VERIFICATION OF A WAVE REFRACTION MODEL UTILISING RECORDED AND OBSERVED WAVE DATA

BY G HENDERSON[1] and N B WEBBER[2]

SUMMARY

There are few references in the published literature to the verification of wave refraction models utilising field data. More often, such models have been compared to the results of analytical solutions or using laboratory models.

This paper reviews the present state of knowledge of such verifications and describes a method which has been successfully employed at a coastal site in the central English Channel. The procedure involves hindcasting recorded Waverider Buoy wave information from a nearshore region to deep water. A comprehensive coverage of wind data has been utilised to provide the offshore wave approach direction.

Wave orthogonals have then been tracked inshore and the breaking wave heights and directions compared with observed data.

The results show reasonable comparison where the waves are free from diffraction. However, for oblique wave attack, diffraction around headlands produces evident anomalies.

1 INTRODUCTION

In many coastal or marine engineering problems wave refraction models are employed to determine the wave pattern throughout the nearshore region for a range of offshore wave conditions. But they are by no means precise tools and if the wave refraction model is to play an important role, then some critical assessment of its validity is needed. In many cases small variations of predicted wave height and direction from those actually occurring can produce quite different results. In the present case, the wave refraction model was to be used to make estimates of longshore drift but similar applications are made for design and site selection of harbours, breakwaters and offshore structures (Skovgaard and Bertelsen, 1974).

There are few references to the verification of a wave refraction model utilising field data. In the majority of cases the computed height and direction of orthogonals are compared with known analytical results or correlated with laboratory data. However, an important question is how well a real sea spectrum of wave frequencies, heights

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1. Post-doctoral Researcher, Department of Civil Engineering, University of Southampton, UK.

2. Senior Lecturer, Department of Civil Engineering, University of Southampton, UK.

and directions can be approximated by a single selected frequency and direction in a wave refraction model.

More recently, the direction of wave trains has been observed from radar stations and related to computed wave patterns. Such an instrument was not available in the present instance and, in any case, this would not provide information regarding wave heights. Wave directions may also be examined on aerial photographs, but such flights are seldom made in high wind and hence wave conditions when they would be of most value. Three sets of aerial photographs have been obtained for the region concerned and these were compared with wave patterns from the wave refraction model. However, they do not verify the model and in fact result in more questions than answers.

Having reviewed some of the methods described above, it was decided that a new technique using actual field data was required. This was achieved utilising the wave recordings obtained from a Waverider Buoy stationed near the centre of the modelled area and daily beach observations of breaking wave height and direction. The results of this study also provided useful information regarding the relative accuracy of computed wave directions and heights for waves with varying shoreline approach angles.

2 WAVE REFRACTION DIAGRAMS

The plotting of wave refraction diagrams is fairly commonplace in most countries of the world. Early procedures were to employ graphical techniques (Johnson et al, 1948), although, today, computers are almost invariably employed.

The method of wave refraction has been considered in detail by Henderson and Webber (1979(a)). Briefly wave refraction is analogous to the refraction of other types of wave such as light and sound. In these circumstances for a parallel contoured seabed Snell's Law is applicable where

$$\frac{c_1}{c_2} = \frac{\sin \alpha_1}{\sin \alpha_2} \tag{1}$$

where c_1, c_2 are wave celerities at locations 1 and 2, and α_1, α_2 are the corresponding angles made by the wave crest with the bed contour.

With a knowledge of seabed depths the refraction behaviour may be analysed and plotted in the form of a diagram.

Wave heights may be obtained by considering that the rate of transmission of energy remains constant between adjacent orthogonals. Thus, by equating wave power at the two locations, it follows that:

$$\frac{\rho g}{8} H_1^{\,2}\, b_1\, c_{g1} = \frac{\rho g}{8} H_2^{\,2}\, b_2\, c_{g2} \tag{2}$$

or
$$\frac{H_1}{H_2} = \left[\frac{b_1}{b_2}\right]^{\frac{1}{2}} \left[\frac{c_{g1}}{c_{g2}}\right]^{\frac{1}{2}} \qquad (3)$$

or
$$\frac{H_1}{H_2} = K_R\ K_S \qquad (4)$$

where K_R, the coefficient of refraction is $(b_1/b_2)^{\frac{1}{2}}$

and K_S, the coefficient of shoaling is $(c_{g1}/c_{g2})^{\frac{1}{2}}$

Thus, it is possible to evaluate all the wave characteristics at any point in the refraction diagram, which may, if desired, be related to the incident wave height H_o in deep water. But in this procedure certain assumptions are made:

(i) waves are of constant period, small amplitude and monochromatic, so that linear wave theory is applicable.
(ii) direction of wave advance is perpendicular to the wave crest.
(iii) changes in the bed topography are gradual.
(iv) effects of currents, local wind and reflection from bed or shoreline are negligible.
(v) wave energy is confined between orthogonals and remains constant; thus there is no viscous dissipation of energy.

Consequently, the refraction analysis is more appropriate to long period swell than it is to short crested storm waves. On the other hand, the refraction diagram occupies a relatively greater area with consequently more scope for minor divergencies.

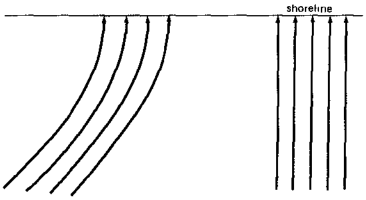
3 METHODS OF VERIFICATION

3.1 Analytical

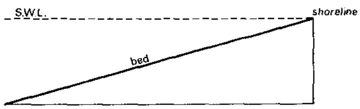
The direction and height of wave orthogonals passing over regular known bed forms can be derived from the governing equation. A commonly used cross-section is a uniformly sloping bed with parallel contours as shown in Fig. 1 with the resulting orthogonal propagation. For orthogonals impinging at right angles to the bed contours no refraction takes place, while for the oblique path the orthogonals refract to impinge at right angles to the shoreline.

A more severe test for wave refraction is shown in Fig. 2 for movement towards a circular island. In this case the wave orthogonals are again refracted to impinge at right angles to the island surround. The island can be reduced to the extreme of an isolated point of land shown in Fig. 3.

Fig. 4 shows the orthogonal propagation over a circular shoal and the formation of caustics or crossed wave orthogonals in the lee.

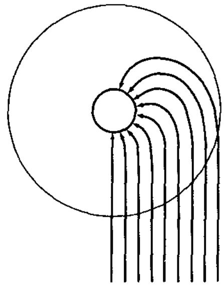


(a) Refraction diagram



(b) Cross-section of sea bed

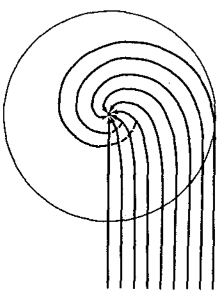
Fig. 1 Wave refraction over a sloping bed with parallel contours



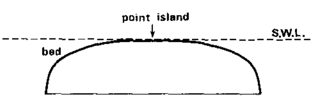
(a) Refraction diagram

(b) Cross-section of the sea bed

Fig. 2 Wave refraction at a circular island

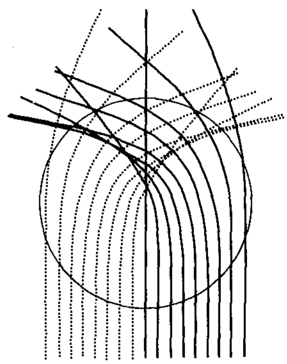


(a) Refraction diagram

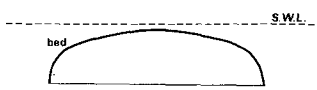


(b) Cross-section of the sea bed

Fig. 3 Wave refraction at a point island



(a) Refraction diagram



(b) Cross-section of the sea bed

Fig. 4 Wave refraction over a circular shoal

The application of analytical verification was first applied by Arthur (1946) for the direction of wave orthogonals propagating over a number of bed forms. This has since been extended to include wave heights as described by Vastano and Reid (1967), Berkhoff (1972 and 1976), Smith and Sprinks (1975) and Radder (1979).

3.2 Laboratory Models

Laboratory models can be used to simulate wave refraction and enable the recording of directions and heights of wave orthogonals. They have been used to check the analytical solutions described above and computer derived wave refraction diagrams. The most commonly used model is that of a circular shoal first investigated by Pierson (1951). Subsequent studies have included that of Chao and Pierson (1970), Ito and Tanimoto (1972), Whalin (1972) and Berkhoff (1976).

3.3 Radar Observations

Radar observations can be used to identify wave patterns and hence verify the directions of wave orthogonals produced in a refraction diagram. However, radar images cannot be used to estimate wave height.

The use of radar to observe wave trains was described by Oudshoorn (1960), Ijima et al (1964), Loewy et al (1976) and Mattie and Harris (1978).

3.4 Aerial Photography

If the modelled region has been surveyed by aerial photography then it is often possible to determine the direction of incident waves and compare these with a wave refraction diagram. However, as with radar observations the wave height cannot be derived from aerial photographs.

The seaward limit of the photography is limited by the requirement of a recognisable section of land on the photograph. Flying at greater heights will increase the sea coverage but the wave crests become more difficult to distinguish. A major problem when photographing wind waves is that flights are often postponed in high wind which is when waves are most pronounced. This limits the applicability of this method for wind wave verification. Swell waves can more readily be photographed in lower wind speeds, but often the sea surface disturbances are so small that they cannot be easily recognised.

Bryant (1974) has shown reasonable agreement between aerial photographs and wave refraction diagrams for a wind wave and a swell wave case. With this exception no other such comparisons between aerial photography of real sea waves and wave refraction diagrams could be found in the published literature.

3.5 Observed and Measured Wave Data

Although radar observations and aerial photographs can be used to validate the directions of computed wave orthogonals, the verification of wave heights cannot be made for the case of real sea data. Few references to this topic exist but it appears to be a problem which is undergoing current investigation.

Bryant (1979) has shown a reasonable correlation between breaker wave heights for long period, unidirectional swell waves in Broken Bay, Australia. Offshore wave height was recorded by a Waverider Buoy 30 km from the shoreline, while deep water wave direction was measured at the Buoy. Data for wind waves was not analysed in their study.

King and Hardcastle (1980) refracted a Pierson-Moskowitz wind wave spectrum from deep water and compared this to measured wave heights at three shoreline target areas in Start Bay, UK. Offshore wave height was obtained from a Waverider Buoy located 6 km from the coastline and deep water direction was provided by radar observations. The comparisons between computed and measured nearshore wave heights were reasonable, although the method is undergoing further refinement.

4 WAVE RECORDING IN POOLE BAY

From June 1974 to March 1979 waves were recorded by a Waverider Buoy at a coastal location in Poole Bay, central south coast of England. The Buoy was located (Fig. 5) in a water depth of 14 m below chart datum and was approximately 800 m offshore from Southbourne. Wave information was transmitted from the Buoy to a receiver unit at Boscombe Pier approximately 3 km distant, and waves were recorded for 20 minutes every 3 hours. The wave data was analysed by the Tucker-Draper method (Tucker, 1961 and Draper, 1963) to record parameters such as H_s, H_{max}, T_z etc.

Throughout the operation of the Waverider Buoy two or three observations of the breaking wave height and direction were made at the beach each day. The wave height was estimated to the nearest 10 cm by observing the average peak to trough breaking wave height against a groyne with planks spaced 30 cm apart. Due consideration was given to the tidal height at the time of recording such that the breaking waves were observed. Wave direction was recorded to the nearest 1^o using a prismatic compass, the angle between the wave crests and shoreline being recorded. The coastline at this location faces almost due south.

5 THE WAVE REFRACTION METHOD

There are a number of wave refraction methods designed for computer application and many of these have been reviewed by Skovgaard et al (1975). In the present case, the Hydraulics Research Station method was employed which computes the direction of wave orthogonals over a grid of water depths covering the region of interest (Brampton, 1977). This method has been extended to include the calculation of refraction and shoaling coefficients at any position along a wave orthogonal.

Two grids of water depths were used in the present analysis as shown in Fig. 6. The coarser offshore grid extended 50 km south of the Bay shorelines to a depth contour of about 60 m. This was the location

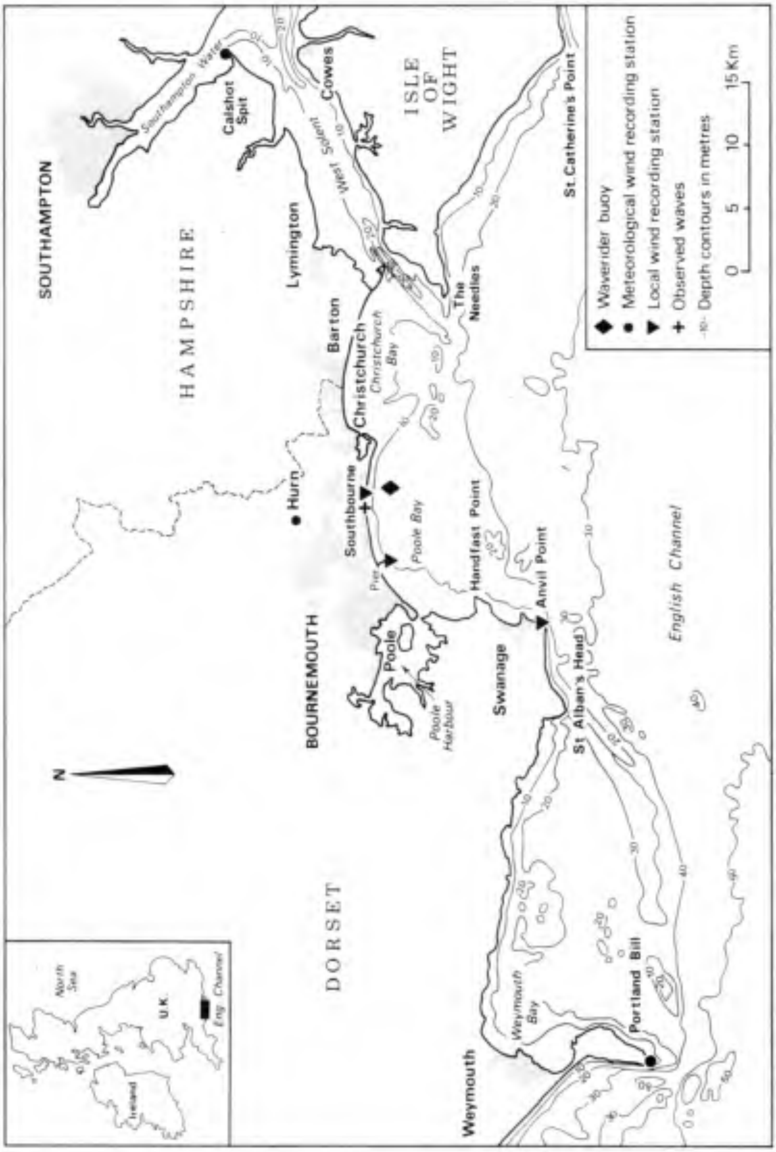


Fig. 5 Location map

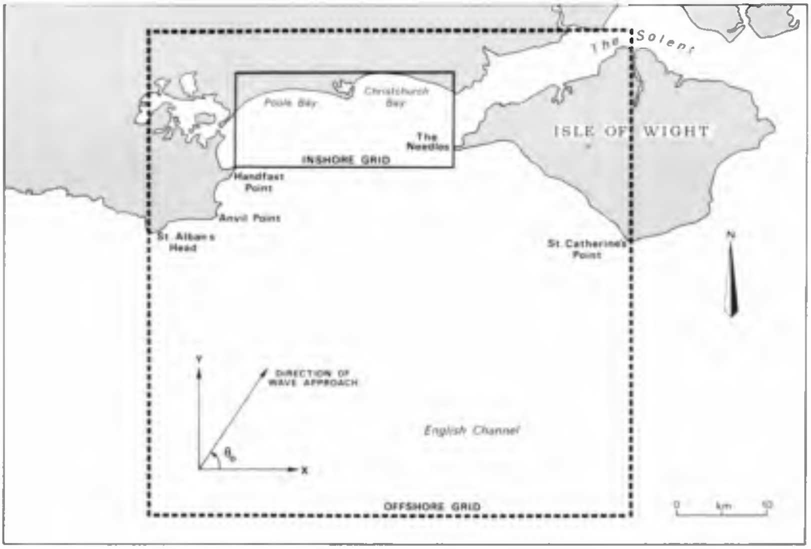


Fig. 6 The two grids of water depths

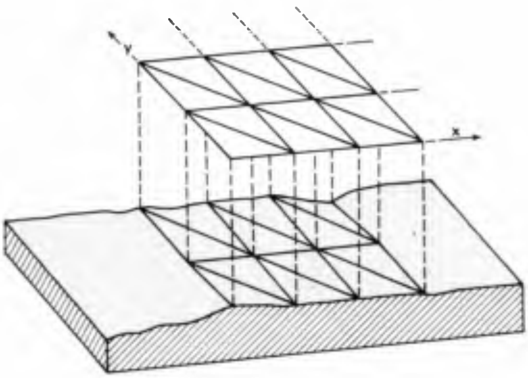


Fig. 7 Schematic representation of sea bed

of deep water for all waves up to 9 seconds period. At approximately the position of the 20 m depth contour, some 10 km from the shoreline, a finer inshore grid was used. Wave orthogonals travelling from deep water over the offshore grid were transferred to the inshore grid over which they moved to the shoreline.

The grids were aligned in the north-south, west-east direction. The bathymetry in the region of interest generally changes more rapidly in a north-south direction and so a rectangular shaped grid element was chosen with greater dimensions in the west-east direction. The offshore grid element size was 1 km west-east by 250 m north-south. For the inshore grid the element size was reduced to 125 m west-east by 31.25 m north-south. The grid of depth values was expressed relative to mean sea level, but a facility was introduced to add or subtract any value to reduce the depths to any tidal condition.

A wave orthogonal originating in deep water with a known period was propagated towards the shoreline. The direction of wave approach was expressed as the anticlockwise angle in degrees made by the wave orthogonal and a positive x-axis as shown in Fig. 6.

Assuming a constant wave period the wave orthogonals having traversed the offshore grid were transferred to the inshore grid before impinging on the shoreline. A new wave orthogonal was then originated in deep water.

The wave orthogonal moved in a series of steps through a set of right-angled triangular elements having vertices at the grid points as shown in Fig. 7. At each step the refraction and shoaling coefficients were computed which permitted the wave height to be calculated using Equation (4) where location 2 is in deep water, thus

$$H_s = K_R K_S H_{so} \tag{5}$$

The wave orthogonals were stopped at the shoreline when the wave height H_s was related to the water depth, d, by the breaking condition (Munk, 1949)

$$H_s = H_{sb} = 0.78d \tag{6}$$

The breaking wave height H_{sb}, and direction of wave orthogonal approach relative to a positive x-axis, θ_b, were stored. The final wave orthogonal co-ordinates could be adjusted by changing the co-ordinates of the orthogonal at its point of origin in deep water.

It was a simple procedure to change the method of forward progression of wave orthogonals to a back-tracking process. A series of wave orthogonals radiating from a particular point could be transferred in a "fan" to deep water. This enabled wave heights recorded at the Waverider Buoy site to be hindcast using refraction and shoaling coefficients to a deep water wave height for a particular offshore approach angle.

6 COMPARISON WITH AERIAL PHOTOGRAPHS

A number of organisations were approached with regard to obtaining aerial photographs of the region under study. The only available photographs were the property of the Ministry of Defence and, after inspection, it was apparent that only three flights had yielded recognisable wave patterns from a reasonable portion of the Bays. These had been flown on the 7th July 1959, 6th July 1960 and 20th November 1962. Specimen photographs for 7th July 1959 are shown in Figs. 8 and 9.

The offshore wave approach direction and period were required to simulate the wave patterns on the computer. Since no directional wave data was available it was necessary to estimate this value from wind data, assuming that wind waves would follow the path of the wind.

The mean hourly speed and direction during the day of the flights was available from the Meteorological Office wind station at Calshot, located as shown in Fig. 5. As an example, on 7th July 1959 winds were approximately 12 knots (6 m/s) from a direction of 150^o from a positive x-axis for seven hours centred about mid-day. The wave approach angle in deep water was assumed to be from this direction. The significant wave height was estimated using an expression relating U to H_s as described by Henderson and Webber (1979(b)) for this particular site and given by:

$$H_s = 8.26 \times 10^{-3} U^{1.627} \tag{7}$$

for onshore winds greater than 9 knots (4.5 m/s) where U is the wind speed in knots and H_s is in metres.

A scatter diagram (Henderson and Webber 1979(c)) was used to show that the estimated value of H_s of 0.5 m, in this case, was associated with an upward zero crossing wave period, T_z, of 4.5 s.

Fig. 10 shows the computer simulated wave orthogonals for a wave period of 4.5 s and an offshore approach angle of 150^o from a positive x-axis.

When Figs. 8 and 9 are compared with Fig. 10 reasonable comparability can be seen at locations where wave crests can be identified on the aerial photographs. The wave direction throughout the modelled area and at the shoreline are well depicted by the refraction diagram with the exception of the "shadow region" in Christchurch Bay. In this area, wave diffraction has occurred at the Needles bringing more energy into the Bay than is shown on the refraction diagram which ignores the effects of diffraction. Regions of crossed wave orthogonals can be identified from the aerial photographs in approximately the same positions as those in the refraction diagram.

A comparison of the results of 6th July 1960 and 20th November 1962 for approach angles from the south-west give similar results. Fig. 11 shows the refraction diagram modelling conditions on 6th July 1960 and it is evident that, without diffraction, no disturbances in

Fig. 8 Aerial photograph for 7th. July 1959 (British Crown Copyright Reserved / D.O.E. Photograph)

Fig. 9 Aerial photograph for 7th. July 1959 (British Crown Copyright Reserved / D.O.E. Photograph)

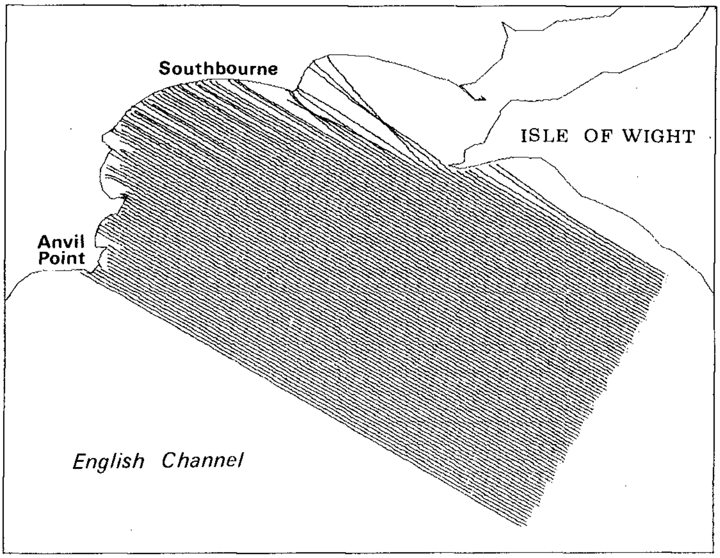


Fig. 10 Computer simulated wave orthogonals for 7th. July 1959

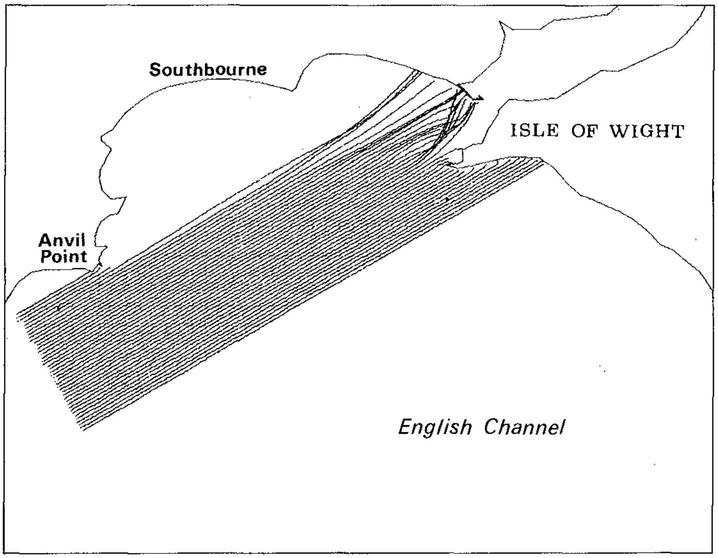


Fig. 11 Computer simulated wave orthogonals for 6th. July 1960

the lee of the headland at Anvil Point are predicted - a feature contrary to actual conditions shown in the aerial photographs.

Althouth the general conclusions noted above are useful, no detailed analysis has been possible. The aerial photographs are difficult to interpret because the sea surface is reasonably calm and no information is given concerning the variation of the angle at the shoreline as compared with those predicted in the model. In addition, as noted above, no indication of the comparison of wave height values is given. The aerial photographs have, therefore, provided little confidence in the refraction diagram especially in the important region at the shoreline.

7 VERIFICATION UTILISING RECORDED AND OBSERVED WAVE DATA

The aerial photographs having provided only some general indications as to the applicability of the wave refraction model and with no radar observations available, it was necessary to verify the refraction model using some alternative procedure. The method adopted made use of the recorded Waverider Buoy data, the observed breaking wave data and wind information from local Meteorological Office Stations as well as observed winds from coastguards and other personnel.

Listed tables of recorded wave parameters from the Waverider Buoy were inspected on a daily time basis. To avoid the difficulties of simulating swell waves with regard to offshore direction and in an attempt to select unidirectional wind wave trains only, limitations were placed on data that was considered of use in the present analysis. These were:

(1) Consecutive values of H_s must be rising from a sea state with H_s less than 0.5 m . Values of H_s must return to below 0.5 m before data is considered.
(2) The values of H_s must exceed 1 m.
(3) It was evident that the maximum available water depth at the beach site, taking into account tidal variation, was 2.5 m. Hence the value of H_s should be less than 2.0 m.
(4) A beach observation of breaking waves must have been made at approximately the same time as the data recording from the Waverider Buoy.

A total of 76 records were classified as having satisified these conditions. The data available for each record for a known day and time consisted of the values of H_s and T_z at the Waverider Buoy site and the observed breaking wave height, H_{bo} and breaking wave angle, θ_{bo}.

At the particular time of each of these records, wind data from six sources was considered in detail as shown in Fig. 5. Portland Bill, Hurn and Calshot Spit are authoratative Meteorological stations recording mean hourly wind speeds and directions. Anvil Point wind data, recorded at the Lighthouse Station, consisted of direction estimated by compass and speed measured by an anemometer at three hourly intervals corresponding to the recording of wave data by the Waverider Buoy. The Bournemouth Pier data consisted of an estimated direction and speed at approximately mid-day. The Southbourne data was recorded by the wave observer and comprised wind direction and speed.

Utilising this wind data a fairly comprehensive picture of the wind field was available. With consideration given to the fluctuation of wind direction over the preceding six hours, it was possible to estimate the offshore approach angle of the wind to the nearest 10^o. With the conditions listed above, the waves were assumed to follow the wind thus providing the vital offshore wave approach direction, θ_o.

For a particular comparison, the recorded H_s was hindcast to deep water using values of K_R and K_S, and to correspond to the correct angle θ_o. The wave period was assumed constant and equal to T_z. This yielded the deep water significant wave height H_{so}. The grid depths were adjusted to be equivalent to the tidal level at the time of the comparison. For some of the more acute angles (e.g. $\theta_o = 30^o$) it was impossible to track the wave orthogonals towards the shoreline from deep water and obtain sufficient refraction for the waves to impinge at the correct location. In such cases the wave orthogonals were started within the Bays and so the resulting waves would be more locally generated.

With values of H_{so}, T_z and θ_o wave orthogonals were run at an offshore spacing of 50 m until they were stopped at the breaking condition. Provided they had reached the correct location at the shoreline, a region of 250 m width at the Southbourne beach observer site, the values of H_{sb} and θ_b were stored and averaged.

These wave parameters were compared with the observed values of breaking wave height, H_{bo} (equivalent to the significant wave height at breaking) and the breaking wave approach angle θ_{bo}.

8 COMPARISON OF BREAKING ANGLES

The observed (θ_{bo}) and computed (θ_b) breaking angles made by the wave orthogonals with a positive x-axis at the shoreline have been plotted in Fig. 12.

There are three interesting portions to the graph:

(1) For angles of θ_{bo} between 76^o and 100^o there is reasonable agreement between the two values with differences of 3^o at the most.

(2) For angles of θ_b less than 90^o the value of θ_b is less than θ_{bo} by an average of 3.6^o, although variations of up to 14^o are illustrated. This suggests that the real sea waves undergo greater deviation than is predicted in the model, such that the wave crests are more parallel to the shoreline at breaking.

(3) For angles of θ_b greater than, or equal to 90^o, the value of θ_b is greater than θ_{bo} by an average of 7.2^o although individual points differ by as much as 20^o. A similar implication to that in (2) can be made in that the modelled orthogonals are more perpendicular to the coastline at breaking.

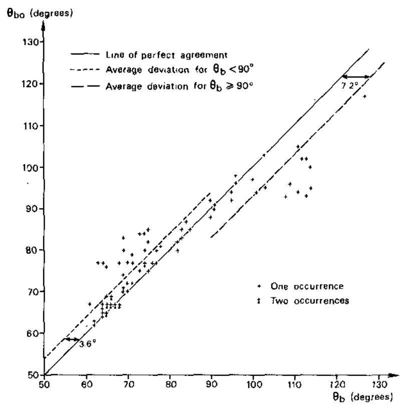


Fig. 12 A Comparison of observed and predicted breaking approach angle

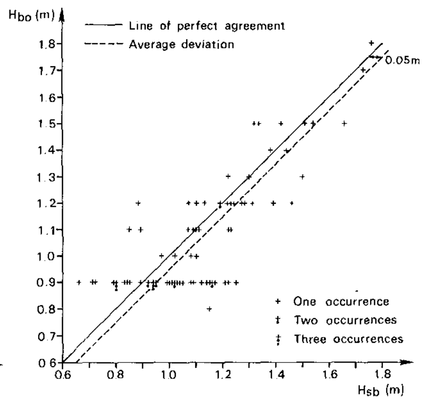


Fig. 13 A Comparison of observed and predicted breaking wave height

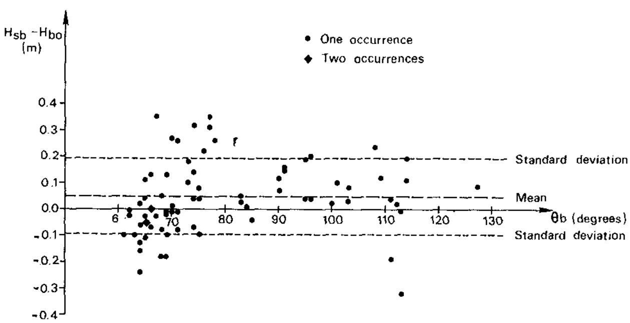


Fig. 14 The difference between predicted and observed breaking wave height as a function of predicted breaking approach angle

These results may indicate that the omission of diffraction effects produce modelled wave orthogonals which undergo less movement than is recorded in the field. This is most apparent when wave orthogonals enter the Bay area at oblique angles, there being only minor deviations for approach angles close to due south. It appears that wave orthogonals are modelled more accurately with westerly than easterly components, probably because of the more complex bed topography and greater occurrence of shoals for waves from easterly directions.

It should, of course, be noted that the method of verification is subject to certain inaccuracies, especially with regard to the prediction of the offshore approach angle θ_o which was approximated to the nearest 10^o.

9 COMPARISON OF BREAKING WAVE HEIGHTS

Fig. 13 shows a plot of the observed (H_{bo}) and computed (H_{sb}) breaking wave heights. There is a fair degree of scatter of the points but, on average, values of H_{sb} are 0.05 m greater than H_{bo}.

In Fig. 14 variations between H_{sb} and H_{bo} have been plotted against θ_b. Also shown is the mean of the wave height difference and the standard deviation. The graph shows that for values of θ_b close to due south the wave height values are more comparable but that greater deviations occur as the approach angles become more oblique. This confirms the comments already made in that for approach angles close to due south when diffraction effects are least, the model reasonably predicts conditions at the shoreline. However, for orthogonal approach directions with westerly or easterly components there is a lateral shedding of wave energy, resulting in a smaller wave height at the shoreline than is predicted by the model.

10 DISCUSSION

Already a number of possible inaccuracies have been suggested but it is considered that the model input data was expressed as precisely as was possible without additional instrumentation. One of the major sources of error was in obtaining an offshore approach angle. The method described using incident wind direction appears to have provided a reasonably good value but there are no data to confirm this.

A further study was undertaken to give an indication of the effect of grid size on the angle of approach of the breaking waves. The inshore grid was made sixteen times coarser by increasing the element size from 125 m by 31.25 m to 1000 m by 250 m. The effect for a variety of offshore approach angles and wave periods was that the breaking wave orthogonal approach angle was increased by less than one degree using the coarser grid. In addition, the same angle showed much smaller differences for a grid four times coarser than the one employed for the analysis. Thus, it seems that the wave refraction model is not unduly affected by changes in grid size for the region considered.

The verification has been undertaken for only a small portion of the modelled area at a relatively exposed position. An indication has been given of possible correction factors to breaking wave direction and height to bring the model more in line with real wave conditions. However, it would be very difficult to predict similar correction factors for other locations in the modelled region. Certainly the situation in Christchurch Bay would be more complex because water depths are less and a number of shoals exist offshore.

It is, however, evident that wave heights and approach angle parameters could be obtained more accurately which would be of benefit to calculations such as those for longshore drift using the C.E.R.C. formula.

In the present analysis, care has been taken to select recorded and observed data pertaining to unidirectional wave trains. For the more complex situation of superimposed waves from varying directions, no conclusions can be drawn concerning the breaking wave height and direction - apart from the fact that the wave refraction model itself cannot reproduce such conditions.

Although swell waves were not considered in the present analysis it would be possible to undertake a similar comparison provided an offshore approach angle can be assumed or recorded. This is often a fairly simple task since swell waves are unidirectional and, in addition, would be modelled more realistically by the refraction analysis.

Finally, the major criticism of the present model is the omission of diffraction. This is because other phenomena which would change wave height and direction in shallow water are considered to be relatively unimportant in the present case. Friction and percolation effects are probably small and currents, which rarely exceed 0.5 m/s, would cause only minor modifications.

11 CONCLUSIONS

There are few references to the verification of wave refraction models using field data in the published literature, despite the fact that such models are widely used in engineering practice.

A study of aerial photographs show that some general comparisons of wave patterns with refraction diagrams can be made, but that specific details cannot be examined.

A method of verification of such wave refraction models has been described in this paper. It utilises recorded and observed wind and wave data, and could be readily applied in other regions of the world.

At the site it is evident that for unidirectional southerly waves, the observed and computed breaking height and angle are reasonably comparable. For waves approaching with westerly or easterly components, the effects of diffraction are such that the actual wave crests impinge more parallel to the shoreline than is predicted in the model and with slightly lower wave heights. The mean variation in wave breaking angle is 3.6^{o} and 7.2^{o} for westerly and easterly waves, respectively and a breaking wave height difference of 0.5 m is suggested.

The authors would like to stress the importance of such verifications if wave refraction models are to be used with confidence. There is also a need to verify such models using field data in areas of shoals and complex bed topography where caustics may be formed.

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REFERENCES

Arthur, R.S. 1946. Refraction of water waves by islands and shoals with circular bottom contours. Trans. Am. Geophys. Union. Vol. 27, No. 2. pp 168-177.

Berkhoff, J.C.W. 1972. Computation of combined refraction-diffraction. Proc. 13th Conf. on Coastal Eng., Vancouver, Canada. pp 471-490.

Berkhoff, J.C.W. 1976. Mathematical models for simple harmonic linear water waves: wave diffraction and refraction. Delft Hydraulics Lab. Pub. No. 163. 111 pp.

Brampton, A.H. 1977. A computer method for wave refraction. Hydraulics Research Station, Wallingford, U.K. Rep. No. INT 172. 48 pp.

Bryant, E.A. 1974. A comparison of air photograph and computer simulated wave refraction patterns in the nearshore area, Richibucto, Canada and Jervis Bay, Australia. Maritime Sediments. Vol. 10, No. 3. pp 85-95.

Bryant, E.A. 1979. Comparison of computed and observed breaker wave heights. Coastal Engineering. Vol. 3. pp 39-50.

Chao, Y.Y. and Pierson, W.J. 1972. Experimental studies of the refraction of uniform wave trains and transient wave groups near a straight caustic. Jour. Geophys. Research. Vol. 77, No. 24. pp 4545-4554.

Draper, L. 1963. Derivation of a "Design Wave" from instrumental records of sea waves. Proc. Inst. Civ. Eng. Vol. 26. pp 291-304.

Henderson, G. and Webber, N.B. 1979(a) The application of wave refraction diagrams to shoreline protection problems: with particular reference to Poole and Christchurch Bays. Q. Jour. Engng. Geol. Vol. 12. pp 319-327.

Henderson, G. and Webber, N.B. 1979(b) Wind-wave relationships for a coastal site in the central English Channel. Estuarine and Coastal Marine Science. Vol. 9. pp 29-39.

Henderson, G. and Webber, N.B. 1979(c) Summary of wave conditions in Poole Bay, 1975-78. Internal Report of Dept. of Civil Eng., Univ. of Southampton, Southampton, U.K. 38 pp.

Ijima, J. Takahashi, T. and Sasaki, H. 1964. Application of radars to wave observations. Proc. 11th Japanese Conf. on Coastal Eng. pp 81-88.

Ito, Y. and Tanimoto, K. 1972. A method of numerical analysis of wave propagation - application to wave diffraction and refraction. Proc. 13th Conf. on Coastal Eng., Vancouver, Canada. pp 503-522.

Johnson, J.W., O'Brien, M.P. and Isaacs, J.D. 1948. Graphical construction of wave refraction diagrams. U.S. Naval Oceanographic Office, Washington, D.D., U.S.A. H.O. No. 605, TR-2. 45 pp.

King, H.L. and Hardcastle, P.J. 1980. The evaluation of wave refraction calculations using observed wave data. Draft report of Institute of Oceanographic Sciences, Taunton, Somerset, U.K.

Loewy, E., Witthaus, K.G., Summers, L. and Maddrell, R.J. 1976. Data collection and analysis for coastal projects. Proc. 15th Conf. on Coastal Eng., Honolulu, Hawaii. pp 43-59.

Mattie, M.G. and Harris, D.L. 1978. The use of imaging radar in studying oceanwaves. Proc. 16th Conf. on Coastal Eng., Hamburg, Germany. pp 174-189.

Munk, W.H. 1949. The solitary wave theory and its application to surf problems. Annals of the New York Academy of Sciences. Vol. 51. pp 376-462.

Oudshoorn, H.M. 1960. The use of radar in hydrodynamic surveying. Proc. 7th Conf. on Coastal Eng., The Hague, The Netherlands pp 59-76.

Pierson, W.J. 1951. The interpretation of crossed orthogonals in wave refraction phenomena. U.S. Army Corps. of Engineers, Beach Erosion Board. Tech. Mem. No. 21. 83 pp.

Raddar, A.C. 1979. On the parabolic equation method for water-wave propagation. Jour. Fluid Mech. Vol. 95. pp 159-176.

Skovgaard, O. and Bertelsen, J.A. 1974. Refraction computation for practical applications. Proc. Int. Sym. on Ocean Wave Measurement and Analysis, New Orleans, U.S.A. 1974. pp 761-733.

Skovgaard, O., Jonsson, I.G. and Bertelsen, J.A. 1975. Computation of wave heights due to refraction and friction. Jour. of the Waterways, Harbors and Coastal Eng. Div. A.S.C.E. Vol. 101, No. WW1. pp 15-32.

Smith, R. and Sprinks, T. 1975. Scattering of surface waves by a conical island. Jour. Fluid Mech. Vol. 72. pp 373-384.

Tucker, M.J. 1961. Simple measurement of wave records. The Dock and Harbour Authority Vol. 42. p 231.

Vastano, A.C. and Reid, R.O. 1967. Tsunami response for islands; a verification of a numerical procedure. Jour. of Marine Research. Vol. 25, No. 2. pp 129-139.