



Hirtshals Harbor, Denmark

PART I

THEORETICAL AND OBSERVED WAVE CHARACTERISTICS

Hanstholm Harbor, Denmark





CHAPTER 1

EXTREME LEVELS ARISING FROM METEOROLOGICAL SURGES

by

P Ackers and T D Ruxton

ABSTRACT

The design of coastal works depends on estimating the probabilities of extreme water levels, as well as of waves. Previous studies of surge-affected levels have extrapolated observed annual maxima or the n highest levels in n years to predict rarer events. In addition to using these well-established methods, in this study of tide levels on the Essex coast of Britain a long term record of extreme levels was synthesised by adding surge residuals at the time of predicted HW to predicted HW levels, treating them as statistically independent events. Many more large surge residuals have been measured than extreme water levels as many surges are associated with small tides. Events with return periods up to 1000 years may be estimated without extrapolating beyond the range of observed surge residuals and predicted tides. This method is assessed in relation to previous methods and information relevant to the design of coastal works in the south western part of the North Sea was obtained. In addition to forecasting the probabilities of high tide levels, the study included wave forecasts and the encounter probabilities of combinations of sea level and wave height for various aspects of coastal developments.

Extreme levels arising from meteorological surges, by Peter Ackers, hydraulics consultant, and David Ruxton, chief engineer, Binmie and Partners, Artillery Row, London.

EXTREME LEVELS ARISING FROM METEOROLOGICAL SURGES

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P. Ackers and T. D. Ruxton

INTRODUCTION

In connection with developments proposed on the Essex coastline north of the Thames estuary (see Fig. 1a for location), the effects of tide, surges, wind and waves had to be assessed, to determine the probabilities of extremely high water levels, of large waves and of their simultaneous occurrence. The importance of this aspect of design is amply illustrated by the catastrophic effects of the 1953 North Sea surge tide which breached the coastal defences of England and Holland. On that occasion a surge of 6.8 ft was added to a predicted high tide level of 8.3 ft above O.D.N. High spring tides here have a range of about 19 ft, rising to 10.5 ft above O.D.N. (ordnance datum based on mean sea level at Newlyn).

Previous studies of extreme levels around Britain's coasts have used past observations of annual maximum levels at long established tide gauges, or the number of highest levels observed in a similar number of years, extrapolating these observations to predict rarer events (Lennon, 1963; Suthons 1963). Similar methods have also been used elsewhere (Dronkers, 1960; Wemelsfelder, 1939). To design coastal works, for slope protection, overtopping or drainage, requires a full assessment of the probabilities of combinations of sea levels and wave heights. In order to combine wave forecasts with associated water levels, the observations of extreme levels had to be classified against wind data so that cross-probabilities could be assessed. As winds and surges are both dependent on similar meteorological influences, it was appropriate to separate surge residuals from observed tidal elevations by subtracting predicted astronomical tides. This separation led to the concept of also synthesising a longer record of extreme water levels by adding the distribution of surge residuals at HW to predicted tide levels at HW, as if they were independent events.

South-east England is undergoing a change of sea level relative to the land. This secular trend has also to be taken into account. The level of coastal works relative to the sea is dropping at the rate of about 0.34 m per century, and this has a significant effect on the design of tide-excluding works. No new work was undertaken on this aspect, previous studies (Rossiter 1972) having established the current secular variation. Results may thus be expressed in terms of the year 2000, by adding 0.34 mm per year to levels related to the present, or to earlier years.

DATA AVAILABLE

Tide levels around south-east England have been observed for many years. There are reports of extraordinary tides in the 13th century, 1663, and on three occasions in both the 18th and 19th centuries. Since the storm surge of 1928 a reliable gauge has been operated at Southend, and in 1956 the Storm Tide Warning Service (STWS) was set up as a result of the 31st January/1st February 1953 calamity.

Positive surges have been classified into three groups external, generated north of Scotland and propagated southwards through the North Sea; internal, generated within the area by northerly winds; easterly, arising from the set-up by strong local easterly winds in the southern north sea. The distribution of the storm surge additions to predicted water levels is thus associated with the distribution of winds.

Previous studies have shown that the record from the gauge at Southend Pier is the best available in the area. A near-continuous record exists since 1929, the gauge support is firm, and the site is close enough to deep water to avoid local shallow-water effects. These data had also been used in determining the secular variation.

The Institute of Oceanographic Sciences (IOS) had listed all levels above 11.0 ft ODN for the period 1929 to 1968. Values for the last five years were added to complete the list. None of these high levels occurred in the summer months and more occurred in October than in any other month. The analysis therefore used a July to June "storm-surge year" rather than the calendar year. 10 year running means show some grouping of levels above 11.0 ft O.D.N. into adjacent years, the average varying from 13 to 31 in a 10 year period. This bunching is apparent in the historic data as well, although the reason is unknown.

Predictions of astronomical tides are available in Admiralty Tide Tables (ATT) for yearly periods, based on tidal theory. The tidal coefficients have been adjusted from time to time on the basis of new observations. Until 1950 the Equation Method was used for Southend, from 1951 to 1968 the Harmonic Shallow Water Correction method, and from 1969 the Extended Harmonic method. In this study the distribution of astronomical tide levels have been taken from ATT for 1969-73, to avoid times when the methods, coefficients or datum have been adjusted. It was not practicable to average over the 19-year cycle of the nodal tide, but this 19 year variation is of very small amplitude.

IOS also provided lists of all days in the period 1929-1969 when surge residuals (observed water level minus predicted water level at HW) exceeding 2 ft and 3 ft occurred at Southend. Data was available on the distribution of surge residual either side of HW (actually at clock hour intervals, which could differ by $\pm \frac{1}{2}$ hr from hourly intervals relative to HW). Graphical records were obtained from the STWS for all surges over 2 ft from 1956, for the months between September and April when the service operates.

ANALYSES AND RESULTS

Annual maxima of tidal levels

The prediction of extreme values is affected by the extent to which the spread of the frequency distribution (defined by the standard deviation) varies as the duration of record is increased. If the standard deviation decreases there may be a theoretical upper limit to the level that may be obtained; if the standard deviation increases there is no such limit. The ratio of the standard deviations of the one-year maxima (σ_1), and of the two-year maxima (σ_2) indicates the curvature of the function. Gumbel (1934) assumed that the transformed frequency curve defined by $Y = \ln(-\ln P)$ was a straight line and that $\sigma_1 = \sigma_2$. Barricelli (1943) allowed σ_1/σ_2 to vary between 1 and 1.21, the value associated with a normal distribution of annual maxima. Jenkinson (1955) fitted a curved function to the data, given by

$$Y = \frac{1}{k} \ln \left(1 - \frac{H-H_0}{a} \right) \quad \dots \text{equ 1}$$

where H is an observed height, k, a and H_0 are empirical constants with k defined by

$$k = \frac{\log \sigma_1 - \log \sigma_2}{\log 2} \quad \dots \text{equ 2}$$

If k is positive, the curve is convex upwards approaching a theoretical limit. If k is negative, the reverse curvature indicates no such limit. When k = 0, the Gumbel result emerges.

Lennon (1963) showed that for west coast tidal data the Gumbel method was less suitable than the alternatives. Suthons (1963) preferred Jenkinson's non-linear theory for east and south-coast ports. As there is now a 30 percent longer record for Southend than when Suthons made his analysis, it was desirable to repeat the study, using all high tide levels greater than 11 ft ODN adjusted for secular variation to the base year 2000, and using a storm-surge year in defining annual maxima. The results are plotted in fig. 2, together with the Jenkinson curve for $\sigma_1/\sigma_2 = 0.894/0.992 = 0.900$.

The broken line includes the necessary adjustment if the secular variation continues beyond year 2000 at its present rate of 0.011 ft/yr. The results are also expressed as encounter probabilities in table 1. This probability is given by $(1-P_n)$ where

$$P_n = e^{-N/T} \quad \dots \text{equ 3}$$

T is the calculated return period of a particular high tide-level and N is the encounter period.

Table 1. Encounter probabilities of high water levels.

Level (ft)	Referred to 1973	13.7	14.2	14.7	15.2	15.7	16.2	16.7	17.2
	Referred to 2000	14.0	14.5	15.0	15.5	16.0	16.5	17.0	17.5
Encounter period (N) years	10	0.46	0.23	0.18	0.12	0.08	0.05	0.03	0.02
	25		0.57	0.42	0.27	0.18	0.12	0.08	0.06
	50			0.62	0.46	0.34	0.23	0.15	0.11

Combination of predicted tides and surge frequency distribution

The high water levels in the ATT for the 5 year period 1969-1973 were enumerated into 0.5 ft intervals, and probabilities of occurrence were assigned to each range. This distribution of astronomical tides is shown in fig 3. The predictions by the EH method for this period were compared with the HSWC method predictions for 1964-1968, and there were noticeable differences especially for tides in the range 10.5 to 11.4 ft. The more recent method of prediction is presumably the more accurate, and has the added advantage of providing hourly height predictions as well as high and low waters. The two methods have been described by Doodson (1957) and Rossiter and Lennon (1968).

The distribution of surge heights was based on the IOS listing of residuals exceeding 2 ft for 41 years of record. This was extended to lower values graphically, assuming that half the 705 tides each year have a positive discrepancy from predicted levels because of meteorological influences. Corrections were made for gaps in the record, giving the following frequency distribution

Table 2 Frequency distribution of surge residuals.

Range of HW surge residual (ft)	-1.0	1.1	2.1	3.1	4.1	5.1	6.1
	to +1.0	to 2.0	to 3.0	to 4.0	to 5.0	to 6.0	to 7.0
Average number of occasions per year	637	30	3.71	0.53	0.122	0.025	0.049

The combined frequency of statistically independent events is obtained by the product of their separate frequency distributions. This assumption may be questioned because both surges and high tides show seasonal effects so that they could have a different chance of occurring simultaneously than if they were randomly distributed in time. Also there is likely to be some interaction between surges and tides, the linear super-position of meteorological surges on astronomical tides ignoring non-linear features of tidal propagation.

The interdependence due to seasonal variations was examined by a more detailed analysis based on six two-monthly periods per year. In most instances an equal or slightly greater probability is predicted from the seasonal analysis. The small difference is attributed to the different seasonal distributions of the two events, the times of equinoctial tides being a period of average surge activity only. As the annual data are easier to use and provide greater detail, the use of annual data was considered justified.

The possible interaction of large surges with large tides is influenced by the limited energy that can be introduced into the sea by combinations of astronomical and meteorological forces. This is believed to be partly the reason that the peak of the surge residual tends to avoid the time of HW. It may also transpire that whereas a 6-7 ft surge residual at HW occurs twice in 40 years when associated with HW levels of 9.5 ft ODN or less, such a surge may not be physically possible with HW levels greater than say 10 ft ODN when the sea will have less capacity for absorbing more tidal energy. Although no quantitative assessment of these facets was possible with the data available, the assumption of independence and linear addition are likely to be conservative on the open coastline. This would not be so in estuaries which cause tidal amplification.

The combined frequencies of predicted tides and surges are shown in table 3.

Table 3. Number of occasions per year for combinations of predicted tide and surge addition at HW.

PREDICTED TIDE ft		7.2	7.7	8.2	8.7	9.15	9.65	10.15	10.6	11.1
SURGE ADDITION		OCCASIONS PER YEAR								
0	ft	63.7	72.0	87.2	94.2	71.3	42.0	21.0	7.0	1.27
1.35	ft	3.00	3.39	4.11	4.44	3.36	1.98	0.99	0.33	0.06
2.35	ft	0.371	0.419	0.507	0.548	0.415	0.244	0.122	0.041	0.007
3.4	ft	0.053	0.060	0.073	0.078	0.059	0.039	0.018	0.006	0.001
4.4	ft	0.012	0.013	0.017	0.019	0.014	0.008	0.004	0.001	<0.001
5.4	ft	0.003	0.003	0.003	0.004	0.003	0.002	0.001	<0.001	<0.001
6.4	ft	0.005	0.006	0.007	0.007	0.005	0.003	0.002	0.001	<0.001

Heights of predicted tides are in ft above ODN as at 1971, and the medians of the class intervals are given. Surge additions are in ft, and also are given as the medians of the class intervals. From Table 3, the number of times a given high water level was reached or exceeded was extracted, and adjusted to year 2000. These data are presented in fig 4 in terms of return periods for given levels, and in effect form a synthesised record of extreme water levels extending to events with a return period of 1000 years. Also shown

on fig 4 are the actual observations of high levels over the 44 years of record at Southend.

It will be appreciated that this method implicitly assumes that the two distributions are in fact truncated, there being no predicted tides above elevation 11.4 ft ODN (1971) to extend table 3 to the right to the next interval and no surge residuals exceeding 7.0 ft to extend the table downwards to another interval. The first of these implicit assumptions is readily accepted: there is an upper limit to the predicted tides which is very closely approached in any 5 year period. The second assumption might be questioned. The distribution of surge residuals could be extrapolated beyond the range of observations, for example on the basis of extreme value theory, and incorporated as an additional row in Table 3. The effect on the overall distribution would be small however.

Comparison of methods

Both the observed and synthesised data in fig 4 show a change in slope at about elevation 13.3 ft ODN (2000). Levels above this value are only reached by surges greater than 3 ft, and any attempt to predict the probabilities of rarer events from lower values could have been misleading. The agreement between observations and synthesised data for return periods up to 44 years suggests that the assumptions made may be reasonable, but clearly scope exists for detailed statistical research.

The results in terms of encounter probability are given in table 4.

Table 4. Probabilities that certain levels will be exceeded in a given period of years.

Level (ft ODN) (year 2000)		14.0	14.5	15.0	15.5	16.0	16.5
Return period, T, yrs		12.2	19.5	32	55.5	103	203
Encounter period, yrs	10	0.56	0.40	0.27	0.16	0.09	0.05
	25	0.87	0.72	0.54	0.36	0.22	0.11
	50	1.00	0.99	0.98	0.59	0.38	0.22

We may also compare the predicted return periods by extrapolation from the annual maxima frequency analysis with those deduced from the combination of predicted HW levels and the frequency distribution of observed surges.

Table 5. Comparison of return periods of extreme water levels.

Level, (ft ODN, year 2000)	12.0	13.0	14.0	15.0	16.0	17.0
Annual maxima method	0.66	3.9	12.2	32	100	424 yrs
Combination method	0.86	5.0	19.2	52	150	305 yrs
Actual observation	0.86	4.0	11.0	44yrs		

Other results

It was clear when tabulating extreme water levels that surges tend to affect groups of successive tides, so that they are not randomly distributed in time. In 40 years, only 571 of 1388 surge residuals greater than 2 ft, and 226 of 426 surge residuals greater than 3 ft, were on isolated days. All other surge-affected tides occurred in association with similar surges on one or more adjacent days. It follows that when large surges and tides coincide very high levels are likely to be reached by a number of successive tides, and the encounter probabilities deduced must be viewed with this important fact in mind. In 1965/6 there was a succession of 15 days when the surge residual > 3 ft (and 16 > 2 ft). In the notable 1953 surge sequence, there were 3 days > 3 ft and 7 > 2 ft.

The design of coastal works is dependent on the durations for which levels may exceed selected values. An analysis was based on the cumulative durations for the decade 1951-1960 in excess of levels equivalent after secular adjustment to 9, 10, 11 and 12 ft ODN (1973). When divided by the number of events, average durations are obtained. These are compared with the 1953 surge in table 6.

Table 6. Durations of level exceedances.

	> 9ft	>10ft	>11ft	>12ft
Average (hrs)	1.35	1.02	1.00	1.16
1953 event (hrs)	5.6	5.1	4.5	3.8

This illustrates the prolongation of high water levels by meteorological surges. This is also shown in fig. 5 which compares some recorded tide curves of extreme events with the sinusoidal shape to which the predicted curves of a mean spring tide closely approximate.

WAVE GENERATION

A detailed account of the study of waves is beyond the scope of this paper. Forecasts were based on an analysis of Shoeburyness anemograph records for the same period, 1929-68, as was covered by the IOS data on surge residuals. The wind data were classified into three populations, depending on whether there was a surge residual of > 3 ft, < 3 ft but > 2 ft, or under 2 ft at HW on the day in question, because of the correlation between

the incidence of surges and particular weather systems in the southern North Sea. All maximum hourly wind speeds in the Meteorological Office's (MO) daily listings in excess of 27 knots (force 7) were considered, together with hourly maxima on every day for which a surge residual over 2 ft had been recorded. The resultant wind roses, are given in fig. 6, and the distributions within the three populations are shown in table 7.

Table 7. Number of occasions in 40 years when winds coincided with surges.

Wind speed (Beaufort scale)	10	9	8	7	6	5	4	3	2
No surge	4	47	251	594	← 12,370 →				
Surges 2 ft - 2.9 ft	1	6	33	95	203	297	259	53	5
Surges ≥ 3 ft	2	7	19	60	103	112	80	10	3

The Essex coast is exposed to north east and easterly winds but the wind records show that these are not directions from which gales often blow. The most relevant sector is from 40 deg. to 120 deg. from true north, with an average of 5 gales a year. Standard methods were used to estimate the waves that would arise for given wind condition in the range 7 to 10 on the Beaufort scale. (Bretschneider, 1970, Ippen, 1966). Allowance was made for shallowing water as the coast is approached, and for the fetch. The longest fetch is 650 km on 40 deg. bearing but the last 70 km are in shallow water (see fig. 1). The highest waves are generated over a 280 km fetch on bearing 60 deg, which follows the general alignment of submerged channels in approaching the coast, thus being less affected by shallow water and refraction. The computational scheme used for wave forecasting is shown in fig. 7.

The likelihood of winds, and hence of waves, occurring with high water levels can be assessed by combining the chance of the two eventualities, wind frequency having been separated (admittedly crudely) into three surge-associated populations. Waves exceeding a significant height of 7.5 ft are likely to occur on a day when the tide level exceeds 11.8 ft ODN (2000) about once in 50 years, and waves over 10.5 ft height about once every 500 years. The chances of high wave activity on a day when abnormally high water levels occur are very remote. With a tide level of 14.8 ft ODN (2000) it may be only once in 5000 years, so that the chance of waves with significant height of 7.5 ft or larger occurring with the level reached by the 1953 storm surge is too remote for such a prediction to be justified by the data.

This infrequency arises because here the predominant winds are off-shore ones, and strong winds from the north-east and east are few in number. Table 8 shows the combined tide, surge and wave probabilities. Combinations with a probability of 1 in 1000 in any year are

- a) 13.2 ft (4.0 m) ODN (2000) with waves > 7.5 ft (2.3 m)
- b) 12.8 ft (3.9 m) ODN (2000) with waves > 9.1 ft (2.8 m)
- c) 12.6 ft (3.85m) ODN (2000) with waves >10.5 ft (3.2 m)

The combined distribution of water levels with waves exceeding 7.5 ft (2.3 m) has also been added to fig. 4

CONCLUDING REMARKS

In connection with the design of coastal works, the probabilities of combinations of waves and tides have to be assessed so that slope protection, crest elevations, drainage works etc. can be designed for events of appropriate probabilities. The proposed developments on the Essex coastline required a comprehensive study of both waves and tides. Surge affected tides were considered by several methods, including a new approach that treats surge residuals and predicted astronomical events as statistically independent. Comparison with other results suggests that the method is useful, but further research into the validity or limitations of the assumptions is necessary.

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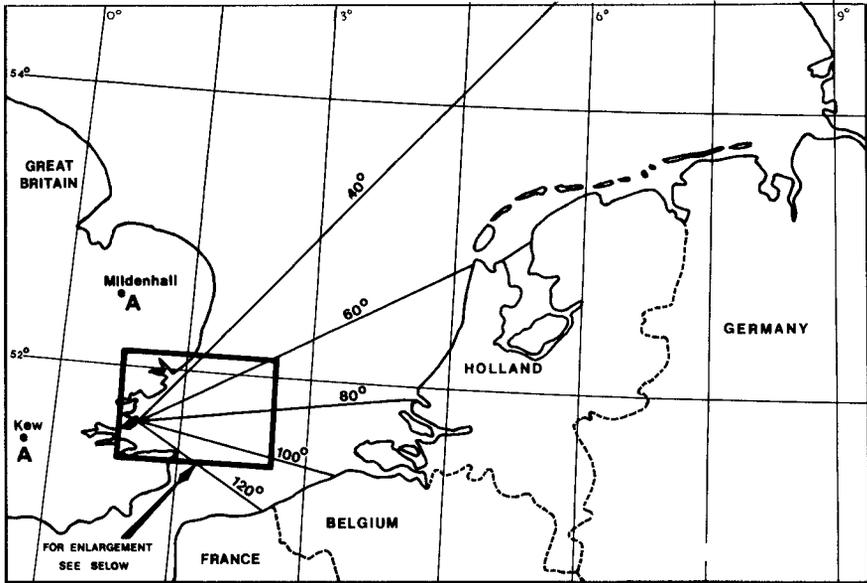
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TABLE 8

Combined tide, surge and wave probabilities

LEVEL EXCEEDED				WAVE HEIGHT (ft)							
Level in ft ODN	Number of occasions level exceeded in 1000 years			Probability that wave occurs on a day of stated surge	a) >3ft surge	b) 2-3ft surge	c) <2ft surge	7.5 - 9.0	9.1 - 10.4	10.5 - 12.0	>7.5
	year 1971*	year 2000*	TOTAL								
17.0	17.3	1	-	2.55 x 10 ⁻³	-	-	-	2.55 x 10 ⁻³	-	-	0.005
16.5	16.8	3	-	7.65 x 10 ⁻³	-	-	-	7.65 x 10 ⁻³	-	-	0.015
16.0	16.3	6	-	15.3 x 10 ⁻³	-	-	-	15.3 x 10 ⁻³	-	-	0.031
15.5	15.8	12	-	30.6 x 10 ⁻³	-	-	-	30.6 x 10 ⁻³	-	-	0.061
15.0	15.3	22	-	56 x 10 ⁻³	-	-	-	56 x 10 ⁻³	-	-	0.112
14.5	14.8	37	-	94 x 10 ⁻³	-	-	-	94 x 10 ⁻³	-	-	0.184
14.0	14.3	61	-	0.155	-	-	-	0.155	-	-	0.31
13.5	13.8	101	-	0.258	-	-	-	0.258	-	-	0.52
13.0	13.3	164	-	0.40) 0.49	-	-	-	0.40) 0.49	-	-	0.91
12.5	12.8	405	-	0.60) 2.73	-	-	-	0.60) 2.73	-	-	3.86
12.0	12.3	800	60	0.835) 5.2	-	-	-	0.835) 5.2	-	-	8.36
11.5	11.8	2620	1380	1.05) 10.45	-	-	-	1.05) 10.45	-	-	19.55
11.0	11.3	6478	4630	1.20) 17.35	-	-	-	1.20) 17.35	-	-	38.82

*Rise in sea level of 0.011ft/year assumed up to these dates no rise subsequently



(a) SOUTHERN NORTH SEA Fetch Lines

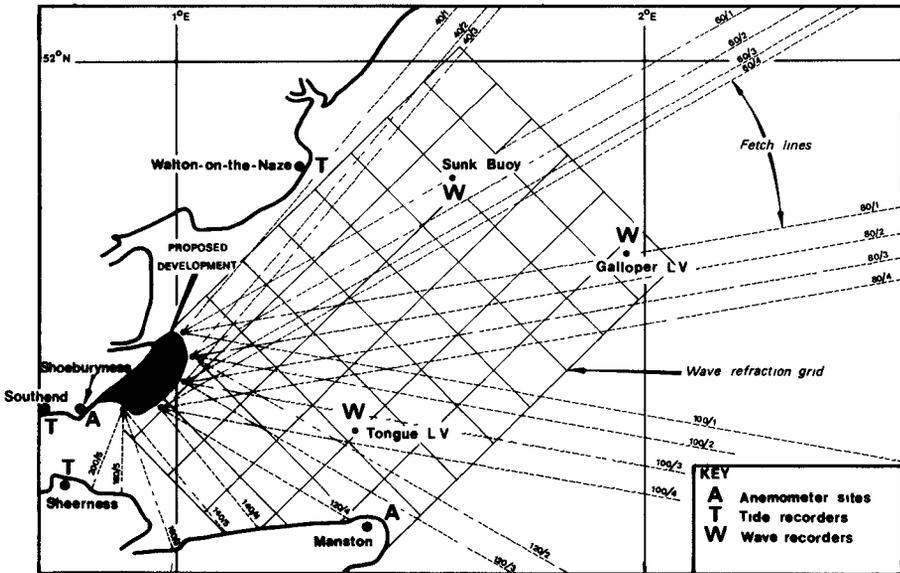


Fig 1

(b) STUDY AREA showing refraction grid and fetch lines used in wave generation analysis

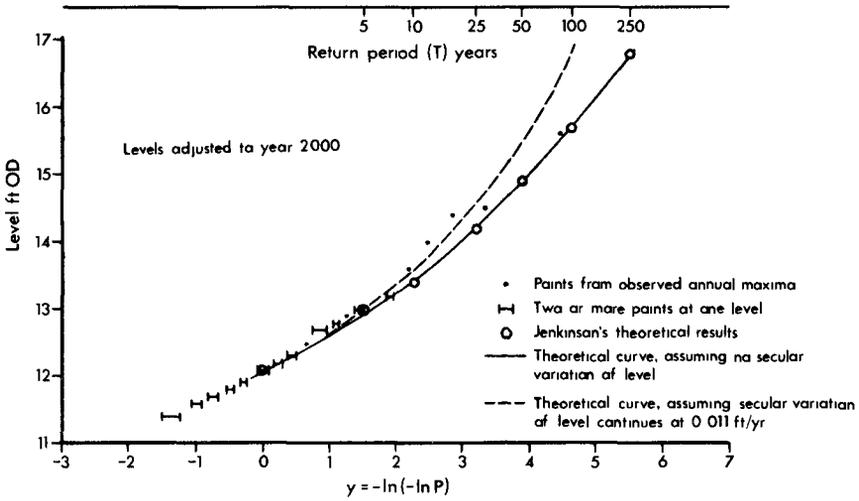


Fig 2 RETURN PERIODS OF EXTREME WATER LEVELS AT SOUTHEND
(Predicted by considering annual maximum high water levels)

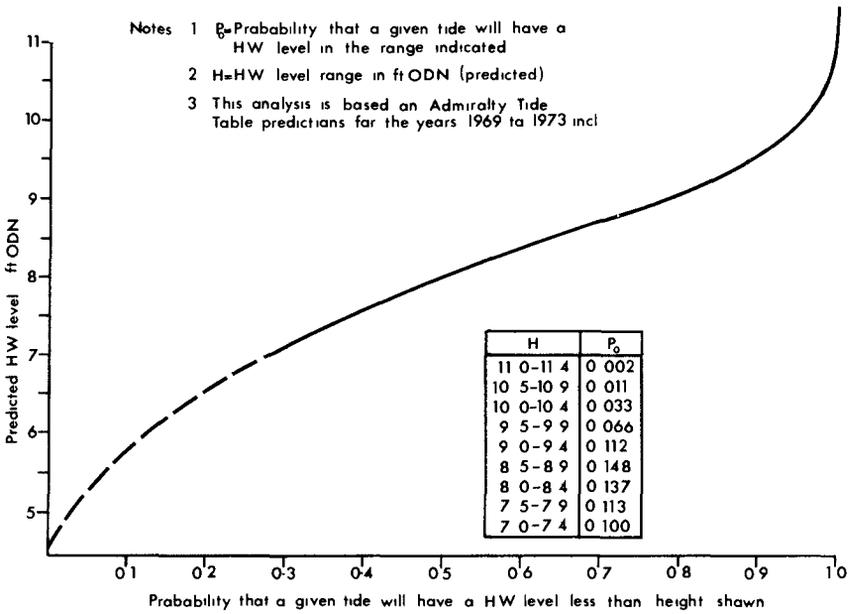


Fig. 3 PROBABILITIES OF PREDICTED HIGH WATER LEVELS AT SOUTHEND

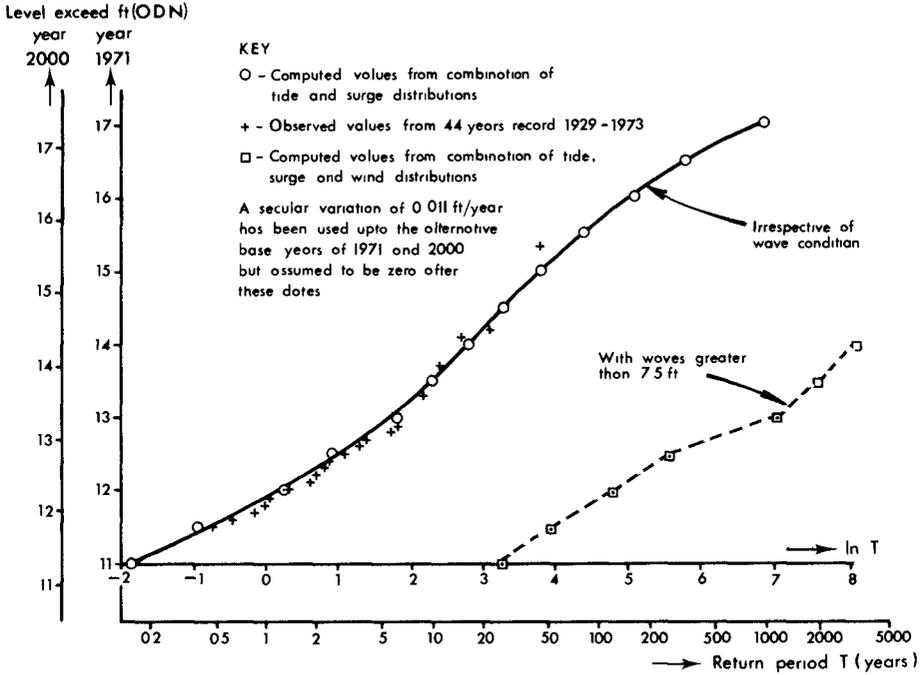


Fig 4

RETURN PERIODS OF EXTREME WATERLEVELS WITH STATED WAVES AT SOUTHEND
(Predicted by combining tide, surge and wind probabilities)

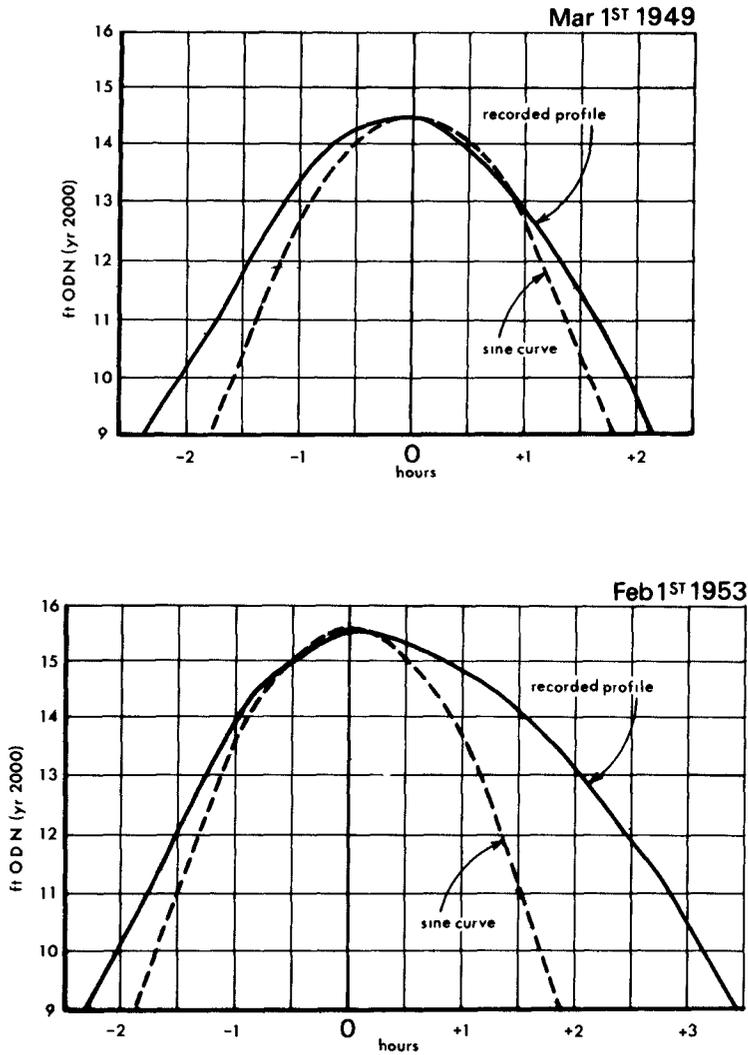
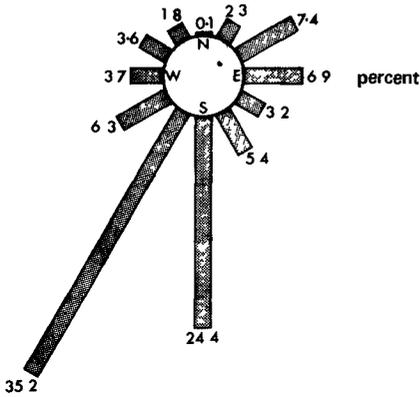


Fig 5

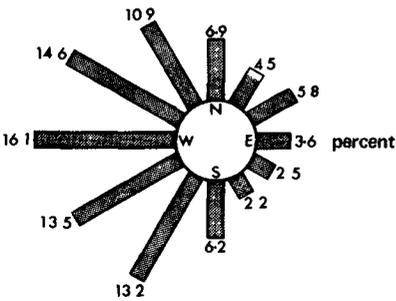
PROFILES OF EXTREME EVENTS



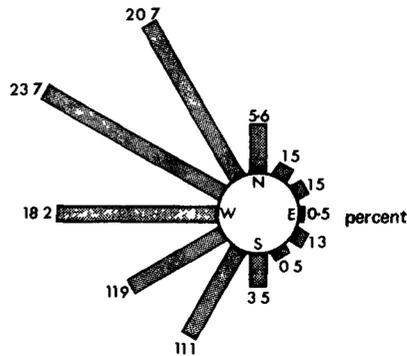
a) FREQUENCY DISTRIBUTION OF WINDS GREATER THAN FORCE 7

Wind speed Beaufort scale	NUMBER OF OCCASIONS WHEN WINDS COINCIDED WITH		
	No surge	Surges 2'0"-2'9"	Surges \geq 3'0"
10	4	1	2
9	47	6	7
8	251	33	19
7	594	95	60
6	12,370	203	103
5		297	112
4		259	80
3		53	10
2		5	3
Less than 2	-	-	

d) COINCIDENCE OF STORMS AND SURGES



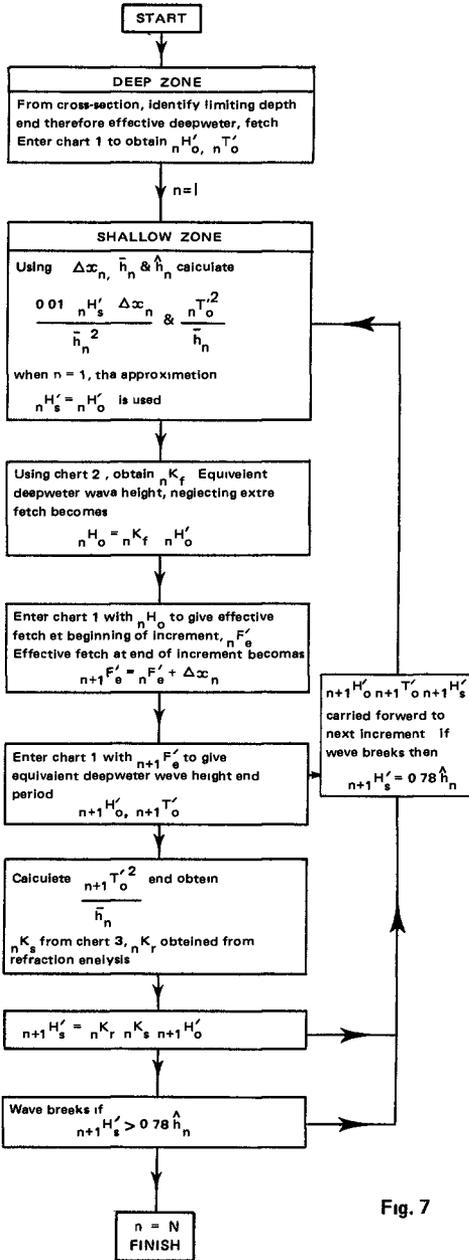
b) FREQUENCY DISTRIBUTION OF WINDS WITH 2'0"-2'9' SURGES



c) FREQUENCY DISTRIBUTION OF WINDS WITH SURGES \geq 3'0'

NOTES 1 Figures refer to the 40 years of wind record at Shoeburyness from 1929 to 1968, and surges of Southend for the same period
 2 All winds are the maximum mean hourly winds for a given day

Fig 6 SHOEBURYNES WIND ANALYSIS



Notation -

- Chart 1 Bretschneider (1970) deepwater chart
- Chart 2 Ippen (1966) Fig 3 20
- Chart 3 Ippen (1966) Fig 3 21

- $n H'_o$ deepwater wave significant height at start of increment 'n'
- $n T'_o$ deepwater wave significant period at start of increment 'n'

- Δx_n length of fetch increment
- \bar{h}_n mean depth of fetch increment
- \hat{h}_n minimum depth occurring in increment

- $n H'_s$ significant wave height at start of increment
- $n+1 H'_s$ significant wave height at end of increment (becomes $n H'_s$ for next increment)

- $n K_f$ friction coefficient
- $n H_o$ equivalent deepwater wave height neglecting additional fetch

- $n F'_e$ effective fetch at start of increment
- $n+1 F'_e$ effective fetch at end of increment (becomes $n F'_e$ for next increment)

- $n+1 H'_o$ equivalent deepwater wave significant height at end of increment including additional fetch (becomes $n H'_o$ for next increment)
- $n+1 T'_o$ equivalent deepwater wave significant period at end of increment including additional fetch (becomes $n T'_o$ for next increment)

- $n K_s$ shoaling coefficient
- $n K_r$ refraction coefficient
- N number of shallow zone increments

Fig. 7

WAVE FORECASTING
COMPUTATION SCHEME