CHAPTER FIVE

WAVE KINEMATICS AND DIRECTIONALITY IN THE SURF ZONE

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ABSTRACT

Measurements of surface elevations and internal velocities have been conducted in a natural surf zone. The results were used to investigate the quantitative performance of linear theory in predicting the wave kinematics from the surface elevations. It appears that linear theory systematically overpredicts the horizontal velocities by 20 % in the frequency range around the peak, where the coherence with the surface motion is high, by 15 % at 2 times the peak frequency, changing in an underprediction of 15 % at higher frequencies. In these higher frequency ranges the rate of turbulent energy induced by breaking, contributes to the variance, so that the ratio of measured to theoretical r.m.s. fluctuation shows a trend of 25 % theoretical overprediction at negligible turbulent energy rates to 5 % underprediction at high turbulent energy rates. Furthermore the results were used to investigate the linear prediction of radiation stress and the effect of directionality on the radiation stress. Prediction of the radiation stress by unidirectional, linear theory gives an overestimation of 50 % at negligible turbulent energy rates to 35 % at high energy rates, which percentages reduce to 45 % and 25 % when the effect of shortcrestedness is taken into account.

1. Introduction

The T.O.W. programme for Coastal Sediment Transport in the Netherlands consists of theoretical studies, laboratory investigations and investigations in the field and is carried out by 8 task groups. Within the framework of this study programme field campaigns were held in 1981 and 1982/83 covering simultaneous measurements of currents, surface elevations, wave kinematics and sediment concentrations in the surf zone on the Dutch coast near Egmond (Derks and Stive, 1984). The data are used to investigate several aspects of coastal processes. In the task group "Velocity Field in Waves" specific attention is given to the investigation of the relation between surface elevation and wave kinematics. This paper presents an analysis of the 1981 field measurements as carried out by this task group.

The quantitative performance of linear theory in predicting the wave kinematics from the surface elevation is investigated on basis of the squared coherence-, gain- and phase spectra between surface elevation and both horizontal and vertical velocity. In addition the measured

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and theoretical r.m.s. values are compared. Relevant earlier studies on this topic are e.g. those of Mitsuguchi et al. (1980) and of Guza and Thornton (1980). Their findings are that linear theory generally overestimates wave induced horizontal velocities by 10 % to 30 %. Mitsuguchi et al. merely state their conclusion without analysing apparent trends in their data with e.g. increasing frequency. They only consider a limited set of horizontal velocity data. Guza and Thornton obtain their overall conclusion merely on basis of the r.m.s. fluctuation of the horizontal velocity as measured and as predicted with linear theory. The present study confirms the conclusions of the above investigation by and large, but extends the analysis in depth by investigating the relation with the rate of turbulent kinetic energy generated by breaking.

A second topic of attention is the directional spreading of the wave motion in the surf zone, which aspect has received very little attention sofar. The directional spreading is used to investigate the effects of non-linearity and directionality on the prediction of the principal radiation stress component. Knowledge of the radiation stress is important for the study of phenomena as set-up and long-shore currents.

In this paper only a limited number of results is presented. A more extended publication will appear elsewhere.

2. Measurements

2.1 Introduction

The field experiments were conducted on the Dutch coast near Egmond in May/June 1981. The Dutch coast is part of a concave sandy beach with coastal dunes extending from Cape of Gris Nez to the island of Texel, see fig. 1. The exposed sandy beach is typically gently sloped and barred with fairly parallel bottom contours.

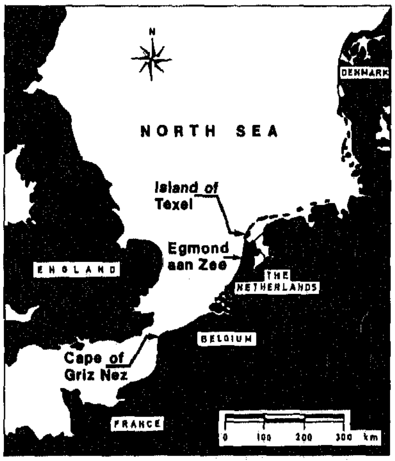

fig. 1 : Situation.

The measurements were made at three locations 20 m apart in the surf zone along a line normal to the shore. In addition measurements were made at two stations outside the surfzone as reference. The stations were numbered 1 to 5 from shore to sea. The local mean tidal range is approximately 2 m. This implies that at low tide station 1 was situated on the dry beach and nearly all wave energy was dissipated on the first breaker bar, see fig. 2. Therefore, all measurements were made around high tide.

During the 5 week campaign actual measurements were made at five different days, each with a duration of about 4 hours. Offshore significant wave heights were varying from 0.50 m - 1.80 m.

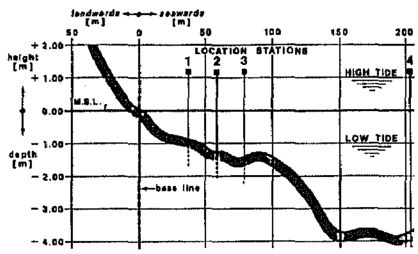

fig. 2: Location stations

2.2 Measuring stations

The stations in the surfzone consisted of a platform resting on transparent space trusses, a sensor pile and, with exception of station 1, a wave gauge. The sensor pile and wave gauge were spaced 2 m apart along a line nearly parallel to the shore. The sensor pile was placed 1 m seaward from the platform and was equiped with a measuring car in order to change the elevation of the sensors. On both sides of the socket longitudinal pipes were welded in a direct line parallel to the coast in order to intercompare different types of velocity meters at the same depth. Nearly all measurements were made at an elevation of about 1 m above the bottom. Some measurements were made at 0.20 m above the bottom.

2.3 Instruments

Velocities were measured at each of the three locations, both with conventional current meters and a newly developed current meter, viz. a so called vector-akwa, a three-dimensional meter based on the principle of travel time of acoustic pulses. Temperature and salinity variations are automatically corrected for. A meter of this type designed for use in physical models has been described by Botma (1978), who also designed the vector-akwa. The sensor is highly transparent and has four 0.23 m long survey lines (see fig. 3). The advantage of the fourth survey line is, that for the calculation of the three mutually orthogonal velocity components the survey line most influenced by the sensor itself can be eliminated. From calibration tests it was found that the inaccuracy of this instrument is ± 5%.

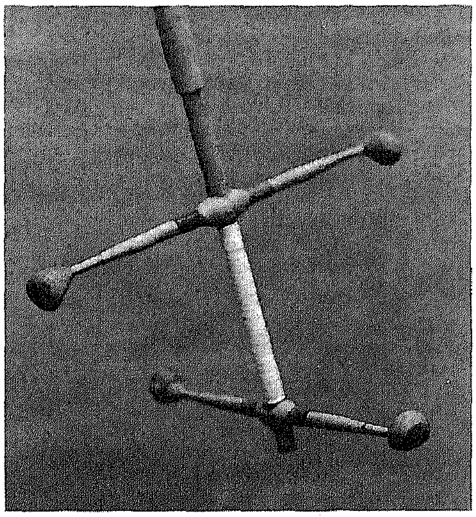

fig. 3: Vector-akwa velocity meter.

Surface elevations were measured using resistance wave gauges. These gauges consisted of resistance wires mounted inside a protection tube provided with slits. The tube caused a wave height reduction as well as a phase shift. To investigate the influence of this tube experiments were carried out in a large scale laboratory flume. This experiment showed a maximal reduction of 6% depending on the steepness of the waves. Since in the laboratory flume the conditions of Egmond were not reproduced exactly, the maximal reduction is estimated to be 10%.

The phase shift due to the tube appeared to be not considerable, but difficult to determine, since it is neither linear nor constant. This phase shift was modelled mathematically. It appeared to depend on a large number of parameters. Since several of these parameters, such as the shape of the wave, are difficult to determine, the phase shift can only be estimated with a limited accuracy. The maximal phase shift due to the tube appeared to be 13°/Hz.

For data storage during the experiment a pulse code modulator system (P.C.M.) was used. With this system 112 channels can be sampled and recorded simultaneously. The data were recorded with a 14 track tape recorder. The sample frequency of the system at the lowest record speed (1 7/8 i.p.s.) is 133 samples per second per channel.

3. Data analysis procedure

Standard procedures as described by Bendat and Piersol (1971) and Jenkins and Watts (1968) have been used to calculate mean values, variances, auto- and cross spectra, which yield coherence, gain- and phase spectra. The main procedure of the computer program is Singleton's F.F.T. procedure (Singleton, 1969) using subrecords. The length of the analysed records has been taken 1800 s. For the calculation of the spectra the records are divided in 30 subrecords. Because no data window has been used the number of degrees of freedom is 60 and the resolution is 1/60 Hz.

Mean values, variances and auto spectra were calculated of the surface elevation (ζ) and the three orthogonal velocity components (u,v,w).

To intercompare the velocity meters cross spectral calculations were carried out between the onshore wave velocity components (v) of the two velocity meters fixed at the same sensor pile. For the same reason cross spectral calculations were used between these components and the surface elevation. These calculations have also been used to calculate the coherence-, gain- and phase spectra. However, this method cannot be used for the calculation of the coherence-, gain- and phase spectra of the surface elevation and the resultant velocity component in the horizontal plane ($\tilde{u}$) because of the shortcrestedness of the waves. Therefore, the gain spectrum of ζ and $\tilde{u}$ has been calculated from:

$$H_{\zeta\tilde{u}} = \{(S_{uu} + S_{vv}) \;/\; S_{\zeta\zeta}\}^{1/2}$$

in which S_{uu}, S_{vv} and $S_{\zeta\zeta}$ are the auto spectra of the two horizontal velocity components, u, v, and the surface elevation ζ. This procedure does not permit the estimation of confidence intervals. For the coherence- and phase spectra the spectra of ζ and v are used, since v contains the major part of the wave energy in the horizontal plane.

Assuming the water motion and the measurements to be linear and noise-free, the calculated auto- and cross spectra of (u,v,w) can be used to estimate the directional properties of the waves by standard procedures (see Borgman, 1979). Using the auto- and cross spectra the truncated Fourier series and the parameters of the $\cos^{2s}(\Theta/2)$-model of the directional spectrum have been calculated for different frequencies (Longuet-Higgins et al., 1963 and Mitsuyasu et al., 1975). The spreading parameter of this model can easily be expressed in degrees.

4. Intercomparison of velocity meters

One of the objectives of the field campaign was to investigate the performance of several types of current meters in a natural surf zone by intercomparison. To this end the velocity meters were closely placed at the same height above the bottom. The meters have been compared on basis of the r.m.s. values of $\tilde{v}$ and of the squared coherence and gain of the two onshore wave components at the peak frequency, f_p. Due to the lack of an absolute measurement result and of insight into the spatial variability of the velocity field these comparisons give no definite answer to the question which meter is the better one. The only quality assessment of the meters may be based on the squared coherence between ζ and v. The results of the 1981 campaign indicate that the hydrodynamically well-designed vector-akwa shows in general a higher coherence (0.80 - 0.95) with the surface elevation than the signals of the other types of current meters. This intercomparison is based on a limited set of data obtained in the lower half of the water column. An extension of the intercomparison was realized in the 1982/83 field campaign of which the results are summarized in Derks and Stive (1984).

5. Wave kinematics results

5.1 Introduction

A comparison of measurement results with linear theory has been made in two ways. Firstly, the gain- and phase spectra are considered and compared with those according to linear theory. Secondly, the r.m.s.

values of the horizontal and vertical velocity components are compared with the estimated variances derived from the surface elevation spectra with linear theory.

This paper presents one typical example of squared coherence-, gain- and phase spectra of surface elevation and horizontal velocity component of one of the stations in the surf zone and the r.m.s. values of all horizontal velocity results.

5.2 The spectra

The surface elevation spectrum, $\hat{S}_{\zeta\zeta}$, and the corresponding 90% confidence interval is shown in fig. 4. The peak frequency appears at 1/6 Hz and, since we are dealing with breaking waves, second harmonics appear around twice the peak frequency. The local significant wave height in this example was about 1 m, the elevation of the velocity meter above the bottom was 0.80 m and the mean water depth was 2.30 m.

The squared coherence spectrum between surface elevation and onshore velocity component, $\hat{\gamma}^2_{\zeta v}$, is shown in fig. 5. The dashed lines indicate the 90% confidence interval. In the frequency range where the bulk of the energy is concentrated the coherence is quite high. This implies a nearly linear relationship between ζ and v and a relatively small contribution to the variance of the turbulent motion.

Fig. 6 exemplifies the gain spectra of surface elevation and horizontal velocity component in the propagation direction $\hat{H}_{\zeta\tilde{u}}$. This example shows a typical overestimation of the horizontal velocity component by linear theory for the frequency range of 0.1 to 0.4 Hz of about 10 %, which changes in an underprediction of 20 % at higher frequencies. This can be seen more clearly in figure 7, where the ratio between the measured and the theoretical gain according to linear theory has been plotted versus frequency. It must be noted that this result is not corrected for the reduction caused by the tube of the wave gauge, which was estimated to be maximally 10 %. The phase spectrum of ζ and v, $\hat{\phi}_{\zeta v}$, is shown in fig. 8. This phase spectrum has been corrected for time delays due to: the tube of the wave gauge, the electronics of the wave gauge and the distance between wave gauge and velocity meter. The magnitude of these delays could only be estimated. The inaccuracy of the estimated phase corrections for this example is -28°/Hz to +33°/Hz. This phase spectrum shows a slight trend with frequency which, however, may be explained by the inaccuracies of the applied corrections, indicated by the thick broken line. Another reason may be that for the correction due to the spacing the main wave direction was used. Neglect of the wave spreading results in an overestimation of the time delay. Summarizingly, it can be concluded that the phase spectrum of ζ and v is consistent with linear theory within the accuracy margin.

In view of the above results concerning the phase spectrum of the horizontal onshore velocity component and the vertical velocity component, $\hat{\phi}_{wv}$, are of particular interest since this spectrum is neither influenced by a lag between two instruments nor by a spacing. This spectrum is shown in fig. 9. The theoretically expected value between these components is within the 90 % confidence interval of the estimate, confirming the theoretically predicted quadrature relation between these velocity components.

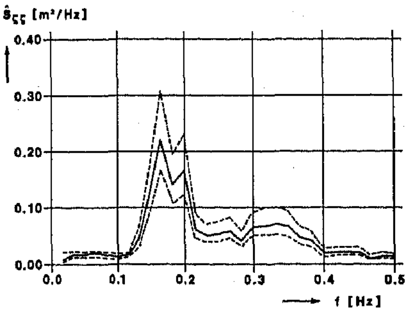

fig. 4 : surface elevation spectrum.

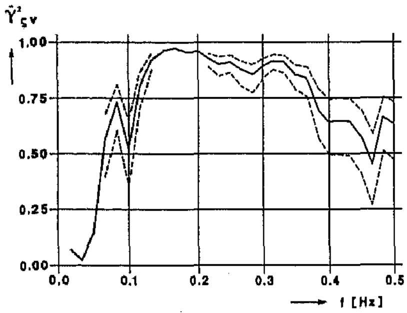

fig. 5 : squared coherence spectrum of surface elevation and onshore velocity component.

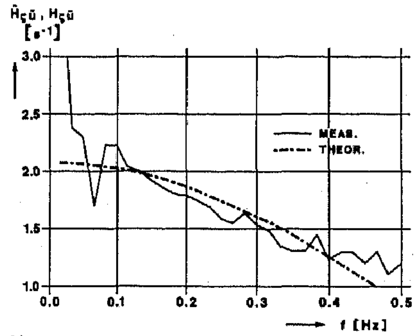

fig. 6 : gain spectrum of surface elevation and horizontal velocity component in the propagation direction.

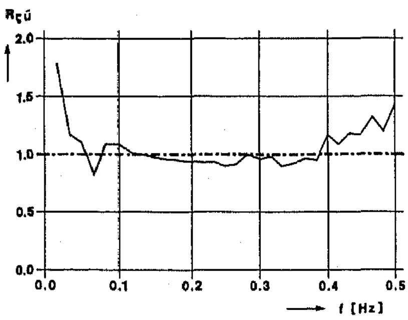

fig. 7 : ratio measured to the theoretical gain spectrum of surface elevation and horizontal velocity component in the propagation direction.

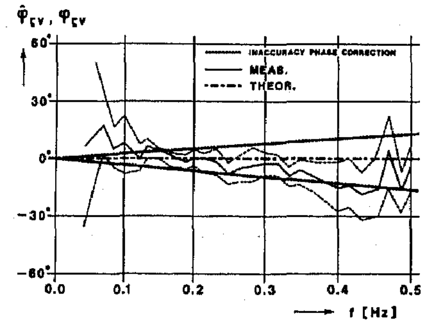

fig. 8 : phase spectrum of surface elevation and horizontal onshore velocity component.

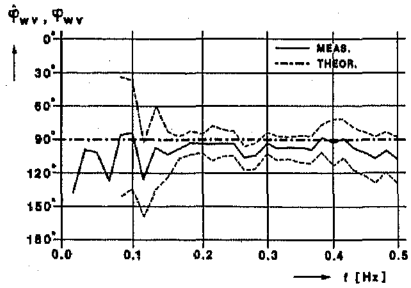

fig. 9 : phase spectrum of vertical and horizontal onshore velocity component.

5.3 The r.m.s. values

A correlation between the measured and theoretical r.m.s. values of the horizontal velocity component in the propagation direction is shown in fig. 10. No discrimination has been made between the r.m.s. values calculated from the measurements made at different elevations, because of the depth-uniformity of the horizontal velocity field in the lower water column. For the low r.m.s. values the deviations are generally outside the ± 10 % interval, for the higher values they are generally within this interval. Again : these values are not corrected for the reduction due to the tube of the gauge (which would increase the theoretical estimate by 10 % maximally).

To investigate whether a systematic relationship between the discrepancy with linear theory and the relative turbulent energy level exists, a dimensionless parameter for this energy level has been used, defined as $\hat{q}^2$:

$$\hat{q}^2 = \rho h q^2 / E_{kin,\,inc}$$

in which ρ = water density [kg/m³], h = local water depth [m], q^2= turbulent kinetic energy [m/s], $E_{kin,inc}$ = incident kinetic energy = $\frac{1}{16}\rho g \, H_{rms}^2$ [J/m²] , g = gravity accelleration [m/s²].

The turbulent kinetic energy is derived from : $q^2 \simeq (D/\rho)^{2/3}$ Battjes (1975). Here D is the energy dissipation due to breaking which is approximated by : $D=\frac{1}{4}\rho g \, f_p \, Q_b \, H_m^2$, according to Battjes and Janssen (1978), H_m being the maximum wave-height and Q_b the fraction of breaking waves.

The relation between this parameter and the ratio of the measured r.m.s. value of the horizontal velocity component to the theoretical one is shown in fig. 11. The results indicate that the discrepancy with linear theory is correlated with the rate of turbulent energy.

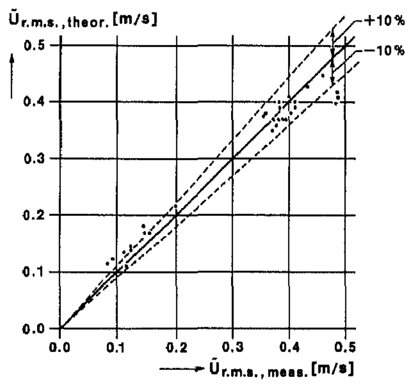

fig. 10 : Correlation measured and theoretical r.m.s. values of the horizontal velocity component in the propagation direction.

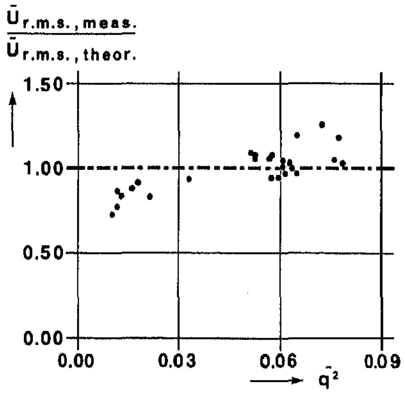

fig. 11 : ratio measured r.m.s. values of the horizontal velocity component in the propagation direction to the theoretical ones as a function of the relative turbulent energy level.

6. Wave directionality and radiation stress

An example of the wave direction results is shown in fig. 12. The upper diagram gives the main wave direction, θ_0 , as a function of frequency for the three stations in the surfzone. The lower diagram in this figure gives the spreading of the waves as a function of frequency. This spreading has been defined more or less analogously to the standard deviation of the Gaussian distribution and is expressed in degrees, see Van der Vlugt et al. (1981). Between this parameter and the spreading parameter of the $\cos^{2s}(\theta/2)$ model the following relation exists (Kuik et al., 1984):

$$\sigma = \sqrt{\frac{2}{s+1}} \cdot \frac{360°}{2\pi}$$

The upper diagram shows that two different wave fields were present, one coming from the sea with a frequency of 0.10 Hz - 0.30 Hz and another caused by local winds at higher frequencies with the same direction as the wind direction, θ_w. The wave directions of both wave fields clearly show refraction effects (station 3 is the most seaward station).

The spreading of the waves has a minimum at the peak frequency, which was also noticed from measurements made in deeper water, see Mitsuyasu et al. (1975). Another phenomenon which is clearly shown in this example is the decrease in spreading as the waves travel towards the shore. This can also be ascribed to refraction.

One of the effects of shortcrestedness is a decrease of the radiation stress. In a statistically homogeneous and stationary wave field the principal radiation stress component in the main wave direction is

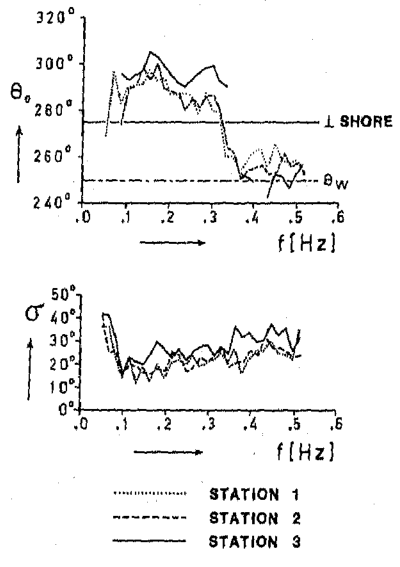

fig. 12 : Main wave direction (upper diagram) and wave spreading (lower diagram) as a function of frequency for the three stations located in the surf zone.

given, correct to second order in wave elevation (Battjes 1972), by :

$$S_{11,\,meas} = \frac{1}{2}\rho\, g\, \overline{\zeta^2} + \rho \int_{-d}^{o} (\overline{v_*^2} - \overline{w^2})\, dz$$

where $\overline{v_*^2}$ is the variance of the horizontal orbital velocity in the main wave direction, which term can be derived from the measured variances $\overline{u^2}$, $\overline{v^2}$ and the cross variance $\overline{u.v}$ (Battjes and Van Heteren, 1980). Assuming *a linear longcrested wave field, the above expression reduces* to an expression in which the main principal radiation stress component is :

$$S_{11,\,theor} = \int_{o}^{\infty} S_{\zeta\zeta}(f)\ .\ \{2kh/\sinh(2kh) + \tfrac{1}{2}\}\, df$$

where k is the linear wave number. Battjes (1972) shows how the reducing effect of shortcrestedness on $S_{11,theor}$ may be incorporated. For the simplified case of shallow water the reduction factor is given by $(1-2/3.\varepsilon)$ where $\varepsilon = (2s_o+1).(s_o+1)^{-1}(s_o+2)^{-1}$ in which s_o is the spreading parameter of the $\cos^{2s}(\theta/2)$ model. The radiation stress has been calculated for $S_{11,meas}$ and for $S_{11,theor}$ and for $S_{11,theor}$ corrected for shortcresstedness. The results are shown in fig. 13. The results show that the reducing effect of shortcrestedness is 10% typically.

The correlation between the ratio of measured to theoretical estimates of the principal radiation stress component and the relative turbulent energy level is presented in fig. 14. This result clearly shows a trend with the rate of turbulent energy. The unidirectional linear theory overestimates the radiation stress by 40 % at negligible turbulent energy rates and by 25 % at higher rates. Corrected for shortcrestedness these percentages decrease to 35 % and 15 % respectively (these percentages are not corrected for the reduction caused by the tube of the gauge).

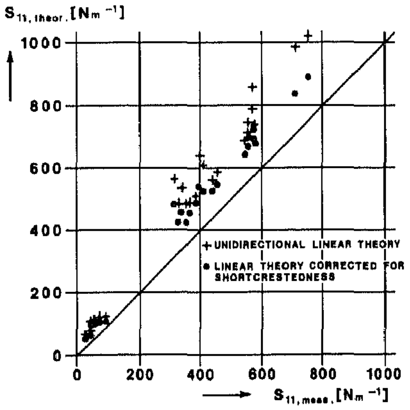

fig. 13: correlation measured and theoretical values of principal radiation stress component.

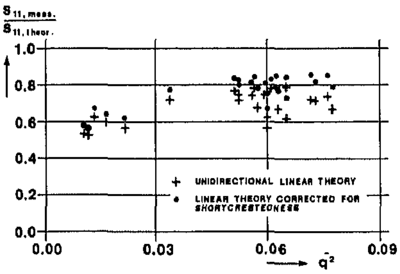

fig. 14: ratio measured values of principal radiation stress component to theoretical ones as a function of the realative turbulent energy level.

9. Conclusions

The following conclusions have not only been based on the examples presented in this paper, but more generally on the results of all measurements made in the surf zone of the beach near Egmond during the 1981 T.O.W. measuring campaign. All given values in this paragraph have been corrected for the reduction of surface elevation caused by the tube of the wave gauge which was estimated to be maximally 10 %. For this correction the mean value was used (5 %) accepting a random error of ± 5 %. Furthermore, the inaccuracy of the velocity meter must be taken into account, which was found to be also ± 5 %.

(1) In the surf zone linear theory systematically overpredicts the horizontal velocity component in the frequency range of high coherence with surface elevation. Average values of 21 % at the peak frequency and 17 % at two times the frequency have been found. This overprediction changes in an underprediction (in some cases as high as 15 %) at higher frequencies which is due to the presence of turbulent energy. Resultingly, the ratio of measured to theoretical r.m.s. fluctuations of the horizontal velocity shows a trend correlated with the turbulent energy rate from 25 % theoretical overprediction at negligible turbulent energy rates to 5 % underprediction at high turbulent energy rates.

(2) The estimated phases of the horizontal velocity component and surface elevation are generally consistent with linear theory within the margin of the sampling variability and the accuracy of the corrections applied. Corrections were needed due to the time delays caused by the sensor systems as well as by the distance between wave gauges and velocity meters.

(3) The wave direction results clearly show refraction effects. The spreading of the waves has a minimum at the peak frequency and decreases in onshore direction. Shortcrestedness decreases the magnitude of the radiation stress. Prediction of the radiation stress by unidirectional linear theory leads to an overestimation of 45 % at negligible turbulent energy rates and of 30 % at higher rates. These percentages reduce to 40 % and 20 % after correction for the effects of shortcrestedness.

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