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A REVIEW OF METHODS FOR REAL-TIME COASTAL WAVE FORECASTING

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ABSTRACT

The report reviews the methods presently available for the prediction of waves at a coast, with particular emphasis on techniques which can be used in real time. The interest in these techniques stems from the increasing awareness, in local district councils and regional water authorities, of the role of wave action in coastal flooding.

It is already normal practice in many parts of the country for regional water authorities to be sent early warning of high tidal levels by the Storm Tide Warning Service. When such a warning has been issued, it falls to local duty officers to decide whether any further action should be taken, perhaps including the evacuation of low lying areas. This decision, however, is heavily influenced by the expected level of wave activity around the time of high water.

On most coasts, modest wave activity occurring at the time of a high tidal level occurring, say, once in 10 years will produce a much more dangerous situation than a 1 in 100 year tide occurring when the weather was calm. It therefore follows that a reliable prediction of wave conditions at a coast at such times will assist in the assessment of the likelihood of flooding.

However, the complicated sea bed contours along many coasts often make it a difficult task to convert estimated wave heights offshore into corresponding values near the shoreline. This problem is made more difficult by the limited time available to the duty officer between receiving a storm tide warning and deciding on an appropriate course of action.

This report reviews the possible techniques which might be of use, and recommends a method which minimises calculations in real time. Instead, results are provided in the form of look-up tables or graphs, sets being provided for key locations along a coast, each covering a wide range of tidal levels and wave conditions offshore. This technique is relatively cheap to apply, and can also be extended for use in design calculations if required.

CONTENTS

FIGURES

1 INTRODUCTION

Much of the theoretical development which forms the basis of methods to predict wave conditions close to a coast has been presented in previous reports (eg Refs 10, 12), and is therefore not reproduced here. This report concentrates instead on an overview of those methods which may be useful to engineers who wish to forecast wave activity in real-time. The use of such techniques would be to predict wave heights and periods perhaps 4-6 hours ahead of their occurrence, and they are likely to be combined with results from tidal forecasts such as provided by the Storm Tide Warning Service. Armed with the prediction of water levels and wave conditions, it should then be possible for the engineer to make an accurate judgement on the likelihood of overtopping, flooding, and the necessity for any evacuation.

The specific impetus for producing this review stemmed from a request to produce material for a manual being prepared by the Institution of Water Engineers and Scientists (Ref 13); this report expands and extends the discussion presented there. In general outline, Chapter 2 deals with the prediction of wave in deep water, followed by a description of the effects of shallow water in Chapter 3. An important aspect of the use of such methods is their accuracy and this aspect is considered in Chapter 4 together with some comments on the costs and benefits of their use. Finally in Chapter 5 a summary and some overall conclusions are presented.

2 DEEP WATER WAVE FORECASTING

Apart from simple, empirical methods for predicting extreme wave heights during severe storms, the first attempts to forecast wave conditions from wind data in the UK were made during the Second World War. Not surprisingly these early methods were rather crude, partly because of the lack of accurate wave recording instruments. Almost continuous research over the last 40 years has, however, greatly increased the accuracy and sophistication of the methods available. Nevertheless, even in deep water, there are still considerable difficulties in making accurate predictions. It is worthwhile reviewing the processes involved and some of the problems encountered.

In the first instance the mechanism by which wind energy is transferred to the sea to form surface waves is highly complex and as yet not completely understood. However, three broad processes have been identified.

- The flow of air over the sea exerts a tangential stress on the water surface resulting in the transfer of energy to the water and the formation and growth of waves. This process is dominant in the very early stages of wave growth.

- Because the air flow is always turbulent over the sea surface, wind eddies are formed and these create rapid variations in the pressure and shear stress on the water surface. When these changes in pressure and shear stress "match" ie, have the same length and velocity as any existing water waves, these will be amplified. This process occurs once water waves have been established.

- When waves of a certain size have been created, the wind can add further energy to the waves by "form drag", ie, by exerting greater force directly on the rear (upwind) side of the crest than on the front face which is sheltered. The maximum wave growth will be obtained when the average wind speed matches the speed of the water waves.

The second of the wave generation processes mentioned above implies that, because of turbulent eddies in the wind, waves with different periods and directions can be created even when the wind has a constant mean speed and direction. As a result the sea state during a storm is always short-crested and irregular. Of course, in most storms both the average wind strength and direction vary in time and space, making the process of wave growth even more complex. Waves created in this way at, or close to the site of interest form an important part of the deep-water wave field. These waves are generally referred to as "wind waves" or "storm waves". Their periods are usually within the range 2 seconds to 16 seconds.

Extreme tidal levels due to surges usually occur in stormy weather making the prediction of wind waves vital at such times. In addition to the wind waves, which predominant around much of the UK shoreline, there are also waves generated further afield which can form a significant contribution to the energy arriving at a coast. These waves are referred to as "swell". Typically they have quite a different character to storm waves due to the long distances that they have travelled. Swell can easily be recognised by the long crests and nearly regular period of the waves. Waves resulting from a storm will travel away from the generation area in much the same way that waves radiate from a point where a stone has been thrown into a pond. At a large distance from the generation area, therefore, the waves will appear to be almost uni-directional and long-crested. These waves will, moreover, usually have only a narrow range of periods. The reason for this is that the waves of different periods travel at different speeds as they propagate away from the generation area. The longer period waves travel more rapidly than the shorter period ones. Therefore, although originally all wave components of different periods exist together in the generation area, in time they separate from one another with the longest period components reaching a distant site first, followed by the shorter period components up to several days later.

The periods of swell waves actually tend to be somewhat longer, say 12 seconds to 25 seconds, than those in locally generated storms. There are two reasons for this. Firstly, there is a certain amount of interaction between wave components as they begin to travel outwards from the generation area. This has the effect of transferring energy from the shorter period components to the longer period ones. Secondly, the shorter period components tend to lose their energy through viscous effects more readily than the longer period waves. This energy loss to short period waves can be quite significant when these waves have travelled large distances.

The extent to which swell waves need to be taken into account in coastal flood warning depends on the location being considered. For example, recent observations of waves off the Outer Hebrides indicate that up to 60% of their energy can be attributed to swell generated in the North Atlantic (Ref 1). For coasts open to waves generated in the Atlantic Ocean, therefore, it may be necessary to include swell in wave predictions. Forecasting swell waves is rather difficult since their height, period and time of arrival usually bears no relation to local wind conditions. In areas such as the Irish Sea, however, only wind waves are likely to be important.

In the following description of methods used for predicting waves in deep water it is convenient, in the first instance, to consider the simplest types of techniques. These assume a constant wind speed and direction over the whole generation area throughout the duration of a storm. In addition, the direction of the generation area is reduced to a single length, measured in the direction of the wind across the area to the point of interest. This length is known as the fetch and usually varies with direction.

The earliest types of wave prediction methods used a combination of simple formulae and empirically determined factors to give the wave height and period for a variety of steady wind conditions. Usually these methods are presented as graphs from which the wave height and period can be read off for a range of storm conditions. Among these methods can be mentioned:-

(i) The SMB (Sverdrup-Munk-Bretschneider) method (Ref 2). This method uses empirical expressions derived from a comprehensive series of observations at locations in the North Pacific, North Atlantic and Great Lakes.

(ii) The Darbyshire-Draper method (Ref 3). This method is based on observations around the UK coast, and is only valid for these areas.

These two methods are usually used to provide an estimate of just the wave height and period.

In addition to these basic methods, it is also possible to use more sophisticated techniques to give information on the wave frequency spectrum, ie, the distribution of wave energy as a function of frequency (the inverse of wave period). The most important of these, for applications around the UK coastline, is the JONSWAP method (Ref 4). This method uses a semi-empirical formula derived from specifically designed experiments carried out in the southern North Sea during the Joint North Sea Wave Project (hence the acronym). The extra information on the frequency spectrum, however, will be lost if the results derived from using this method are simply used to produce forecasting curves.

The advantages of using such curves, from any of the above methods, are speed and simplicity. However, some accuracy is lost by assuming a steady wind and a greatly simplified description of the geometry of the generation area. A typical method of simplifying the shape of the generating area is to just take the length across it in the wind direction. This latter simplification can be avoided if the point at which predictions are required is known in advance, and this is likely to be the case in the context of flood warnings. In this situation, it is possible to improve on, say, the general JONSWAP method by incorporating more detailed information in the geometry of the generation area.

A suitable method for this purpose was proposed by Seymour (Ref 5). He suggested that a set of radial fetch lines should be drawn at say 10° intervals originating from the point at which predictions are required (Fig 1). Wave conditions at the 'target' point are calculated by summing contributions arriving along each ray which is within 90° of the wind direction. Such calculations can be carried out rapidly with a simple computer program for a wide range of hypothetical wind conditions. The results obtained can then be presented as a set of site-specific forecasting curves. Each graph would give predictions for a fairly narrow range of wind directions, and the whole set can be prepared well in advance of being required for application.

Such a method is certainly an improvement on using more general forecasting curves, and may be sufficiently accurate in many areas for flood warning purposes. It also has the advantage of being very simple to use. However, it cannot deal properly with wind conditions which may vary either in space or time during a storm, nor can it predict the arrival or intensity of swell.

To tackle these more complicated problems it is necessary to turn to correspondingly more sophisticated numerical models. Generally, such models use a finite difference grid over the generation area, and require wind conditions to be specified at regular intervals both in space and time.

The more detailed specification of wind conditions will certainly improve the accuracy of wave predictions, but many of the advantages of the simple methods are lost. In particular it becomes impossible to carry out calculations for all possible wind fields, and this prevents carrying out calculations well in advance of a possible flood event. As a consequence, it becomes necessary to run such a model in real time in order to provide predictions for flood warnings.

A large variety of computer models have been developed in recent years to tackle this type of problem, and a number have been recently reviewed by MIAS (Ref 6). It would also be possible for a potential user to develop a specific model for his own particular application. However, the requirement to predict swell can be a major complicating factor. In view of this it is likely that most users will find the existing fine-mesh wave model (Ref 7) run by the Meteorological Office to be the most suitable way to provide the information they require. This model covers the whole North-West European continental shelf and further afield, at a grid spacing of 25km. In addition, it adjoins a coarser mesh model which covers the North Atlantic and provides information on waves generated in that area and travelling towards the British Isles.

The fine-mesh model is run twice a day and provides deep water storm wave and swell predictions for up to 36 hours in advance at 3 hourly intervals. These results, together with forecasts of wind conditions, are then distributed using the Public Switched Telephone Network (PSTN) to subscribers, by a document facsimile system. The mesh size is generally sufficient to represent the shape of the generation areas accurately, and the model also incorporates the effects of water depth (Ref 7).

As with the other models described above the fine mesh wave model is not designed to include the effects of near-shore topography where both depth and wave wind conditions may vary substantially over lengths of a kilometre or less. Nevertheless it may, on exposed coasts, produce impressively accurate predictions of the wave heights and the time of their occurrence (see Fig 2 showing a comparison between model predictions in January 1984 at Seaford in the English Channel and recorded near-shore wave heights). More often, however, the coastal topography may provide considerable shelter, and it will be found that deep-water wave predictions will substantially over-estimate near-shore wave heights. This problem is discussed next.

3 PREDICTING WAVES CLOSE TO A COAST

The previous section described a variety of methods which predict the growth and propagation of waves in the open sea. Most of these models, however, do not explicitly allow for the effects of changing water depth. The JONSWAP model, for example, was developed and validated using measurements from the southern North Sea. It cannot be readily adopted to give accurate predictions of wave growth in a deep ocean or in very shallow water adjacent to a coast. Even the Meteorological Office fine-mesh wave model, which does include shallow water effects, can only do so at a coarse scale in the context of coastal bathymetry.

Close to the shoreline, however, waves that have been generated over many tens or hundreds of kilometres are substantially modified and finally destroyed in a very narrow strip of shallow water. In this section, therefore, attention is turned to describing both the processes that occur in this important area and the methods available to model them. As in previous sections, the main purpose of this review is to identify methods of calculations which can be applied quickly and easily in order to produce results in real time.

There are a large number of processes which affect waves as they approach a coast and they can be conveniently grouped into two classes. Firstly there are the phenomena which only alter the spatial distribution of wave energy over the sea surface. These processes include shoaling, refraction and diffraction and are termed 'non-dissipative'.

In contrast, there are a variety of 'dissipative' processes which alter the total energy of waves as they travel shorewards, converting it first into turbulence and hence into heat and movement of the sea bed material. Wave breaking and dissipation due to frictional effects fall into this category.

Most of the shallow water processes mentioned above are usually only significant in a narrow strip of water immediately adjacent to the coast. Typically this strip is only a few kilometres wide and within this region it is usually reasonable to ignore any increase in wave energy due to wind action, at least in comparison with the rapid decreases caused by refraction or frictional dissipation. This simplification also reduces the complexity of subsequent calculations.

As with models for wave growth in the open sea, there are a variety of techniques for predicting the change in wave characteristics in shallow water. For sea bed contours that are straight and parallel it is possible to use a very simple graphical method to calculate the shoaling and refraction of waves of uniform period and direction (Ref 8). However, this idealised situation is unlikely to be even a reasonable approximation to conditions around our coastline, especially during storms. In consequence, it becomes necessary to construct a specific numerical model for each stretch of coast that needs to be considered. For flood warning purposes this means that the model has to be set up well in advance of its use in real time.

In choosing a suitable model for calculating shallow water effects, the engineer is faced with a variety of decisions. First it is necessary to define the area covered by the model. Generally speaking, a single model will cover perhaps 5 - 10km of the coastline, although on straight coasts which have uniform offshore wave conditions, this dimension may be increased whilst retaining a manageable model. Along the UK coastline, however, the often rapid changes in beach orientation and wave exposure will usually lead to the use of several small models rather than a single large one.

The seaward limit of any model will have to be defined carefully, especially in areas such as the North Sea or Irish Sea. Here it is impractical to choose an offshore boundary seawards of which waves do not refract at all, since the area so defined would include most or all of the area in which the waves are generated. The choice of the offshore boundary is therefore a compromise depending on the distance offshore and the character of the likely wave conditions. As a very rough guide, in shallow seas, the seaward limit of a shallow water model corresponds to a minimum water depth of 15m - 25m. On Atlantic coasts where the wave periods tend to be greater, the offshore boundary would normally be further offshore in depths of perhaps 40m - 60m.

Between this offshore boundary and the coast it is necessary to represent the sea bathymetry by setting up an internal grid mesh, usually using rectangular elements. The longer sides of these elements are aligned roughly parallel to the coast. This reduces computational effort whilst retaining accuracy. The dimensions of the grid elements will depend on the irregularity of the sea bed contours, but typically vary from 500m in deeper water down to perhaps 50m close to the coast.

Having decided on a suitable grid system, it is then necessary to decide on the physical processes that need to be taken into account. Almost without exception both wave refraction and shoaling will be included, since these are usually regarded as the most important of the shallow water phenomena. If a particular area of interest is partly sheltered by a headland or an offshore island, it may be necessary to include wave diffraction effects as well. If these are the only important processes, then the production of results for use in real-time forecasting is greatly simplified, since linear wave theory can be used. This aspect is discussed in more detail later.

In areas where the sea bed slope is very shallow, or where an offshore bank crest is close to the water surface, it may be necessary to include dissipative effects such as wave breaking or attenuation due to friction. To do so requires a more complex model, and a very substantial increase in computational effort to produce suitable results in advance of real-time forecasting.

The next decision concerns the specification of the wave and tidal conditions which are to be input to the model. This includes choosing one or more tidal elevations (including the effects of a surge), and perhaps providing information on tidal currents (at the chosen water level) if they are sufficiently strong to alter the wave propagation pattern.

For each or all of these 'flat surface' situations, it is then necessary to specify the incident wave conditions at the outer edge of the grid system. At the minimum, some estimate of the offshore wave height, direction and period are required to enable the subsequent calculations to be carried out. In areas where swell is important, as well as locally generated seas, this type of information is needed for both types of waves. However, it is usually necessary to provide rather more than this very basic information to obtain accurate answers. For example, most numerical models now deal with wave conditions specified as directional spectra, ie with the wave energy defined as a function of both frequency and direction. Although this improves the accuracy of the modelling of shallow water effects, it clearly also increases the computational effort required. This becomes a disadvantage for real-time forecastng, unless a substantial portion of the calculations can be carried out in advance.

At this stage it becomes useful to concentrate on a single modelling technique which is likely to be useful in real-time flood forecasting. Whilst discussing the particular method, however, other possible approaches are compared both in terms of their accuracy and their ease of application.

The method chosen as an example includes the effects of both wave refraction and shoaling, and produces results at a single location, usually chosen close to a coast. It can also be adapted, if necessary, to include diffraction around, say, an offshore island. The model uses wave 'rays' ie, lines perpendicular to the wave crests, and tracks the ray paths seawards from the chosen point towards deep water. Because the ray paths are reversible, this gives information on the way that wave energy travels from the seaward edge of the model grid to the point of interest. This technique was originally suggested by Dorrestein (Ref 9) but has since been considerably extended by many organisations and can now also deal, for example, with the effects of tidal currents (Refs 10, 11).

A significant advantage of this technique is that the whole computational effort is directed towards obtaining results for one specific point, usually just offshore from a particular area of concern. Many other models deliver results along a longer stretch of coast but, for the same computational effort, consider many fewer wave conditions.

In addition to using a reverse-tracking ray technique, the example method also uses linear wave theory. As will be seen later this greatly simplifies the calculations, and allows most if not all of those calculations to be carried out in advance of being needed for real-time coastal flood warnings. A disadvantage, however, is that the model cannot properly include dissipative effects such as bed friction or wave breaking. As a result it will tend to somewhat over-estimate wave heights close to the shore.

In essence, the model works as follows. For each chosen still water level, a large number of different incident wave conditions are considered, each having a single direction and period. A large range of directions and periods are used (perhaps 250); they are all assumed (at this stage) to have unit height and can be termed "components". The results from the modelling of these components are stored in a set of matrices, in which each row corresponds to an offshore direction and each column to a wave period. Each matrix entry gives information on the change in the character of that component (eg, its energy) between the offshore edge of the grid system and the chosen inshore site of interest. These matrices are therefore known as transfer functions. They contain all the information necessary to calculate the refraction behaviour of more complex incident wave conditions and produce corresponding conditions at the inshore location. An example of one such matrix is presented as Figure 3.

To study any particular offshore wave conditions, whether locally generated, swell, or a combination of both, the procedure is as follows. The specified incident wave field is first represented by a weighted combination of the components, with the weighting factors entered into a matrix of the same form as the transfer functions. The corresponding inshore wave conditions that result are then obtained by a multiplication of the transfer functions and the weighting factors matrix. This is a trivial operation on a computer, and could easily be carried out in real-time if necessary.

In practice, however, it is simpler to anticipate a wide range of offshore wave conditions, and carry out these operations well in advance of any application. In this way results can be presented in the form of graphs or tables which can be used rapidly to produce estimates of nearshore wave conditions during a storm. A typical set of graphs from such an exercise are presented as Figures 4 - 6. The first, Figure 4, contains curves which enable the engineer to calculate the inshore wave height given the offshore wave direction (horizontal axis) and the (zero-crossing) wave period (labelled curves). Notice that the inshore wave height has to be evaluated using the ratio of inshore/offshore heights (vertical axis).

It should be noted here that in order to use such a simple graph, it is necessary to make some assumptions about the form of the frequency spectrum, and also the directional spread of wave energy offshore. However, it is usually found that these assumptions can be made to match the site being considered, and the results obtained are reliable.

Figure 5 works in a similar way but returns the inshore (zero-crossing) wave period, while Figure 6 is simpler still and directly gives the inshore wave direction (in degrees North). Note that a set of these curves would be required for each tidal stage considered (usually at a specified high water level). A separate set of transfer functions, and results, are needed for each different location along a coast. Even so, the real-time prediction of nearshore wave conditions can be carried out using an easily manageable number of graphs.

An alternative way of presenting results would be to use tables rather than graphs. As an example, Figure 7 shows a table of inshore/offshore wave height ratios arranged by offshore wave direction (columns) and wave height (rows). Although this is a slightly different method of presentation, it is clearly still simple to use.

In areas where both locally generated waves and swell occur, the result tables or graphs could be used twice, ie, for both components separately. The total inshore wave height (H_T) would then be obtained by using the formula:

$$H_T^2 = H_L^2 + H_{SW}^2$$

where H_L is the calculated nearshore wave height due to the locally generated waves and H_{SW} that due to swell. Rough estimates can also be made of the resultant total wave period and mean direction of the inshore location. This calculation, however, is always likely to be difficult because of the problems in specifying the swell waves accurately.

It can be seen from the above that the example method chosen, ie, using reverse ray-tracking and linear wave theory, is both versatile and produces results in a simple format which is suitable for real-time forecasting.

For more sophisticated models, which include dissipative effects such as wave breaking and frictional dissipation, these substantial advantages disappear. This is because it is no longer possible to represent the modification of any required offshore wave condition by combining the results from the component waves introduced above. As a result, no transfer function can be produced and each offshore wave condition has to be studied individually.

It is conceivable in the future that such modelling could be done in real-time. Certainly the Meteorological Office Fine Mesh Wave Model can produce predictions of offshore waves as a discretised spectra, including both the swell and locally generated waves, and this information is precisely what a computational model requires as input. However, it seems unlikely that the sophisticated system that would be needed to accept this data from the Meteorological Office, and then run a specific shallow water wave model, is likely to be appropriate at present.

Probably the most effective way of incorporating dissipative effects into real-time wave prediction is to obtain some idea of the extent to which the ray-tracking model overpredicts the nearshore wave heights. This might be done directly, ie, by measuring waves at the chosen point of interest and then comparing actual conditions with those forecast by the model. Such an exercise would probably need to be carried out at normal tidal levels (eg, at High Water of Spring Tides), and would give the best possible validation of the model predictions. This topic is discussed further in Chapter 4 below.

Alternatively, a more sophisticated numerical model could be run, to estimate the effects of dissipative phenomena, for a modest selection of likely storms.

The results would then be compared with those from a ray-tracking model to give guidance on the latter models over-estimation of wave heights. This, of course, would be done in advance of needing results for real-time predictions.

In conclusion, there are a large number of numerical models available to predict wave conditions in shallow water. At present the more sophisticated methods, whilst perhaps producing more reliable results, are probably too cumbersome to use in real-time. Simpler models, based on linear wave theory are cheaper to run, and much easier to use, although they may over-estimate wave conditions close to a coast. For further details on the subject the reader is referred to Reference 10.

4 VALIDATION AND VALUE

Two important features of any mathematical modelling technique are its accuracy and its cost. Both of these types are considered in this chapter, starting first with a discussion of the accuracy of the results which can be expected and how that accuracy might be improved at any particular site by local measurements. This is followed by a discussion of the value of the techniques mentioned, in terms of both the costs involved and the benefits likely to accrue.

4.1 Accuracy and validation of the prediction techniques

The accuracy of the prediction of waves and the coast depends on three main factors, namely the forecasting of winds, and the modelling of both the growth of waves in deep water, and their subsequent modification as they travel to the coast.

It is beyond the scope of this report to comment on the methods used by meteorologists to model the lower levels of the earth's atmosphere. Suffice it to say that the sophisticated computer models used at present are particularly good at predicting wind conditions many hours in advance. The likely errors are therefore not likely to be large, especially in view of the possible inaccuracies in the subsequent wave modelling.

The forecasting of wave growth under the action of winds has advanced very considerably over the last decade or so, and is much more reliable as a result. An example of the wave conditions off the Sussex coast forecast by the Meteorological Office fine mesh wave model is presented in Figure 2 together with recorded wave conditions nearby (off Seaford). It is worth making the point here that this sort of comparison is rather rare. Usually hindcast wave conditions are compared with wave records, so that actual measured wind speeds are used in the forecasting model, after the event. The predicted wave conditions in Figure 2 use predicted wind speeds up to 24 hours in advance. Despite this, and the fact that no wave refraction modelling had been carried out to adjust the offshore predictions to give more refined forecasts for the nearshore wave recording site, the accuracy is very good. Both the timing and height of the large wave conditions were well anticipated and could be used with some confidence in a real-time forecasting situation. There is little difference between the accuracy of the 12 hour and 24 hour forecasts in the example, but it seems likely that forecasts will be rather more accurate for shorter periods (ie 3 to 6 hours in advance as would be likely in a flood forecasting situation). Another point worth making is that the location for which the wave predictions were made in Figure 2 lies in the English Channel and is open to swell waves propagating up the south western approaches from the Atlantic. The long fetches in this direction, together with the shorter areas across the Channel make the task of forecasting waves rather difficult, and so the success of the model is particularly re-assuring.

In the particular case at Seaford, however, the coast is relatively straight and the sea bed has rather smooth contours. As a result there was no great need to adjust the offshore waves to improve the predictions for the inshore wave recording site which was in 10-15m of water. This will certainly not always be the case, and shallow water effects will generally need to be modelled as well. Necessarily this further stage in the prediction method introduces yet another source of possible error, the size of which depends on the difficulty of the area being considered.

The main source of difficulty is likely to be when either offshore banks or very shallow sea bed slopes cause non-linear effects such as wave breaking or bottom friction to become important. Usually around the coast of this country such effects are only important near the large estuaries, eg the Thames Estuary, Morecambe Bay, and The Wash. Such effects are also at their least significant at high tidal levels, which is the situation of most interest for real-time flood warnings.

Eventually, of course, breaking limits the height of the incident waves on all low lying coasts, and it is therefore normally the practice to try to predict waves at some distance seaward of the surf zone. Subsequent uses of the wave conditions obtained, for example the calculation of set-up, run-up or wave overtopping discharges, usually involve techniques which take account of the wave breaking further inshore (eg the sea wall overtopping model, SWALLOW, Ref 14), often relying on scale model experiments or prototype observations.

If a good wave refraction model is used to predict wave conditions just seawards of the breaker line, as is normally the case, then it can be expected that the accuracy of the results obtained will be within about ±10% except in areas of complex bathymetry where ±20% is probably more likely. Work is presently continuing at Wallingford on verifying such models and a more comprehensive report, complete with case histories, should be available in 1988.

Overall, therefore, the coastal engineer would normally expect the combination of wind forecasts with wave growth and refraction models to give predictions accurate to about ±20%. On particularly open coasts with simple contours offshore and only local generated waves, this figure may drop to ±10%. On rocky Atlantic shores where distant swell and offshore breaking are complicating factors, the accuracy may be less than ±30%.

In any situation, however, the accuracy of such predictions may be improved substantially by wave measurements. Of course it is not likely that the combination of an extreme high tidal level and storm waves would occur in, say, a one-year measurement program. However, the careful analysis of wave records, in comparison with predictions from mathematical models, at more normal tidal levels (eg MHWS) will give much greater confidence in future applications. Some adjustment of the models is usually possible, for example to adjust nearshore wave heights for the effects of bottom friction, and extrapolating the models to greater tidal levels can then be carried out with less doubt. The disadvantage of such a method for calibrating the mathematical models is the added cost of installing the wave records. The question of expense is dealt with next.

4.2 Costs and benefits of real-time wave forecasting

In this section, the benefits of modelling waves in real-time are outlined, followed by some comments on the likely costs. The major benefits arise from the improvement in the accuracy of flood warnings. It is therefore worth drawing attention to the importance attached to such warnings.

A recent paper (Ref 15) showed the rate of grant available for flood warning schemes was the same as that for urban sea defences. More importantly, a letter from MAFF to the Regional Land Drainage Committees, dated 9 January 1985, set out priorities for schemes attracting grant aid. Flood warning was placed top of the list, even above urban sea defences. Even though each application for grant aid is treated on its own merits, the perceived value of flood warnings is very clear.

There are two ways in which modelling waves can improve flood forecasts. If large waves are predicted to occur at the same time as a tidal level which itself would cause no difficulties, then early warnings will produce considerable savings. The calculation of such benefits can be assessed in a similar way to that used for fluvial floods. Useful reports on such method (Refs 16, 17) have been produced by the Flood Hazard Research Centre (Middlesex Polytechnic), including aspects such as intangible benefits. However, only a percentage of the potential savings can reasonably be claimed as benefit. This is because of the difficulties in contacting all the people likely to be affected by flooding in good time (see Chapter 4, Ref 13).

In contrast, if predicted wave heights are small then even a very high tide may not cause flooding. There would be some direct savings as a result of not issuing, or continuing a flood warning. For example, it would not be necessary to mobilise emergency services. In addition, there would be some benefit in the relief from stress or anxiety amongst the local populace. Perhaps more important, however, would be the increased confidence in the flood warning system. The danger of "crying wolf" is very real, and could lead to much more serious damage in the long term.

As well as the above advantages of improved flood warnings, there are other benefits from the models used. For example, extreme wave conditions can be predicted close to the shore and used in the design of coastal defences. Similarly by use of the models, the nearshore wave climate can be calculated. The resulting information can then form the input to models of alongshore sediment transport, or to indicate the likelihood of calm conditions necessary to operate floating plant. Both these pieces of information would be valuable in assessing a beach nourishment exercise. Alternatively, of course, much of the cost of a wave forecasting exercise could be saved by setting up similar models for specific design tasks.

Turning finally to the costs of a wave forecasting system two main aspects have to be considered. Firstly, the mathematical models need to be established and run. Then, optionally, specific wave measurements may be carried out to improve the accuracy of the forecasts from those models.

To an extent the cost of both of these exercises will depend on the size of the area considered, and the complexity of the sea bed contours. On straight coasts, with steeply shelving, regularly contoured beaches setting up a depth grid is very simple. In addition only one or two points along the coast may need to be considered, reducing both time and effort. In such an area the cost of the mathematical modelling would probably be less than £15,000. More complicated areas would require greater effort and this would be reflected in the costs. Even so, a very large model considering several sites and tidal levels would rarely exceed £50,000.

The cost of wave measurements also depends on the number of sites that have to be considered. Additionally, however, the length of deployment of a recorder also affects the expense incurred. As a rough guide a years' recording at a single site would cost about £20,000 to £25,000. For some studies both offshore and nearshore wave recording may be justified, perhaps involving several locations close to the coast. This is more likely for a major capital works scheme than for a real-time forecasting exercise. More usually a single wave recorder at a crucial position is used. Although this is less than ideal, it will still significantly improve the wave predictions in most situations. This improvement will also carry over to estimates of extreme waves.

In view of the possible damage in low-lying areas caused by a single unanticipated flood, the above costs are comparatively modest. Indeed in many situations the cost/benefit ratio of mathematical modelling and wave recording will be favourable on the basis of real-time forecasts alone. The added benefits of better information on extreme waves, or on the general wave climate, will improve the ratio sufficiently of many other sites. Finally, since the responsibility for the coast in this country is divided amongst many authorities, it is sometimes possible to share resources. In the present context a wave forecasting model may well be constructed to serve two or more authorities, bringing about savings for both.

5 SUMMARY AND CONCLUSIONS

This report has considered the methods available to improve coastal flood warnings by predicting wave conditions at high water. A variety of possible techniques for real-time forecasting have been considered, first to predict waves in deep water and then to calculate the modification they undergo as they travel to the shore.

For deep water waves, two methods seem useful. Firstly the Meteorological Office Fine Mesh Wave Model can be used, especially on open coasts. This model not only predicts wind waves but also swell and this is important on coasts open to the Atlantic. Alternatively a simpler model of wave generation can be used for more confined areas, where more detail in the generating area may be useful. The Irish Sea is an obvious example. This simpler model cannot predict distantly generated swell.

To modify such offshore waves to obtain corresponding conditions just seaward of the breaker line, a further model is required. It is concluded that running such a wave refraction model in real-time would be difficult. Instead, calculations can be carried out well in advance. Results can then be stored in the form of look-up tables, which can be rapidly used during a flood alert. The tables can cover a range of tidal levels and incident wave conditions for a single site on the coast. To consider several locations, a corresponding set of tables would be required for each.

Finally the likely benefits and costs of such modelling have been reviewed. Even if specific wave recording is carried out to improve the predictions made, it seems that such modelling will be well worthwhile in many areas.

6 ACKNOWLEDGEMENTS

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FIGURES

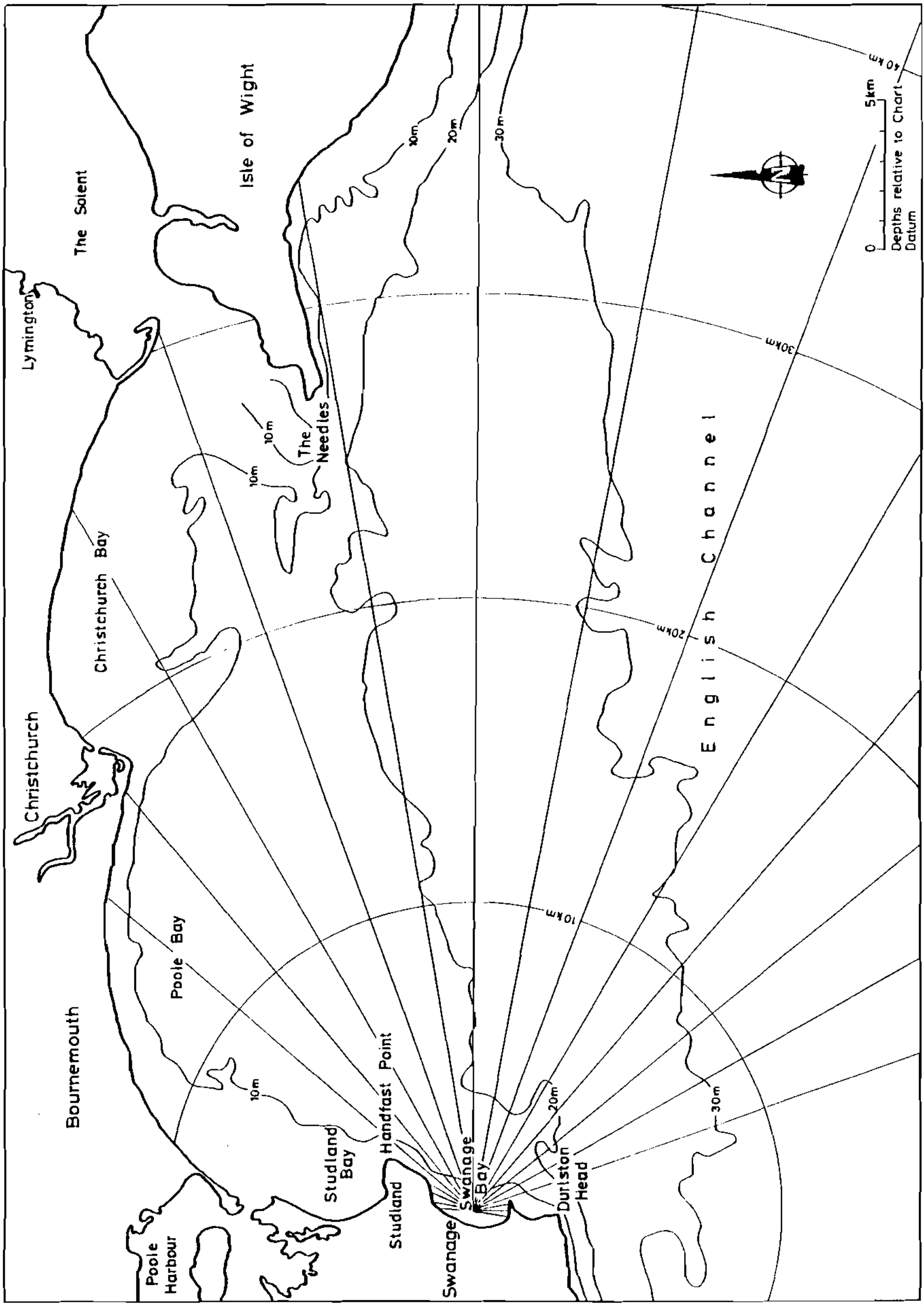

Fig 1. Radial fetches for wave prediction

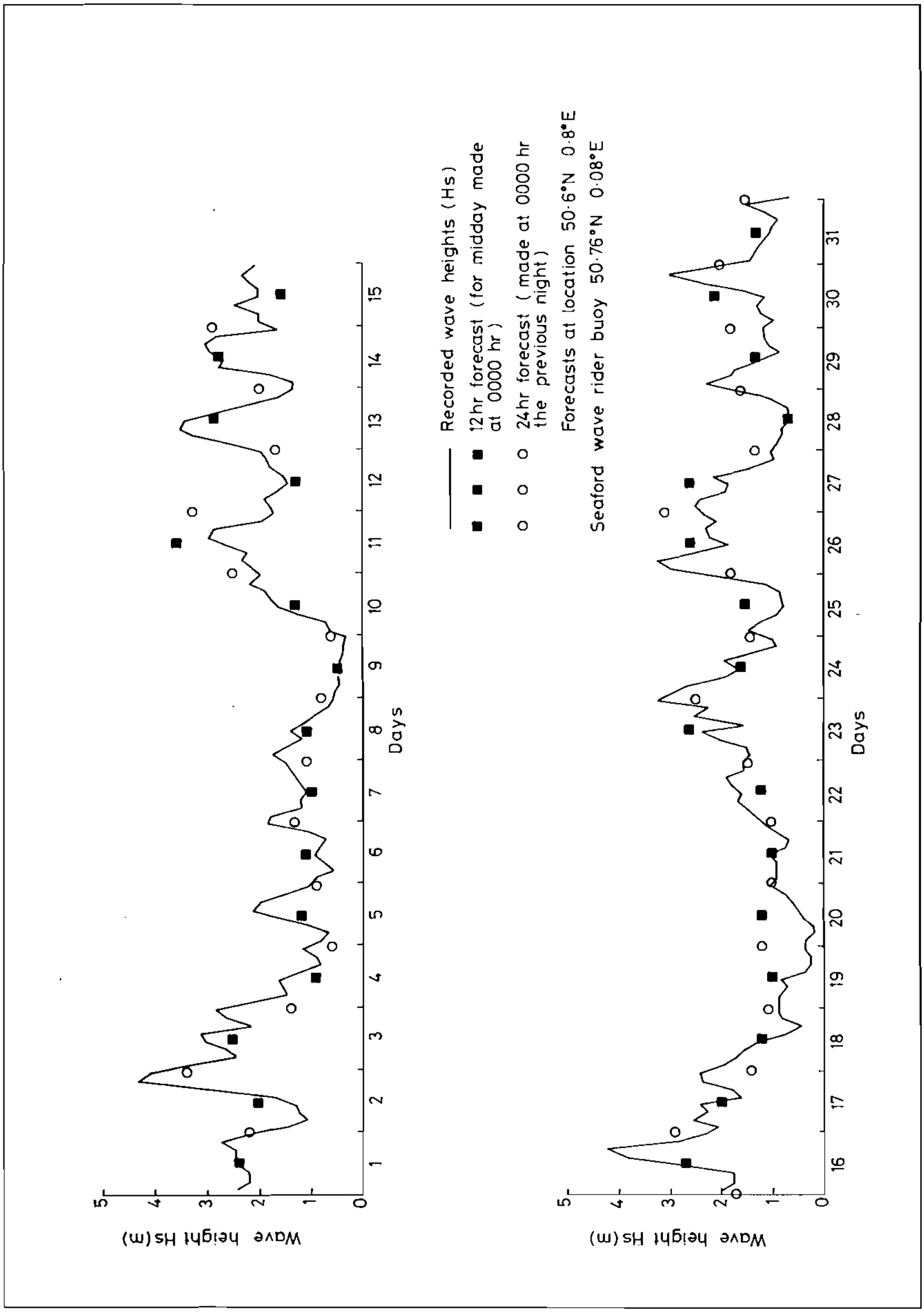

Fig 2. Comparison of wave heights, actual and forecasted for Seaford - January 1984

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                    TRANSFER FUNCTION TN
                    ********************

FREQUENCY (HZ)  0.667  0.333  0.222  0.167  0.133  0.111  0.095  0.083  0.074  0.067  0.061  0.056  0.051  0.048
--------------  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----  -----

ANGLE (DEG NORTH)
-----------
 000-010        0.000  0.000  0.531  0.000  0.000  0.000  0.000  0.000  0.083  0.042  0.043  0.346  0.522  0.525
 010-020        0.000  0.418  0.000  0.117  0.068  0.074  0.157  0.408  2.006  2.293  2.363  2.081  1.921  1.668
 020-030        0.699  0.507  0.194  0.117  0.341  2.028  2.218  2.133  0.684  0.439  0.446  0.404  0.410  0.411
 030-040        0.900  0.689  0.387  0.820  2.036  0.976  1.066  0.849  0.889  0.912  0.880  0.890  0.851  0.914
 040-050        1.000  0.886  0.858  1.286  0.730  0.687  0.570  0.711  0.637  0.599  0.612  0.622  0.630  0.580
 050-060        1.000  0.985  0.852  0.581  0.446  0.179  0.101  0.000  0.000  0.058  0.000  0.000  0.000  0.000
 060-070        1.000  0.985  0.848  0.463  0.221  0.267  0.301  0.324  0.349  0.308  0.378  0.460  0.469  0.476
 070-080        1.000  0.985  0.657  0.454  0.375  0.283  0.220  0.244  0.131  0.206  0.357  0.294  0.300  0.305
 080-090        1.000  0.985  0.749  0.225  0.075  0.094  0.110  0.122  0.393  0.413  0.214  0.295  0.301  0.467
 090-100        1.000  0.985  0.749  0.448  0.373  0.860  1.130  1.394  1.370  1.595  1.736  1.634  1.836  1.624
 100-110        1.000  0.788  0.562  1.336  1.861  1.250  1.037  1.182  1.438  1.462  1.365  1.677  1.271  1.666
 110-120        1.000  0.591  0.187  0.110  0.293  1.161  1.668  1.505  1.359  1.306  1.468  1.341  1.678  1.322
 120-130        1.000  0.591  0.187  0.330  0.218  0.194  0.121  0.284  0.159  0.172  0.183  0.286  0.099  0.305
 130-140        0.100  0.788  0.281  0.220  0.364  0.194  0.241  0.140  0.156  0.252  0.267  0.279  0.288  0.296
 140-150        0.000  0.295  1.592  1.431  1.537  0.582  0.481  0.558  0.929  0.919  0.882  0.828  0.857  0.879
 150-160        0.000  0.000  0.749  1.103  1.321  3.295  4.169  4.396  4.704  4.641  4.809  4.553  4.789  4.616
 160-170        0.000  0.000  0.000  0.662  1.247  1.260  1.076  1.103  1.531  1.644  1.474  1.803  1.672  1.619
 170-180        0.000  0.000  0.000  0.330  0.877  1.455  1.801  2.510  2.168  2.253  2.293  2.391  2.470  2.436
 180-190        0.000  0.000  0.000  0.000  0.000  0.097  0.481  0.559  0.775  1.004  1.061  1.106  1.143  1.173
 190-200        0.000  0.000  0.000  0.000  0.146  0.000  0.480  0.417  0.463  0.333  0.440  0.274  0.283  0.485
 200-210        0.000  0.000  0.000  0.000  0.000  0.291  0.120  0.414  0.456  0.900  1.034  1.444  1.495  0.861
 210-220        0.000  0.000  0.000  0.000  0.000  0.097  0.000  0.000  0.000  0.166  0.525  0.456  0.660  1.546
 220-230        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 230-240        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 240-250        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 250-260        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 260-270        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 270-280        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 280-290        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 290-300        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 300-310        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 310-320        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 320-330        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
 330-340        0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.035  0.027  0.046  0.053  0.048  0.069  0.066
 340-350        0.000  0.000  0.000  0.000  0.236  0.261  0.232  0.214  0.193  0.203  0.174  0.208  0.218  0.442
 350-360        0.000  0.000  0.000  0.282  0.067  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
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FIG 3.   Example of a transfer function matrix

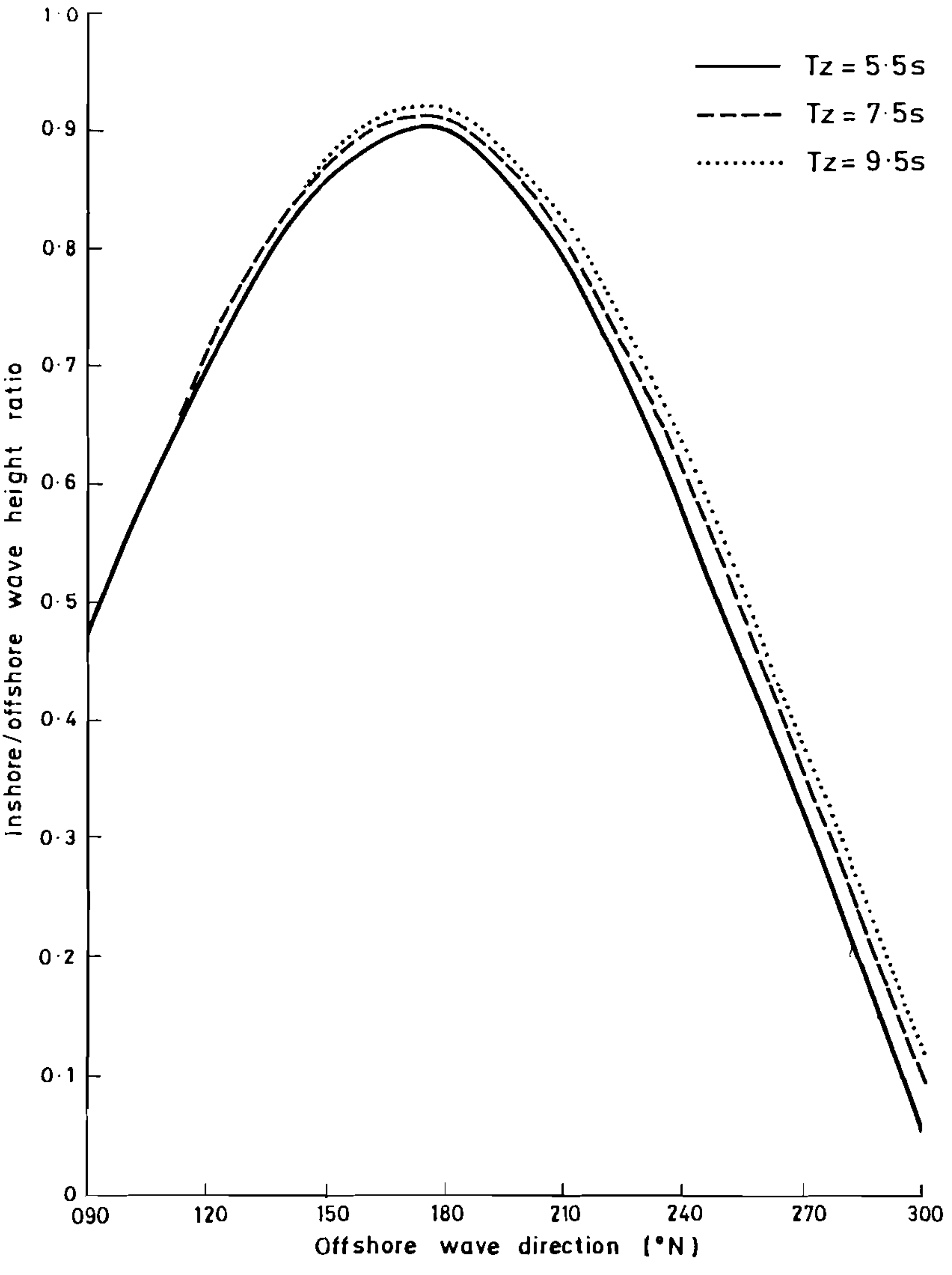

Fig 4 Ratios of calculated inshore/offshore wave heights

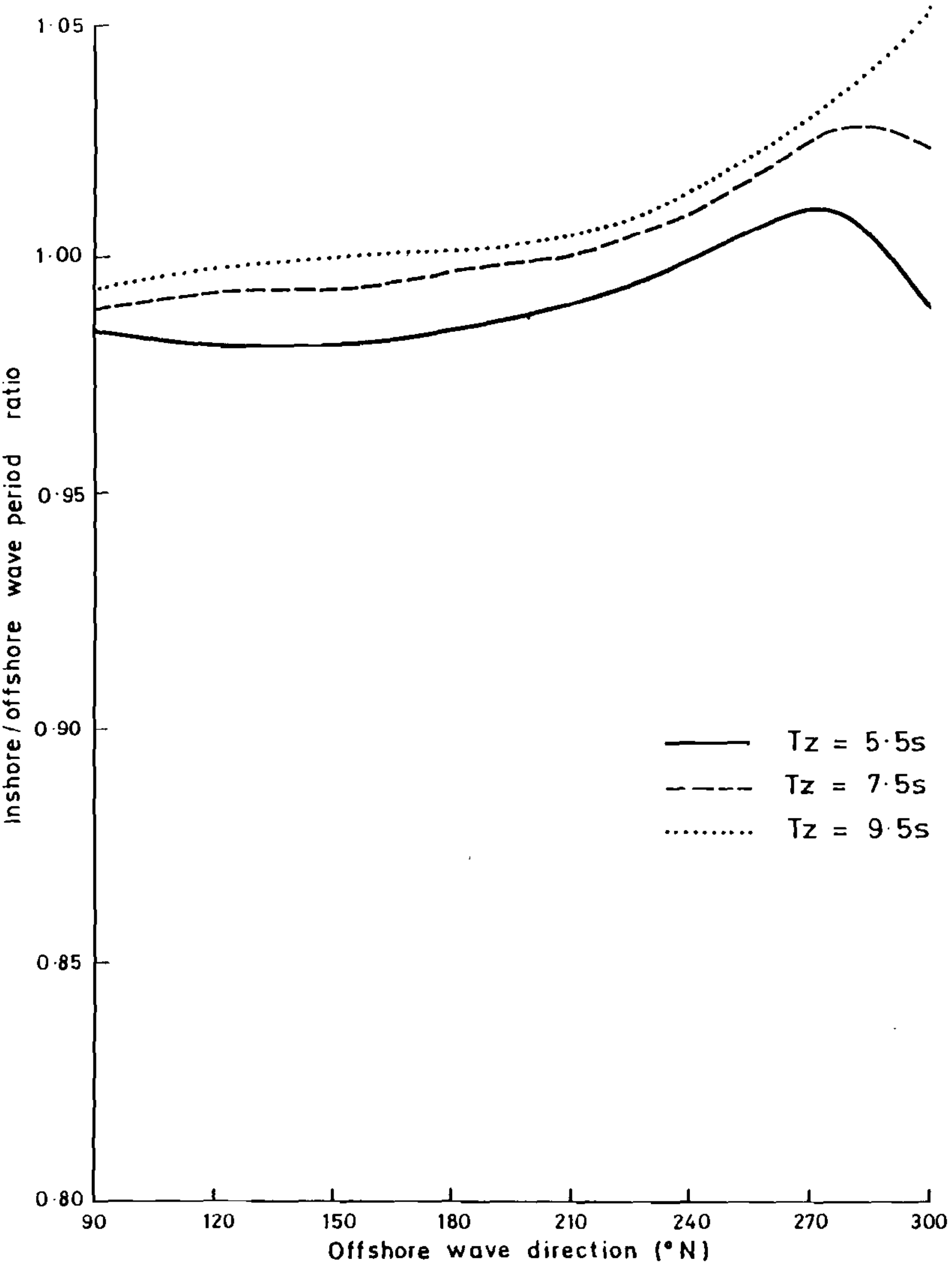

Fig 5 Ratios of calculated inshore/offshore wave periods

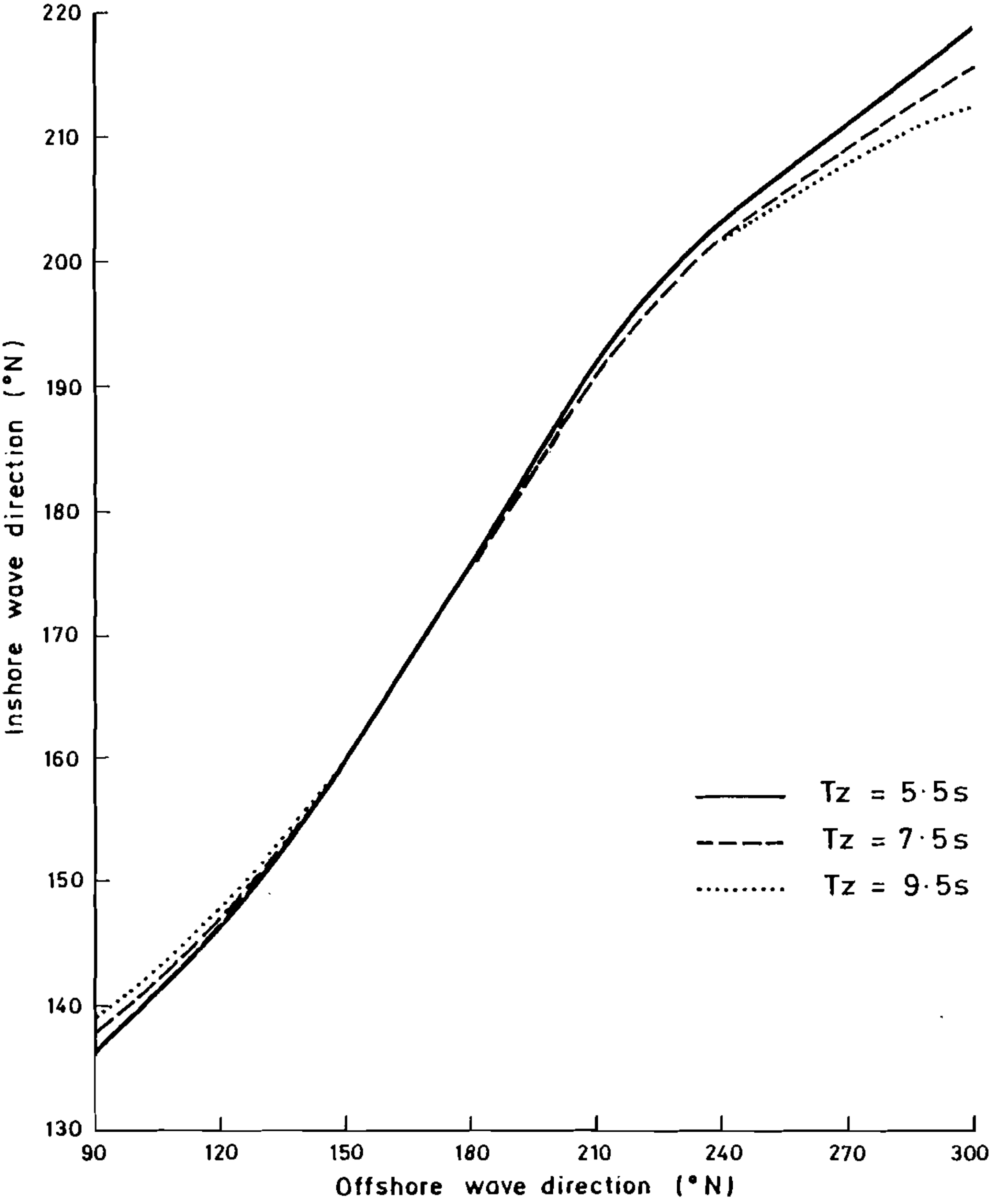

Fig 6 Inshore wave directions (calculated)

Inshore/offshore wave height ratios.

Offshore	Offshore wind direction (°N)								
Hs(m)	280	300	320	340	0	20	40	60	80
0.5	0.637	0.770	0.861	0.899	0.875	0.777	0.624	0.452	0.268
1.0	0.558	0.719	0.821	0.870	0.850	0.752	0.606	0.446	0.236
1.5	0.498	0.662	0.781	0.842	0.827	0.736	0.601	0.438	0.226
2.0	0.466	0.620	0.744	0.815	0.819	0.741	0.614	0.430	0.221
2.5	0.443	0.595	0.725	0.804	0.821	0.749	0.616	0.427	
3.0	0.420	0.576	0.712	0.801	0.824	0.755	0.617		
3.5	0.405	0.563	0.703	0.805	0.829	0.761			
4.0	0.398	0.550	0.699	0.808	0.833				
4.5	0.394	0.548	0.700	0.810					
5.0			0.700						

Fig 7. Example table of calculated inshore/offshore wave height ratios