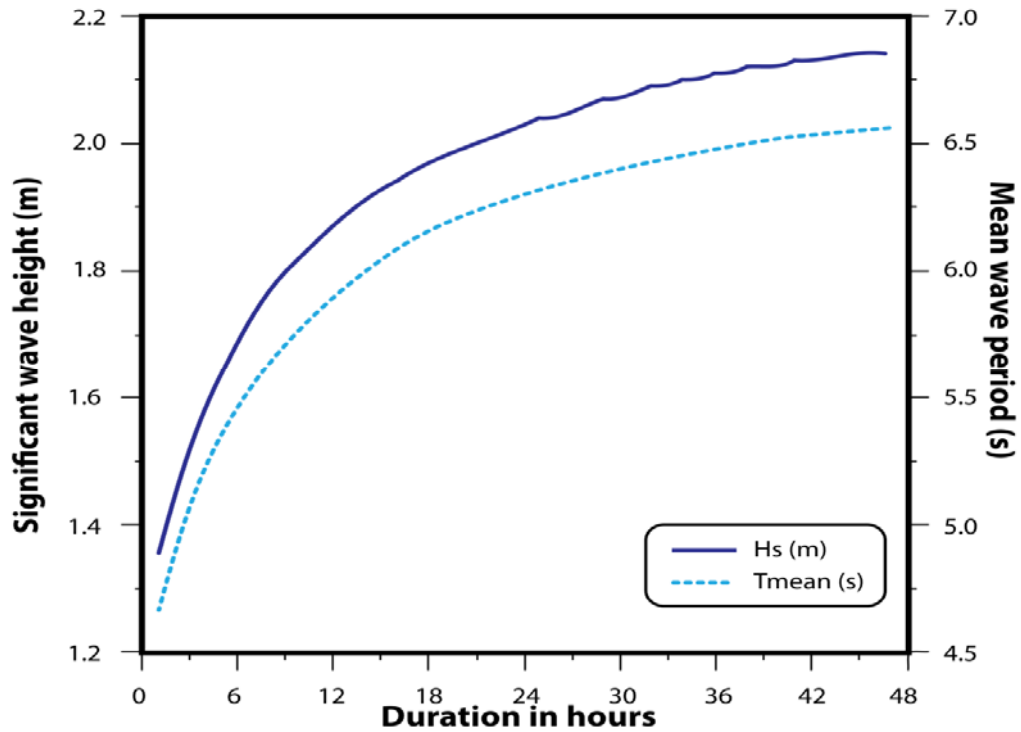


Fig. 11. Evolution of wave components with time in a constant uni-directional wind field blowing over the entire region

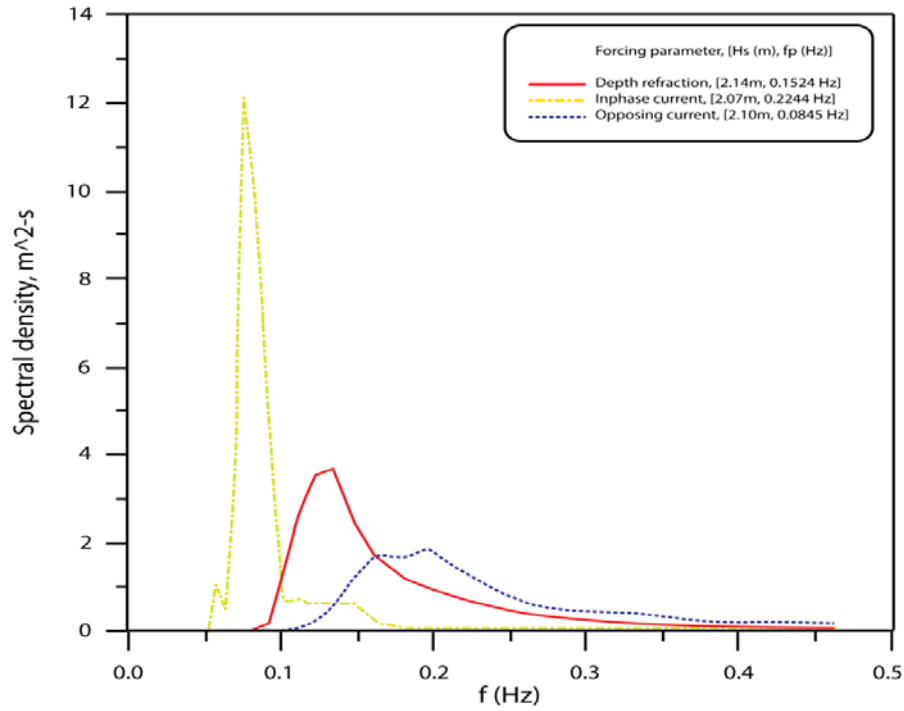


Fig. 12. Variation of generated wave spectra under different wind and current fields

3.0 NEARSHORE WAVE PROPAGATION MODELLING:

SWAN (Simulating Waves Nearshore)

There are currently several nearshore wave transformation models available for use in practical engineering and research problems. Generally, these models differ greatly with regard to the basic modeling approach, the selection of model inputs, as well as user control over the formulation of the model. For the present assignment, the shallow water wave model, SWAN v30.74 (Simulation of Waves Nearshore) by Riset *al.* (1998) is selected.

One key factor in selecting this particular model is their current use and acceptance by the coastal engineering community. It is also important that the model computations utilize wave spectra, which is a statistical representation of a measured wave field. A two-dimensional wave spectrum describes a random wave field as a distribution of wave energy in terms of frequency and direction. A wave spectrum can be thought of as describing a collection of several individual monochromatic wave trains, with varying wave height and direction of travel. The selection of the model, SWAN is also based on the ease of model set-up.

SWAN Features

The basic assumptions used in the formulation of SWAN and a more detail discussion concerning modeling of some specific phenomena, such as wave breaking criteria included in SWAN are presented.

The numerical wave transformation model SWAN was developed at Delft University of Technology, Delft, The Netherlands. The formulation of SWAN is based on the spectral wave action balance equation. This model currently has many well developed features, which give the user many options on how each model run is executed. These features range from purely convenient options that allow several different formats for input and output data, to options that allow control of fundamental physical processes in the model, like wave generation, dissipation, and interaction. Similar sources of input and dissipation of energy in the wave spectrum are a part of SWAN, including wind wave generation, whitecapping, non-linear wave interactions, and depth induced wave breaking.

SWAN uses a wave spectrum to describe two-dimensional wave propagation. The spectral definition of the wave field is used even in areas of the model domain where non-linear phenomena dominate, such as the surf zone, or any location where waves are breaking. The authors of SWAN suggest that even in these areas, reasonable accuracy is still possible in the second order moment (the standard deviation) of the wave spectrum (Riset *al.*, 1998). SWAN is a finite difference model. SWAN does not model wave diffraction or reflection, and is therefore most useful in applications where accuracy of the computed wave field is not required in the immediate vicinity of obstacles. Only linear wave refraction is included in the model. Bottom friction can be included in the model computations. Bottom friction is often used as a tuning parameter, which allows small adjustments in the model output for better comparison to actual data.

In SWAN, it is possible to define different spectral conditions at different points along the open boundary of a model domain. This feature is most useful when SWAN is linked to large scale ocean wave models such as WAM and WaveWatchIII. Thus, more detailed computations are possible, without requiring the same degree of detail throughout the computational domain. In addition to the varying spectral input, other model inputs (wind, water level elevation, and currents) are allowed to vary spatially over the model domain. This feature makes SWAN useful for the computation of wave fields during storm surges in large estuaries, where it is possible to have significant variations in surge levels throughout a model domain.

SWAN has the ability to compute a time dependent, time varying solution, rather than just a series of steady state solutions. The difference between steady state and dynamic solutions is most apparent in applications where wind driven waves do not have sufficient time to reach the maximum height possible, for a given wind strength and duration. Waves that reach the maximum height are described as fetch-limited waves. During hurricanes and other fast moving storms, it is possible that wave conditions may not be fetch limited, due to the quickly changing wind field. For the type of wave conditions and results necessary for this study however, the dynamic capabilities of SWAN are not required.

SWAN is a full of 360° model, which means that it can propagate waves in any direction. Input wave spectra can have a full of 360° directional spread, but it is also possible to activate only a sector of a full circle. The ability of SWAN to propagate waves in all directions is the result of its numerical scheme, which makes four separate passes of the model domain, one for each quadrant of a full circle. The numerical scheme used by SWAN is a first order implicit, upwind scheme in geographic space. Because the four passes require that all data remain in memory during the computation, SWAN uses a much larger data array. This requires substantially more machine memory to run.

Model Formulation

Though SWAN includes several sources of wave energy input and dissipation, the only process that is considered fundamentally important for this study, beyond the formulation of the governing equation, is the process of wave breaking. For the most part, the model selected is used to solve the distribution of wave heights along cross-shore where the model is driven solely by an input spectrum at the open boundary. Other phenomena included in the wave transformation models under consideration (i.e., the effects of wind, whitecapping, water currents and wave diffraction) are considered less important to the scope of the study (i.e., open coastline with incident wave spectrum driving the open boundary), and are not discussed in detail here.

The governing equation of wave transformation, using the action balance spectrum, in geographical space is written (Riset *al.*, 1998) as,

$$\frac{\partial N}{\partial t} + \frac{\partial c_x N}{\partial x} + \frac{\partial c_y N}{\partial y} + \frac{\partial c_\sigma N}{\partial \sigma} + \frac{\partial c_\theta N}{\partial \theta} = \frac{S}{\sigma} \quad (1)$$

where

$N(\sigma, \theta)$ = action density spectrum,

$S(\sigma, \theta)$ = wave energy sources and sinks (e.g., wind induced growth, depth induced breaking),
 c = propagation velocities of wave action (energy and currents).

The first term is the change in action density with time. The second and third terms represent wave propagation in geographical space. The fourth term represents the shifting of the relative frequency due to variations of depth and currents, while the fifth term represents changes in the action spectrum due to depth and current induced refraction.

Wave Breaking

In the surf zone, the dominant process of wave energy dissipation is depth induced breaking. The wave breaking is always included as a dissipation term in the model's governing equation. The amount of energy dissipation at any point is a strong function of depth and wave height. The model takes advantage of the work of Battjes and Janssen (1978), where in addition to specifying a maximum limit to zero-moment wave height (H_{mo}), it uses a dissipation function to compute the fraction of waves in a random wave field that will break at a point. By applying this dissipation model, wave breaking begins earlier, in deeper water, but very gradually at first. The equation used to determine the fraction of breaking waves Q_b is

$$\frac{1 - Q_b}{-\ln Q_b} = -8 \frac{E_{tot}}{H_{mo(max)}^2} \quad (2)$$

where E_{tot} is the total energy contained in the wave spectrum. The maximum wave height is computed using an equation of the form,

$$H_{mo(max)} = \gamma d \quad (3)$$

However for most bottom conditions γ is not a constant value, but rather a function of bottom slope β expressed as

$$\gamma = 0.55 + 0.88 \exp(-0.012 \cot \beta) \quad (4)$$

In circumstances where there is a negative bottom slope (increasing depth) SWAN uses a constant value for the breaking criterion, $\gamma = 0.73$. After computing Q_b and $H_{mo(max)}$, the mean energy dissipation rate D_{tot} is computed using the relationship,

$$D_{tot} = -\frac{1}{4} \alpha Q_b \left(\frac{\bar{\sigma}}{2\pi} \right) H_{mo(max)}^2 \quad (5)$$

where $\bar{\sigma}$ is the peak frequency and α is a constant of the order 1 (Battjes and Janssen, 1978). Finally, the dissipation rate $S_{Dis}(\sigma, \theta)$ of each spectral component is determined by the expression,

$$S_{\text{Dis}}(\sigma, \theta) = -D_{\text{tot}} \frac{E_{\sigma, \theta}}{E_{\text{tot}}} \quad (6)$$

where $E(\sigma, \theta)$ is the energy contained within the spectral component with frequency σ and direction θ .

Limitations

Diffraction is not modeled in SWAN, so SWAN should not be used in areas where variations in wave height are large within a horizontal scale of a few wave lengths. Because of this, the wave field computed by SWAN will generally not be accurate in the immediate vicinity of obstacles and certainly not in harbours.

SWAN does not calculate wave-induced currents. If relevant such currents should be provided as input to SWAN.

As an option SWAN computes wave-induced set-up. In (geographic) 1D cases the computations are based on exact equations. In 2D cases, the computations are based on approximate equations and the effects of wave-induced currents are ignored.

This version of SWAN (40.11) can be used on any scale relevant for wind generated surface gravity waves. However, SWAN is specifically developed for coastal applications which would usually not require such flexibility in scale. The background for providing SWAN with such flexibility is:

- a) to allow SWAN to be used from laboratory conditions to shelf seas (but not harbours, see above) and
- b) to nest SWAN in the WAM model or the WAVEWATCH III model

SWAN is certainly less efficient on oceanic scales than WAVEWATCH III and probably also less efficient than WAM (SWAN does not parallelize or vectorize well).

It is recommended to use the following discretization in SWAN for applications in coastal areas:

Direction resolution:

For wind sea conditions $\Delta\theta = 10^\circ - 15^\circ$

For swell conditions $\Delta\theta = 2^\circ - 5^\circ$

Frequency range:

$f_{\text{min}} = 0.04 \text{ Hz}$

$f_{\text{max}} = 1.00 \text{ Hz}$

Spatial resolution: $\Delta x, \Delta y = 50 - 1000 \text{ m}$

For the first SWAN runs, it is strongly advised to use the default values of the model coefficients. First it should be determined whether or not a certain physical process is relevant to the result. If this cannot be decided by means of a simple hand computation, one can perform a SWAN computation without and with the physical process included in the computations, in the latter case using the standard values chosen in SWAN.

After it has been established that a certain physical process is important, it may be worthwhile to modify coefficients.

Hands-on exercises

1. Assume a rectangular domain of width 80km and a length of 1200km (East-west). Adopt a grid of size 20mx20m. For a uniform wind field of 15 m/s (west to east), evaluate the wave evolution (H_s and T_m) along the centreline of the domain from the ordinate of 0m to 1200km. Compare the estimate with the estimation from spectral models and SMB prediction curves. Use either WAM or WW3.
2. Allow an offshore wave climate represented by $H_s=2.2\text{m}$ & $T_m=8\text{s}$ to propagate towards the coast from the distance of 100km offshore. You can choose a grid size of 2km in SWAN modelling.

Tutorial: Wave prediction in the surf zone

In this assignment, it is required to predict the wave climate and in particular, wave breaking. There are two distinguished variables in the wave prediction. These are the sea bottom slope and sea state/ wind force characteristics. The purpose of SWAN model is wind-wave propagation model which can take into account the wind field in the domain of interest. The model is customized so that only the required parameters need to be changed in the input file. The input data preparation for a standard SWAN model is an extensive task and hence, a user friendly FORTRAN executable code is developed to prepare the input files required by SWAN.

The following data would be required from the user to prepare the SWAN input files.

i) INPUT: SEASTATE (1) OR BEAUFORT WIND SCALE(2)

The user has the option to select the deep water wave climate either in terms of sea state or in terms of Beaufort wind force.

ii) SEASTATE (or) Beaufort Wind Scale

Sea state varies from 0 – 9 and wind force varies from 0 – 12 in terms of Beaufort wind scale. Based on the selection in the first step (i), the user selects the sea state or wind scale. The wave characteristics in each of the sea state and wind scale are presented in Tables 1 and 2, respectively. The same table is incorporated in the program.

iii) User provided bathymetry file? yes (1)/ no(2)

One of the important criteria of wave breaking is based on the sea bottom bathymetry. This program can simulate bottom profile for given slope. For a field condition, the user can input the actual sea bottom level at equal grid distances.

iv) File name (max 12 characters)

If the selection for the step (iii) is (1), then provide the file name which has the sea bottom levels. The mean sea surface is +0.0m and at each grid point inside the sea has positive depth values. Any land points can be denoted by 0.0m or as negative elevation

v) Spacing (dx), No.of grid points

For the data given in the above file, the grid spacing and the number of grid points have to be specified in this step.

vi) BOTTOM SLOPE, n (slope 1 in n)

If the selection for the step (iii) is (2), then the bottom profile will be simulated in the program and will be written to the file 'slope.txt'. The user has to feed in only the average bottom slope. The number of grid points is 411 (default) including land points and the grid spacing is by default 10m. The maximum water depth is 100m.

After that it assumes flat bottom. Fig.13 shows the simulated computational domain.

However, if the wave period is greater than 20s (which are very long waves), the default grid spacing is 50m and the maximum water depth is 250m.

Table 1. Deep water wave climate for different Sea States

SeaState	Sea Description	Wind speed Knots	Significant wave height (m)	Average wave period (s)	Peak wave period (s)
0	Calm (Glassy)	0.0	-	-	-
1	Calm (Rippled)	5.0	0.09	1.4	2.0
2	Smooth	12.0	0.67	3.4	4.8
3	Slight	18.0	1.86	5.1	7.2
4	Moderate	22.0	3.05	6.3	8.9
5	Rough	28.0	3.96	7.9	11.3

6	Very rough	32.0	7.92	9.1	12.9
7	High	38.0	12.19	10.7	15.4
8	Very high	50.0	22.25	14.3	20.2
9	Phenomenal	61.0	39.01	18.0	26.0

Table 2. Deep water wave climate for different wind conditions

Wind Force	Wind Description	Wind speed Knots	Significant wave height (m)	Average wave period (s)	Peak wave period (s)
0	Calm	0.0	-	-	-
1	Very light	2.0	0.02	0.5	0.7
2	Light breeze	5.0	0.09	1.4	2.0
3	Gentle breeze	12.0	0.67	3.4	4.8
4	Moderate breeze	16.0	1.40	4.6	6.5
5	Fresh breeze	20.0	2.44	5.7	8.1
6	Strong breeze	26.0	4.57	7.4	10.5
7	Near gale	32.0	7.92	9.1	12.9
8	Gale	40.0	13.72	11.4	16.1
9	Strong gale	46.0	19.51	13.1	18.5
10	Storm	54.0	28.96	15.4	21.8
11	Violent storm	59.5	35.36	17.0	24.0
12	Hurricane	61.0	39.01	19.0	26.0

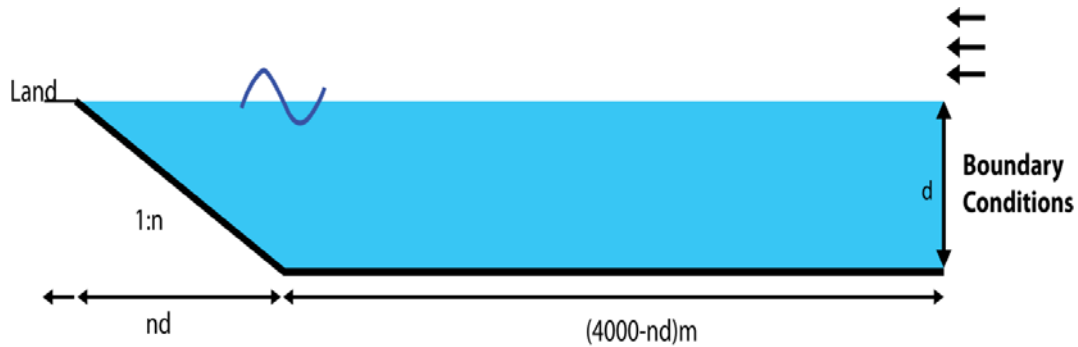


Fig.13. Computational domain

SWAN execution

Once the input data is generated, SWAN can be executed through the SWAN.BAT file by given the input file *.SWN. The output file *.OUT would be produced by SWAN. The output file provides the cross-shore wave transformation from the open boundary to the shore.

For the detailed information on SWAN, the users are referred to its user manual (Ris et al., 1998).

SAMPLE RUN

A batch file 'run.bat' has to be executed. The batch file executes sequentially three programs. First, it executes a FORTRAN code to generate input files necessary for running SWAN. Next, given these input files (*.SWN and bottom slope), 'SWAN.bat' will execute to simulate shallow water wave fields in the surf zone. The model also predicts the energy dissipation wherever the wave breaks.

Input data:

INPUT: SEASTATE (1) OR BEAUFORT WIND SCALE(2)

1

SEASTATE (or) Beaufort Wind Scale

4

User provided bathymetry file? yes (1)/ no(2)

2

BOTTOM SLOPE, n (slope 1 in n)

30

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