AN OVERVIEW OF GENERATION, THEORIES, FORMULAS AND APPLICATION OF SEA WAVES

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ABSTRACT

Marine and offshore structures are constructed worldwide for a variety of functions and in a variety of water depths, and environmental conditions. The determination of wave characteristics and the interrelation of those characteristics is an important part of many offshore structure problems. The average height of a particular irregular wave characteristic may be calculated and estimated either from measurement or from the physical or numerical simulation. All sea motion can be determined by the difference between water particle velocities and pressure in functions of its position and time. For the design of the offshore structures, the designers should evaluate the sea waves to make sure that they do not damage the offshore structures during the time. The objectives of this paper are to give a general overview of the sea wave generation, sea wave formulas/spectrum and sea wave theories in shallow, transitional and deep waters. This information gives a good guide to the marine and offshore engineers to calculate the sea wave characteristics and the parameters needed to calculate the hydrodynamic forces due to sea waves applied to the onshore and offshore structures.

Keywords: Wave Mechanics, Wave Generation, Wave Theories, Sea, Onshore, Offshore

INTRODUCTION

Offshore structures are subject to a wide variety of environmental loads such as wind and wave. The dominant load, however, is normally due to wind-generated waves. Therefore, to predict the distribution of the wave hydrodynamic loading on the onshore and offshore structures during their service lives is significant to the designers. Fatigue damage due to the effect of waves over the lifetime of the onshore and offshore structures is also a very important design factor.

Early work by Newton, Laplace, Lagrange, Poisson, and Cauchy made theoretical advances in the linear theory of sea waves. Gerstner considered nonlinear waves, and the brothers Weber performed fine experiments. Later Russell, Green, Kelland, Airy, and Earnshaw all made substantial contributions, setting the scene for subsequent work by Stokes and others.

Sverdrup and Munk (1947), who combined classical equations of hydrodynamics with empirical data to provide relationships for a wave, made the first great advance in the last seven decades, in the art of wave forecasting.

Bretschneider, JONSWAP (which is the abbreviation of the Joint North Sea Wave Project) and Pierson-Moskowitz spectrums and formulas are typically employed in the calculation and analysis of the wave parameters in the seas and oceans (U.S. Army Corps of Engineers, 2002; U.S. Army Coastal Engineering Research Center, 1980; Sadeghi 2008).

SEA WAVES

Sea waves are surface waves, a mixture of longitudinal and transverse waves. Surface waves in ocean graph are the deformation of the sea surface the deformation propagate with the wave speed, while the water molecules remain at the same positions can average. Energy, however, moves towards the shoreline.

Wave Mechanism and Wave Theories

Wave mechanics and wave theories including wave classifications, governing equations of waves theories, different wave theories such as Airy, Stokes', Stream Function, Cnoidal, Solitary and Trochoidal waves.

Stream Function, Solitary, Airy and Cnoidal wave theories are used mainly for evaluation of waves in the shallow waters, where the sea waterdepths are less than half of the wavelength. Airy and Stockes' (second, third and fifth orders), as well as the Trochoidal wave theories which are used to determine the wave characteristics in deep waters, are used in numerical simulations. See (Sadeghi 2001; Sarpkaya et al. 1982) for more information in this regard.

All sea motions can be determined by differences between water particle velocities and pressures in functions of its position and time. Basic governing equations of hydrodynamic sea motion are continuity equation (expresses by the Laplace equation) and momentum equation (expresses by the Bernoulli equation). In all cases, fluid is assumed incompressible, inviscid and irrotational. Velocity Potential Function (Φ) is defined so that its negative partial derivatives in different directions submit the water particle velocity components in the directions of x, y and z (u, v and ω). Figure 1 shows schematically a wave profile.

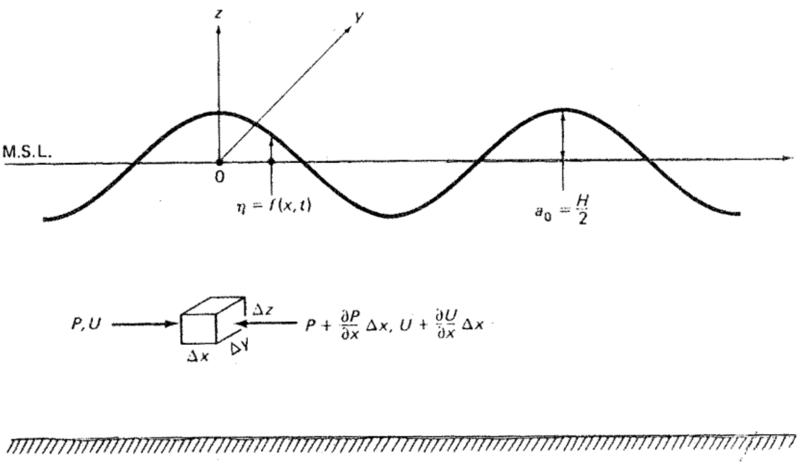

Fig. 1. Wave profile scheme

The Continuity equation (Laplace equation) is as follows:

$$\frac{\partial^2 \varphi}{\partial x^2}+\frac{\partial^2 \varphi}{\partial y^2}+\frac{\partial^2 \varphi}{\partial z^2}=0 \quad (1)$$

And the momentum equation (Bernoulli equation) is:

$$\frac{\partial \varphi}{\partial t}+\frac{1}{2}(u^2+v^2+\omega^2)+\frac{P}{\rho}gz=f(t) \quad (2)$$

By applying boundary conditions for sea surface level and seabed level, Φ from one of the theories (such as Airy, Stokes "second, third and fifth orders", Stream Function, Cnoidal, Solitary and Trochoidal wave theories) and the other wave characteristics are found.

In the references 2, 3 (Sadeghi1989, 2001) and 4 (Sarpkaya et al.) the complete Tables of equations for Airy, Stocks (second, third and fifth orders), Stream Function, Cnoidal, Solitary and Trochoidal wave theories are submitted and specified. An example of such Tables for Stockes second orders wave theory is given below:

$$\varphi = \frac{\pi H}{kT}\frac{\cosh(ks)}{\sinh(kd)}\sin\theta + \frac{3}{8}\frac{\pi H}{kT}\left[\frac{\pi H}{L}\right]\frac{\cosh(2ks)}{\sinh^4(kd)}\sin 2\theta \quad (3)$$

$$\eta = \frac{H}{2}\cos\theta + \frac{H}{8}\left[\frac{\pi H}{L}\right]\frac{\cosh(kd)}{\sinh^3(kd)}\left[2+\cosh(2kd)\right]\cos 2\theta \quad (4)$$

$$\xi = -\frac{H}{2}\frac{\cosh(ks)}{\sinh(kd)}\sin\theta + \frac{H}{8}\left[\frac{\pi H}{L}\right]\frac{1}{\sinh^2(kd)}\left[1-\frac{3\cosh(2ks)}{2\sinh^2(kd)}\right]\sin 2\theta + \frac{H}{4}\left[\frac{\pi H}{L}\right]\frac{\cosh(2ks)}{\sinh^2(kd)}(\omega t) \quad (5)$$

$$\xi_v = \frac{H}{2}\frac{\sinh(ks)}{\sinh(kd)}\cos\theta + \frac{3H}{16}\left[\frac{\pi H}{L}\right]\frac{\sinh(2ks)}{\sinh^4(kd)}\cos 2\theta \quad (6)$$

$$u = -\frac{\pi H}{T}\frac{\cosh(ks)}{\sinh(kd)}\cos\theta + \frac{3}{4}\frac{\pi H}{T}\left[\frac{\pi H}{L}\right]\frac{\cosh(2ks)}{\sinh^4(kd)}\cos 2\theta \quad (7)$$

$$w = -\frac{\pi H}{T}\frac{\sinh(ks)}{\sinh(kd)}\sin\theta + \frac{3}{4}\frac{\pi H}{T}\left[\frac{\pi H}{L}\right]\frac{\sinh(2ks)}{\sinh^4(kd)}\sin 2\theta \quad (8)$$

$$\frac{\partial u}{\partial t} = -\frac{2\pi^2 H}{T^2}\frac{\cosh(ks)}{\sinh(kd)}\sin\theta + \frac{3\pi^2 H}{T^2}\left[\frac{\pi H}{L}\right]\frac{\cosh(2ks)}{\sinh^4(kd)}\sin 2\theta \quad (9)$$

$$\frac{\partial w}{\partial t} = -\frac{2\pi^2 H}{T^2}\frac{\sinh(ks)}{\sinh(kd)}\cos\theta - \frac{3\pi^2 H}{T^2}\left[\frac{\pi H}{L}\right]\frac{\sinh(2ks)}{\sinh^4(kd)}\cos 2\theta \quad (10)$$

$$P = -\rho g z + \frac{1}{2}\rho g H\frac{\cosh(ks)}{\cosh(kd)}\cos\theta + \frac{3}{4}\rho g H\left[\frac{\pi H}{L}\right]\frac{1}{\sinh(2kd)}\left[\frac{\cosh(2ks)}{\sinh^2(kd)} - \frac{1}{3}\right]\cos 2\theta - \frac{1}{4}\rho g H\left[\frac{\pi H}{L}\right]\frac{1}{\sinh(2kd)}\left[\cosh(2ks)-1\right] \quad (11)$$

$$E = \frac{1}{8}\rho g H^2\left(+0\left[\varepsilon^4\right]\right) \quad (12)$$

$$p = \frac{1}{16}\rho g H^2 c\left[1+\frac{2kd}{\sinh(2kd)}\right]\left(+0\left[\varepsilon^4\right]\right) \quad (13)$$

Where:

ϕ: Velocity potential,

$C^2 = \frac{\omega^2}{k^2} = \frac{g}{k}\tanh(kd)$: represents dispersion relation, (14)

η: Surface elevation,

ξ: Horizontal particle displacement,

ξ_V: Vertical particle displacement,

u: Horizontal particle velocity,

w: Vertical particle velocity,

$\frac{\partial u}{\partial t}$: Horizontal particle acceleration,

$\frac{\partial w}{\partial t}$: Vertical particle acceleration,

P: Pressure,

E: Average energy density,

p: Energy flux.

Wave Generation Mechanism

A summary of the wave generation mechanisms, the progress of waves toward the shoreline (see Fig. 2), and the calculation of wave height, wave period using the wave prediction methods for shallow waters, transitional waters and deep waters along with the effective factors to analyze the coastal and marine structures subjected to wave hydrodynamic loading are submitted below. Figure 2 shows schematically the progress of wave from deep water toward the shoreline.

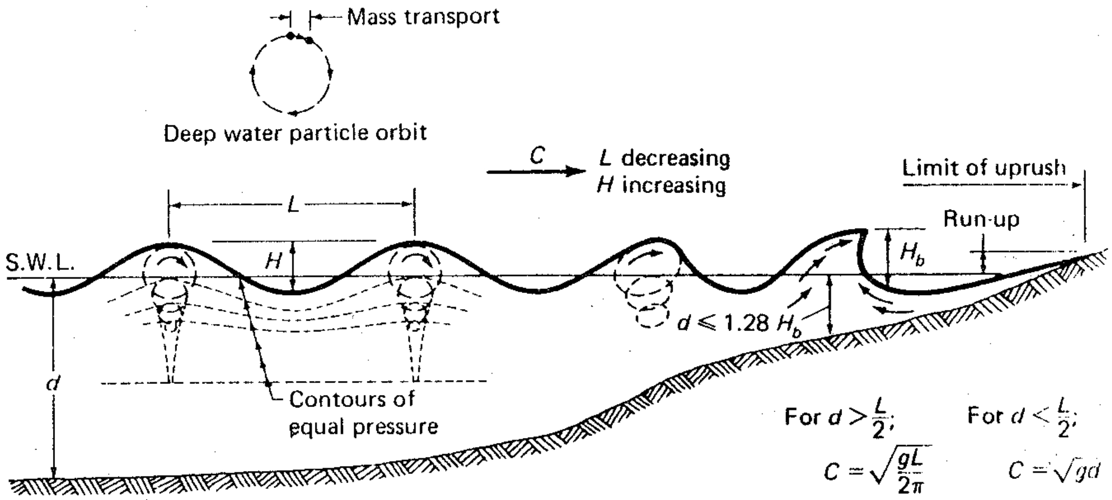

Fig. 2. A scheme showing the wave progress toward shoreline (Gaythwaite, 1981)

Bretschneider formulas along with the other required equations are usually used to predict the wave period (T) and wave height (H) for different conditions of water depths (d). Bretschneider formulas are also used to calculate the spectral wave height (H_{m0}), peak spectral period (T_m) and wind duration (t) in deep water conditions for a limited fetch length (F). Shoaling, refraction, reflection, diffraction and wave breaking are the main factors that effect on the wave characteristics. See (Sadeghi 2001, 1980; U.S. Army Coastal Engineering Center, 2002) for more information in this regard.

Sea Wave Formulation

For the design of the coastal, port and offshore structures, the wave, wind and current data are required. Wave height (H), wavelength (L) and waterdepth (d) are the three independent characteristic parameters necessary to calculate the wave characteristics.

Wave characteristic data are calculated by employing the numerical simulation or collected by recording from satellites or using measuring equipment such as buoys in oceans and seas or measuring by making physical simulation models in laboratories. Providing data by measuring equipment and satellites are time and money consuming. Moreover, these data are not available for all points of oceans and seas. Consequently, the numerical simulation methods can be employed simply and they are applicable everywhere by choosing the valid formulas, spectrums, and software.

Bretschneider, JONSWAP and Pierson-Moskowitz spectrums and formulas are typically employed in the calculation and analysis of the wave parameters in shallow, transitional and deepwaters. Stream Function, Solitary and Cnoidal wave theories are used mainly for evaluation of waves in shallow waters. Airy and Stokes' (second and fifth orders), as well as Trochoidal waves which are used to determine the wave characteristics in deep waters, are used in numerical simulations. See (Sadeghi 2001; Sarpkaya et al. 1982) for further information in this regard.

Fig. 3 shows the graph proposed by Le Mahaute indicating the validity of different wave theories for different water depths and for various wave characteristics.

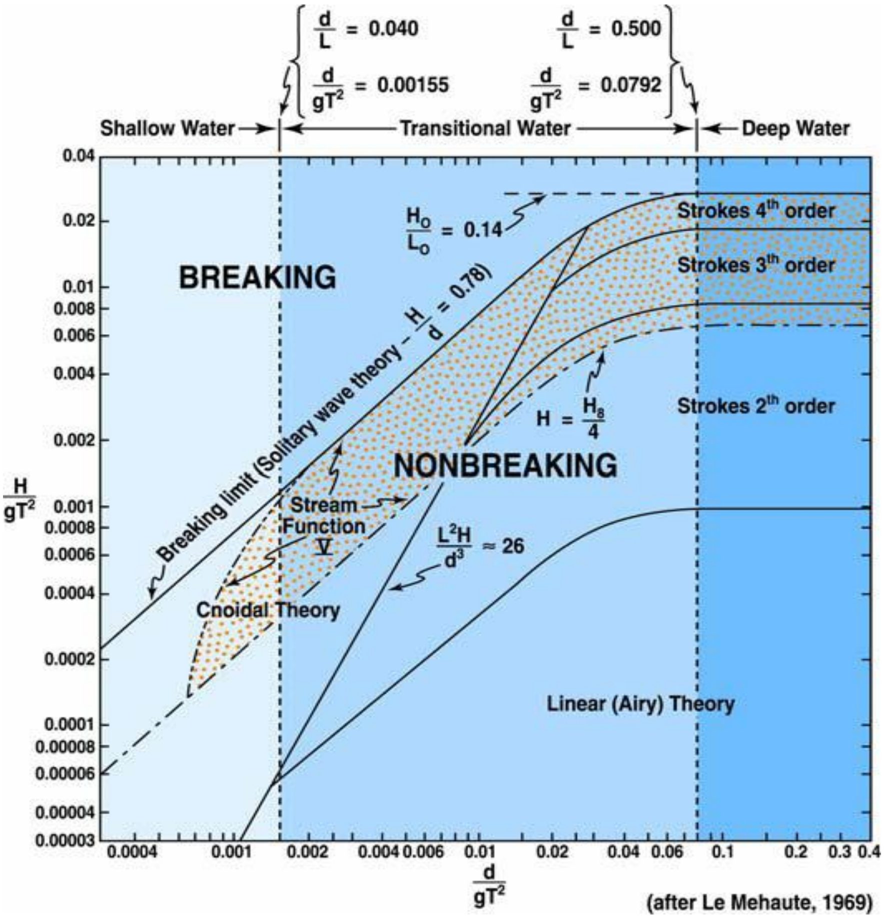

Fig. 3. Graph indicating the validity of wave theories (Le Méhauté, 1976)

Calculation of waves

General

To simulate the wave characteristics, in shallow, transitional and deep waters, the wind data, along with mostly the Bretschneider formulation and, Airy and Solitary wave theories (Sadeghi, 2001) are employed.

Calculation of fetch length using spherical coordinates

To find the fetch length, Nouban (2015) adopts the spherical coordinate system as follows:

The Fetch length (F) between two points $P_i(\Theta_i, \phi_i)$ and $P_j(\Theta_i, \phi_j)$ at the sea surface along the surface of the Earth (the arc length) is proposed by Nouban (2015) as follows:

$$F = R\sin^{-1}\left[\frac{d_{ij}}{2R^2}\left(4R^2 - d_{ij}^{\ 2}\right)^{1/2}\right] \quad (15)$$

With:

$$d_{ij} = R\left\{2 - 2\sin\theta_i \sin\theta_j \cos(\phi_i - \phi_j) - 2\cos\theta_i \cos\theta_j\right\}^{1/2} \quad (16)$$

Where:

R represents the radius of the Earth (at sea surface level) (i.e. R = 6,378 Km),

θ_i represents the angle between the line joining point i to the center of the Earth and Z-axis passing the Earth's poles. The latitudes of point i (λ_i) equals ($\pi/2 - \theta_i$),

θ_j represents the angle between the line joining point j to the center of the Earth and Z-axis passing the Earth's poles. The latitudes of point i (λ_j) equals ($\pi/2 - \theta_j$),

ϕ_i represents the longitude of points i,

ϕ_j represents the longitude of point j (Nouban & Sadeghi, 2014).

Since for the elevations of points Ri and Rj on the sea level, the values of (Rj-Ri) are negligible, it is typical for the sea level for the radial distance R to consider a fixed value the average radius of the Earth (R = 6,378 Km) (Earth Fact Sheet, 2015).

Fetch lengths are calculated based on the spherical Earth assumption (ignoring ellipsoidal effects). As stated previously, it is acceptable for most purposes.

Formulas used for transitional and shallow waters conditions

When waves travel into areas of shallow water, they begin to be affected by the ocean bottom. The free orbital motion of the water is disputed and water particles in orbital motion no longer, the swell becomes higher and steeper. Ultimately assuming the familiar sharp-crested wave shape. After the wave breaks, it becomes a wave of translation and erosion of the ocean bottom intensifies.

The effects of sea bottom on the wave characteristics such as refraction, refection, shoaling and wave breaking conditions are also considered in the numerical simulation.

In deepwater where waterdepth is greater than the half of wavelength (d>L/2), there is not any effect from the seabed on the wave characteristics. This effect is applied to the wave characteristics in transitional and shallow waters conditions (d<L/2). To calculate the wave height (H) in transitional and shallow waters locations, the deepwater wave height (H_o) is multiplied by the shoaling factor (Ks) and refraction factor (Kr) (U.S. Army Corps of Engineers, 2011):

$$H = H_0 \times K_r \times K_s \tag{17}$$

K_r and K_s are calculated from Equations (18) and (19):

$$K_s = \sqrt{\frac{C_{go}}{C_g}} \tag{18}$$

$$K_r = \left[\frac{1 - Sin^2\theta_o}{1 - Sin^2\theta}\right]^{1/4} \tag{19}$$

The wave simulation can be performed using the formulas extracted from Airy wave theory as follows (U.S. Army Corps of Engineers, 2011):

$$C_{go} = \frac{gT}{4\pi} \quad \text{(in deepwater: } d \geq L/2) \tag{20}$$

$$C_g = \frac{1}{2}\left[1 + \frac{\frac{4\pi d}{L}}{Sin(\frac{4\pi d}{L})}\right]\frac{gt}{2\pi}Tanh\left(\frac{2\pi d}{L}\right) \quad \text{(for transitional waters: } L/2 \geq d \geq L/25) \tag{21}$$

$$C_g = \sqrt{gT} \quad \text{(for shallow waters: } d \leq L/25) \tag{22}$$

$$\sin\theta = \frac{c \sin\theta_0}{C_0} \quad \text{(Snell's law)} \tag{23}$$

$$C_0 = \frac{gT}{2\pi} \quad \text{(in deepwater: } d \geq L/2) \tag{24}$$

$$c = \frac{gt}{2\pi}Tanh\left(\frac{2\pi d}{L}\right) \quad \text{(for transitional waters: } L/2 \geq d \geq L/25) \tag{25}$$

$$c = \sqrt{gd} \quad \text{(for shallow waters: } d \leq L/25) \tag{26}$$

Where L represents wavelength, g represents gravity acceleration (9.81 m/s^2), d represents the waterdepth, θ_0 represents the angle between the wave crest front and the seabed contourline at waterdepth equals L/2,θ represents the angle between the wave crest front and the seabed contourline at waterdepth d.

For breaking wave height (H_b), the following equation is applied (U.S. Army Corps of Engineers, 2011):

$$H_b = 0.78d \tag{27}$$

Equations of Airy, Stokes' (second, third and fifth orders), Stream Function, Cnoidal, Solitary and Trochoidal wave theories can be used in the simulation to find velocity and acceleration of water particles Nouban (2015).

Formulas used for deepwater conditions

The waves in the waterdepths (d) greater than the one-half of the wavelength (L/2), the waves are called deep-sea waves. Deep-sea waves have no interference with the ocean bottom, so they include all wind-generated waves in the open ocean. Wave characteristics including wave height, wavelength and wave period in deepwater, transitional and shallow waters, are simulated in the numerical simulation by implementing the wave data and seabed specification.

The Bretschneider formulas can be employed in the numerical simulation to calculate the wave height, wavelength, wave period and the other wave parameters in deepwater for the different wind blowing durations and different values of fetch length. (Sadeghi, 2008, 2007a, 2007b; Sadeghi and Nouban 2013; U.S. Army Coastal Engineering Research Center 1980) as follows:

According to the Bretschneider formulas and spectrum, The spectral wave height (H_{m0}) (i.e. significant wave height "H_S or H_{33}"), the peak spectral period (T_m), the significant wave period (T_S) and the time duration of wind (t) adopted to the applied fetch length are calculated as follows:

$$U_A = 0.71 U^{1.23} \quad \text{(U in m/s)} \tag{28}$$

$$U = R_T \cdot U_{(10)} \tag{29}$$

a) - For limited fetch length cases:

$$\frac{g H_{m0}}{U_A^2} = 1.6 \times 10^{-3} \left[\frac{gF}{U_A^2} \right]^{\frac{1}{2}} \tag{30}$$

$$\frac{g T_m}{U_A} = 2.857 \times 10^{-1} \left[\frac{gF}{U_A^2} \right]^{\frac{1}{3}} \tag{31}$$

$$\frac{gt}{U_A} = 6.88 \times 10 \left[\frac{gF}{U_A^2} \right]^{\frac{2}{3}} \quad \left(\text{or } F = 1.75 X 10^{-3} X \left(\frac{U_A^2}{g} \right) \left(\frac{gt}{U_A} \right)^{1.5} \right) \tag{32}$$

b) - For the fully developed wave cases:

$$\frac{g H_{m0}}{U_A^2} = 2.433 \times 10^{-1} \tag{33}$$

$$\frac{g T_m}{U_A} = 8.134 \tag{34}$$

$$\frac{gt}{U_A} = 7.15 \times 10^4 \tag{35}$$

With:

$$H_S = H_{mo} \tag{36}$$

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$$T_S = 0.95 T_m \tag{37}$$

Where: F represents fetch length, $U_{(10)}$ represents wind speed at 10m above the sea level and R_T represents the Stability Factor. The graph to find the stability factor (R_T) given in Fig. 2 allows considering the air-sea temperature difference in the Bretschneider equations.

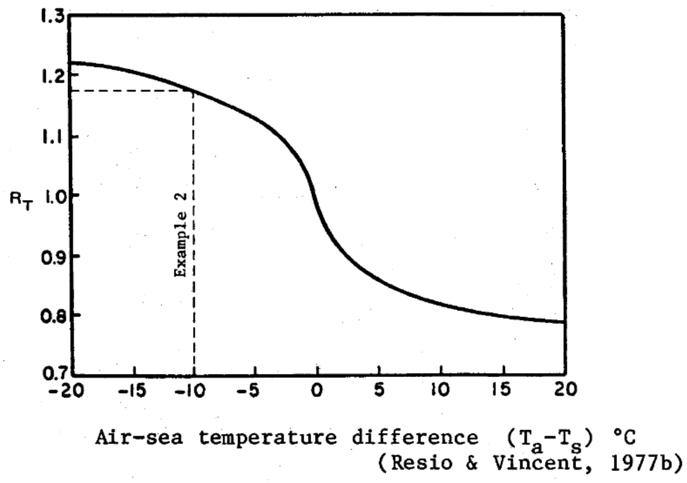

Fig. 2. The graph to find the stability factor R_T

For additional information about the environmental data together with necessary formulas and the data needed for design and analysis of such structures, the instructions, data and recommendations given by API (2010), Sadeghi (1989, 2001, 2007a, 2007b, 2008, 2013), US Army Coastal Engineering Research Center (1980), Sadeghi and Nouban (2013), US Army Corps of Engineers (2002) and Nouban (2015) can be used.

Wave Spectrums

Pierson-Moskowitz wave spectrum

The Pierson-Moskowitz (PM) spectra is an empirical relationship that defines the distribution of energy with a frequency within the ocean. Developed in 1964 the PM spectrum is one of the simplest descriptions of the energy distribution. It assumes that if the wind blows steadily for a long time over a large area, then the waves will eventually reach a point of equilibrium with the wind. Moskowitz submitted three equations for a wave spectral and then the following equations were presented in 1964:

$$\mathrm{E}(\omega)\,d\omega = \left[ag^2 / \omega^5\right] e^{-\beta\left(\omega_0^4 / \omega^4\right)} d\omega \tag{38}$$

$$\mathrm{E}(\omega)\,d\omega = \left[ag^2 / \omega^5\right] e^{-\beta\left(\omega_0^4 / \omega^4\right)} d\omega \tag{39}$$

JONSWAP Spectrum

Hasselmann et al. in 1973and 1976 proposed the following equations which are known as JONSWAP (Joint North Sea Wave Project).

JONSWAP spectrum is an empirical relationship that defines the distribution of energy with a frequency within the ocean. Its equation is as follows:

$$S(w) = \frac{a g^2}{w^5} \exp\left[-\beta \frac{w_p^4}{w^4}\right] \gamma^a \tag{40}$$

Where

$$a = \exp\left[-\frac{(w - w_p)^2}{2 w_p^2 \sigma^2}\right] \tag{41}$$

$$\sigma = \begin{cases} 0.07 \; if w \leq w_p \\ 0.09 \; if w > w_p \end{cases} \tag{42}$$

$$\beta = \frac{5}{4} \tag{43}$$

Where α is a constant that relates to the wind speed and fetch length. Typical values in the northern North Sea are in the range of 0.0081 to 0.01,

ω represents the wave frequency,

W_p represents the peak wave-frequency.

CONCLUSION

An overview of the sea wave generation together with a general guidance of application of the existing sea wave theories, formulas and spectrums are presented in this paper. This information gives a good guide to the onshore, marine and offshore engineers to predict and calculate the sea wave characteristics as well as the parameters needed to calculate the hydrodynamic forces due to sea waves applied to the onshore and offshore structures.

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