CHAPTER 6

WIND AND WAVE RELATIONSHIPS IN A SHALLOW WATER AREA

by J.S.Driver* and J.D.Pitt**

1. ABSTRACT

An instrumentation system to record direct measures of both wind and wave conditions has been installed at the Wash. Data from these instruments are used in conjunction with long term wind records from another station to predict the frequency and duration of extreme conditions.

2. INTRODUCTION

A proposed freshwater storage scheme on the foreshore of the Wash[4] (a 25 km square bay on the East coast of England) involves the construction of sand fill embankments up to 14 m high in an intertidal area.

An assessment of wave characteristics is required for the design of surface protection on the seaward facing slopes, and in planning construction.

Methods of wave prediction such as those set out by Ippen[1] have limited application in shallow water areas. Although some allowance can be made for the effects of shoaling, friction and refraction, such calculations are a poor substitute for field data. The situation in the Wash is particularly difficult as a tidal range of over 8 m acts over an area of complex topography with extensive drying banks.

An instrumentation system comprising three wave recorders and three anemometers was installed in the locations shown in Figure 1 and tide levels were recorded nearby at West Stones.

The paper describes the type of instruments used, the data obtained and the method of analysis.

3. DEFINITIONS

Wave analysis:

T_z	- Mean zero-crossing period (for upward zero-crossings)
H^1_1	- Total of the highest crest above mean water level and lowest trough below mean water level, after depth attenuation correction.
H^1_2	- Total of the second highest crest above mean water level and the second lowest trough below mean water level, after depth attenuation correction.
H_s(3 hours)	- Significant wave height (average height of the highest one third waves).
H.W.	- High Water
H.W.period	- The period at and around H.W. for which the water depth is sufficient to support waves.

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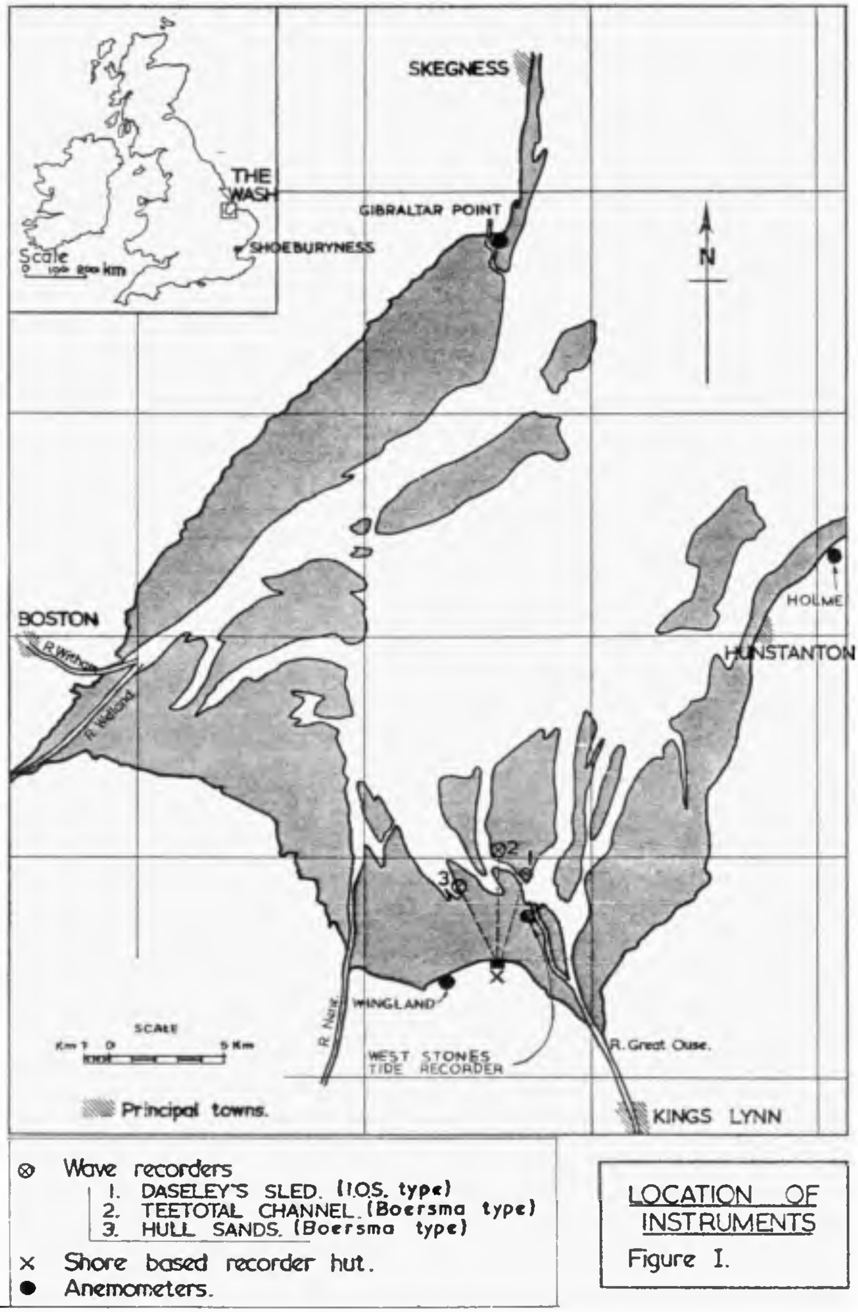


LOCATION OF INSTRUMENTS

Figure I.

Wave event - A H.W. period accompanied by measured waves of 1.0 m or greater.

Storm event - The occurrence of a storm in which the maximum wind speed is force 7 or greater (Beaufort scale - U.K.).

4. OBJECTIVES

In the design of rip rap or other surface protection against wave attack, it is necessary to determine not only the magnitude of the waves to be expected but also the duration of attack and the probability of occurrence of any event. It may prove more economical to design for waves with a return period of 10 years (say) on the basis that occasional damage can be repaired at a lower cost than the additional sum involved in providing longer term protection.

A study of the frequencies of events is therefore necessary so a method of analysis has been adopted which enables an estimate of the return periods of wave events to be made. However, it is equally important to determine which parameters relating winds and waves are dominant in this situation. The maximum wave height may be governed either by the severity of the worst storms expected or by physical restraints such as water depth and fetch length.

5. INSTRUMENTATION

5.1 Wave Recorders (Figure 2)

5.1.1 Choice of instrument

Three types of instrument were considered as possibilities for this situation:

1. Surface piercing (wave staff)
2. Accelerometer buoy
3. Sub-surface transducer

The first system was not chosen because of its vulnerability to damage and fouling which is unfortunate since the inherent wide frequency response of such a system would enable both short period waves and tides to be measured.

The buoy measuring systems, perhaps best exemplified by the Waverider, would also have adequately measured the short period waves (but not the tides). However, the difficulties of mooring wave buoys in narrow channels precluded their use.

Two types of pressure transducer were considered possibilities on grounds of their rugged and proven designs and also their availability bearing in mind that the installation was programmed to take place within six months of defining the requirement. The two systems chosen were:-

(1) The Van Reijsen-Boersma Seawave Meter
(2) The Institute of Oceanographic Sciences (previously National Institute of Oceanography) F.M. wave recorder. Both systems could be connected to shore by cable link.

All wave measurement systems represent a compromise and in this instance the errors introduced by depth attenuation correction and the difficulties of laying long cables were the disadvantages to be set against operational reliability. Identical instruments had been used on the Dee Estuary Study[4] in Cheshire during 1969/70 with acceptable results.

Figure 2. Wave Recorder

Figure 3. Cable Laying

The use of radio transmission for relaying the signals to shore would have been ideal but no suitable equipment was available, neither was the use of a transmitting aerial at the sea end considered a reliable proposition.

The operating principles for both systems are indicated in Figure 4. Both pressure transducers modulate a carrier frequency with the pressure information. These signals are relayed to the shore along the armoured cables and amplified before being demodulated. Further amplification is then necessary to drive the chart recorder pen movements. Some obvious differences between the Boersma and IOS instruments lie in the transducer operating principles: in the Boersma a metal bar is maintained in low frequency operation and this carrier frequency is then modulated by the force applied to the end of the bar, but with the IOS transducer a deflecting diaphragm causes the gap between the plates of a capacitor to vary and this modulates the frequency of a 100 kHz oscillator. Additionally the IOS instrument filters out tidal information so as to record wave data only.

5.1.2 Choice of Sites

Having thus chosen the instruments it became necessary to site both sea units and shore recording stations in such a way that the maximum cable lengths for each site should not exceed about 7 km. Figure 1 indicates the sites chosen. All transducers were mounted in protective housings of a common type designed for the Dee Estuary Study but modified to suit the Wash sites. In each case the housings were installed on sandbanks but near deepwater channels. The supporting columns for the housings were jetted into the sand to a depth of 6 metres. At a high water spring tide the depths of water above each pressure transducer were typically:

Site 1 - 3.5 m
Site 2 - 3.5 m
Site 3 - 4.7 m

The cable routes across the sea bed to the shore station site are also indicated on Figure 1. Again a compromise was involved since road access in this area of reclaimed land is very limited.

5.1.3 Power supplies and wave recorder sampling clock

The nearest source of mains power was 5 km from the shore station so an inverter system was designed to provide a 240 volt 50 Hz sypply from a 12 volt Nickel Cadmium battery pack. The batteries were replaced about once every two weeks with a freshly charged set. A separately powered Keinzle impulse clock movement was modified as follows: the escapement oscillation rate was slowed by adding a little additional mass to either side of the balance wheel. In this way the 12 hours rotation of the hour hand was increased to a nominal 12 hours 26 minutes. A pair of cams were then fitted to the hour hand shaft and these operated a low torque switch, the result being a 15 minute 'on' period once every high tide. The switch in turn controlled a relay which energised the inverter and hence simultaneously switched on the three wave recorders.

5.1.4 Cable laying (figure 3)

The laying of long cables in an intertidal area was a major achievement and the work was undertaken by a specialist contractor who had successfully carried out a similar operation in the Dee estuary. Cable lengths in the Wash were 5,600 m, 6,600 m and 6,400 m for sites 1, 2 and 3 respectively, and had to be routed across areas where conditions varied from firm sand to soft silt.

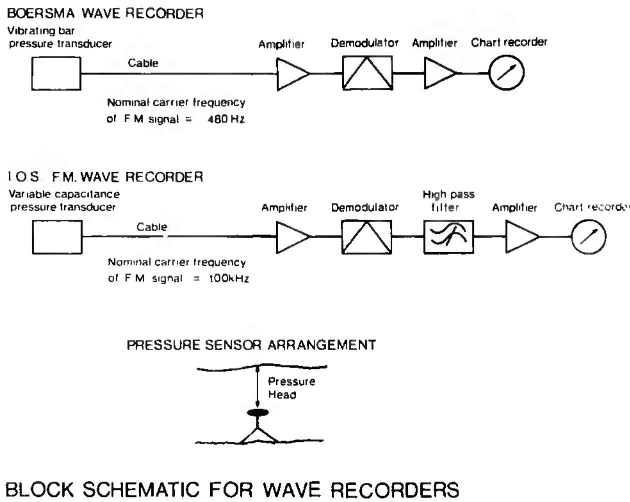


Figure 4. Block Schematic for Wave Recorders

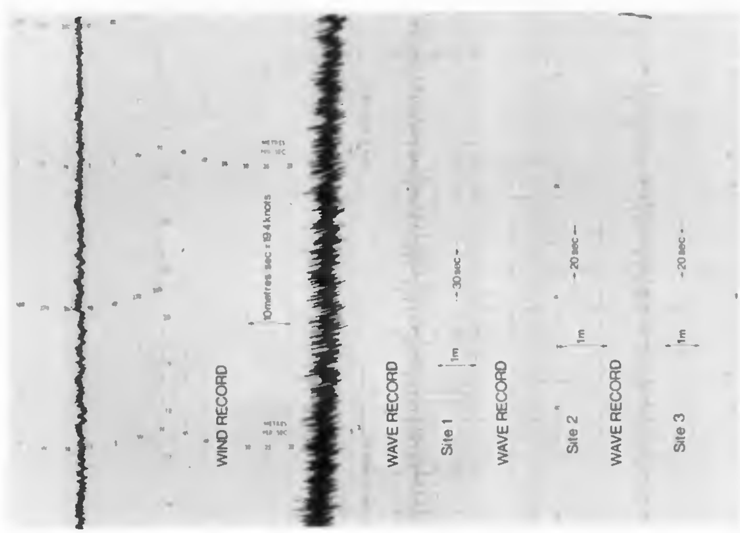


Figure 5. Typical Data in original form

Cables were buried to a depth of 0.5 m using a mole plough which was towed across the sand banks by modified agricultural plant. The equipment was loaded on to an ex-army landing craft and work was carried out at low water after the craft had grounded. Each cable run took several low water periods to complete, the equipment being re-loaded on to the landing craft at high water. Towing the plough when submerged under water enabled cable routes to cross the many shallow channels.

5.1.5 Operational problems

When the cables were first laid a crosstalk problem manifested itself between the Boersmas and the IOS recorder. This was traced to the land link where an unscreened cable had been used on one section. Replacement of this cable and re-arrangement of the earthing within tbe shore hut did much to reduce the effect.

From time to time some impulsive interference was observed on the signals being received from the transducers. This appeared as random 'spikes' on the wave records. It has not been possible to trace the origin of this interference but neither has it been difficult to carry out a 'smoothing' operation by eye when analysing the wave records. One of the problems inherent to measuring waves with pressure transducers in a sheltered area is that many recordings show no wave activity and in this situation any electrical interference present will predominate. Clearly the effects of such interference should only be assessed at a time when reasonable wave activity is present.

The IOS instrument incorporated a galvonometer pen recorder of 100 mm chart width which has proved reliable under conditions of greatly varying temperature and humidity. The Boersma shore unit was, however, interfaced with a two channel potentiometer recorder the feedback loop of which demonstrated instability in these conditions. This recorder was replaced by a new type with a 240 mm chart width. Considerable trouble was then experienced with changes in paper width under varying humidity and at the time of writing a third type of two channel recorder is in use, this time with a 100 mm chart.

The duration of the tidal cycle deviates from the mean by up to an hour and furthermore the difference between the time of high water and its predicted value may be as much as 30 minutes. The time lag between high water and time of recording may therefore be considerable and careful adjustment of the tidal clock is required to minimise the effect so that records are not taken except at or near to high water.

5.1.6 Calibration of instruments

All three transducers were tested over the range 0 - 276 KN/m^2 in a pressure vessel at the IOS Wormley laboratory using a Budenburg deadweight pressure gauge as a reference. With the sensitivities thus obtained it was then possible to calibrate the recording electronics with the following full scale deflections:

Boersma : $\pm$ 4.0 m initially but changed to $\pm$ 4.5 m and $\pm$ 6.5 m when the replacement potentiometer recorders were fitted.

IOS : F.M.: $\pm$ 2.5 m.

A larger full scale deflection was necessary with the Boersma recorder since the tidal information was also being displayed.

DATE	SITE	WAVE PARAMETERS				WIND VELOCITY		WATER DEPTH
		H_1'	H_2'	H_s (3 hrs)	Period T_z	KNOTS	DIR.^{n}	(metres)
	1.	3·32	3·10	2·53	5·28			4·5
2-4-73	2	1·15	1·09	0·99	5·46	44	330	4·9
	3	1 63	1·58	1·40	5·64			5·5
	1	1·95	1·76	1·15	4·04			4·0
19-9-73	2	0·98	0·96	0·64	3 72	33	330	4·4
	3	1·09	1 04	0·79	4·36			5·0
	1							
21-10-73	2					34	290	
	3	1·70	1·48	1·17	3·86			4·3
	1	1·33	1·19	0·94	4·44			3·8
26-11-73	2					24	315	
	3							
	1	1·37	1·34	0·97	5·70			
8-12-73	2					20	350	4·3
	3							
	1	1·45	1·03	0·95	5·00			4·0
13-12-73	2	1·81	1·71	1·26	4·80	40	310	4·4
	3	1·84	1·57	1·31	4·92			5·0
	1	1·45	1·31	1·08	4·92			4·1
14-12-73	2	1·58	1·46	1·20	4·88	31	320	4·5
	3	1·63	1 45	1·19	5·14			5·1
	1	0·74	0·66	0·46	3·90			3·9
8-1-74	2					46	140	
	3	1·21	1·04	0·74	4·12			4·9
	1	1·54	1·34	0·97	5·04			3·8
17-1-74	2					40	310	
	3	2·02	1·66	1·24	4·52			4·8
	1							
16-4-74	2					18	050	
	3	1·76	1·52	1·20	4·22			3·2
	1							
24-5-74	2	1·02	1·00	0·81	5·18	25	060	4·8
	3	3·33	2·48	2·17	4·68			5·4

TABLE 1. WAVE EVENTS DECEMBER 1972 – MAY 1974

5.1.7 Measurement accuracy of instruments

In a system using pressure measurement to derive wave height the corrections for the depth attenuation effect introduce the largest single source of error. This is particularly so with the Wash installation where relatively short period waves have been recorded and correction factors of the order of 0.5 are typical. The errors are considered to be at least ± 10%.

An estimated total error of 3% can be attributed to the following effects:

1. Dynamic pressures on the measuring head caused by the wave particle velocity.
2. A non-linearity of the transducer calibration curves.

A further ± 5% is allowed for instrumental error where this constitutes the effects of component tolerance, discriminator non-linearity and chart recorder inaccuracies. The Boersma system has exhibited a zero drift problem which appears also to have affected the overall gain to the extent of possibly 10%. However, further work is to be carried out in order to assess both the reasons for this drift and to quantify the error.

5.2 Wind Recorders

Three continuously recording Munro "rotating cup" anemometers were installed in the Autumn of 1972 to obtain data on the local winds over the Wash. The distribution of wind recorders around the coast enables the variation in wind velocity over the area to be detected. The specification of instrumentation and the method of analysis are in accordance with standards laid down by the British Meteorological Office so that data is compatible with that from other recording stations.

Data return was 93% overall from Gibraltar Point - an extremely high value resulting from diligent inspection by a local warden who took on the job of maintaining the instrument.

6. DATA

The available data comprises wind records and wave records from the instruments described in section 5 together with 40 years of wind data from Shoeburyness (Figure 1). Other wave data in the form of visual observations by the Kings Lynn pilots have been obtained and these will be of use in correlating wave conditions at the recorder sites and those in the channels.

The total population of events being considered includes storm events in addition to wave events. (Not all storms generate waves). Problems in commissioning and maintaining the instruments have resulted in some events passing when not all the wave recorders were operating. It is, however, encouraging to note that some data have been recorded for all events since November 1972.

The 11 wave events recorded up to May 1974 are listed in Table 1. Water depths given in column 9 were obtained using tide recorders installed in the Wash. The measurement of sea level in the Wash is discussed in detail by Pugh and Waller[5].

7. ANALYSIS

Two distinct approaches are possible in assessing the frequency of events. The first is along the lines proposed by Gumbel in which the magnitude of the waves would be plotted against the frequency of occurrence. Extrapolation of the best fit line gives an indication of the frequency of extreme events.

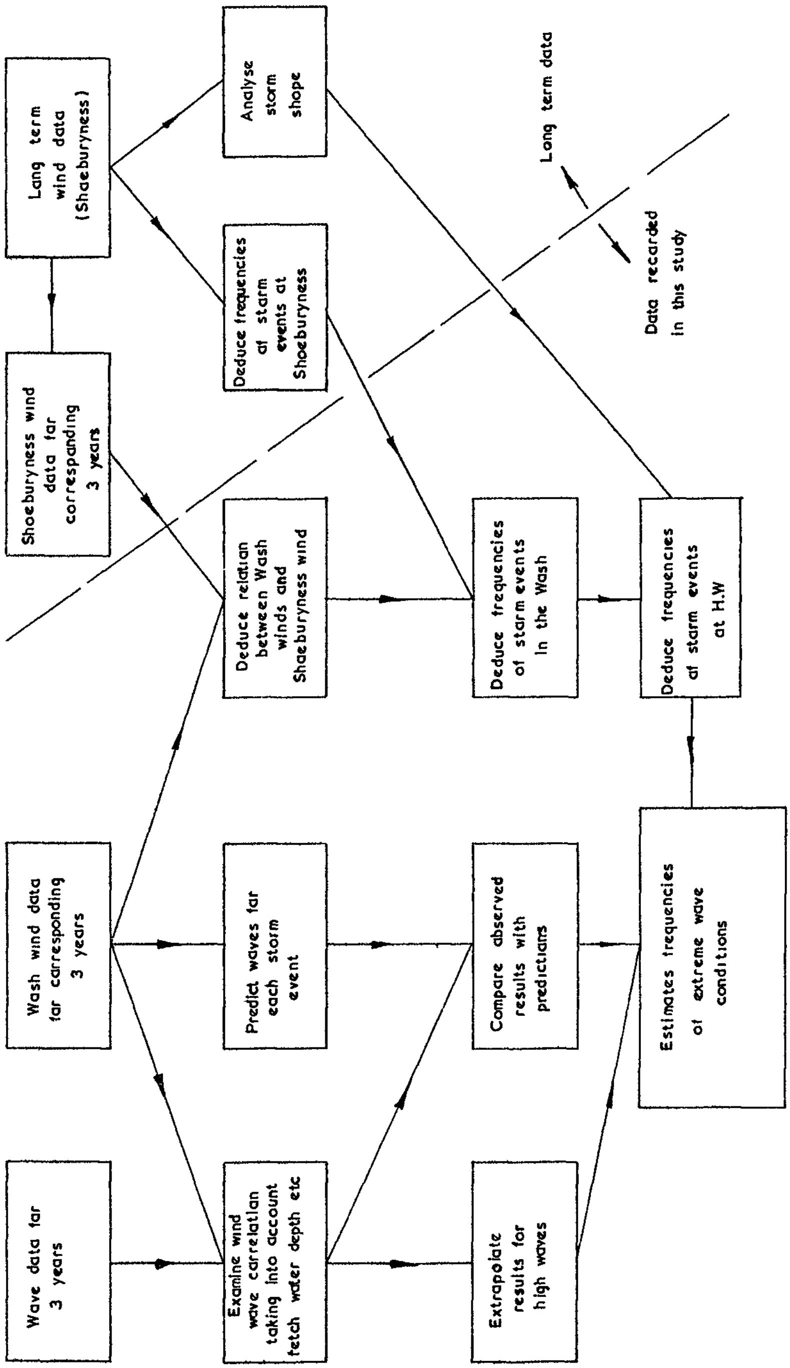


Figure 6 FLOW DIAGRAM FOR DATA ANALYSIS

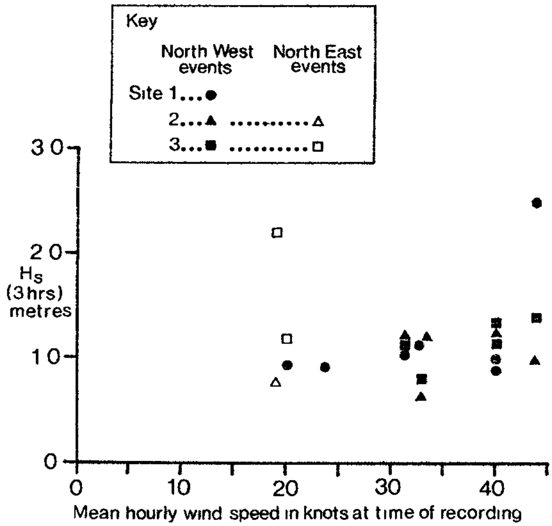


Figure 7 WAVE HEIGHT / WIND SPEED SCATTER DIAGRAM

Class	High water level (metres) O D (Newlyn)	Approximate water depth at sites (metres)	Probability of occurrence on any tide
1	0·75 - 1 25	2·0	0·0007
Mean Neaps 2	1 25 - 1·75	2·5	0·0034
3	1·75 - 2·25	3·0	0·168
4	2 25 - 2·75	3·5	0·250
Mean Springs 5	2·75 - 3·25	4·0	0·291
6	3·25 - 3·75	4·5	0 208
7	3·75 - 4·25	5·0	0·460
8	4·25 - 4 75	5·5	0·0003

TABLE 2 TIDE LEVEL ANALYSIS

This method however relies on there being complete data available over a long period and data from 2 or 3 years records are not sufficient.

The second approach, adopted here, has been to study case histories and use existing theories on wave generation to correlate wave height and period with the prevailing wind conditions and water depth. The frequency of occurrence of wind conditions is then assessed using available long term wind data. Figure 6 illustrates the flow diagram for data analysis.

In the analysis of the wave data, the method used was that proposed by Draper[2].

8. WIND WAVE CORRELATION

8.1 Wind direction

For the purpose of this analysis, wind direction has been divided up into four 90° sectors, namely 45° either side of SE, SW, NW and NE. Selection of these sectors is hased on inspection of the orientation of the Wash (Figure 1).

8.2 South East sector

Storm events from the south east sector occur several times each year but since the winds blow offshore over a short shallow fetch, large waves are not generated in the area of interest. Only one storm event has been accompanied by a wave event and on this occasion the maximum wave height was 1.2 m with a wind speed of 46 kts.

8.3 South West sector

Storm events from the south west are the most frequent but again the winds are offshore and over a short shallow fetch. Although these storm conditions need to be assessed in considering construction, the generation of large waves does not occur. The maximum wind recorded during a high water period was 50 kts and the wave height was only 0.6 m.

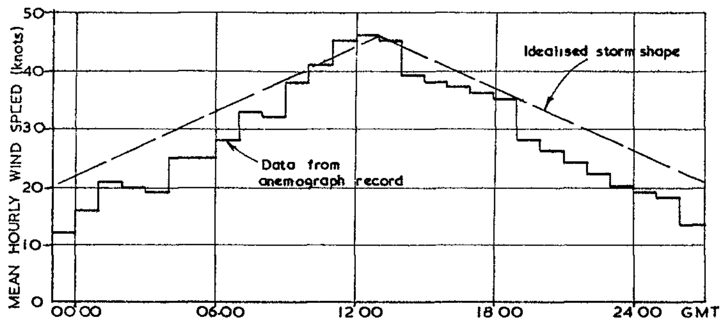
8.4 North West sector

Waves generated by winds from the NW sector have been dominant amongst the data collected so far, and account for eight of the eleven wave events listed in Table 1.

An important observation is that the wave period even of the largest waves is only about 5 seconds. The implication is that waves are generated over a short fetch (less than 30 km) and during a period of only one or two hours. It is therefore evident that waves are generated locally within the Wash rather than further out in the North Sea.

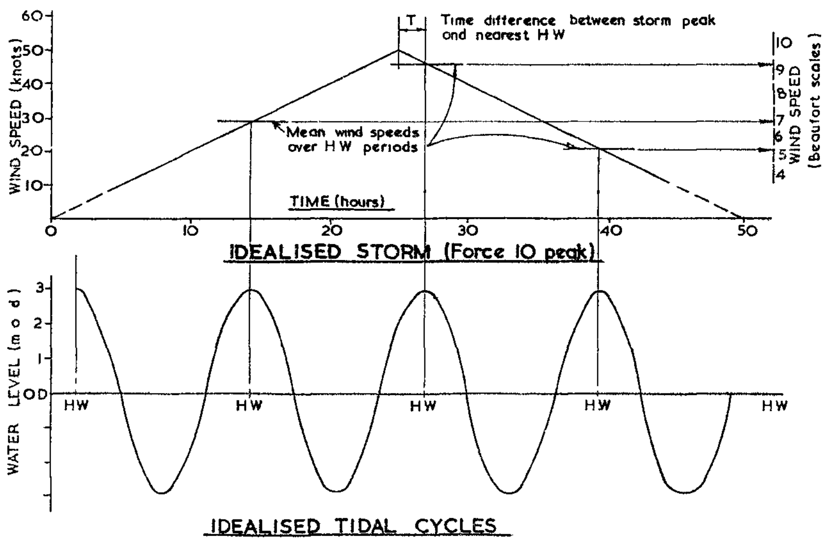
The wave events for the NW sector are represented on a scatter diagram (Figure 7) showing the mean hourly wind speed and wave height. With the rather limited data it is not considered valid to put in a best fit line yet, but it can be seen that with the exception of one extreme event, the data are reasonably consistent. It is tempting to dismiss this one point as "experimental error", but visual ohservations by the Kings Lynn pilots have confirmed that waves of this size do occur, and some explanation must be sought. To some extent, it can be accounted for by the fact that water depth on this occasion was greater than on others and that the wind direction was more in line with the deep shipping channel nearby.

The waves so far recorded do not appear to be depth limited but in extreme wind conditions, the maximum wave size expected in a three hour period would be so limited on a mean tide.



Storm of 20th January 1965 showing how a typical storm is idealised as a triangular distribution of wind speed with time

Figure 8 STORM SHAPE



IDEALISED TIDAL CYCLES

Figure 9 Example of wind speeds at consecutive HW for force 10 storm event

SECTOR.	N_F : Nº OF STORM EVENTS WHEN MAX WIND IS FORCE F			
	N_{10}	N_9	N_8	N_7
S. E.	0·04	0·31	2·15	3·85
S. W.	0·14	1·00	4·32	9·61
N. W.	0·01	0·09	0·56	1·34
N. E.	0·01	0·08	0·61	2·91

TABLE 3. AVERAGE Nº OF STORM EVENTS PER YEAR.

F MAX FORCE OF STORM EVENT	CORRESPONDING Nº OF H W. PERIODS WITH MEAN WIND SPEED F.			
	F = 10	F = 9	F = 8	F = 7
10	0·20	0·56	0·48	0·48
9	–	0·28	0·64	0·56
8	–	–	0·36	0·72
7	–	–	–	0·36

TABLE 4. Nº OF HIGH WATER PERIODS AFFECTED BY STORMS

SECTOR.	Nº OF HIGH WATER PERIODS WITH STORMS			
	F = 10	F = 9	F = 8	F = 7
S. E	0·008	0·11	1·00	3·08
S. W	0·028	0·36	2·26	7·20
N. W.	0·002	0·031	0·26	0·94
N. E	0·002	0·028	0·28	1·53

TABLE 5. AVERAGE Nº OF H.W. PERIODS WITH STORM EXPECTED EACH YEAR.

8.5 North East sector

Only two events from the NE have been recorded during the period of study though the wind analysis (section 9) shows that their frequency of occurrence is as great as for storms from the NW. It is particularly important to assess the wave conditions accompanying storms from the NE since this is the direction in line with fetch lengths up to 800 km extending across the North Sea from Denmark. Large waves can therefore be expected at the mouth of the Wash but an extensive sand bar limits the progression of such waves into the bay so maximum wave heights are likely to be depth limited. It becomes important to know what water depths are to be expected and Table 2 gives the results of an analysis of predicted tide levels.

9. PROBABILITY OF OCCURRENCE OF STORM EVENTS AT H.W.

9.1 Correlation of data.

In a recent report by Binnie and Partners[4] on "Waves and Tides at Maplin" an extensive analysis of wind data from Shoeburyness (Figure 1) was made. In that study, Shoeburyness was selected not only because of its proximity to the area of interest but because the data available covered a 40 year continuous period. In predicting event frequencies the length of available data is of great importance. It was felt that if an overall correlation between Shoeburyness winds and the winds over the Wash could be found then the results of the earlier analysis would be most valuable. Direct correlation for every storm could not be expected because of the considerable distance between the two areas (approx. 150 km) but results were sufficiently good to be used.

9.2 Frequency of storm events

Having established the correlation between the Wash winds and those at Shoeburyness, we can now extract from the results of the Maplin analysis, the frequencies of storm events. Table 4 shows these data in a modified form.

To assume that all storm events are such that the peak coincides with H.W. is unnecessarily conservative and the following sections describe a method in which the frequencies of storm events are converted into frequencies of "H.W. events", i.e. occasions when strong winds occur at H.W.

9.3 Storm shape

Shellard[5] demonstrated that there was a relationship between the maximum hourly mean and the maximum mean over 3, 6, 12, and 24 hours for a particular storm. This theory was corroborated by analysis of 20 storms at Shoeburyness and the Wash and leads to the idealisation of storms as a standard shape. It was further shown that a triangular distribution of wind speed with time was most consistent with the data - as shown in Figure 8.

9.4 Effect of time difference between storm peak and H.W.

For any event when the storm peak occurs at a known time from the nearest H.W. then, using the storm shape obtained in section 9.3, we can deduce the average wind speed both at that high water and at adjacent high waters. Each storm event in fact affects up to 3 H.W.'s by varying degrees (Figure 9). This analysis leads to the results given in Table 4 and when combined with the storm frequency data, the number of H.W. events accompanied by winds of various forces is derived (Table 5).

10. FREQUENCY OF EXTREME CONDITIONS

The return periods of large waves can be estimated from the figures in Table 5, which gives the average number of storm events occurring at H.W., together with a knowledge of the wind-wave relationship. Figure 7 shows the available data on this but until a further year's data are available, it is not proposed that any firm results are abstracted.

11. CONCLUSIONS AND FURTHER WORK

1. The complex topography, shallow water and high tidal range of the Wash largely invalidate the use of conventional methods in assessing the wave characteristics at the proposed construction sites.
2. The chosen approach of measuring waves at the sites and relating these to the observed winds and long term wind records has so far given encouraging results.
3. The installation of suitable instrumentation presented difficult engineering problems but these have now been successfully overcome.
4. Results to date indicate that waves in the Wash are locally generated and that fetch length is normally the limiting parameter. Only 2 storms from the N.E. have been recorded but in extreme conditions it is expected that waves would be depth limited.
5. A method of analysis has been developed which enables long term wind data to be used to estimate the probability of occurrence of extreme wave events. The probability of storm events occurring at high water was assessed and taken into account.
6. A further year's data are being obtained.
7. Future work proposed includes the use of a wave refraction programme to plot back tracks of wave fronts from the wave recorder sites. It is intended that this will help in understanding the progression of wave trains across the Wash.

12. ACKNOWLEDGMENTS

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