New equations of wave energy assessment accounting for the water depth

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HIGHLIGHTS

- New wave energy assessing equations accounting for the water depth are derived.
- The derived equations improve the accuracy of wave energy calculation obviously.
- The derived equations are applicable in various water depths with higher accuracy.

ARTICLE INFO

ABSTRACT

The assessment of wave energy resources is critical for site selection before deploying wave energy converters (WECs). Usually, a simplified wave energy assessment equation (SWEAE), using bulk wave parameters such as significant wave heights, peak periods, etc., is employed to estimate the wave energy flux. However, it neglects the effects of water depth on wave group velocities, thus being more suitable for deep waters. Considering most of the WECs are installed in nearshore zones or around islands, a more accurate wave energy assessment equation is needed. In the present work, a general wave energy assessment equation (GWEAE) for both shallow and deep waters is derived by introducing an explicit wave dispersion equation. Both GWEAE and SWEAE are applied in the assessment of wave energy fluxes in the coastal waters surrounding Qingdao City, China. Wave energy fluxes calculated by integration over all frequency and direction bins of the random waves, which can be regarded as the most accurate equation, are used for validating the two equations. It is demonstrated that the GWEAE significantly improve the accuracy of the wave energy estimation for various water depths compared with the SWEAE, especially for nearshore shallow water areas. Because the improved equation is free of integration calculations and iterative computations, it is a simple and accurate tool for estimating wave energy fluxes.

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1. Introduction

The resource crisis and the environmental crisis have caused serious impacts on human beings. With the rapidly developing of science and technology, renewable energy has been becoming increasingly important in energy consumption reduction and environment protection. The wave energy, with the advantages of predictability, high energy density, and low environmental impact, is one of the most important renewable energy resources with a significant potential. Various wave energy technologies are currently being developed based on different principles [1–3]. However, efficient extraction from ocean waves is still challenging the engineering community. One of these challenges is to accurately estimate the wave energy potential, which is essential for optimizing the design of the wave energy converters (WECs) and the subsequential tuning of design parameters [4,5].

A review of current literature reveals that many efforts have been made in order to investigate wave energy potentials on a global scale ([6–9]), as well as regional and local scales for selected sites [2,3,5,10–21]. Neill et al. [17] simulated the wave climate around the Orkney, and investigated the inter-annual and inter-seasonal variability of the wave power resource. Morim et al. [20] presented a long-term assessment of the wave energy resource for the Australian southeast shelf from deep to shallow water, based on a 31-year (1979–2010) wave hindcast. Zheng

and Li [21] explored the climatic long term trends of wave energy in the China Seas for the period 1988–2011, using WAVEWATCH-III (WW3) [22] hindcast wave data. By gathering data across long time domains, different wave energy assessing equations can be used to determine the overall wave energy distribution. Except for the equations in these references, Myrhaug et al. [23,24] adopted a bivariate distribution of wave energy and associated sea-state parameters of wave height and wave period. Izadparast and Niedzwecki [25] derived conditional probability distribution functions of the wave energy in order to reduce the uncertainty in wave energy estimations.

Since the wave dispersion equation is implicit, iterative computation is required to solve it. Hence, the wave dispersion equation is simplified to deep water conditions by neglecting the effects of water depth. This simplified wave energy assessment equation (SWEAE), which is more suitable for deep waters, was employed in most previous wave energy assessment studies [26–39]. However, wave energy converters are usually deployed in nearshore zones to minimize the electricity wastage due to long cables and the expenditure involved in building and installing. Thus, a more accurate wave energy assessment equation is need. In the present work, an explicit approximation of the wave dispersion equation, derived by Beji [40], is introduced to the wave energy assessing equation and used to generate a general wave energy assessment equation (GWEAE). Then, wave energy fluxes calculated by a wave energy flux equation (WEFE), which can be regarded as the most accurate results, are used for validating the SWEAE and the GWEAE. The results show that, the GWEAE can be applied for seas of various water depths with acceptable accuracies (compared with the SWEAE), especially for nearshore zones. Because the GWEAE is explicit, it is free of integration calculations and iterative calculations thus the computational time is shorter and memory requirement is lower compared with the WEFE and other equations [23–25].

The article is structured as follows. In the next section, the theory of wave energy assessment and an explicit dispersion equation are described. The wave model MIKE21 SW set in the computational area is described and the validation of wave parameters is carried out with in situ measurements in Section 3. Section 4 presents a general wave energy assessment equation (GWEAE), which is considered reasonable for most of the sea areas. In order to get more accurate results, some details are analyzed around Qingdao city in Section 5. Finally, conclusions and summaries are given in Section 6.

2. Mathematical background

For regular waves, the wave energy flux per unit crest width can be defined as [41,42]:

$$P = \frac{1}{8}\rho g H^2 C_g \tag{1}$$

where ρ is the water density, g is the gravitational acceleration, and H is the wave height.

The wave group speed, C_g, which can be given by:

$$C_g = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(2kh)}\right]\frac{L}{T} \tag{2}$$

where h is the water depth, T is the wave period, $k = \frac{2\pi}{L}$ is the wave number, and L is the wave length.

For random waves, the wave energy flux P is defined by a wave energy flux equation (WEFE) [43]:

$$P = \rho g \int_0^{2\pi}\int_0^\infty C_g(f,h)S(f,\theta)df d\theta \tag{3}$$

where $S(f,\theta)$ is the spectral energy density, $C_g(f,h)$ is the wave group speed, f is the frequency, θ is the direction of the wave propagation.

As previous studies shown, the significant wave height H_s is usually defined as $H_s = 4\sqrt{\sigma^2}$ [44], where σ^2 is the variance of surface elevation time series. Then $H = \frac{\sqrt{2}}{2}H_s$ [1] and thus the wave energy flux for random waves in terms of the significant wave height can be given by:

$$P = \frac{1}{16}\rho g H_s^2 C_g(T_e,h) \tag{4}$$

where T_e is known as the energy period and $C_g(T_e,h)$ is the group velocity of a wave with the energy period T_e in the water depth h.

Combining Eqs. (2) and (4), the wave energy flux for random waves can be approximately calculated by the following equation:

$$P = \frac{1}{32}\left[1 + \frac{2kh}{\sinh(2kh)}\right]\rho g H_s^2 \frac{L}{T_e} \tag{5}$$

As the dispersion equation $L = \frac{gT^2}{2\pi}\tanh(kh)$ is implicit, the wave energy assessment equation cannot be calculated explicitly. However, for deep waters ($h > \frac{L}{2}$), $C_g(T_e,h) = L/T_e$, $L = gT_e^2/2\pi$, the wave energy equation can be simplified further as [26–39]:

$$P = \frac{\rho g^2}{64\pi}H_s^2 T_e \tag{6}$$

Eq. (6) is the simplified wave energy assessment equation (SWEAE) which has been widely used to assess wave energy resources around the world. However, the above simplifications are not suitable and cause obvious errors in the shallow water ($h < \frac{L}{2}$). The following Sections 4 and 5 will give details of the errors analysis.

In the present work, an explicit dispersion equation is adopted in the wave energy assessment equation. The dispersion parameters $\mu = kh = \frac{2\pi h}{L}$ and $\mu_0 = k_0 h = \frac{2\pi h}{L_0}$ are used here with k_0 the deep water wave number, L_0 the deep water wave length calculated from $L_0 = \frac{gT^2}{2\pi}$. The approximate dispersion equation is defined as [40]:

$$\mu = \mu_0[1 + \mu_0^{1.3}e^{-(1.1+2.0\mu_0)}]/\sqrt{\tan\mu_0} \tag{7}$$

Eq. (7) is utilized in the wave energy calculation (Eq. (5)) and used to generate a general wave energy assessment equation (GWEAE):

$$P = \frac{\pi\rho g h H_s^2}{16T_e}\left[\frac{1}{\mu} + \frac{2}{\sinh(2\mu)}\right] \tag{8}$$

3. Wave data

3.1. Study area and model setting

The study area (Fig. 1) is located in the southeast of Shandong peninsula, China (36.05–37.10°N and 120.40–122.20°E). A third generation spectral wind wave model, MIKE21 SW, is applied to simulate the wave climate in the study area [45]. The MIKE21 SW can output the wave energy flux P (calculated by the WEFE), which can be regarded as a standard value for the wave energy since the real topography with various water depths is input by the wave model SW.

The directional distribution is divided into 12 equal direction bins in the 360° rose. The number of frequency bins is 25, with the minimum frequency of 0.055 Hz and the frequency factor of 1.1. The exponential wind growth with coupled air-sea interaction is turned on [46]. Dissipation due to white capping, bottom friction and depth-induced wave breaking is activated. Energy transfer