# Wave Power Estimates on Eastern Mediterranean Coast

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## Introduction

The 1973 energy crisis intensified the search for nonconventional energy sources. One of the alternatives usually proposed is the use of power from waves at the sea, e.g., Salter (5).

The average power per unit length of shoreline as well as the way this power is distributed in time and according to the sea state, are crucial factors in the design of adequate energy extracting devices and in the appraisal of their feasibility and competitive value. Concerning the eastern Mediterranean coast, this important information has, to the knowledge of the writers, not been published so far.

## Data

The present note has its origin in a deep-water wave climate study performed at the Israel Coastal and Marine Engineering Research Institute (see Ref. 3). The study consisted in sorting, after suitable transformations to deep water conditions, a sample of 5,168 raw data events, collected at Ashdod between 1958 and 1971 and between 1973 and 1975, by the Coastal Study Division of the Israeli Ports Authority. Each raw data event was composed by visual observations of direction in deep water, period, and maximum wave height of wave trains of duration 5 min to 10 min. Between 1958 and 1971 the information refers to maximum breaker height while between 1973 and 1975 the wave heights were observed at a point where the water depth was approx 12 m.

The observations were carried out three times daily, although the event considered for inclusion in the sample was selected according to the largest among the three wave height maxima.

The deep water wave climate resulting from the sorting is represented by a three-dimensional array, where each element $P_{j,k,l}$ of the array is defined as the frequency of occurrence of a given sea state within the sample. A sea state is characterized by the triad $j$, $k$, $l$ as follows:

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1. The symbol $l$, representing the observed period in seconds

$$T_l = l; \quad l = 3, 4, \ldots 13 \qquad (1)$$

According to the second writer (6), the observed periods relate quite closely to the periods of maximum spectral energy.

2. The symbol $k$, representing the significant wave height in deep water, in meters

$$H_k = 0.25 + 0.5k; \quad k = 0, 1, \ldots, 16 \qquad (2)$$

3. The symbol $j$, representing the cosine of the angle between wave fronts and bottom contours

$$C_j = \cos(22.5j - 69); \quad j = 1, 2, \ldots 5 \qquad (3)$$

The bathymetry of the Israel Mediterranean coast is fairly smooth, thus, bottom contours were assumed to be straight and parallel to the shoreline. The values $j = 1, 2, \ldots 5$ represent waves approaching from directions WSW, W, WNW, NW, and NNW, respectively. The value 69° is obtained as the difference between the SW azimut and the azimut of the Ashdod shoreline (i.e., 225°–294°). Satisfactory agreement is obtained when comparing the table $p_{kl} = \Sigma_{j=1}^{5} P_{jkl}$ with Tables 19 on page 472 and page 630 in Ref. 7, which refer to observations from United States Navy ships in deep water in the central and south-eastern Mediterranean areas, respectively. This agreement is quite encouraging if the very different nature of the two data sources is considered. It seems to justify the use of our wave power estimates, at least as a first approximation for most of the eastern Mediterranean coast.

## Average Wave Power

The wave energy flux towards the shore per unit length of shoreline, for a certain sea state $(j, k, l)$ is given by

$$EF_{j,k,l} = \frac{\rho g^2}{64\pi} T_l H_k^2 C_j \qquad (4)$$

in which $\rho$ = the density of water, and $g$ = the acceleration of gravity.

The theoretical justification for Eq. 4 may be found in Jonsson (2) and Longuet-Higgins (4). Both authors refer to the computation of the entire spectral energy with the aid of the significant wave height $H_k$, but do not comment on the choice of the adequate period.

We have chosen the observed periods $T_l$ to be included in Eq. 4, having some evidence that they are close to the period of peak spectral energy. It is shown in Appendix I that, at least in the case of a fully developed sea, the period of maximum spectral energy is a reasonable choice.

Using the wave-climate array $P_{j,k,l}$ Eq. 4 and definitions in Eqs. 1 2, and 3, the (yearly) average wave power per meter length of shoreline is obtained

$$Q = \sum_{j=1}^{5} \sum_{k=0}^{16} \sum_{l=3}^{13} EF_{j,k,l} P_{j,k,l} = 7.2 \text{ kW} \qquad (5)$$

Similar computations for the summer season (April to September) and winter season (October to March), for which the corresponding wave climates $P^s_{j,k,l}$ and $P^w_{j,k,l}$ were available, yielded the (seasonal) average wave power values 3.9 kW/m and 10.5 kW/m, respectively.

## Power Distribution According to Sea-State Classes

The preceding computed yearly and seasonal average values, although important in themselves, might be, like every average value, somewhat misleading. In

**TABLE 1.—Classification of Sea States for Deep Water Offshore Ashdod**

| Class ($i$) (1) | Designation (2) | Range of significant wave height, in meters (3) | Range of observed wave period, in seconds (4) |
|---|---|---|---|
| 1 | Calm sea | <1 | ≤7 |
| 2 | Stormy sea | [1–3) | (5–9] |
| 3 | Very stormy sea | [3–5) | (7–11] |
| 4 | Extremely stormy | ≥5 | >9 |
| 5 | Other | — | — |

**TABLE 2.—Frequency of Occurrence, Relative Contribution to (Yearly) Average Power, and Actual Energy Flux for Various Classes**

| Class ($i$) (1) | Frequency of occurrence $p_i$, as a percentage (2) | Relative contribution to average power $q_i$, as a percentage (3) | Actual power per unit length of shoreline $EF_i$, in kilowatts per meter (4) |
|---|---|---|---|
| 1 | 59 | 8 | 1 |
| 2 | 29 | 38 | 9.4 |
| 3 | 4.5 | 36 | 57.6 |
| 4 | 0.5 | 10 | 144.1 |
| 5 | 7 | 8 | 8.2 |
| Total | 100 | 100 | |

order to illustrate this point, the sea states were classified in five classes, as defined in Table 1. The different classes consider waves coming from all directions.

The frequency of occurrence $p_i$ of each of these classes, their relative contribution $q_i$ to the yearly average wave power $Q$ (normalized to 100%), and the actual power per unit length of shoreline carried by waves in each class, averaged over the sea states in the class (i.e., $EF_i = 7.2\ q_i/p_i$) are presented in Table 2.

As an example, 0.5% of all waves in the sample belong to class 4, (i.e., waves that may have any direction, significant heights in deep water equal to or greater than 5 m, and periods greater than 9 sec). This very small portion contributes, however, 10% of the (yearly) average wave power $Q$ (see Eq.

5). This is due to the large $H^2$ and $T$ values in Eq. 4, resulting in an energy flux of 144 kW/m length of shoreline, a power that is available unfortunately, only 0.5% of the time.

On the other hand, for class 1, only 8% of the power is obtained over 59% of a year's time, the waves being so small that they result in an energy flux of 1 kW/m length of shoreline.

The preceding results clearly indicate the very uneven nature of the sea conditions, in which a wave energy extracting device has to operate. They also point to the necessity for some energy storing means during the heavy storm sea conditions.

## Appendix I.—Use of Observed Period, $T_l$, in Fully Developed Sea

The Pierson-Moskowitz spectrum (see Ref. 1), originally designed for a fully developed sea reads

$$\frac{1}{\rho g}\frac{dE}{df} = S(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \quad (6)$$

in which $E$ = the wave energy per unit horizontal area; $\rho$ = the density of water; $g$ = the acceleration of gravity; $f$ = the wave frequency (inverse of wave period); $S(f)$ = the energy density; $f_p$ = the frequency at the peak energy density; and $\alpha$ = a dimensionless quantity.

By definition, the energy density $S(f)$ is maximum at $f = f_p$. Now, the adequate periods to be used in Eq. 4 are related to the average group velocity, which is the speed of propagation of wave energy, computed as the ratio between the total spectral energy flux to the total spectral energy. The relevant periods are thus computed according to:

$$\tilde{C}_G = \frac{\int_0^\infty C_G S(f)\, df}{\int_0^\infty S(f)\, df} \quad (7)$$

in which $\tilde{C}_G$ = the relevant average group velocity for a given sea state, and $C_G(f)$ = the group velocity of each spectral component. The group velocity in deep water is half the phase velocity, thus we have

$$\tilde{C}_G = \frac{1}{2}\frac{g\tilde{T}}{2\pi} \quad \text{and} \quad C_G = \frac{1}{2}\frac{g}{2\pi f} \quad (8)$$

in which $\tilde{T}$ = the relevant period to be considered in Eq. 4.

Substitution of Eqs. 6 and 8 in Eq. 7 yields

$$\tilde{T} = \frac{\int_0^\infty f^{-6} \exp\left[-1.25\left(\frac{f}{f_p}\right)^{-4}\right] df}{\int_0^\infty f^{-5} \exp\left[-1.25\left(\frac{f}{f_p}\right)^{-4}\right] df} \quad (9)$$

After performing the integrals, one eventually obtains

$$\tilde{T} = \left(\frac{5}{4}\right)^{-1/4} \Gamma \frac{5}{4} T_p \approx 0.86 T_p \quad \text{(10)}$$

in which $\Gamma$ = the Gamma function, and $T_p$ = the inverse of $f_p$.

The 14% difference between $T_p$ and $\tilde{T}$ shows that, in the case of a fully developed sea, the use of the observed periods $T_l$ (nearly equal to $T_p$) in Eq. 4 is reasonable.

## Appendix II.—References


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## Appendix III.—Notation

*The following symbols are used in this paper:*

$C$ = cosine of angle between wave fronts and bottom contours;
$C_G$ = group velocity of waves of frequency $f$ in deep water, L/T;
$\bar{C}_G$ = group velocity averaged over all components of Pierson-Moskovitz spectrum;
$E$ = wave energy per unit horizontal area for waves of frequency $f$, $FL/L^2$;
$EF$ = wave energy flux per unit length of shoreline, $FLT^{-1}/L$;
$f$ = wave frequency (inverse period), $T^{-1}$;
$f_p$ = peak frequency, value of $f$ at which energy density is maximum, $T^{-1}$;
$g$ = acceleration of gravity, $LT^{-2}$;
$H$ = significant wave height in deep water, L;
$i$ = index representing class composed by various sea states;
$j,k,l$ = sea-state identifiers, representing wave direction, height, and period respectively;
$P_{j,k,l}$ = frequency of occurrence of given sea state (wave climate);
$P^s, P^w$ = seasonal wave climates for summer and winter, respectively;
$p$ = frequency of occurrence summed over directions;
$Q$ = (yearly) average wave power per unit length of shoreline, $FLT^{-1}/L$;
$q_i$ = relative contribution of class $i$ to power $Q$;

$T_l$ = observed wave period, T;
$T_p$ = peak period ($=f_p^{-1}$), T;
$\tilde{T}$ = average period defining $\tilde{C}_G$, T;
$\alpha$ = dimensionless parameter in Pierson-Moskovitz spectrum;
$\Gamma$ = Gamma function;
$\pi$ = 3.1416; and
$\rho$ = density of water, $FT^2L^{-4}$.

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