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APPLICATION OF MONOCHROMATIC OCEAN WAVE FORECASTS TO PREDICTION OF WAVE-INDUCED CURRENTS

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16. Abstract

The use of monochromatic wind-wave forecasts in prediction of wind-wave-induced currents was assessed. Currents were computed for selected combinations of wind conditions by using a spectrum approach which was developed by using the Bretschneider wave spectrum for partially developed wind seas. These currents were compared with currents computed by using the significant and average monochromatic wave parameters related to the Bretschneider spectrum. Results indicate that forecasts of significant wave parameters can be used to predict surface wind-wave-induced currents. Conversion of these parameters to average wave parameters can furnish reasonable estimates of subsurface current values.

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APPLICATION OF MONOCHROMATIC OCEAN WAVE FORECASTS TO PREDICTION OF WAVE-INDUCED CURRENTS

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SUMMARY

An assessment has been made of the use of monochromatic wind-wave forecasts, such as those available from the National Weather Service, in predicting wind-wave-induced currents. A technique was developed for computing the currents induced over the Bretschneider wave spectrum. For selected combinations of input wind conditions which result in partially developed seas, and two water depths, the currents computed by using this spectrum approach were compared with currents computed by using the significant and average monochromatic wave parameters related to the Bretschneider spectrum. Results indicate that Weather Service forecasts of significant wave parameters can be used in prediction of surface wave-induced currents. Conversion of these parameters to average wave parameters gives reasonable estimates of subsurface current values.

INTRODUCTION

Because of the increasing interest in offshore petroleum reserves and the proposed construction of offshore nuclear plants and port facilities, more emphasis is being placed on studies of marine-related safety and pollution problems. A primary ingredient in any study of this sort is an understanding of local ocean circulation patterns, both on a seasonally averaged basis and as perturbed by transient conditions such as wind and waves. A recent study (ref. 1) presents results indicating that over continental shelf regions in which seasonal flow velocities are small in comparison with major ocean currents, transient currents induced by the passage of surface waves can make a significant contribution to the total circulation patterns.

In order to predict the magnitude of these wave-induced currents for a particular region and time span, one must first forecast the corresponding wave climate for the region. Although there are numerous techniques for forecasting waves, the techniques can be grouped into two general method categories. One of these is the "spectrum" method (such as that of ref. 2), which yields a forecast of the wave energy density spectrum by specifying spectral components either as they are generated by meteorological conditions and propagated across the ocean or as an empirical function of meteorological variables such as wind speed and duration. The second category can be designated the "singular" method (such as that of ref. 3), in which a forecast is made of single values such as the significant height and period (the average height and period of the highest one-third of the local waves), or the average height and period, as empirical functions of meteorological variables.

The National Weather Service has adopted a singular method (ref. 4), based on the Sverdrup-Munk forecasting system (ref. 3), for its global wave forecasting program because of its simplicity in comparison with using the spectrum method and because of the adequacy of singular forecasts for most users. Weather Service forecasts of significant height, period, and direction are available for both ocean swell (which are waves generated by a distant storm and propagated into the local region of interest) and locally generated wind waves (sea). In reality, neither ocean swell nor wind waves can be represented as monochromatic disturbances, but recent photographic observations (ref. 5, p. 37) and experimental wave data (ref. 6, p. 71) tend to confirm that ocean swell is nearly monochromatic in nature. Thus, prediction of swell-induced currents by calculations using singular forecasts for swell height and period can be considered to be physically reasonable.

Wind-wave spectra, on the other hand, can exhibit broadband characteristics, significant contributions to the total energy coming from waves in several frequency bands. In light of these characteristics, several recent papers (refs. 7 and 8) have presented techniques for calculating wind-wave-induced currents which consider the entire wave spectrum rather than singular wave parameters. Even so, because of the relative simplicity of singular current calculations and the availability of singular Weather Service wave forecasts, it would be desirable to predict wind-wave-induced currents by using monochromatic inputs.

The purpose of the present paper is to assess the validity of wind-wave-induced current calculations made by use of monochromatic techniques. A method similar to that presented in reference 7 is developed for computing numerically the wave-induced currents over the wave spectrum suggested by Bretschneider. (See ref. 9.) These calculations are compared with wave-induced currents computed by using both the significant and average monochromatic wave parameters which are related to the Bretschneider spectrum. Calculations are made for a variety of weather conditions which result in partially developed seas and for two water depths. Comparisons of surface currents and current profiles (variability with distance beneath the surface) computed by using spectrum and monochromatic approaches should lead to some conclusions as to the validity of using Weather Service wave forecasts to predict wind-wave-induced currents.

SYMBOLS

A	nondimensional coefficient defined by equation (4)
D	duration or length of time that a steady wind blows, hours
D'	nondimensional duration given by gD/W
D_{min}	minimum duration below which waves are duration limited, and above which waves are fetch limited, hours
d	water column depth, meters
F	fetch length or distance over which wind blows in essentially a fixed direction at constant speed, kilometers
F'	nondimensional fetch given by gF/W^2
F_1	nondimensional wave generation parameter defined by $g\overline{H}/W^2$
F_2	nondimensional wave generation parameter defined by $g\overline{T}/2\pi W$
$f(\omega)$	Pierson-Moskowitz spectral density, meter^2-seconds
g	acceleration of gravity, meters/second^2
H	wave height, trough to crest, meters
$H_{1/3}$	significant wave height, average height of the highest one-third waves, meters
$\overline{H}$	average wave height, meters
$\overline{H^2}$	mean-square wave height, mean of the squared wave heights, meters^2
k	wave number, $2\pi/L$, meter^{-1}
L	wave length, length between successive wave crests, meters

r — coefficient of linear correlation between wave height and wave length in Bretschneider spectrum

$S_{H^2}(\omega)$ — Bretschneider spectral density, meter^2-seconds

T — wave period, elapsed time between successive wave crests, seconds

$T_{1/3}$ — significant wave period, average period of the highest one-third waves, seconds

$\overline{T}$ — average wave period, seconds

$\overline{U}(z)$ — total average wave-induced current at vertical coordinate z, meters/second

$\overline{U}(z,\omega)$ — average current induced at vertical coordinate z by an infinitesimal range of components of the wave frequency spectrum, meters/second

W — wind speed, meters/second

z — vertical coordinate measured positive downward from still-water surface, meters

α — coefficient defined by equation (6)

ω — wave frequency, $2\pi/T$, radians/second

$\omega\big|_{f_{max}(\omega)}$ — wave frequency at which peak in Pierson-Moskowitz spectrum occurs, radians/second

STOKES' WAVE-INDUCED CURRENT

The passage of surface waves over a water column causes a near-elliptical orbital motion of the water particles in the vertical plane beneath the wave profile. However, the beginning and end points of each orbit do not coincide; hence, there is a progressive advance of the particle orbits. The rate at which orbits advance is the wave-induced current, whose direction is the same as the direction of motion of the passing wave crests.

It is assumed in this study that wave-induced currents can be estimated by using a second-order Stokes' theory. (See ref. 10.) The Stokes' theory assumes an irrotational fluid and results in a positive (rather than null) net mass transport. References 11 and 12 (p. 504), respectively, have concluded that irrotationality and positive mass transport are valid conditions for deep-water, open-ocean studies. By Stokes' theory, the wave-induced currents averaged over 1 wave length for a monochromatic wave are given by

$$\overline{U}(z) = \frac{H^2 \omega k \cosh 2k(d - z)}{8 \sinh^2 kd} \tag{1}$$

This equation is valid for waves which fulfill the conditions that insure convergence of the power series approximations of the Stokes' theory. These conditions are (from ref. 13)

$$\left.\begin{array}{ll} \frac{L}{d} \leq 7.13 & \text{(For any } H/2d) \\ \frac{L}{d} \leq 2\pi\sqrt{\frac{8}{3}\frac{d}{H}} & \text{(For smaller amplitude waves; } H/2d < 1.0) \end{array}\right\} \tag{2}$$

BRETSCHNEIDER WAVE SPECTRUM

The Bretschneider wave spectrum is a one-dimensional spectrum which is closely related to the Sverdrup-Munk singular wave forecasting system. The spectrum was proposed in an attempt to investigate the joint relationship between wave height and wave period. The spectrum was coupled with nondimensional wave generation parameters originally proposed by Sverdrup and Munk to characterize the growth of wind waves in deep water under the influence of wind. The Bretschneider spectrum, in its general form, in terms of wave frequency, can be written as (from ref. 9)

$$S_{H^2}(\omega) = A\alpha g^2 \omega^{-5} e^{-0.675\left(g/F_2 W\omega\right)^4} \tag{3}$$

where

$$A = \frac{\left[1 - r + 0.927r\left(\frac{g}{F_2 W\omega}\right)^2\right]^2}{1 + 0.273r^2} \tag{4}$$

$$F_2 = \frac{g\overline{T}}{2\pi W} \tag{5}$$

$$\alpha = 3.437 \frac{F_1^{\,2}}{F_2^{\,4}} \tag{6}$$

$$F_1 = \frac{g\overline{H}}{W^2} \tag{7}$$

Directly related to the Bretschneider spectrum for any fixed set of wave-generation parameters $(F_1, \ F_2, \text{ and } \ r)$ are two monochromatic waves. One of these is the average wave, with period $\overline{T}$ and height $\overline{H}$ given, respectively, in equations (5) and (7). The other related monochromatic wave is the significant wave, whose period and height are the average period and height of the one-third highest waves. The significant period and height are related to the average period and height by the following equations (from ref. 9):

$$T_{1/3} = (1 + 0.6r)^{1/2}\overline{T} \tag{8}$$

$$H_{1/3} = 1.6\overline{H} \tag{9}$$

Evaluation of Spectrum Parameters

The nondimensional growth parameters F_1 and F_2, as well as the correlation coefficient r, are functions of several wind conditions: the wind speed W, the fetch length F which is the distance over which the wind blows in essentially a fixed direction at a constant speed, and the duration D which is the length of time the wind blows.

Reference 9 also presents wave forecasting relationships which are revisions of the original Sverdrup and Munk relationships. (See ref. 3.) For a given set of wind conditions, spectrum parameters are presented as graphical functions of a nondimensional fetch (ref. 9, p. 143) expressed by

$$F' = \frac{gF}{W^2} \tag{10}$$

Also given as a function of the nondimensional fetch is a minimum duration, expressed nondimensionally as $D_{min}W/F$, which indicates whether the waves are fetch limited or duration limited. If, for a given fetch, the duration D is greater than this minimum duration D_{min}, the waves are fetch limited; if D is less than D_{min}, the waves are duration limited. For cases in which the waves are duration limited, spectrum parameters are presented alternatively as graphical functions of a nondimensional duration expressed by

$$D' = \frac{gD}{W} \tag{11}$$

Limits for Fully Developed Seas

As the fetch length or duration increases, a condition will be reached above which there will be no further wave growth for a particular wind speed. When such a condition is attained, the sea is said to be fully developed for the particular wind speed in question. The limits at full development of the wave growth parameters of the Bretschneider spectrum, which are $F_1 = \frac{g\overline{H}}{W^2} = 0.178$, and $F_2 = \frac{g\overline{T}}{2\pi W} = 1.95$, are somewhat unrealistic and perhaps only are attained at very low wind speeds. (See ref. 14, p. 158.) More realistic criteria for fully developed conditions can be found by using the spectrum for fully developed seas proposed by Pierson and Moskowitz (ref. 15), which can be written as

$$f(\omega) = 8.1 \times 10^{-3} \frac{g^2}{\omega^5} e^{-0.74(g/W\omega)^4} \tag{12}$$

By differentiating equation (12) with respect to ω and setting the resulting expression equal to zero, one can determine the frequency at which the peak of the fully developed spectrum occurs, which is

$$\omega \Big|_{f_{max}(\omega)} = 0.877 \frac{g}{W} \tag{13}$$

For a particular wind speed, the peak in the Bretschneider spectrum for partially developed seas occurs at successively lower frequencies as the fetch or duration increases. Thus, equation (13) can be used to define the lower limit of the frequency at which the peak in the Bretschneider spectrum occurs. Combinations of wind parameters which result in a lower frequency for the spectrum peak would result in physically unreasonable values for the significant and average wave period. Observance of this lower frequency limit for the Bretschneider spectrum should also eliminate any physically unreasonable values for the maximum Bretschneider spectral density itself and, accordingly, corresponding values for significant and average wave height.

Currents Induced Over Bretschneider Spectrum

By definition, the mean square wave height $\overline{H^2}$ of an infinitesimal range $d\omega$ of wave components about a mean frequency ω is given by

$$\overline{H^2} = S_{H^2}(\omega)\, d\omega \tag{14}$$

The average current induced by this infinitesimal range of wave components, if it is assumed that the Bretschneider spectrum is valid in waters of finite depth, can be written by using equation (14) in equation (1) as

$$\overline{U}(z,\omega) = \frac{S_{H^2}(\omega)\, \omega k \cosh 2k(d - z)\, d\omega}{8 \sinh^2 kd} \tag{15}$$

where k can be found as a function of ω by solution of the dispersion relationship

$$\omega^2 = gk \tanh kd \tag{16}$$

The total average wave-induced current is simply a sum of component-induced currents over the entire frequency range. In the limit as $d\omega \to 0$, the sum becomes an integral, and the total wave-induced current can be expressed as

$$\overline{U}(z) = \int_0^\infty \frac{S_{H^2}(\omega)\ \omega k(\omega) \cosh\left[2k(\omega)(d - z)\right]}{8 \sinh^2\left[k(\omega)\ d\right]}\, d\omega \tag{17}$$

where $k(\omega)$ implies the insertion of a local solution of equation (16).

Wave-Induced Currents Computation

If a set of wind conditions is known for which the resulting Bretschneider spectrum falls within the limits for fully developed seas discussed in the previous section, the appropriate dimensionless curves of Bretschneider can be used to determine the period and height of the related significant wave expressed in normalized form, respectively, as $gT_{1/3}/2\pi W$ and $gH_{1/3}/W^2$, and the correlation coefficient r. The period and height of the average wave can then be computed by using equations (8) and (9). Computation of the wave-induced currents for these monochromatic waves involves specification of a water column depth d and vertical coordinate z (ranging from 0 to d), and by using the appropriate height, frequency $\left(\text{as derived from } \omega = \frac{2\pi}{T}\right)$, and wave number (as determined from solution of eq. (16)) in equation (1).

Computation of the wave-induced currents using the spectrum approach requires integration of equation (17) by some numerical technique. The average wave period and height and the correlation coefficient can be determined by the procedure outlined in the previous paragraph. Use of these values in equations (3) to (7) defines the spectral density at frequency ω; a local solution of equation (16) for $k(\omega)$, and specification of the depth and vertical coordinate completely determines the integrand of equation (17) at frequency ω. Numerical integration can then be carried out in a stepwise manner from $\omega = 0$ to either a specified cutoff frequency or a frequency at which the value of the spectral density $S_{H^2}(\omega)$ falls below some specified lower limit.

COMPARATIVE CASE STUDY

A digital computer program has been developed for calculating the Stokes' wind-wave-induced currents for the Bretschneider spectrum and for the average and significant monochromatic waves associated with the spectrum. The normalized wave growth curves of Bretschneider and a normalized representation of the dispersion relationship (eq. (16)) are input in tabular form to the program. Linear interpolation is used to determine wave growth parameters as a function of fetch length or duration and wave number as a function of frequency. Integration of equation (17) is carried out by using a Romberg quadrature procedure (ref. 16, pp. 259-261) with fixed frequency intervals of 0.02 rad/sec; integration is terminated at a cutoff frequency of 3.0 rad/sec.

Input Conditions

In order to compare Stokes' wave-induced current computations using the spectral and monochromatic approaches over a wide range of input conditions, a series of cases have been run with a constant fetch length (F = 925 km) for selected combinations of wind speed (W = 10, 20, and 30 m/sec) and duration (D = 6, 12, 18, and 24 hr). For the particular fetch length chosen, each combination results in a duration-limited sea for which the Bretschneider spectrum falls within the limit for a fully developed sea as discussed previously. Also, in order to make comparisons of computed currents in waters of different depths, all cases were run first with an input water column depth of 100 m and then were repeated with an input depth of 1000 m. A summary of the various input conditions and depths is given in table I.

TABLE I

INPUT WIND CONDITIONS AND DEPTHS FOR COMPARATIVE CASES

[Fetch length, 925 km]

Duration, hr	Wind speed, m/sec	Depth, m
6	10, 20, 30	100, 1000
12	20, 30	100, 1000
18	20, 30	100, 1000
24	30	100, 1000

Results and Discussion

Plots of the computed Bretschneider spectra for the cases under investigation are shown in figure 1 for durations of 6, 12, 18, and 24 hr. Related to each of these spectra, again, are the average and significant monochromatic waves. Table II presents a list of the period and height of the average and significant waves, as well as the correlation coefficient r, for each of the cases under study, as computed by using Bretschneider's dimensionless curves and equations (8) and (9).

TABLE II

AVERAGE AND MONOCHROMATIC WAVE INPUTS

D, hr	W, m/sec	$\overline{T}$, sec	$\overline{H}$, m	$T_{1/3}$, sec	$H_{1/3}$, m	r
6	10	5.29	0.88	5.40	1.40	0.0706
6	20	8.34	2.47	8.66	3.96	.1301
6	30	10.83	4.51	11.38	7.22	.1747
12	20	10.58	3.49	10.80	5.59	.0706
12	30	13.82	6.45	14.23	10.30	.1003
18	20	12.15	4.20	12.32	6.73	.0463
18	30	15.87	7.87	16.20	12.59	.0706
24	30	17.52	9.03	17.79	14.44	.0518

Shown in figure 2 are wind-wave-induced current profiles in water of 100-m depth for the cases under study at durations of 6, 12, 18, and 24 hr. Profiles computed using the spectrum approach are compared with those computed by using the average and significant monochromatic inputs listed in table II. In comparing the three profiles shown for each combination of wind speed and duration, it can be seen that current values at the water surface ($z = 0$) computed by using significant wave inputs are close approximations to those values computed by using the spectrum approach. In the range of the Z-axis from 10 m to about 60 m, however, the current values computed by using average wave inputs more closely approximate the values computed by using the spectrum approach. It should be noted, though, that in this range the magnitudes of the currents are smaller than the magnitudes of the surface currents by factors ranging from about 2 or 3 at $z = 10$ m to 10 or more at $z = 60$ m. In the overall comparison, the average-wave current profile provides a conservative lower bound for the profile computed by using the spectrum approach, whereas the significant-wave profile provides a somewhat less conservative upper bound except in the region near the surface $z = 0$.

Comparison of the two monochromatic techniques as approximations to the spectrum approach for computation of wave-induced current is summarized in figure 3 for the water depth of 100 m. Shown in figure 3(a) for the cases under study are surface current ($\overline{U}(z = 0)$) values computed by using the two monochromatic values plotted against the values computed for the same cases by using the spectrum approach. It can be seen that the values computed by using the significant-wave technique lie, in general, within ±10 percent of the values computed by using the spectrum approach, whereas the values computed by use of average-wave inputs underestimate the spectrum-computed values by approximately 60 percent. Figure 3(b) is a similar plot for the middepth vertical coordinate $z = 50$ m. (Points for one case have been deleted because of their proximity to the origin.) At this location, the current values computed by using the average-wave technique lie within the range of 0 to -20 percent of the values computed by using the spectrum approach, whereas the values computed by using significant-wave inputs overestimate the spectrum-computed values by approximately 125 percent. Again, it should be noted that the magnitudes of the currents at middepth are much smaller than those of the surface currents. A similar plot (with some points deleted as in fig. 3(b)) in figure 3(c) for bottom currents ($\overline{U}(z) = 100$ m) shows that values computed by using average wave inputs lie in the range of 0 to -40 percent of the spectrum-computed values, whereas use of the significant-wave inputs can result again in overestimation by as much as 125 percent.

As mentioned previously, the cases under study were repeated for a water column depth of 1000 m. For this depth, the exponential decrease in wave-induced current magnitude with increasing z-coordinate is such that only the currents near the surface are of sufficient magnitude to warrant comparison of the techniques. In consideration of this fact, only a comparison of surface currents analogous to figure 3(a) is shown for the 1000-m cases in figure 4. The current values computed by using the significant-wave approach lie within the range of ± 15 percent of the values computed by using the spectrum approach, whereas use of average wave inputs resulted in an underestimation by about 65 percent.

CONCLUDING REMARKS

An assessment has been made of the use of monochromatic wind-wave forecasts, in lieu of techniques involving spectrum forecasts, for predicting currents induced by wind waves. The Bretschneider wave spectrum, closely related to the wave forecasting system of Sverdrup and Munk used by the National Weather Service, was employed in the study. A technique was developed for computing the currents induced by the Bretschneider spectrum; these currents were compared for a variety of wind conditions resulting in partially developed seas, and two water depths, with the currents induced by the average and significant monochromatic waves which are related to the Bretschneider spectrum.

Results indicate that at the water surface, where the magnitudes of the wave-induced currents are greatest and hence the currents contribute most significantly to the overall circulation, the currents computed by using significant monochromatic wave inputs approximate to within 10 to 15 percent those computed by using the spectrum approach. Middepth and bottom currents induced by the Bretschneider spectrum, whose magnitudes are smaller than those of the surface currents by one or more orders of magnitude, are, in general, more closely approximated (to within 20 to 40 percent) by use of the associated average wave inputs rather than by the significant wave inputs. The comparisons suggest that the Weather Service forecasts of significant wave characteristics can be used in prediction of surface wave-induced currents. Conversion of significant input values to average values gives reasonable estimates of subsurface current values.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., December 19, 1974.

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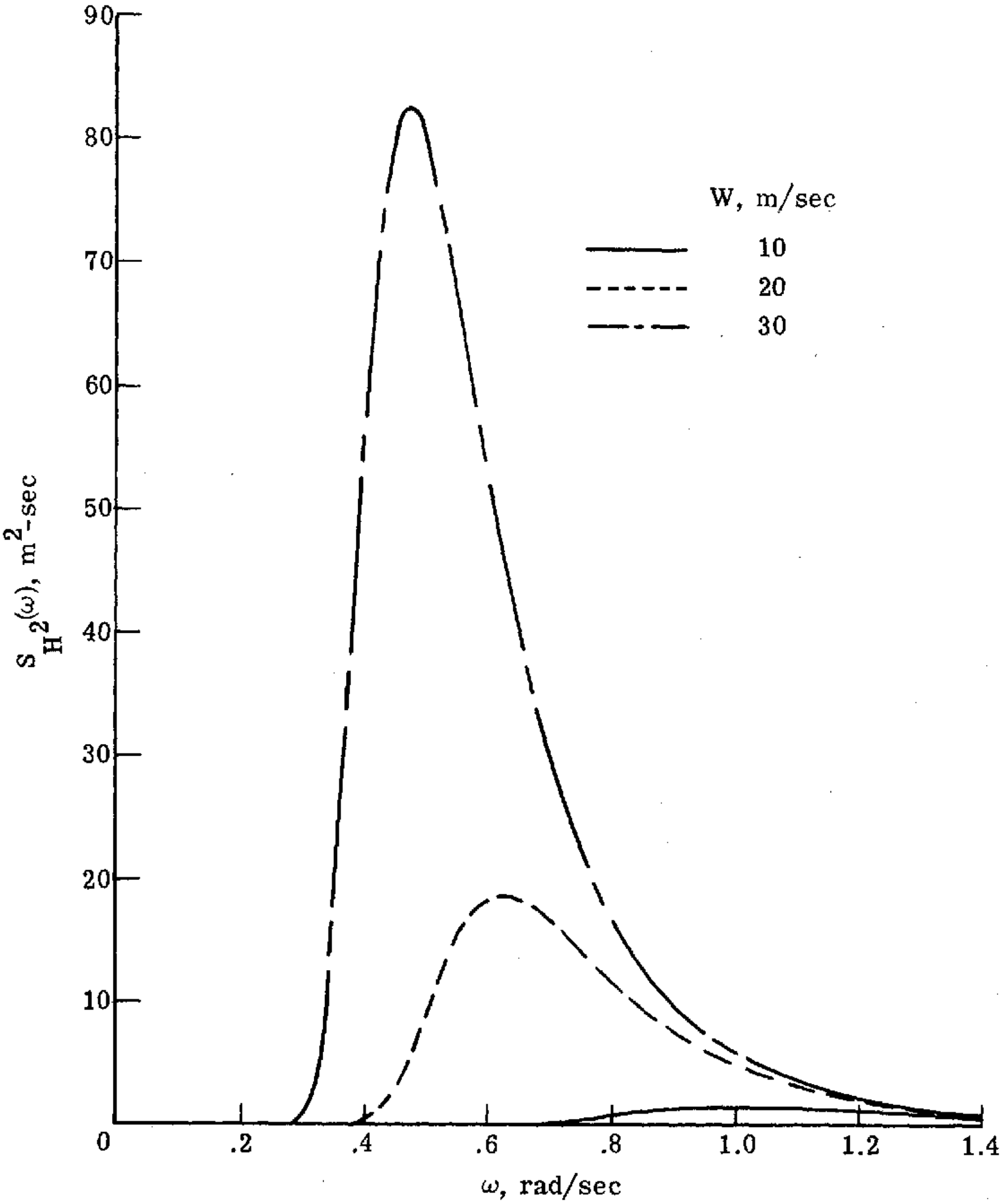
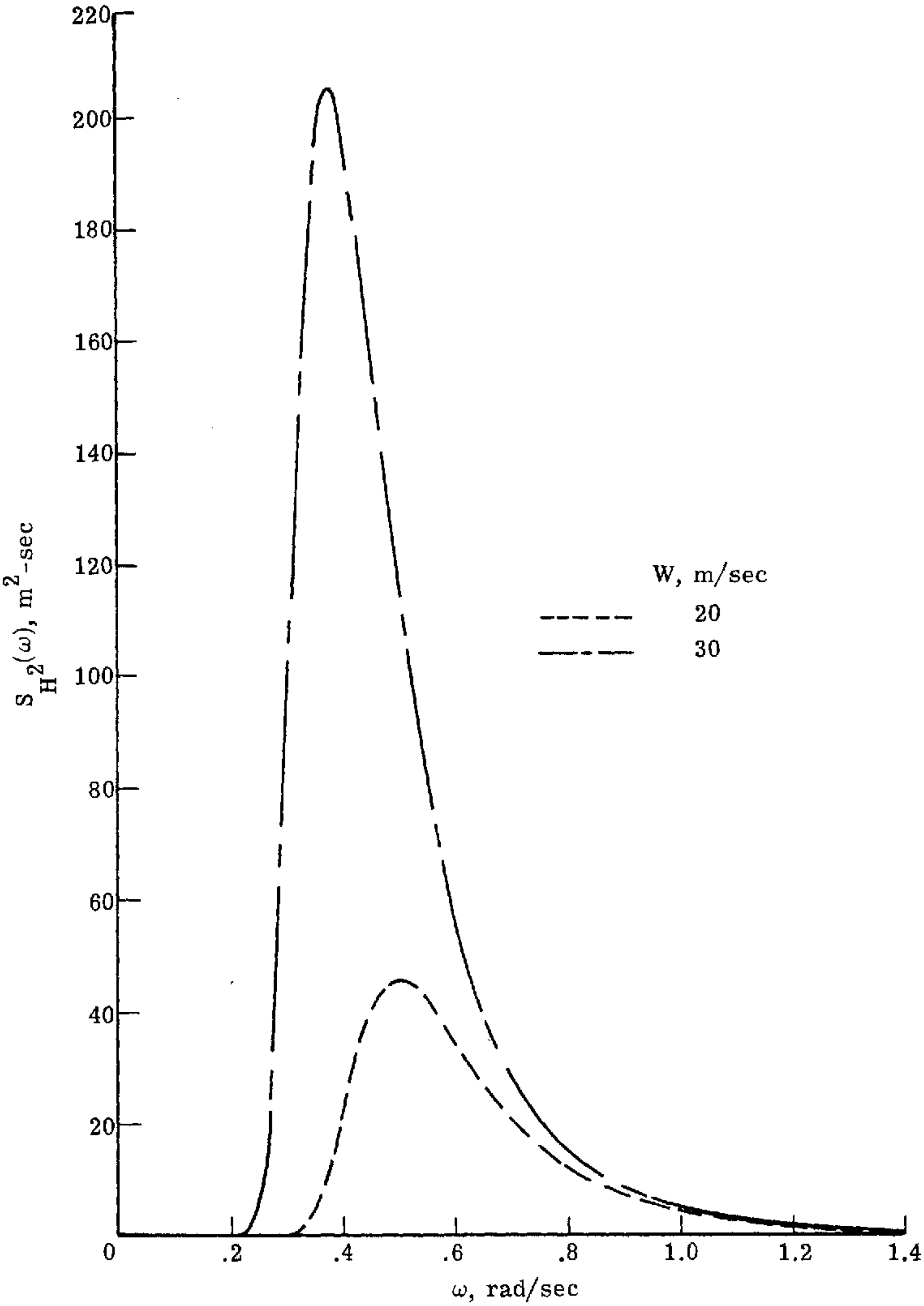


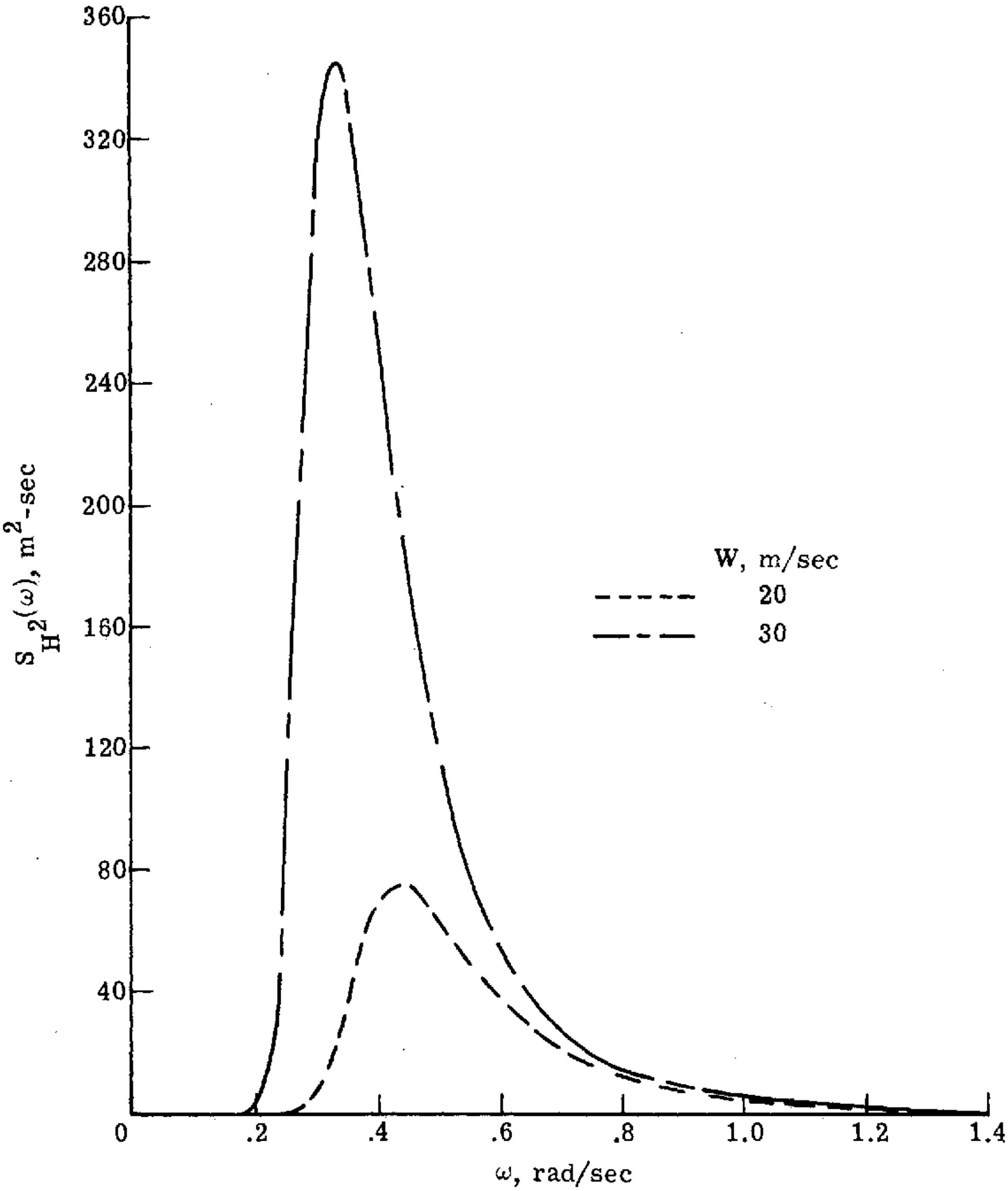
(a) Duration, 6 hr.

Figure 1.- Computed Bretschneider spectra for comparative cases over a fetch length of 925 km.



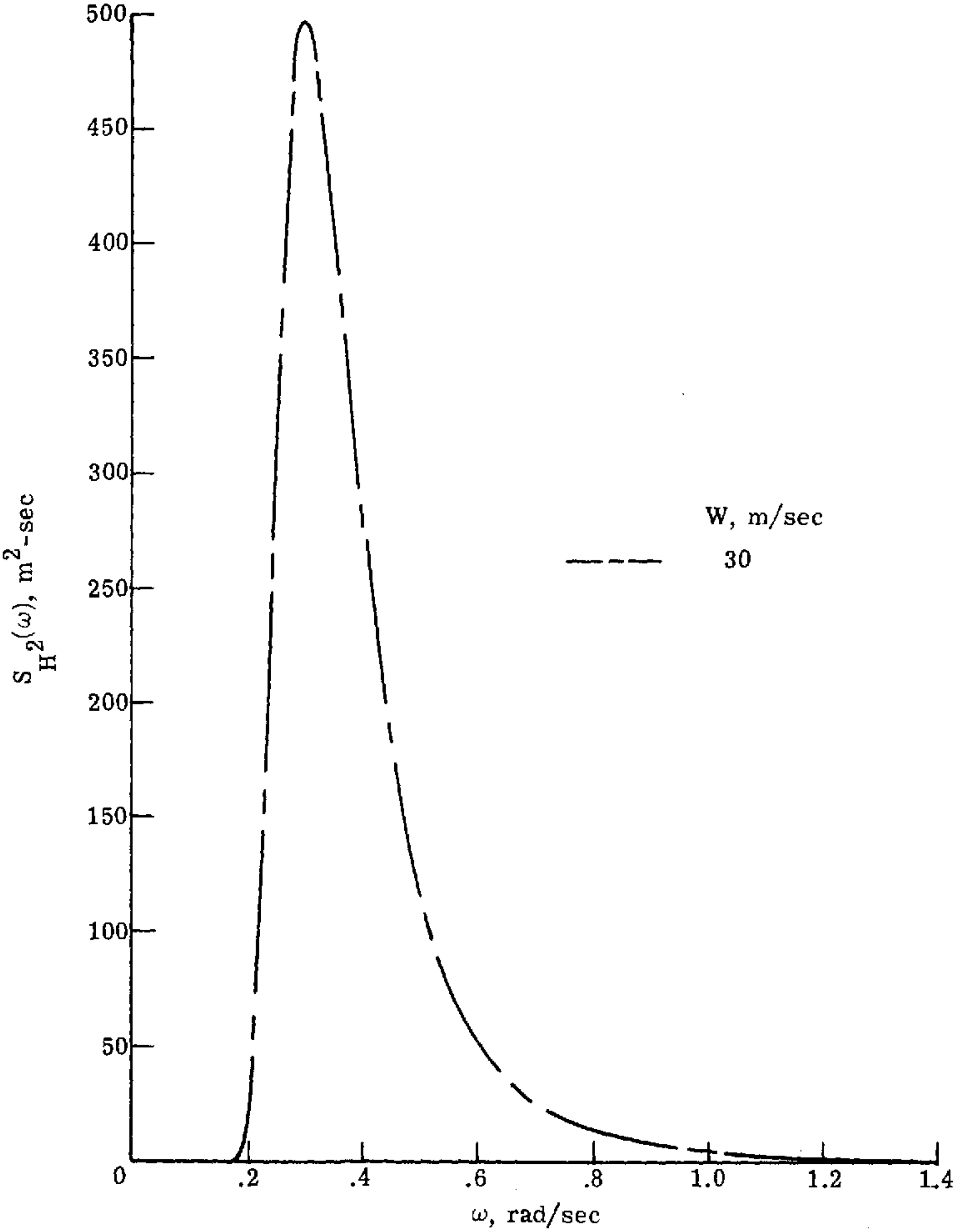
(b) Duration, 12 hr.

Figure 1.- Continued.



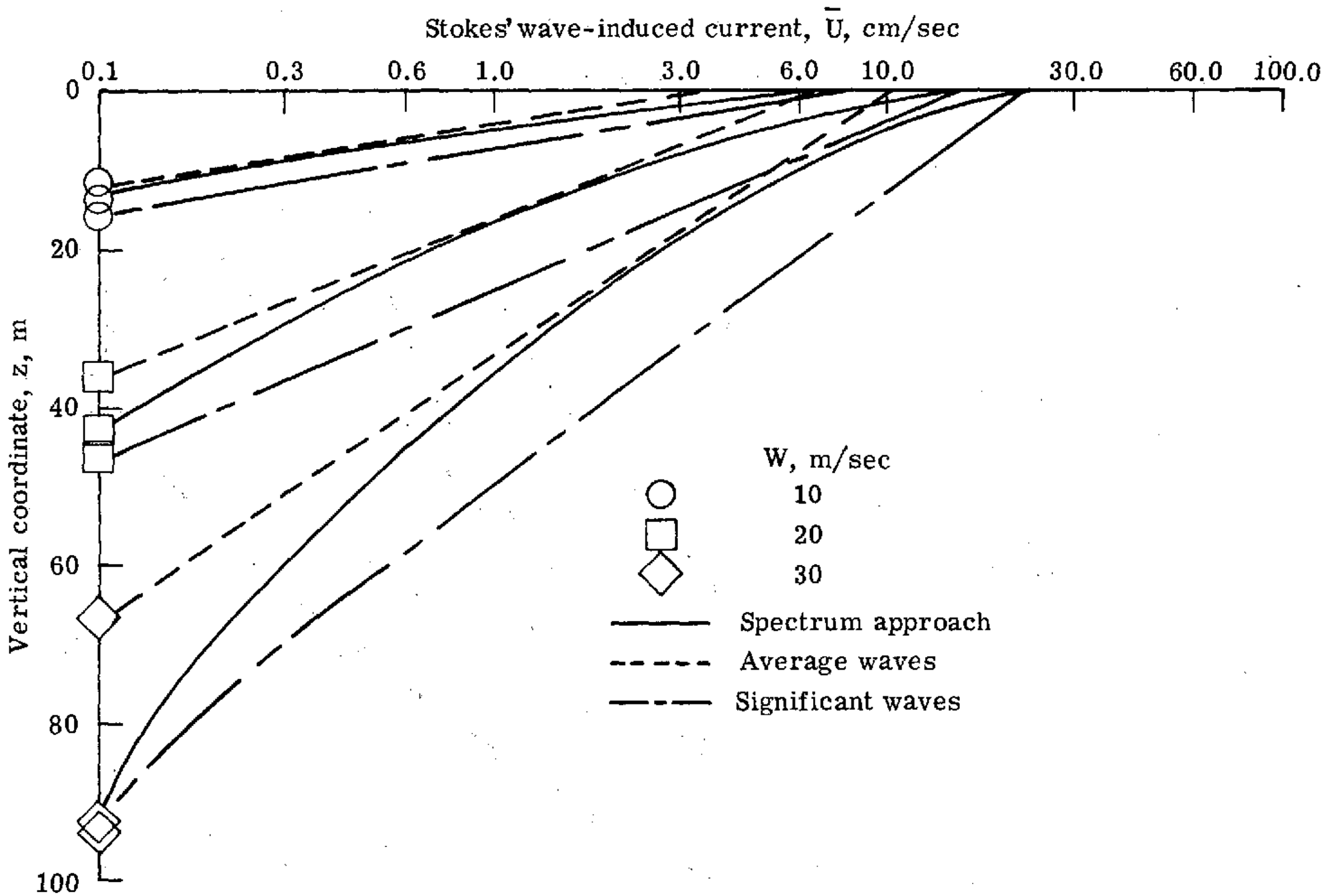
(c) Duration, 18 hr.

Figure 1.- Continued.



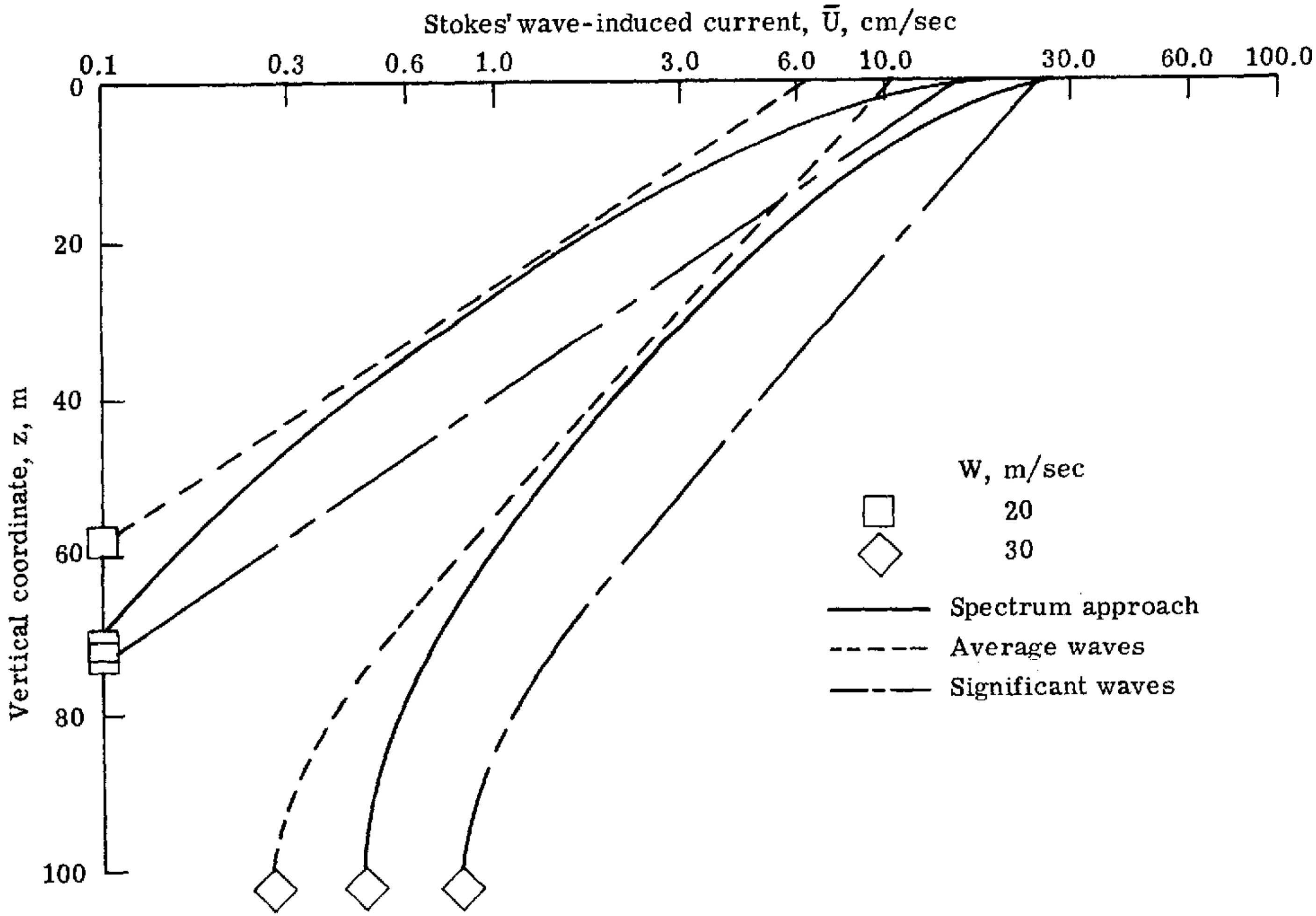
(d) Duration, 24 hr.

Figure 1.- Concluded.



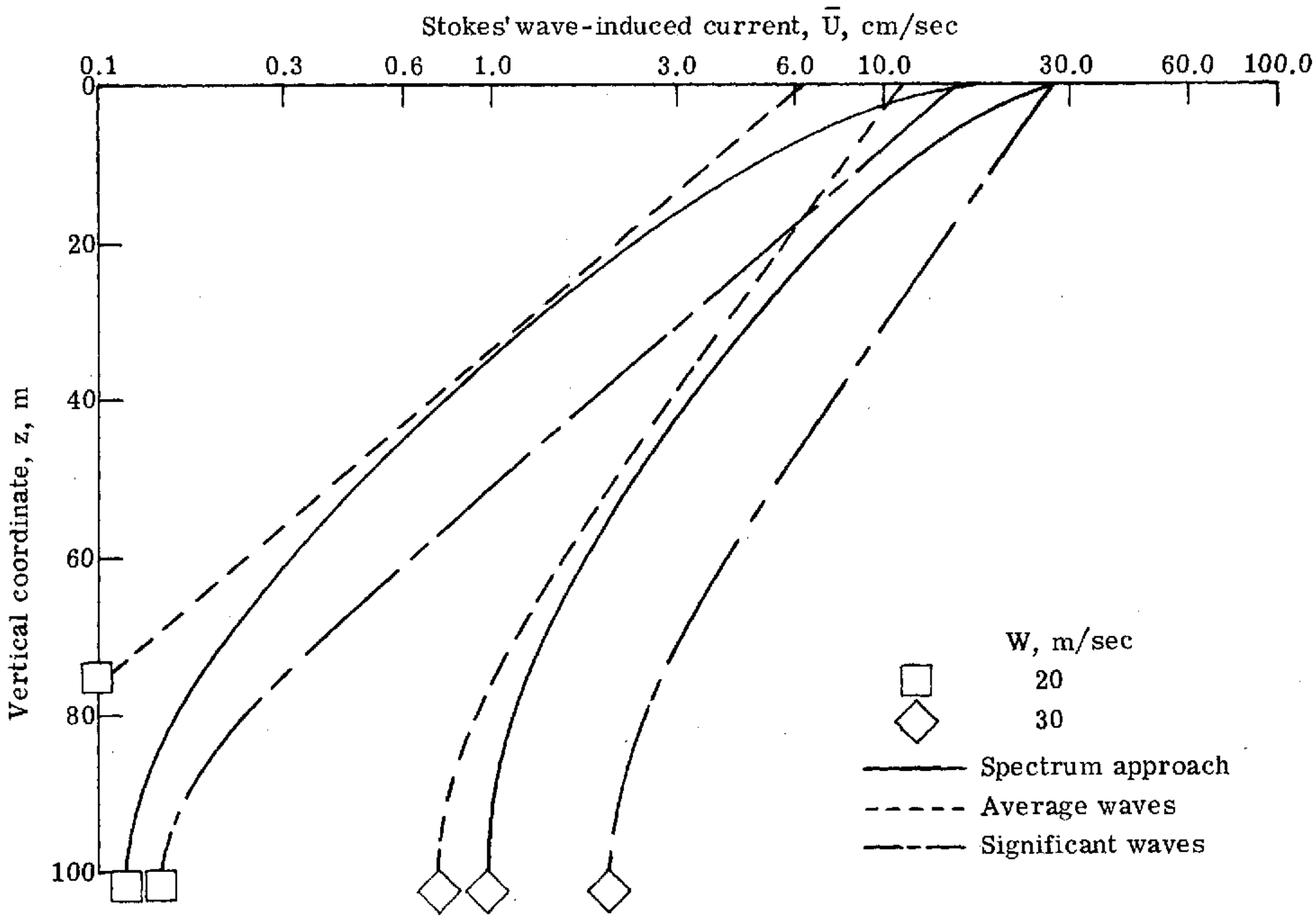
(a) Duration, 6 hr.

Figure 2.- Stokes' wave-induced current profiles in water depth of 100 m for cases under study computed by using spectrum approach and average and significant monochromatic wave techniques.



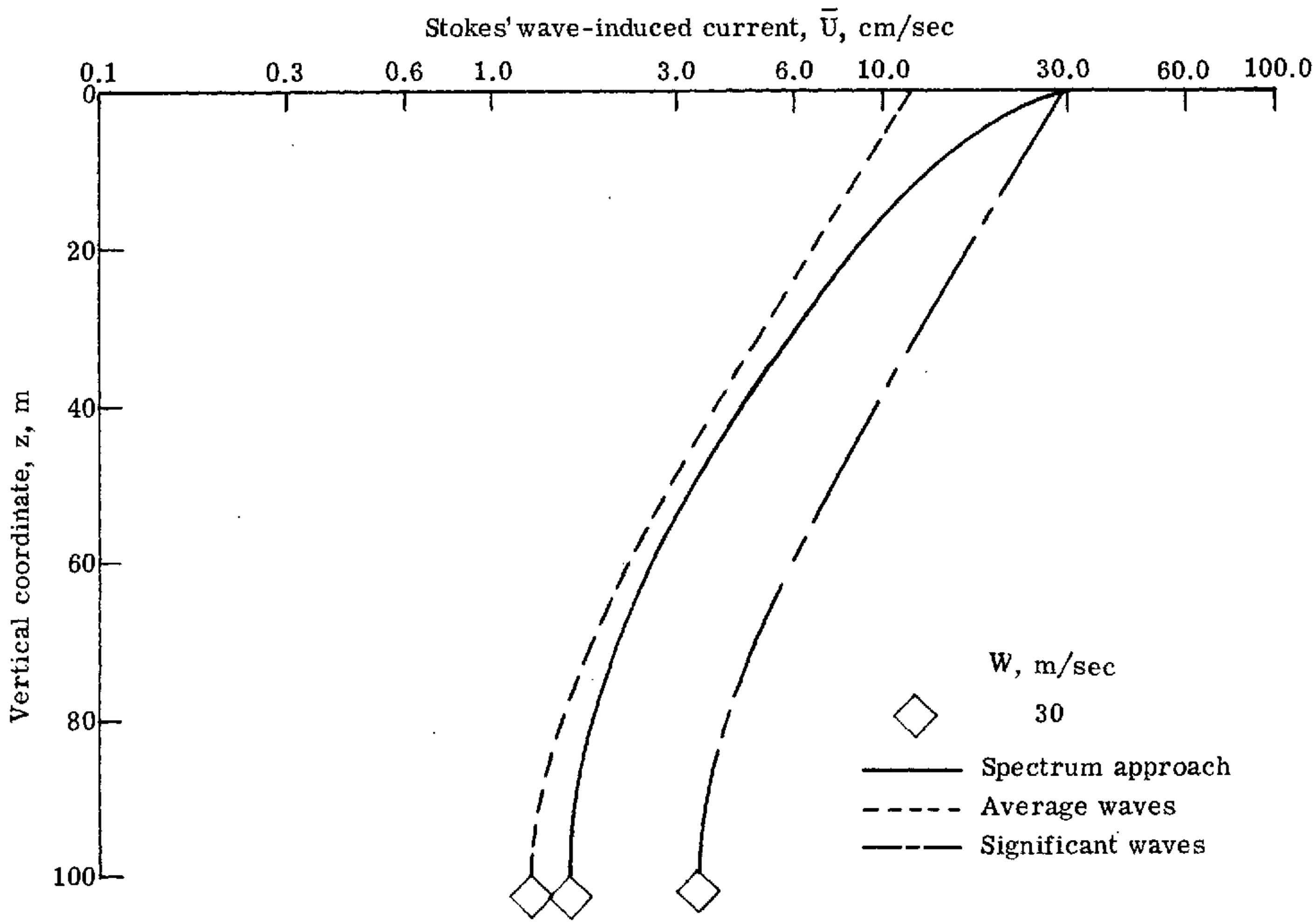
(b) Duration, 12 hr.

Figure 2.- Continued.



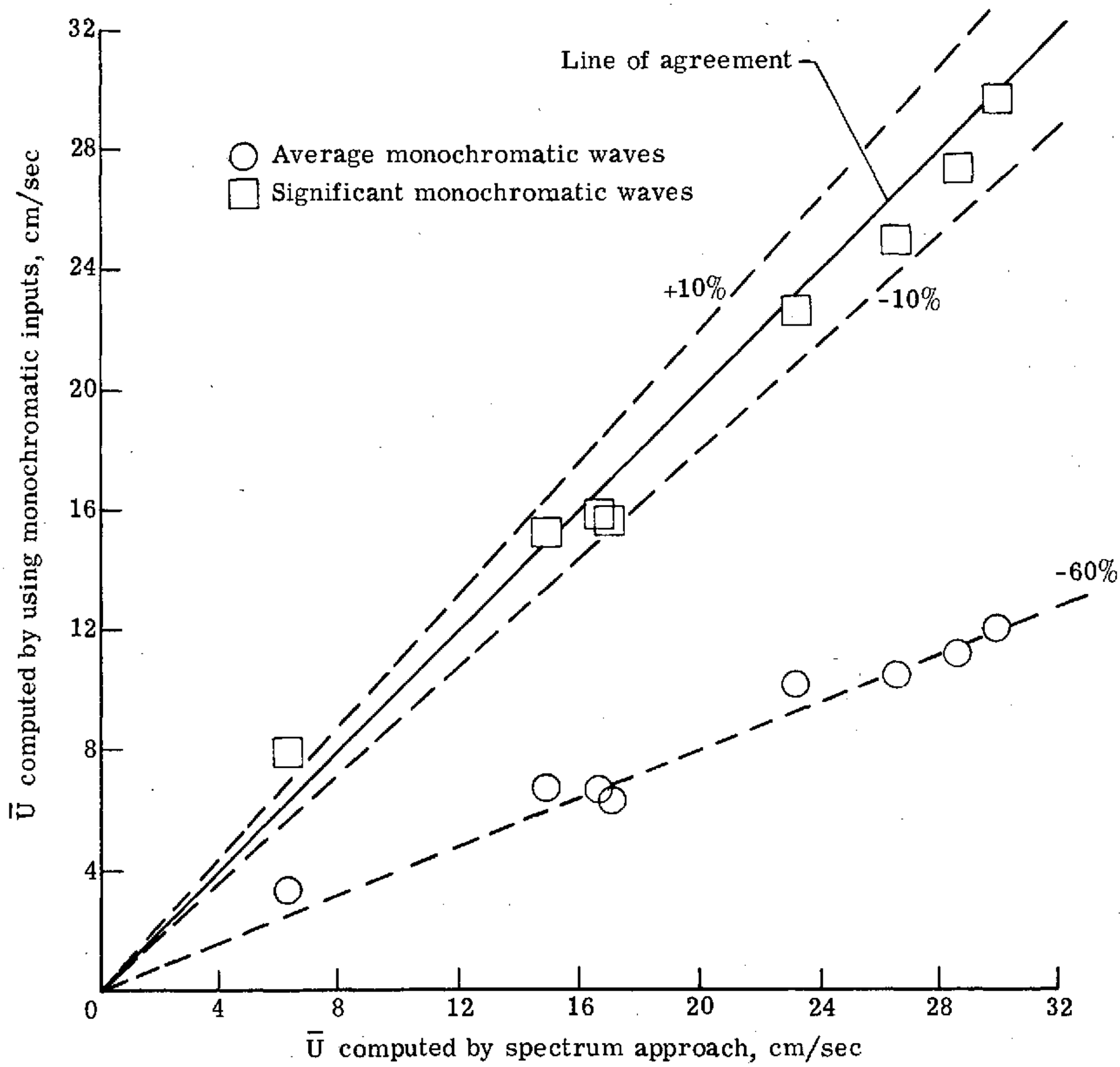
(c) Duration, 18 hr.

Figure 2.- Continued.



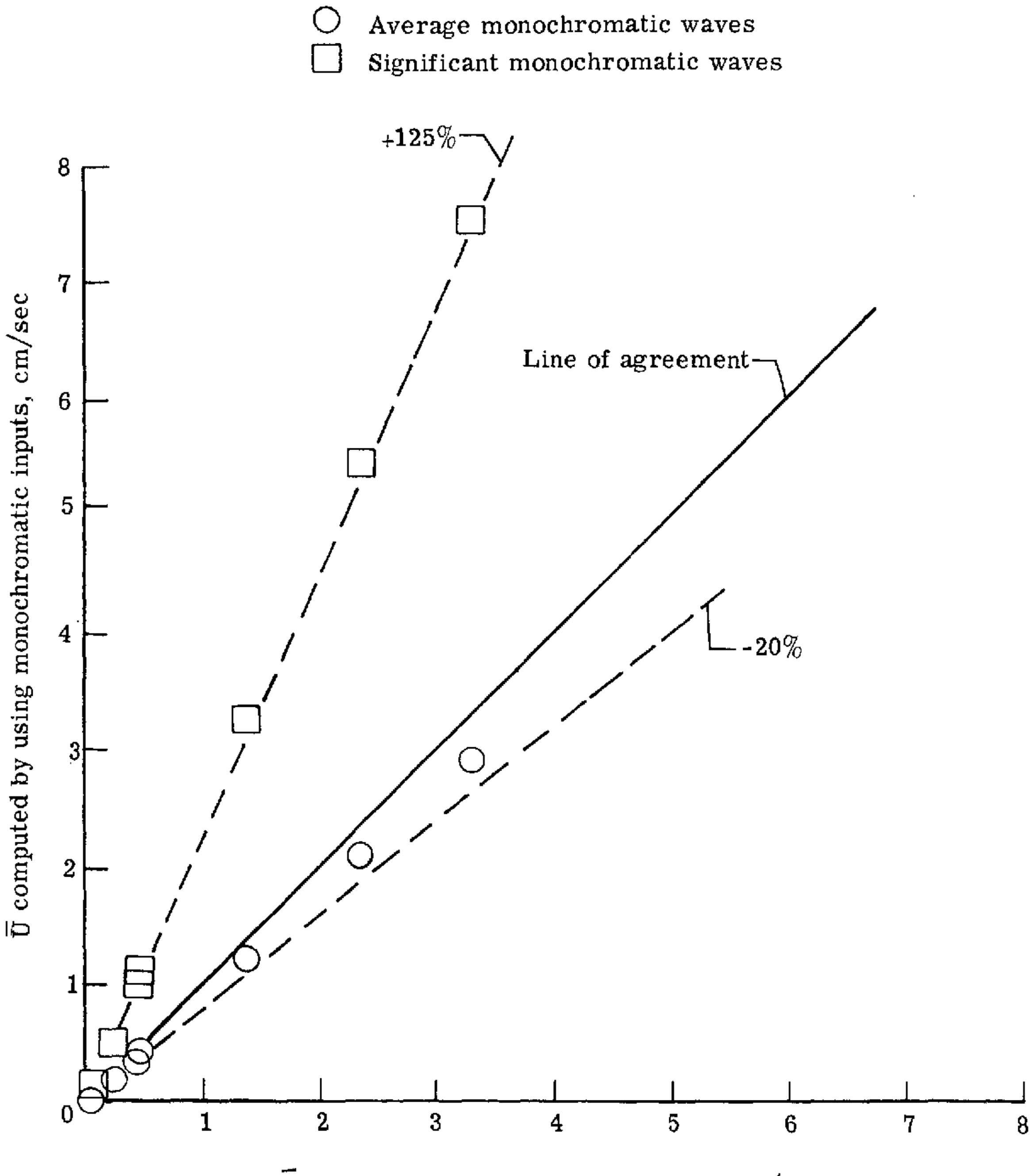
(d) Duration, 24 hr.

Figure 2.- Concluded.



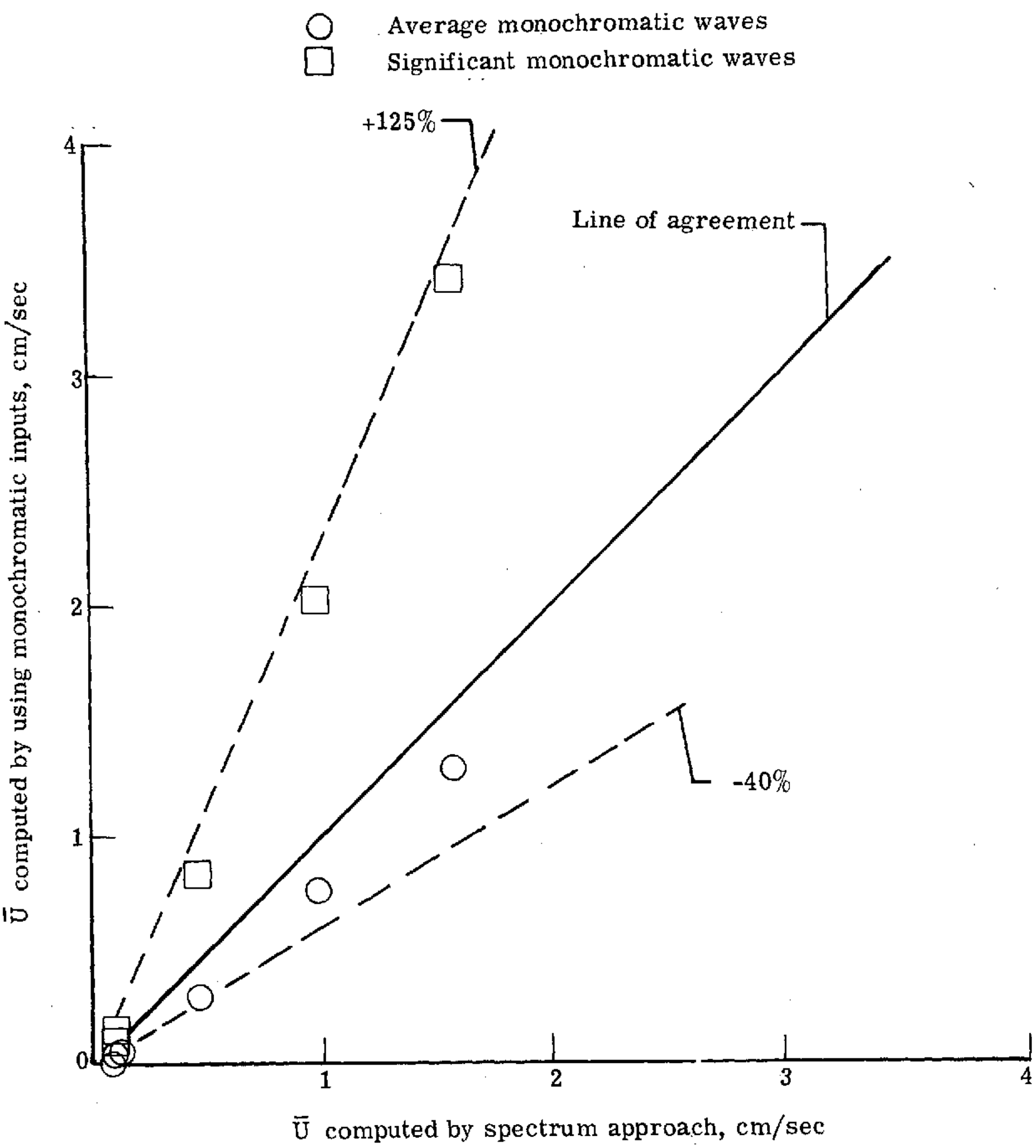
(a) z = 0.

Figure 3.- Comparison of wave-induced currents computed by using spectrum approach with those computed by using monochromatic inputs. Water depth, 100 m.



(b) z = 50 m.

Figure 3.- Continued.



(c) z = 100 m.

Figure 3.- Concluded.

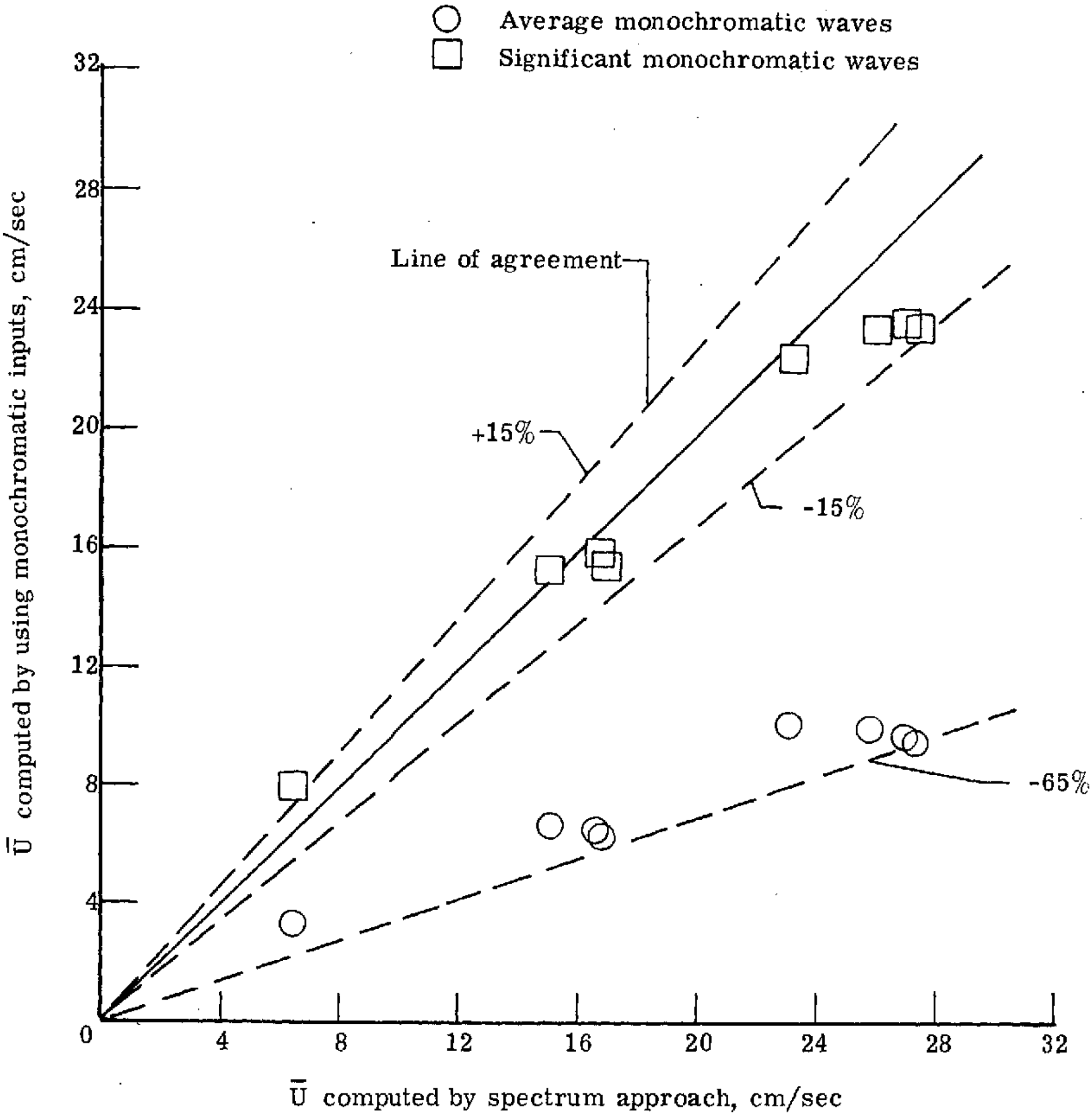


Figure 4.- Comparison of wave-induced currents computed by using monochromatic inputs with those computed by spectrum approach. Water depth, 1000 m; z = 0.

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